# THE DUSTY ENVIRONMENT OF THE YOUNG GALACTIC CLUSTER NGC 2264 

by<br>Barry Allan Meyers-Rice

A Dissertation Submitted to the Faculty of the DEPARTMENT OF ASTRONOMY

In Partial Fulfillment of the Requirements For the Degree of DOCTOR OF PHILOSOPHY

In the Graduate College
THE UNIVERSITY OF ARIZONA

1995

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I wish they had let me keep my working title, "Lusty Dusty Stars...."

## DEDICATION

Doing science has its benefits-a thrill of exploration and discovery, the intrigue of studying cosmic mysteries, satisfaction of understanding our surroundings and how we fit in, and joy in accomplishing difficult goals.

But dwarfing all these pleasures into obscurity, dearer than all else, the greatest treasure astronomy ever gave me is falling asleep in bed, waiting for me to join her.

To Bridgett....

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#### Abstract

This is a study of the young galactic cluster NGC 2264. In it $12-100 \mu$ m IRAS data are used to analyze emission from the cluster dust. This dust is warmed by the young point sources in the cluster. Images of the region were obtained in the $V, R$, and $I$ bands, and the point source data extracted are combined with a pre-existing $J-H-K$ database to produce a six-band photometric survey of the cluster. This 4900-entry catalogue and methods to eliminate spurious detections and non-cluster stars from it are discussed. The cluster is estimated to consist of 350-650 members.

A device to produce polarimetric images was designed, built, and used to obtain data to explore star formation environments. The nature of one such region in NGC 2264 is discussed, and the sources responsible for illuminating this reflection nebula are identified. It is concluded that multiple scattering and a disk geometry can explain the features observed.

Spectra of 361 stars in the cluster region were obtained and by extending the MK system to the red part of the spectrum their spectral types are determined. Many T Tauri stars are identified and aspects of their emission lines are analyzed. It is shown that the spectral lines of many cluster stars of types later than G9 are in emission while those of earlier-type stars show incipient emission diluted by stellar flux. An evolutionary sequence of stars based upon photometry and spectroscopy is proposed. Stars from this spectral survey are dereddened and the extinctions obtained are interpreted. Spectral energy distributions are produced for the dereddened stars, revealing infrared excesses in many. These excesses are modelled by disk-star systems, and it is shown that inner holes are required in the disks to explain the observed levels of short wavelength emission.


## Chapter 1

## THOSE WHO CAME <br> BEFORE

### 1.1 Prologue

Sometime near the Cambrian explosion of life $570 \times 10^{6}$ years ago, primitive astronomical detectors oozed through the seas of the Earth. If the paleoastronomers are correct, the planet was showered with cometary fragments which violently slammed into the atmosphere (Alvarez et al. 1980). Either by their own disintegrations, or material kicked up from the planetary surface, or exhaust from a subsequent global conflagration, vast amounts of dust were thrown into the atmosphere which reddened and extincted the light from the sun. Starved of energy, the organisms developing in the oceans suffered their own extinctions. Fossil beds recorded this event as a mighty depletion of species. Other successful observing runs in the Earth's prehistory includes Permian event $225 \times 10^{6}$ years ago which resulted in a $95 \%$ extinction rate (the most efficient ever), while the Cretaceous extinction is the most famous of all for its destruction of ammonites and
dinosaurs. The latter group was certainly the largest type of land-based detectors ever devised sensitive to the influences of dust-starlight interactions. If periodicity calculations are correct, barring nuclear winters, the next global observing run will not occur for perhaps $13 \times 10^{6}$ years (Gould 1985). Until then, the effects of extreme stellar extinction by dust must be studied with inorganic detectors and organic astronomers. This dissertation is such an inquisition.

### 1.2 Introduction

This is an investigation of stellar and gaseous aspects of the region containing the galactic cluster NGC 2264. This cluster is a fine study object for many reasons. At 790 pc it is reasonably close, so confusion from foreground sources is not serious and the cluster components are easily resolved. It lies immediately in front of a giant molecular cloud which, because its opacity is equivalent to several magnitudes of visual extinction, decreases (but does not quite eliminate) the contamination from background sources. Perhaps most delightful, nearly every aspect of star formation is represented in the cluster-within the cluster boundaries are $0, B$, and Ae stars-while various aspects of lower mass pre-main sequence stars are represented by objects ranging from extremely active continuum stars, to T Tauri stars, to barely active pre-main sequence objects. The cluster is suffused with cold gas which appears here and there as emission nebulae, and dust clouds which introduce various amounts of extinction as well as crawling into view as subtle reflection nebulae. IRAS scans through the cluster easily detected this dust as well as a population of cool embedded sources. Finally, the mighty giant molecular cloud Mon OB1 which lurks behind the cluster is filled with cool gas and outflows, some of which are clearly bipolar.

This work explores aspects of the stellar components of the cluster, as well as the dust and gas that linger in the spaces between them. When studying star formation, it is common for stellar astronomers to consider the evolution of the stars, decoupling them from the interstellar medium. Meanwhile, astronomers that study gas tend to think of stars and their kin as the mundane and even uninteresting final resting places for their precious interstellar material-in effect the refuse pile that remains once the interesting aspects of cloud collapse have reached completion. Both of these perspectives disregard the communication that exists between the point source and the extended interstellar phases of the cluster. In collapsing into stars, mighty winds are initiated which stir the gas into turbulent motion, perhaps regulating the rate of further star formation. Even after the majority of the pre-main sequence evolution has concluded, winds from the stars and accretion from circumstellar disks continue to moderate the appearances of the stars, producing strong infrared excesses and emission features in the stellar spectra. It is very likely that still-unsuspected interactions between the gas and forming stars have profound influences on if, when, and how stars form from the rarified gases and dust clouds. This dissertation, as it examines parts of the star cluster and dusty regions associated with it, addresses how the components interact and conspire to make the greater whole that is the metropolitan NGC 2264 and its outlying suburbs.

In this chapter the development of knowledge about the pre-main sequence sources, dust, and gas involved in star formation is reviewed. Then the history specific to NGC 2264 and the present state of knowledge on it is discussed.

### 1.3 Astronomical Personae

As mentioned in the last section, the processes of stellar formation transform the extended material into compact stellar objects, inextricably coupling these two components. To understand the events in stellar formation it is important to simultaneously consider what is happening to the stars and to their surrounding media, for each effects and can modify and even govern the future of the other. In this section, the principal players-the point sources, the interstellar gas, and the interstellar dust are quickly introduced and reviewed.

### 1.3.1 The Point Sources

## The Silent Majority?

When plotted on an H-R diagram, pre-main sequence stellar objects are immediately identified by their locations above the main sequence, on evolutionary tracks descending to their zero age main sequence locations. It is common to discuss the more exotic and flamboyant sources (see below), but a large number of the pre-main sequence sources encountered are surprisingly unremarkable. They do not exhibit emission lines or spectral veiling, are largely or completely non-variables, are not necessarily associated with obscured regions, and could easily pass for a stoic main sequence object were it not for their higher luminosities and physical associations with young clusters. It is not clear what these sources represent-perhaps one of the final stages of pre-main sequence evolution, or stars which were for some reason cheated of circumstellar material usually awarded young stars, or perhaps these are actually the normal form of solitary pre-main
sequence evolution and phenomena such as T Tauri stars are restricted to more unusual situations such as multiple star systems (Strom et al. 1971).

## Classical T Tauri Stars

First observed by Joy (1945), the Classical T Tauri stars (CTTSs) are characterized as a class by four criteria (Herbig 1962): the presence of Balmer and Ca II H and K emission lines, often a presence of Fe I emission lines at 4063 and $4132 \AA$, the appearance of forbidden emission from O I and S II, and abnormally strong Li I absorption at $6707 \AA$. These requirements were relaxed by Bastian et al. (1983) to just three criteria: association with obscuration, Ca II $\mathrm{H}, \mathrm{K}$ or $\mathrm{H} \alpha$ emission equivalent widths greater than $5 \AA$, and a spectral type later than $F$. After they were discovered, Ambartsumian (1947) was the first to make sense of CTTSs as pre-main sequence objects by noting that they appeared in what he termed T -associations, which he correctly guessed were the low mass analogue to OB-associations.

CTTSs are strongly variable-moderately active individuals can vary by three or even five magnitudes. The variations are irregular, but display typical timescales ranging from 15 minutes to several days. This variability is thought to originate from starspots which may cover $10 \%$ of the stellar surface (Bouvier \& Bertout 1989). It was originally assumed that these starspots are powered by dynamo-driven engines, but rotation measurements indicated surprisingly low T Tauri rotation rates, suggesting that much of the angular momentum loss required by stellar collapse precedes the CTTS phase (Vogel \& Kuhi 1981). In fact, the activity of only the most sedate CTTSs can be explained by dynamo-engines, so the activity may result from internal convection layers, extreme differential
rotation, or fossil magnetic fields (Calvet \& Albarrán 1984). This matter will be raised again in the section on disk sources below.

CTTSs have a few spectral surprises. They often have P Cygni spectral profiles, a signpost for mass outflow. Also, an odd phenomenon called spectral veiling is sometimes apparent. This is a two-fold effect-apparently emission is specifically occurring in the absorption lines, and also some source of continuum radiation is being added to the spectra. Both have the effect of decreasing the absorption equivalent widths. This effect is not well understood, although it must result from some sort of nonphotospheric emission (Finkenzeller \& Basri 1987; Strom 1983). CTTSs also exhibit ultraviolet excesses and even blue continua-two abnormal effects that probably share related origins. In extraordinary cases, extreme T Tauri stars or continuum stars have so many emission features they defy normal photospheric classifications. The literature on CTTSs is large, but for a good review consult Bertout (1989).

Weak Line T Tauri Stars

In contrast with CTTSs, the group of stars called the naked, or preferably weak line T Tauri stars (WTTSs), contains a less active group. These appear as $\mathrm{F}-\mathrm{M}$ emission line stars with other lines being normal or at most veiled. The equivalent widths of the $H \alpha$ emission lines are less than $5 \AA$ wide (Herbig \& Bell 1988). They are X-ray sources (as are CTTSs) and were originally defined as X-ray sources that were associated with pre-main sequence optical counterparts (Walter et al. 1988). It is not clear how CTTSs are related to WTTSs; specifically any evolutionary relationships are uncertain.

## Herbig Ae Be Stars

Herbig AeBe stars were defined by Herbig (1960) as stars in the spectral type range B1-F8 that illuminate nebulosity in their immediate vicinity and that exhibit $\mathrm{H} \alpha$ and perhaps other emission lines. He envisioned them (correctly) as a high mass version of T Tauri stars. In keeping with this analogy, they have infrared excesses, experience brightness variations, and display P Cygni profiles. Furthermore, they are found in association with Herbig-Haro objects, and their ages have been estimated as $10^{5}-10^{6}$ yrs (Hillenbrand et al. 1992; Strom et al. 1972; Finkenzeller \& Mundt 1984).

## Class I Sources and Disk Stars

An excellent method for classifying young stellar objects uses $\log \lambda F_{\lambda}$ vs. $\log \lambda$ diagrams (e.g. Adams et al. 1987). In this presentation, objects are classified on the slope of their spectral energy distributions in the $1-10 \mu \mathrm{~m}$ interval. Class III objects-which appear merely as reddened blackbodies-are characteristic of WTTSs. Class II objects show significant infrared excesses and are akin to CTTSs-their spectral energy distributions cannot be explained by radiation from an object at a single temperature; an additional, cooler source of emission is required. The spectral energy distributions of Class I objects rise into the infrared; these objects are apparently deeply embedded stars with circumstellar disks.

Disks are not unique or even uncommon in the realm of pre-main sequence objects, for they evidently occur in the T Tauri class (Beckwith et al. 1990 and references therein). For example HL Tauri is a CTTS with an edge-on molecular disk approximately 4000 a.u. in extent that has even been detected using speckle
interferometry (Cohen 1983; Beckwith et al. 1984). There is strong evidence that disks power much or all the T Tauri activity; by invoking relations they find in linewidth ratios, Cabrit et al. (1990) argue that disks determine the strengths of stellar winds, and by extension the emission activity.

## Outflows

Deeply embedded within the molecular clouds lurk outflow sources (see Lada (1985) for a review). These extremely young objects produce hypersonic winds laden with energy and momentum that have profound influences on the energy content of the giant molecular clouds that contain them-in fact they are essential in supporting the molecular clouds against a rapid collapse (Margulis et al. 1988). A fascinating feature of outflows is how they are often bipolar, with the oppositely directed lobes being strongly collimated, possibly by massive disks. The velocity structure of these jets is complex, with its principal component directed along the outflow axis (Meyers-Rice \& Lada 1991). The importance of these sources to the energetics and topology of the interstellar gaseous environment probably cannot be overstated.

### 1.3.2 Interstellar Gas

The interstellar gas has a long history of study. Indeed, the brightest emission nebulae such as the Orion Nebula can easily be seen with the naked eye. Sir William Huggins obtained nebular spectra on 29 August 1864, and observed a line of a hitherto unsuspected element-Nebulum-at $5007 \AA$. This element and its lines, especially one at $6583 \AA$, will be discussed more in Chapter 5 of this
dissertation. More subtle is the dark component of the interstellar gas. This was first detected by Hartmann in 1904 when he observed stationary Ca II H and K lines in the double star $\delta$ Ori. The next major development came about forty years later when 21 cm radiation from H I was predicted and then observed (Bakker \& van de Hulst 1945; Ewen \& Purcell 1951). Then the detections of ${ }^{12} \mathrm{CO}$ and ${ }^{13} \mathrm{CO}$ in cold clouds (Penzias et al. 1972) opened the cold interstellar medium to temperature, density, and chemical analyses.

The dense molecular regions of the interstellar material are complex, but can be examined at two extremes of scale. Probably the smallest regions of importance are Bok globules (Bok et al. 1970). These compact objects are heated by cosmic rays and cool by molecular line emission. Dwarfing them and nearly everything else in the galaxy are the giant molecular clouds (GMCs) which are larger than 10 pc on a side, and are the true birthplaces of stars. It is here that many of the sources described in Section 1.3.1 reside, heating the cloud interiors and supporting them against a rapid gravitational collapse. The physical conditions in GMCs are exotic by terrestrial standards, the temperatures being only $10-50 \mathrm{~K}$ and the hydrogen number densities only $100 \mathrm{~cm}^{-3}$, although the number densities of some areas are 100 or more times higher.

### 1.3.3 Dust

Even though the effects of galactic dust extinction are easily visible to the naked eye as dark lanes in the Milky Way, such dark patches were originally explained as a lack of stars in those areas. But a photographic atlas presented by Barnard in 1927 convincingly illustrated that these regions were in fact dark absorbing clouds. In describing a region north of $\theta$ Ophiuchi, Barnard wrote, "That
most of these dark markings which, in a word, ornament this portion of the sky are real dark bodies and not open space can scarcely be questioned." Contemporary with Barnard's work, spectroscopic studies of the glow surrounding the Pleiades revealed spectra similar to the stars in the cluster, indicating the reflection origin of the nebulosity (Slipher 1913). In 1930 Trumpler found that star clusters grew fainter than would be expected from their dimishing sizes, and from this he inferred an interstellar extinction of $0.7 \mathrm{mag} \mathrm{kpc}^{-1}$. This was followed by the observation that extinctions of B stars followed a $\lambda^{-1}$ dependence (Stebbins et al. 1939).

The next breakthrough in dust astronomy occurred when the IRAS mission produced nearly full sky coverage at $12,25,60$, and $100 \mu \mathrm{~m}$ (Beichman et al. 1988). Analysis of these data reaffirmed that the dust grains emitting the long wavelength radiation could be modelled as various distributions of silicate or graphite grains-possibly with icy mantles-or complex polycyclic aromatic hydrocarbons (Draine \& Lee 1984; Léger \& d'Hendecourt 1987). It appears (and is hoped) that the interstellar components of dust and gas are well-mixed, but it is unclear how well they are coupled, and whether the dust heats the gas, or the gas heats the dust (Goldreich \& Kwan 1972; Greene 1991).

### 1.4 Clusters and NGC 2264

It has become clear that the majority of stars are formed not singly but in groups, clusters, and associations. One of the clusters most suitable for studying the processes of star formation is the young galactic cluster NGC 2264. It was first surveyed in detail by Herbig (1954), who found in it $84 \mathrm{H} \alpha$ emission line stars, including a lone Ae star. This study was followed by Walker's in 1956. He was surveying young clusters, and in NGC 2264 found a pre-main sequence population
that floats above the main sequence on colour-magnitude diagrams for stars later than $A 0$. From main sequence fitting he estimated the cluster's distance to be 790 pc , and its age as approximately $5 \times 10^{6} \mathrm{yr}$-a value which after nearly 40 years seems as accurate as any other. More recent work suggests the ages of the most geriatric cluster stars to be as old as $1 \times 10^{7} \mathrm{yr}$, but with the peak rates of star formation occurring 4-5 $\times 10^{6} \mathrm{yr}$ ago for the low mass stars (Cohen \& Kuhi 1979; Adams et al. 1983).

The bulk of the modern work on the stars in NGC 2264 has concentrated on their infrared properties (Strom et al. 1971; Warner et al. 1977). These studies found that as many as $1 / 3$ of the sources exhibit infrared excesses for $\lambda>1 \mu \mathrm{~m}$, excesses which were explained as resulting from warm (a few $\times 10^{4} \mathrm{~K}$ ) envelopes extending around normal photospheres. One of the reasons NGC 2264 is so amenable to study is that it is located immediately in front of the Mon OB1 dark cloud, the giant molecular cloud which formed it. The Mon OB1 cloud is approximately 15 pc long with a virial mass of $3 \times 10^{4} \mathrm{M}_{\odot}$ and contains a population of embedded point sources and molecular outflows (Margulis et al. 1989; and sources therein). It graciously reduces the effect of background star contamination by providing several magnitudes of extinction. Lada et al. (1993) surveyed the region in the bands $J, H$, and $K$, and found more that 1600 stars. They estimate 360 of these are cluster members, perhaps half of which show infrared excesses.

### 1.5 What This Work Attempts

This dissertation attempts to extend the knowledge and understanding of the symbiosis that exists between the stellar and dusty-gas components of NGC 2264.

Since much of the dust is energized by cluster sources and reradiates this
energy at long wavelengths, dust optical depth and temperature maps produced from IRAS data can be used to probe the conditions of the dust and to identify the sources that warm it. Additionally, maps of the total infrared flux from the region can be used to constrain the possible illuminating sources on the basis of energy balance.

The dust can also be examined at shorter wavelengths. It is generally far too cold to produce much thermal radiation at $1.2-2.2 \mu \mathrm{~m}$, but several reflection nebulae exist in the cluster which are bright enough to be studied with an infrared polarimeter. Not only can polarimetric maps identify the sources illuminating the nebulae, but they can be used to study the mechanisms responsible for polarizing the light as well as revealing possible disk structures. Extremely young cluster objects can be identified this way.

In addition to the gas and dust, the cluster is studded with vigorously active, young stars. Previous photometric surveys have shown these stars have broadband colours that are far redder than those of main sequence stars. An unbiased multiband survey in $V, R$, and $I$ would augment previous surveys, especially the $J$, $H$, and $K$ data obtained by Lada et al. (1993). This would help identify the deeply reddened objects in the region. A problem with using photometric colours, even with a multiband survey covering $V, R, I, J, H$, and $K$, is that a source's red colour may not differentiate whether the star is cool, heavily extincted, or associated with a circumstellar disk. In order to identify the intrinsic nature of the stellar sample, it is necessary to determine the photospheric temperature of the sources. This is best done by spectroscopic analysis. This reveals the intrinsic colours of the stars, at least at shorter wavelengths, and allows the determination of extinction corrections which in turn enables the generation of spectral energy distributions in which the effects of dust have largely been removed. Any residual infrared excesses
in these spectral energy distributions indicate the presences of a second component of cooler material, perhaps even circumstellar disks. Furthermore, young stars are known to be spectrally active, and combining photometric observations with spectral information allows various classes of active stars to be identified.

## Chapter 2

## WHAT IRAS TELLS US ABOUT THE STELLAR <br> ROOKERY

### 2.1 Overview

In this chapter, the reduction of long wavelength infrared images from IRAS is described. The results are dependent upon the choice of exponent used in the dust emissivity, but assuming $\epsilon \propto \lambda^{-1}$, the cloud temperature is found to be approximately 30 K . At $100 \mu \mathrm{~m}$ even the maximum observed optical depths are very small ( $\tau \approx 0.001$ ), justifying the assumption of optical thinness. This yields a total dust mass of $3.2 \mathrm{M}_{\odot}$ and an average H atom number density of $70 \mathrm{~cm}^{-3}$. The dust component of the cloud is estimated to radiate with a power of $6700 \mathrm{~L}_{\odot}$, which when combined with the energy produced by the point sources in the cloud, results in a $12-4000 \mu \mathrm{~m}$ cluster luminosity of $1.1 \times 10^{4} \mathrm{~L}_{\odot}$. It is shown that the distribution
and amount of thermal emission are not consistent with the cloud's far-infrared flux being produced solely by the embeddeded population of point sources detected by IRAS. The additional source of energy is evidently the association of young main-sequence cluster stars.

### 2.2 A Dusty Cloud Beckons

The stellar population of NGC 2264 is immersed in and emerging from a large nascent cloud of dust and gas. In optical and near-infrared images this cloud appears as occasional wispy patches of gaseous emission-line nebulosity or subtle foggy banks of dusty reflection nebula. These avatars of the interstellar medium represent the tiny portions of the cloud that lie near luminous stars-the vast bulk of dust and gas remains hidden except at long wavelengths. Thermal emission from the dust occurs at far-infrared and submillimeter wavelengths, and presents the best way to trace these grains. At these wavelengths the scattering is inefficient so the dust is usually optically thin (Greene 1991), which simplifies the analysis. But it is important to remember that the dust is not optically thin to the short-wavelength photons which, it will be shown, must be the dust's main source of energy. But using dust emission to study all the interstella material is risky because the dust that is visible in the far-infrared traces only the warm material, and does not necessarily represent all the dust. Furthermore, the dust represents only $1 \%$ of the cloud mass (Kutner 1984), so only a tiny portion of the interstellar material is being mapped. But if the dust and gas are well mixed then if nothing else the distribution of cloud material can be understood-at least where it is sufficiently energized-even though the overall scalings of the results may be in doubt. Stellar radiation processed by the interstellar medium is not the
only source of infrared emission. Embedded within the cloud are infrared point sources-presumably very young objects of a stellar or prestellar nature-which are important components of the cluster environment.

### 2.3 FRESCO Data and Reduction

The best and most complete long-wavelength infrared database was produced in 1983, when IRAS (the Infrared Astronomical Satellite) flew for ten months and surveyed nearly the entire sky in four infrared bands $-12 \mu \mathrm{~m}, 25 \mu \mathrm{~m}, 60 \mu \mathrm{~m}$, and $100 \mu \mathrm{~m}$ (Beichman et al. 1988). The heart of IRAS was a liquid helium cooled Ritchey-Chrétien telescope with a Beryllium primary ( 57 cm entrance pupil) and a focal plane assembly of 62 detectors (Si:As for $12 \mu \mathrm{~m}, \mathrm{Si}: \mathrm{Sb}$ for $25 \mu \mathrm{~m}, \mathrm{Ge}: \mathrm{Ga}$ for $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ ). The data from this mission were massaged and made available to the astronomical community in a variety of formats. For the study of NGC 2264, the FRESCO data package (Full Resolution Survey Coadds) was most appropriate (Levine et al. 1993; Melnyk 1990). FRESCO data to study the cluster were obtained in all four bands. Default preprocessing was requested, which denotes images $1^{\circ}$ square with a pixel size of $15^{\prime \prime}$. Six such frames in a $2 \times 3$ grid-overlapping on each edge by $3^{\prime}$-provided complete coverage of the region ( $6^{h} 34^{m} 36^{s}-6^{h} 42^{m} 24^{s}, 9^{\circ} 00^{\prime}-11^{\circ} 54^{\prime}$ ). The median detector noise levels in each band for regions relatively devoid of sources were $0.45 \mathrm{MJy} \mathrm{Sr}^{-1}(12 \mu \mathrm{~m})$, $0.59 \mathrm{MJy} \mathrm{Sr}^{-1}(25 \mu \mathrm{~m}), 0.85 \mathrm{MJy} \mathrm{Sr}^{-1}(60 \mu \mathrm{~m})$, and $1.0 \mathrm{MJy} \mathrm{Sr}^{-1}(100 \mu \mathrm{~m})$. The NGC 2264 emission levels were approximately $1.5-150 \mathrm{MJy} \mathrm{Sr}^{-1}, 3.0-384 \mathrm{MJy} \mathrm{Sr}^{-1}$, 5.0-519 $\mathrm{MJy} \mathrm{Sr}^{-1}$, and $30-864 \mathrm{MJy} \mathrm{Sr}^{-1}$ in the four bands. Astronomers were surprised when IRAS $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ data were first obtained and found to be dominated by extended "cirrus" emission due to interstellar dust (Low et
al. 1984). To estimate the extent to which the NGC 2264 frames were potentially contaminated by such cirrus emission, data from the IRAS Sky Survey Atlas (Wheelock et al. 1994) were examined. Cirrus in the cluster region is complicated and clumpy, with peak values near $7 \mathrm{MJy} \mathrm{Sr}^{-1}$ at $60 \mu \mathrm{~m}$ and $30 \mathrm{MJy} \mathrm{Sr}^{-1}$ at $100 \mu \mathrm{~m}$. This is relatively weak compared to the emission from the dusty region of interest. Where optical depths were ultimately calculated, only $0.8 \%$ of the solid angle at $60 \mu \mathrm{~m}$ and $1.1 \%$ at $100 \mu \mathrm{~m}$ had emission weaker than the maximum cirrus levels. At $12 \mu \mathrm{~m}$ and $25 \mu \mathrm{~m}$ the cirrus emission was negligible. In conclusion, cirrus contamination does not present a serious complication for the analysis of NGC 2264.

The principal mission of IRAS was not to measure extended emission, but was instead to search the sky for infrared point sources. So when using IRAS data to study large scale structure an important consideration is the absolute radiometric calibration of the instrument. A comparison of IRAS data with the data from COBE (Cosmic Background Explorer satellite) is useful for this (Wheelock et al. 1994). DIRBE (the Diffuse Infrared Background Experiment) was on this satellite and surveyed the sky in the near to far infrared (Hauser et al. 1990). Although the resolution of DIRBE was only $0.7^{\circ}$, it was equipped with a chopper wheel which enabled it to directly measure the fluxes of point sources passing through its beam. Although data from IRAS were used to calibrate the point source data, comparisons between IRAS and DIRBE measurements for extended emission showed systematic differences (Beichman \& Wheelock 1993). Since the DIRBE mission was designed to measure extended emission its calibration is probably more appropriate. The transformation equations from IRAS to DIRBE fluxes (in $\mathrm{MJy} \mathrm{Sr}^{-1}$ ), which include large gain modifications in the $60 \mu \mathrm{~m}$ and
$100 \mu \mathrm{~m}$ data, are

$$
\begin{align*}
F(12 \mu \mathrm{~m})_{D I R B E} & =(1.06 \pm 0.02) \times F(12 \mu \mathrm{~m})_{I R A S}-0.48 \pm 0.43  \tag{2.1}\\
F(25 \mu \mathrm{~m})_{D I R B E} & =(1.01 \pm 0.02) \times F(25 \mu \mathrm{~m})_{I R A S}-1.32 \pm 0.74  \tag{2.2}\\
F(60 \mu \mathrm{~m})_{D I R B E} & =(0.87 \pm 0.05) \times F(60 \mu \mathrm{~m})_{I R A S}-0.48 \pm 0.65  \tag{2.3}\\
F(100 \mu \mathrm{~m})_{D I R B A} & =(0.72 \pm 0.07) \times F(100 \mu \mathrm{~m})_{I R A S}-0.48 \pm 0.88 \tag{2.4}
\end{align*}
$$

While the effects of the transformation on the $12 \mu \mathrm{~m}$ and $25 \mu \mathrm{~m}$ data are small, they are important for the other two bands. All the optical depth, mass, number density, and luminosity estimates in this paper have been corrected using the DIRBE transformations listed above. All raw data values discussed in this work, given in units $\mathrm{MJy} \mathrm{Sr}^{-1}$, have not been transformed.

### 2.3.1 Pretreatment-Bias Subtraction and Smoothing

It was desired to combine the FRESCO frames into a single mosaic map of NGC 2264 for each band. To do this the images required pretreatment. One of the default steps in the preprocessing of FRESCO images is an automatic zero-point flux calibration. The zero point of each frame was estimated by calculating the median pixel value. While this method worked well for images with only point sources and very little extended emission, the large amounts of dust emission in the NGC 2264 frames skewed the median results to inappropriately high values. This effect was particularly pronounced in the $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ frames near the cluster core. Because of these distorted bias values the images required bias corrections. These were determined by selecting blank regions in each image, and calculating the median pixel values in those regions. When possible, several blank regions were selected from each frame, and a planar fit was made to produce a correction surface.

In these cases the slopes of the correction surfaces were essentially zero, so simple bias offsets were usually sufficient. It might seem that a fine way to determine bias offsets would be to use the lowest pixel value in each image, but such pixels may be distorted by noise and hysteresis problems (see Section 2.3.2). After these manipulations were completed, the flux levels in the overlap regions of adjoining frames were found to be in excellent agreement, verifying the efficacy of the bias corrections. Unfortunately, the bias subtraction algorithm failed for the $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ images covering the cluster core-in these images, the nebulosity and hysteresis problems were so extended that suitably uneventful regions of sky were not present. To bias correct these images, the overlap regions of the frames were employed. By comparing the overlapping region of a bias-corrected image with the same area of sky observed in an uncorrected frame, the offset estimate was determined. By examining all such regions along the boundaries of all the images needing correction, best-fit planar correction surfaces were simultaneously calculated. Not only did these maneuvers set the flux zero-points, they also corrected for the effects of zodiacal light emission.

After these corrections, the separate images in each band were assembled into mosaics of the entire region. Even though biases were calculated as carefully as possible, the images never agreed perfectly which resulted in artificial structure in the overlap regions. (This disagreement is a result of how the individual detector data streams were baseline fitted and calibrated before being coadded into a map (Levine 1991), and is not trivial to correct.) To decrease the effect of this image artifact, the $25 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ images were smoothed by a circular gaussian with a full width at half maximum of 2.5 pixels. The resolution degradation of the images from this smoothing was unimportant since the extended emission was the main thrust of this survey. The $12 \mu \mathrm{~m}$ and $60 \mu \mathrm{~m}$ maps were not smoothed because they
were to be smoothed in the next phase of reduction.

Since most of the information about dust is derived from a comparison of the $60 \mu \mathrm{~m}$ data to the $100 \mu \mathrm{~m}$ data, it was necessary that the spatial resolutions in the two bands matched. They did not, so the $60 \mu \mathrm{~m}$ maps required smoothing. When the IRAS telescope made its passes through NGC 2264, the point spread functions that resulted were essentially long rectangles which could be well approximated by elliptical gaussians. The $60 \mu \mathrm{~m}$ maps were convolved with an elliptical gaussian so they would match the resolution of the $100 \mu \mathrm{~m}$ maps (which had just been smoothed by gaussians 2.5 pixels in size). The sizes of this gaussian in the $x$-coordinate ( $\sigma_{s, x}$ ) and $y$-coordinate ( $\sigma_{s, y}$ ) were calculated by

$$
\begin{align*}
& \sigma_{s, x}^{2}=\sigma_{x}^{2}(100)-\sigma_{x}^{2}(60)  \tag{2.5}\\
& \sigma_{s, y}^{2}=\sigma_{y}^{2}(100)-\sigma_{y}^{2}(60) \tag{2.6}
\end{align*}
$$

where $\sigma_{x}(100)$ is the $x$-coordinate size of the $100 \mu \mathrm{~m}$ point spread function, etc. The input point spread functions needed for these calculations were obtained by measuring several point sources in each frame and averaging the results. The smoothing calculations were complicated slightly because the point spread functions were inclined at an angle of approximately $4^{\circ}$ north of due west, so the actual convolution functions used were inclined elliptical gaussians normalized to be flux conserving. The $12 \mu \mathrm{~m}$ maps were smoothed to the resolution of the $25 \mu \mathrm{~m}$ maps using the same techniques. The $\sigma_{x}, \sigma_{y}$, and rotation angles for the point spread functions of the four bands after smoothing are listed in Table 2.1. The gaussian parameters were defined to equalize the sizes of the point spread functions in the pairs of bands, so after the smoothings $\sigma_{x}(100)=\sigma_{x}(60)$, etc. But the orientation angles were not forced to the same values so there are small and insignificant disagreements among their values.

Since the sky coverage of the mosaics was much greater than the extent of the cluster, they were trimmed to the region $6^{h} 37^{m} 02^{s}-6^{h} 39^{m}, 9^{\circ} 18^{\prime} 45^{\prime \prime}-10^{\circ} 03^{\prime} 30^{\prime \prime}$, an area that both contained the bulk of the long wavelength emission and which complimented the data presented in Chapter 3 and Chapter 5. At last the images were reduced and ready for analysis.

### 2.3.2 Colour Correcting the $12 \mu \mathrm{~m}$ and $25 \mu \mathrm{~m}$ Maps

In the last section it was claimed the images were fully reduced. That is not strictly true, because an important consideration was how to contend with "colour corrections". Colour corrections were required because IRAS data were quoted as monochromatic fluxes while the actual filters were broadband (approximately 8-15 $\mu \mathrm{m}, 18-30 \mu \mathrm{~m}, 45-80 \mu \mathrm{~m}$, and $85-115 \mu \mathrm{~m}$ respectively). In calculating the monochromatic fluxes, the good people entrusted with preprocessing IRAS data assumed input spectral energy distributions which were constant in flux per logarithmic frequency interval. Since this was not true in general, colour corrections were required. Such corrections were multiplicative factors determined by flux ratios, and were made for each pixel of the $12 \mu \mathrm{~m}$ and $25 \mu \mathrm{~m}$ images using a look-up table stocked with values from the IRAS Explanatory Supplement

Table 2.1. Smoothed IRAS Image Point Spread Functions

| Band | $\sigma_{x}$ | $\sigma_{y}$ | $\theta$ |
| ---: | ---: | ---: | ---: |
| $12 \mu \mathrm{~m}$ | $119^{\prime \prime}$ | $47.3^{\prime \prime}$ | $4.3^{\circ}$ |
| $25 \mu \mathrm{~m}$ | $119^{\prime \prime}$ | $47.3^{\prime \prime}$ | $3.7^{\circ}$ |
| $60 \mu \mathrm{~m}$ | $153^{\prime \prime}$ | $107^{\prime \prime}$ | $4.8^{\circ}$ |
| $100 \mu \mathrm{~m}$ | $153^{\prime \prime}$ | $107^{\prime \prime}$ | $3.8^{\circ}$ |

(Beichman et al. 1988). Even though the images were carefully bias corrected, some pixels or even coherent image regions were negative in one or both frames. This was due to both random noise fluctuations and, more seriously, a hysteresis effect called source shadowing. Source shadowing was especially important with point sources, and manifested itself as unpredictable behavior in the detector gain that lasted for a few samples after the detection of a bright source. IRAS scanned through NGC 2264 from the south to the north, and a source shadowing suppression of flux levels is apparent as a hole north of the bright source known as Allen's star (Allen 1972) near $6^{h} 38^{m} 28^{s}, 9^{\circ} 32^{\prime} 15^{\prime \prime}$. This hole appears in the colour temperature maps as a drop of approximately 80 K (Figure 2.1). Because of its unpredictable nature, there was no correction available for source shadowing. Fortunately, the IRAS recovery from source shadowing was relatively fast, and so less than $3 \%$ of the cloud was corrupted by this effect. Another artifact visible on Figure 2.1 is a rectangular annulus of diminished temperatures centered on Allen's star. This moat, a temperature drop of approximately 50 K , indicates that the $12 \mu \mathrm{~m}$ and $25 \mu \mathrm{~m}$ point spread functions are still not quite matched. Because of source shadowing and conventional detector noise, negative pixel values prohibit colour corrections in $16 \%$ of the image frames (mostly in regions outside the cloud region), so these pixel fluxes in the colour corrected images were set to zero. The colour temperatures derived from the $12 \mu \mathrm{~m} / 25 \mu \mathrm{~m}$ flux ratios are in the range $50-300 \mathrm{~K}$ for the cloud, with a median value near 270 K . This is far too hot for an equilibrium dust temperature-indeed most of the $12 \mu \mathrm{~m}$ radiation and perhaps much of the $25 \mu \mathrm{~m}$ radiation is thought to arise from stochastic radiation processes involving very small grains (Sellgren 1984), or perhaps even exotic polycyclic aromatic compounds similar to $\mathrm{C}_{24} \mathrm{H}_{12}$ (Léger \& Puget 1984). This compound in particular has emission bands at $7.6 \mu \mathrm{~m}, 8.8 \mu \mathrm{~m}$, and $11.9 \mu \mathrm{~m}$-in excellent


Fig. 2.1.- The $12 \mu \mathrm{~m} / 25 \mu \mathrm{~m}$ colour temperature map for the region. Typical colour temperature values are near 270 K. See the text and the caption in Figure 2.2 for more details.
agreement with astronomical emission features observed at $7.7 \mu \mathrm{~m}, 8.6 \mu \mathrm{~m}$, and $11.3 \mu \mathrm{~m}$. Figure 2.2 shows the colour corrected $12 \mu \mathrm{~m}$ map. The $25 \mu \mathrm{~m}$ map is not shown since it is very similar in morphology. The image is dominated by four sources arranged in a row from the southeast to the northwest. The point sources in this region were catalogued by Margulis (1987), and from southernmost to northernmost the four bright sources are his sources \#9 (Allen's star), \#12, $\# 18$, and \#21. The nature of his source \#21 is questionable, because it may be an artifact resulting from source-shadowing from source \#18. However, it does appear coincident with Walker's source \#78 so it may be genuine.


Fig. 2.2.- The colour corrected $12 \mu \mathrm{~m}$ map of the cloud is shown for the region $6^{h} 37^{m} 02^{s}-6^{h} 39^{m} 90^{s}, 9^{\circ} 18^{\prime} 45^{\prime \prime}-10^{\circ} 03^{\prime} 30^{\prime \prime}$ (southeast is at bottom left). The division of the bright core at the north into two components may be an artifact of source shadowing (see text). The elongated nature of point sources is instrumental.

### 2.3.3 Analyzing the $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ Maps

The majority of the $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ emission (Figure 2.3) is believed to originate from warm dust (Draine \& Anderson 1985). To determine dust temperatures and optical depths the $60 \mu \mathrm{~m} / 100 \mu \mathrm{~m}$ flux density ratio at each pixel could be used to obtain effective colour temperatures, and then colour corrections could be applied to produce corrected flux densities, but it was just as easy to extract the dust temperatures and optical depths directly from the uncorrected images. To understand how, a small amount of formal derivation is required. Consider dust at temperature $T$, radiating with a blackbody distribution $B_{\lambda}(T)$ which is modified by the dust's wavelength-dependent emissivity $\epsilon_{\lambda}$. The flux $F$ detected by an IRAS pixel was

$$
\begin{equation*}
F=\int B_{\lambda}(T) \epsilon_{\lambda} R_{\lambda} d \lambda \tag{2.7}
\end{equation*}
$$

where the integration was carried out over the bandwidth defined by the pixel's response function $R_{\lambda}$. A monochromatic flux $F^{\prime}$ is defined for each band by assuming a constant flux per logarithmic frequency interval. This flux can be related to the actual dust temperature and emissivity by

$$
\begin{equation*}
F^{\prime}=\frac{\int B_{\lambda}(T) \epsilon_{\lambda} R_{\lambda} d \lambda}{\int R_{\lambda} d \lambda} \tag{2.8}
\end{equation*}
$$

where the value of the normalizing $\bar{\epsilon}$ has been set to unity. Assuming a single temperature $T$ can be used to describe the dust emission in both the $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ bands, a ratio of the two fluxes $F_{60}^{\prime}$ and $F_{100}^{\prime}$ would be given by

$$
\begin{equation*}
\frac{F_{100}^{\prime}}{F_{60}^{\prime}}=\frac{\int_{100} B_{\lambda}(T) \epsilon_{\lambda} R_{\lambda} d \lambda}{\int_{60} B_{\lambda}(T) \epsilon_{\lambda} R_{\lambda} d \lambda} \frac{\int_{60} R_{\lambda} d \lambda}{\int_{100} R_{\lambda} d \lambda} . \tag{2.9}
\end{equation*}
$$

In this wavelength regime, the emissivity is usually expressed as a wavelength dependent power-law (Whitcomb et al. 1981; Gatley et al. 1979; Hildebrand 1983;


Fig. 2.3.- The $100 \mu \mathrm{~m}$ map of the cloud, not colour corrected, is shown for the same region as Figure'2.2. The flux levels of the source towards the southeast (Allen's star) rise to as high as $860 \mathrm{MJy} \mathrm{Sr}^{-1}$.
and others). Writing $\epsilon_{\lambda}=A \lambda^{-n}$, where both $A$ (which cancels instantly) and $n$ are free parameters, the flux ratio in Equation 2.9 is seen to be dependent only upon $T$ and the choice of $n$. Look-up tables were created which contained $60 \mu \mathrm{~m} / 100 \mu \mathrm{~m}$ flux-ratios calculated using Equation 2.9, arranged by choice of $n$. These tables spanned the temperature range of $1-10^{4} \mathrm{~K}$ with increments of 0.01 K . The values $n=1$ and 2 were used, because $n=1$ is the case for Mie-scattering while $n=2$ is better for $\lambda>100 \mu \mathrm{~ms}$ (Greene \& Young 1991; Draine \& Lee 1984; Gatley et al. 1979; Aannestad 1975; Hildebrand 1983; and references contained therein). Using these tables, dust temperatures were determined for each pixel (Figure 2.4). Data points that were negative (because of noise and source shadowing) prevented cloud temperature determinations for $15 \%$ of the trimmed cluster image.

Having calculated dust temperatures, the next step was to calculate dust optical depths. As previously noted, the emissivity is commonly written as a wavelength dependent power law, i.e.

$$
\begin{equation*}
\epsilon_{\lambda}=1-e^{-\tau_{\lambda}} \approx \tau_{\lambda}=\tau_{100}\left(\frac{\lambda}{\lambda_{100}}\right)^{-n} \tag{2.10}
\end{equation*}
$$

where $\tau_{100}$ is the dust optical depths at $100 \mu \mathrm{~m}$-assumed to be much less than unity (Keene et al. 1982). Combining this expression with Equation 2.8, $\tau_{100}$ can be written as

$$
\begin{equation*}
\tau_{100}=\frac{F_{100}^{\prime} \int_{100} R_{\lambda} d \lambda}{\int_{100}^{B_{\lambda}}(T)\left(\frac{\lambda}{\lambda_{100}}\right)^{-n} R_{\lambda} d \lambda} \tag{2.11}
\end{equation*}
$$

Using the temperatures determined from the flux-ratios in Equation 2.9, and the monochromatic $100 \mu \mathrm{~m}$ fluxes in the IRAS maps, $100 \mu \mathrm{~m}$ optical depths maps were produced (Figure 2.5).


Fig. 2.4. - The $n=2$ dust temperature map of the cloud is shown. The temperatures throughout most of the cloud are approximately 25 K , but near the principal point sources rise several Kelvins. The temperature suppressions surrounding the southern sources are artifacts of only a few Kelvins, and the artificially high temperatures fringing the cloud were unimportant for the other analyses.


Fig. 2.5.- The $n=2$ optical depth map of the cloud is shown. The optical depths reach a maximum value of 0.0022 near Allen's star. Distortion from this source and the IRAS scan direction produce a boxy nature to this area of the map. A map for $n=1$ is shown in Chapter 6.

### 2.4 Conditions Within the Cloud

In this section the physical conditions of the extended component of the infrared emission are explored. Dust temperatures, optical depths, and masses are first calculated, then the dust luminosity of the cloud is obtained. The sources that are responsible for energizing the cloud are identified.

### 2.4.1 Temperature, Optical Depth, and Dust Mass

The temperature maps determined by the $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ images show that most of the cluster dust ranges through temperatures of $25-40 \mathrm{~K}$, the highest temperatures occurring on the point sources. The temperatures obtained are dependent upon the choice of emissivity exponent, and for the values $n=1$ and 2 the modal values are 31 K and 27 K . Analysis of the ISSA maps of the region indicate that the $n=1$ and 2 temperatures of the cirrus in the neighborhood of the dust cloud are 27 K and 23 K , a few degrees cooler. Because of the DIRBE transformation equations introduced in Section 2.3, the flux ratios used in Equation 2.9 were modified by a factor of $0.83 \pm 0.09$. As a result, the dust temperatures (for both the cloud and the cirrus) without these corrections would be underestimated by approximately 2 K , a negligible difference.

The optical depths obtained are all very small-the peak values are $\tau=0.002$ for $n=2$, and $\tau=0.001$ for $n=1$. Clearly the linear approximation used in Equation 2.10 is justified, that is

$$
\begin{equation*}
1-e^{-\tau_{\lambda}} \approx \tau_{\lambda} \text { for } \tau_{\lambda} \ll 1 \tag{2.12}
\end{equation*}
$$

Since the optical depths are tiny and the temperature distribution of the dust is
fairly constant, the $\tau_{100}$ maps (Figures 2.5, also in Chapter 6) and the $100 \mu \mathrm{~m}$ map shown in Figure 2.3 are similar except for scaling changes.

Having calculated the optical depth distribution, it was possible to estimate the total dust and gas masses of the cluster. Defining the number density of dust grains as $n_{d}$, a dust grain's infrared extinction cross-section as $\sigma$ (IR), and the path length through the cloud as $\Delta s$, the $100 \mu \mathrm{~m}$ optical depth can be written as

$$
\begin{equation*}
\tau_{100}=n_{d} \sigma(\mathrm{IR}) \Delta s=N_{d} \sigma(\mathrm{IR}) \tag{2.13}
\end{equation*}
$$

where $N_{d}$ is the column density of dust grains. Since dust scattering at $100 \mu \mathrm{~m}$ is very inefficient the only important component of $\sigma$ (IR) is absorption (Hildebrand 1983). In contrast, in the ultraviolet regime where the wavelength is approximately equal to the grain size, both the absorption cross-section $\sigma_{a b}$ and the scattering cross-section $\sigma_{s c}$ are important. The ultraviolet absorption cross-section is approximately equal to the geometric cross-section $\bar{\sigma}$. At these short wavelengths Babinet's principle states that the scattering cross-section $\sigma_{s c}$ is also approximately equal to the geometric cross-section (van de Hulst 1957), so

$$
\begin{equation*}
\sigma(\mathrm{UV})=\sigma_{s c}+\sigma_{a b} \approx 2 \bar{\sigma}=2 \pi a_{d}^{2} \tag{2.14}
\end{equation*}
$$

where $a_{d}$ is the radius of a dust grain. Dividing the infrared and ultraviolet extinction cross-sections by the geometric cross-section yields the extinction efficiencies which, by Kirchoff's law, are the emissivities $\epsilon$;

$$
\begin{equation*}
\frac{\sigma(\mathrm{UV})}{\sigma(\mathrm{IR})}=\frac{\sigma(\mathrm{UV}) / \bar{\sigma}}{\sigma(\mathrm{IR}) / \bar{\sigma}}=\frac{\epsilon(\mathrm{UV})}{\epsilon(\mathrm{IR})} \tag{2.15}
\end{equation*}
$$

The ratio $\epsilon(\mathrm{UV}) / \epsilon(\mathrm{IR})=4000$ at $125 \mu \mathrm{~m}$ (Hildebrand 1983), so the infrared extinction cross-section can be written

$$
\begin{equation*}
\sigma(\mathrm{IR})=\sigma(\mathrm{UV}) / 4000=\pi a_{d}^{2} / 2000 \tag{2.16}
\end{equation*}
$$

Using a powerlaw emissivity, $\sigma(\mathrm{IR})$ can be converted from its value at $125 \mu \mathrm{~m}$ to $100 \mu \mathrm{~m}$ by

$$
\begin{align*}
\sigma_{100} & =\sigma_{125}\left(\frac{125 \mu \mathrm{~m}}{\lambda}\right)^{n} \\
& =\frac{\pi a_{d}^{2}}{2000}\left(\frac{125 \mu \mathrm{~m}}{\lambda}\right)^{n} . \tag{2.17}
\end{align*}
$$

The total dust mass $M_{d}$ contained in a beam penetrating the dust cloud can be written as

$$
\begin{equation*}
M_{d}=\frac{4}{3} \pi a_{d}^{3} \rho_{d} N_{d} \Omega R^{2} \tag{2.18}
\end{equation*}
$$

where $\rho_{d}$ is the mass density of a dust grain, $\Omega$ is the solid angle of the beam, and $R$ is the distance to the cloud. Using Equation 2.13 to eliminate $N_{d}$ from Equation 2.18 and writing the result in terms of the $100 \mu \mathrm{~m}$ extinction cross-section using Equation 2.17 yields

$$
\begin{align*}
M_{d} & =\frac{4}{3} \pi a_{d}^{3} \rho_{d} \Omega R^{2}\left(\frac{\tau_{100}}{\sigma_{100}}\right) \\
& =\frac{8000}{3} a_{d} \rho_{d} \Omega R^{2}\left(\frac{\lambda}{125 \mu \mathrm{~m}}\right)^{n} \tau_{100} . \tag{2.19}
\end{align*}
$$

Using $a_{d}=0.1 \mu \mathrm{~m}, \rho_{d}=3 \mathrm{~g} \mathrm{~cm}^{-3}$, and $R=790 \mathrm{pc}$, the calculation described in Equation 2.19 was performed for each pixel in the optical depth image. Summing the results produces dust cloud mass estimates of $3.2 \mathrm{M}_{\odot}$ and $5.5 \mathrm{M}_{\odot}$ for $n=1$ and 2. Assuming a gas/dust mass ratio of 100 , these values imply a total gas and dust mass in the cloud of approximately $320-550 \mathrm{M}_{\odot}$.

Extinction through the cluster was estimated by dividing the dust masses calculated in Equation 2.19 by $\Omega R^{2}$ to convert them into column densities. Then by using a gas/dust mass ratio of 100 , these can be converted into H column densities. The gas/extinction ratio can be employed (although it is always dangerous to do so because it is measured in diffuse clouds which produce results which are not
necessarily applicable here) to determine optical extinction through the cloud:

$$
\begin{equation*}
\frac{N_{H}}{A_{V}}=\frac{N(H)+2 N\left(H_{2}\right)}{A_{V}}=1.59 \times 10^{21} \mathrm{~cm}^{-2} \mathrm{mag}^{-1} \tag{2.20}
\end{equation*}
$$

Using this method, peak extinctions were measured as $A_{V}=1.7$ magnitudes for the emissivity exponent $n=1$.

The area enclosed by the contour line marking the $100 \mu \mathrm{~m}$ optical depth equal to $1 / 10$ the maximum optical depth was arbitrarily used to define the boundary of the dust cloud. The solid angle enclosed by this boundary varied by approximately $15 \%$ depending upon the choice of emissivity, but was on the order of $\Omega_{d} \approx 6.3 \times 10^{-5} \mathrm{Sr}$. From this, an approximate cloud radius $r_{c}=3.5 \mathrm{pc}$ was estimated using $\Omega_{d} R^{2}=\pi r_{c}^{2}$, where $R=790 \mathrm{pc}$. Further approximating the cloud as a uniform sphere, the H atom number densities for $n=1$ and 2 were calculated as $70 \mathrm{~cm}^{-3}$ and $110 \mathrm{~cm}^{-3}$.

## Comments

The dust temperature calculations for the neighborhood cirrus result in values in general agreement with those reported by Low et al. (1984). Draine \& Lee (1984) predicted values of $T \approx 15-19 \mathrm{~K}$ but explained the high temperatures observed by Low et al. (1984) as originating from small grains with temperatures that, by photon absorption, had temporarily climbed to higher than average temperatures. For the dust in NGC 2264, the dust temperature is further boosted by flux from the associated cluster stars.

Peak visual extinctions were estimated at 1.7 mag by using the gas/extinction ratio. Another way to calculate $A_{V}$ is from the absorption cross-sections. The $100 \mu \mathrm{~m}$ extinctions can be converted into optical extinctions in several steps
(Black 1990). First, assuming a power law the extinction can be converted to a $40 \mu \mathrm{~m}$ value. This can then be converted to a $4.808 \mu \mathrm{~m}$ value (Becklin et al. 1978), subsequently to a $0.726 \mu \mathrm{~m}$ value (Rieke and Lebofsky 1985), and finally to an optical extinction (Seaton 1979). (These conversions were matched using the scaling $A_{V} / E(B-V)=3.1$.) This results in extinction estimates in NGC 2264 of approximately $A_{V}=0.3-2$ magnitudes. It is probable that the dust is very clumpy, so this is only a spatially averaged estimate.

These extinction estimates are all much lower than the canonical value $A_{V}=5$ magnitudes (Lada et al. 1993). This is because the dust in the cluster was only seen by IRAS if it was sufficiently warm-only the energized dust near the cluster center and the bright sources was strongly visible. There is probably more dust present but it was not visible to IRAS. (The 3.5 pc radius estimated for the dust distribution is somewhat smaller than a 4.5 pc radius of the cluster determined by cluster members (Walker 1956). ) Indeed, emission from the giant molecular cloud behind NGC 2264 is not apparent in the $100 \mu \mathrm{~m}$ images. Margulis (1987) measured a total virial mass for the background GMC of $3 \times 10^{4} \mathrm{M}_{\odot}$, only a fraction of which was observed in the IRAS data. Estimating the GMC temperature at approximately 10 K and the extinction through this cloud as $A_{V}=5$ magnitudes, the optical depth would be $\tau_{100}=0.016$ for an emissivity exponent $n=1$. This would produce infrared fluxes equal to $0.002 \mathrm{MJy} \mathrm{Sr}^{-1}$ at $60 \mu \mathrm{~m}$ and $0.55 \mathrm{MJy} \mathrm{Sr}^{-1}$ at $100 \mu \mathrm{~m}$, both values well within the noise of the IRAS data. As stated before, the IRAS fluxes do not measure all the dust along a line of sight through NGC 2264 and the background GMC, rather they only measure the dust grains that are near energizing sources.

### 2.4.2 Energetics

The infrared luminosity of the cloud was measured in order to understand more about the energetics of the region. The total infrared luminosity ( $L_{\mathrm{IR}}$ ) was decomposed into two components. The first is the thermal contribution from warm dust ( $L_{\mathrm{TH}}$ ), and the second is a mixed group of other mechanisms, prominently nonthermal emission from scattered light and molecular emission bands ( $L_{\mathrm{NT}}$ ). Although it is difficult to measure $L_{\mathrm{NT}}$, both $L_{\mathrm{TH}}$ and $L_{\mathrm{IR}}$ can be directly determined.

## Thermal Dust Luminosity

To calculate the dust luminosity $L_{\mathrm{TH}}$, the intensity of the thermal radiation had to be integrated over wavelength, i.e. for each pixel,

$$
\begin{equation*}
F_{\mathrm{pix}}=\Omega_{\mathrm{pix}} \int_{I R} I_{\lambda} d \lambda \tag{2.21}
\end{equation*}
$$

where $\Omega_{\text {pix }}$ is the solid angle of an individual pixel. By resurrecting the optical depth and temperature maps developed in Section 2.3.3, this equation could be rewritten as

$$
\begin{equation*}
F_{\mathrm{pix}}=\Omega_{\mathrm{pix}} \int_{I R} B_{\lambda}(T)\left(1-e^{-\tau_{\lambda}}\right) d \lambda \tag{2.22}
\end{equation*}
$$

The integration was performed over the wavelength range $8-4000 \mu \mathrm{~m}$. Most of the emission faded by $250-300 \mu \mathrm{~m}$ because the cloud temperatures were greater than 25 K , so the long-wavelength limit of the integration was extremely generous (it was actually a computational relic from the first attempt at coding the calculation). The short-wavelength limit was chosen so the results could be easily compared to the estimates of the total infrared luminosity (see below). Summing the pixel fluxes
resulted in a measurement of the total flux from the cluster. Using a distance of 790 pc for the cluster, the dust luminosities for $n=1$ and 2, are $L_{\mathrm{TH}}=6700 \mathrm{~L}_{\odot}$ and $5500 \mathrm{~L}_{\odot}$.

## Total Infrared Luminosity

Estimates of the total infrared luminosity were constructed from two parts. The long-wavelength component consisted of an integration over the interval $60-4000 \mu \mathrm{~m}$ as described in Equation 2.22, since it was expected that the long wavelength luminosity is entirely due to dust emission. Integration over the $\lambda<60 \mu \mathrm{~m}$ component was performed by fitting a first-order line segment to the $12 \mu \mathrm{~m}$ and $25 \mu \mathrm{~m}$ data, and another first-order line segment to the $25 \mu \mathrm{~m}$ and $60 \mu \mathrm{~m}$ data. The area under these lines were integrated from $8-60 \mu \mathrm{~m}$. The short end of this integration was $8 \mu \mathrm{~m}$ instead of $12 \mu \mathrm{~m}$ because of the broadband nature of the IRAS detectors. An integrated flux image for $n=2$ is shown in Figure 2.6, and illustrates that while point sources provide major contributions the the total far-infrared flux from the cloud, they are situated in a large region of fainter, extended emission. Coadding all the pixel results produced estimates for $L_{\mathrm{IR}}$ : $1.1 \times 10^{4} \mathrm{~L}_{\odot}$ and $9.9 \times 10^{3} \mathrm{~L}_{\odot}$, for the emissivity exponents $n=1$ and 2.

## The Contribution from Point Sources

In the last two sections, the total infrared luminosities ( $L_{\mathrm{IR}}$ ) and thermal infrared luminosities ( $L_{\mathrm{TH}}$ ) from the IRAS maps were calculated and, depending upon the emissivity choice, $61 \%$ or $56 \%$ of $L_{\text {IR }}$ is thermal dust emission while the rest is produced by other mechanisms. Adopting the calculated dust cloud


Fig. 2.6. - The $n=2$ integrated flux map of the cloud is shown in a logarithmic stretch. The important contributions from several point sources are clear, and an additional extended region of emission is visible throughout the region.
mass of $3.2 \mathrm{M}_{\odot}$ implied $320 \mathrm{M}_{\odot}$ of gas at 30 K . Assuming this is primarily in the form of molecular hydrogen with approximately $k T$ erg molecule ${ }^{-1}$, the cooling time implied by the total infrared luminosity alone is less than a year. Clearly to maintain this temperature something must be pumping energy into the cloud-what is this source? In a study of the GMC associated with NGC 2264 Margulis (1987) identified thirty point sources, eighteen of which lie within the area of the NGC 2264 dust cloud. The combined infrared luminosity of these sources is $4700 \mathrm{~L}_{\odot}$, a value dominated by the four brightest sources (one of which is Allen's star) which have a combined far-infrared luminosity of $4120 \mathrm{~L}_{\odot}$, nearly half that of the entire cloud. These four sources are visible in Figure 2.2 as the four bright condensations arranged in a row from the southeast to the northwest, which Margulis numbered $\# 9, \# 12, \# 18$, and \#21. As previously mentioned in Section 2.3.2, source \#21 may actually be an artifact of source shadowing from the bright source \#18 immediately to its south-the dust temperature map indicates no temperature rise at the location of source \#21. Margulis identified these four sources-and most of the other objects in his IRAS catalogue-as class I objects (Section 1.3.1). As shown in Figure 2.6, the cloud's far-infrared emission consists of two portions. The first is associated with these bright point sources, but the second is a less luminous haze that permeates the region. Evidently some additional source of energy is also being tapped. What is it? Margulis identified several high velocity molecular outflows in the cloud, but the combined mechanical energy of the six in the survey area was insignificant ( $58 \mathrm{~L}_{\odot}$ ). Also, these outflows were mostly associated with the IRAS sources so they cannot be invoked to power the far-infrared haze. Evidently the cloud-glow is powered by the main sequence and pre-main sequence cluster stars. Indeed, the single brightest star in the cluster, HD 47839, is an $m_{V}=4.6$ O7 star (Cannon \& Pickering 1918; Walker 1956;

Conti \& Underhill 1988) and the absolute bolometric magnitude of such a star is approximately $M_{V}=-8.0$, or $1.4 \times 10^{5} \mathrm{~L}_{\odot}$. This well exceeds the total infrared luminosity of the region-just a few percent of this energy would be sufficient to energize the dust cloud. Since this source lies on the northeast boundary of the cloud it cannot be the supplementary source of energy, but an ensemble of embedded stellar sources of lesser luminosity would suffice. To examine this further, a survey of the cluster stars is described in Chapter 3, and in Chapter 6 the distributions of these sources in the cloud are examined.

### 2.5 Summary

The IRAS images of NGC 2264 were analyzed to probe the physical conditions in the cluster, particularly as they pertained to the dust component. After pretreatment steps including smoothing and colour corrections, temperature maps were produced for the dust cloud based upon the intensity ratio of the $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ maps. Although the results were dependent upon the choice of dust emissivity used, the dust temperatures obtained are approximately 30 K , slightly warmer than found for infrared cirrus.

The optical depths in the cloud are very small, easily permitting column depths through the entire cloud to be calculated. Integrating over the nebula yielded a dust mass of approximately $3.2 \mathrm{M}_{\odot}$. Estimating the radius of the cloud as 3.5 pc , the number density of H atoms in the cloud is $70 \mathrm{~cm}^{-3}$. The $8-4000 \mu \mathrm{~m}$ luminosity of the cloud and embedded sources is measured as approximately $1.1 \times 10^{4} \mathrm{~L}_{\odot}$. This luminosity is greater than the luminosities of the embedded infrared point sources, and so it is concluded that the energizing mechanism must be the embedded point sources detected by Margulis (1987), supplemented by the cluster of main sequence
and pre-main sequence stars which probably lie in front of the embedded sources.

## Chapter 3

## A MULTIBAND <br> PHOTOMETRIC SURVEY

### 3.1 Overview

In this chapter the treatment of two epochs of $V, R$, and $I$ data is discussed. After reduction and point source extraction, the resulting source lists are merged by a complex ordeal into a three-band survey. This is then merged with a pre-existing $J-H-K$ survey. The completeness and reliability of this six-band survey is investigated. Models of the star counts in the survey indicate the presence of 350-650 cluster members. Scientific analysis of the survey is largely reserved for Chapters 4-6 and future work.

### 3.2 Motivation

In Chapter 2 it was demonstrated that the dust in NGC 2264 must be primarily heated by the stellar population. To learn more about these stars, new
observations of the cluster were required. Like most juvenile galactic clusters, NGC 2264 is populated with a wild mix of young energetic stars, including some main-sequence stars, many classical and weak line T Tauri stars, and a scattering of continuum stars and deeply embedded objects. Many of these stars are heavily reddened and may exhibit large infrared excesses. An imaging survey is the best way to learn about the energy distributions of the many stars in this cluster in a reasonable amount of time. But the job is not trivial-there are thousands of stars in the sky containing the cluster so the data product from such an endeavor is necessarily enormous and time consuming to produce. Adding confusion are the many non-cluster objects inevitably included in the survey. The GMC behind the cluster generously helps reduce the contamination from background stars by providing several magnitudes of extinction in the visible, but the extincted background stars remaining may masquerade as heavily reddened cluster sources. Despite the hardships of reduction and the complications from interloping stars a complete survey would be extremely valuable for increasing the understanding of the stellar component of NGC 2264.

### 3.3 V-R-I Image Data

To construct a complete catalogue of the cluster three surveys were made of approximately the same region in the wavelength bands $V, R$, and $I$. These three surveys were to be merged into a master survey which was to be a compendium of astrometric and photometric data.


Fig. 3.1.- Tracings are shown for the near-Landolt filters (Johnson $V$, Cousins $R$, near-Mould $I$ ) used in this survey. The transmission-weighted bandpass centers were at $0.55,0.66$, and $0.82 \mu \mathrm{~m}$.

### 3.3.1 Observations

The survey was made using the Steward Observatory 2.3 m telescope perched atop Kitt Peak near Tucson, Arizona. The data were taken November 1989 (I band) and January 1990 ( $V$ band and $R$ band) using the Steward set of filters which are comparable to those described by Landolt (1983), that is a Johnson $V$ filter and Cousins $R$ and $I$ filters. Actually the Steward $I$ filter is referred to as near-Mould but for the purposes of this study is sufficiently similar to a Cousins $I$ filter. Normalized filter traces are shown in Figure 3.1. Colour equations useful for converting between various systems are given in Taylor (1986). Using a TI $800 \times 800$ CCD (charge-coupled device), frames $778 \times 800$ were produced at a plate scale of $0.6^{\prime \prime} \mathrm{pix}^{-1}$. Integration times of 30 s were used, since longer exposures would have resulted in saturated images for too many of the brighter stars in the cluster.

These cluster images are hereafter referred to as object-frames. Coadded frames of five 1 s images were also taken for data reduction purposes, and are hereafter referred to as zero-frames. A single image frame was nearly $8^{\prime}$ on a side, but the cluster is much larger than this, so for complete coverage of the cluster, grids of 28 object-frames were required. By taking frames every $6^{\prime}$ complete coverage of the cluster was assured along with plenty of overlap between frames. This overlap region was important in maximising the quality of the astrometry of the data, as described in Section 3.3.3. Because of an error during the observing run, the second row of images in the $V$ band and the fifth row of images in the $R$ band were not observed. Those regions were reobserved in December 1992 as described in Section 3.6. The area covered by the survey was approximately $25.8^{\prime} \times 44.1^{\prime}$, and is shown in Figures 3.2-3.4. Images were also taken of the globular clusters NGC 7790 and NGC 2419 for photometric calibration.

### 3.3.2 $V-R-I$ Reductions

A raw CCD frame consists of an image region surrounded by an overscan region. Using the CCDRED image reduction packages in IRAF, the reduction of a CCD image was straightforward. First the overscan region, which contained bias information relevant to the entire image, was fit and this fit was subsequently subtracted from the frame. Having outlived its usefulness, this overscan region was trimmed and discarded, leaving an image measuring $757 \times 798$ pixels, or about $7.6^{\prime} \times 8.0^{\prime}$. Next, the zero-frames were coadded to produce a master zero-frame. This master zero-frame contained the values of the individual biases of each pixel in a frame. The master zero-frame was subtracted from each object-frame. The next step in reduction was to produce a sky-frame, which contained information


Fig. 3.2.- The rectangles indicate the region surveyed by both epoch-1 and epoch-2 $V$ observations. The epoch-1 frames were approximately $8^{\prime}$ on a side and adjacent frames overlapped by $2^{\prime}$. The second row of frames was not observed and this void was partially refilled by the epoch-2 data. These overlapping frames were approximately $5^{\prime}$ on a side, and are shown using dotted lines.


Fig. 3.3.- The rectangles indicate the region surveyed by both epoch-1 and epoch-2 $R$ observations. The epoch- 1 frames were approximately $8^{\prime}$ on a side and adjacent frames overlapped by $2^{\prime}$. The fifth row of frames was not observed and this void was refilled by the epoch-2 data. These overlapping frames were approximately $5^{\prime}$ on a side, and are shown using dotted lines.


Fig. 3.4.- The rectangles indicate the region surveyed by epoch-1 $I$ observations. The epoch- 1 frames were approximately $8^{\prime}$ on a side and adjacent frames overlapped by $2^{\prime}$.
about sky brightness. Ideally sky-frames are produced by offsetting the telescope to a reasonably blank patch of sky, but blank patches of sky were locally mythical since the sky near NGC 2264 is so busy with stars. However, by median-averaging all of the object-frames (or at least those that did not show excessive numbers of stars or patches of nebulosity) all the stars were removed from the averaged image and a fine substitute sky-frame was produced. Subtracting the sky-frame from each object-frame removed the additive effects from sky emission. Dividing each object-frame by the sky-frame accounted for the pixel to pixel variations in gain, and concluded the cookbook steps of image reduction. For ease of interpretation, the images were flipped and reversed so the celestial coordinates were arranged with north at the top and west to the right. All the $V, R$, and $I$ frames were reduced in this way.

### 3.3.3 Source Extractions

The pixel coordinates and instrumental magnitudes of point sources in the object-frames were measured using the IRAF tasks in the APPHOT package. The full-width at half-maxima of unsaturated images in the $V, R$, and $I$ bands are approximately $1.9^{\prime \prime}, 1.4^{\prime \prime}$, and $1.8^{\prime \prime}$, respectively. Instrumental magnitudes were extracted for apertures 3,5 , and 10 pixels in radius using the IRAF routines DAOFIND, PHOT, and their allied programs. The results from the 5 -pixel aperture appear to be the best, because the 3-pixel aperture did not include enough of the stellar flux and the 10 -pixel aperture often suffered from confusion with nearby stars. In principle, profile fitting using routines such as DAOPHOT can yield better photometry, but the coarse pixel sampling and variable point spread funtions obtained with the Steward focal reducer prevented their use.

It was important to determine the celestial coordinates of each object as accurately as possible. Astrometric reference stars (Lapicz 1984; Walker 1956; Adams et al. 1983) were selected and identified on the object-frames. After making a first guess as to the celestial coordinates of the centers for each object-frame, an error function was defined as the sum of the squares of the differences between the celestial coordinates of all these astrometric reference stars and their pixel locations extracted from the object-frames. Using the celestial coordinates of the frame centers as free parameters, the error function was minimized and the best-fit coordinates for all the object-frames were simultaneously determined. In addition to the frame coordinates, the plate scale and frame rotation angle-constrained to be the same for all the object-frames in each band-were also obtained. The best-fit plate scales and grid rotations for the $V, R$, and $I$ surveys are $0.6198^{\prime \prime} \mathrm{pix}^{-1}, 0.6188^{\prime \prime} \mathrm{pix}^{-1}, 0.6197^{\prime \prime} \mathrm{pix}^{-1}$ and $0.811^{\circ}, 0.826^{\circ}, 0.863^{\circ}$ respectively. These astrometric parameters were calculated by Marika Roberson. By comparing the extracted magnitudes of unsaturated standard stars to published values (Walker 1956; Adams et al. 1983; Christian et al. 1985), the zero-point for each wavelength band was established and the instrumental magnitudes were converted into apparent magnitudes.

Using the coordinate transformation parameters determined above, the pixel coordinates of each star were converted 1950.0 celestial coordinates and concatenated into a master list for each band. For the $V, R$, and $I$ surveys, 2623, 3082, and 4285 extractions were detected, respectively. That far more $I$ extractions were detected than $V$ or $R$ sources is partly because there were no missing rows in the $I$ survey. Due to the imbricate nature of the survey frames, these master lists contained a large number of redundant entries. These multiple data entries were in need of merging. Also present in the survey were image artifacts of several
kinds: hot pixels, flares and diffraction rings from nearby bright stars, clumps of nebulosity-all these were sometimes detected as point sources by DAOFIND. As a further complication, saturated sources or marginally resolved multiple stars might be detected as a single source in one band, while in another band DAOFIND might decide to note several tentative locations. While the point source extraction was complete, a great deal of work still needed to be done.

### 3.4 Merging Sources Within a Band

Cleaning and merging the entries of overlapping survey components is a subtle and sometimes exasperating process. Each sort of redundant observation, image problem, or clump of stars must be handled differently. The approach used was to contend with each class of stars in turn, starting with the easiest and progressing to the most irritating. All this clump analysis was performed automatically using FORTRAN programs.

## Methods

In the first stage of merging, singly-detected sources were culled from the master list. A source was defined as singly-detected if there were no other entries on the master list within a search radius of $3.6^{\prime \prime}$. Since only $45 \%$ of the sky covered by each survey was observed just once, any singly detected source immediately qualifies as a possible image defect or artifact. Because of the size of the survey it was prohibitively ambitious to look at each source on the original images to try to determine which were defects, but by plotting the locations of these sources many were immediately identifiable since they occurred in rings or rows. These problem
stars are further discussed in Section 3.9.

The remaining multiply detected stars required careful accounting. First, the stars were grouped together into clumps. Two detections were placed in a clump if they were separated by less than $3.6^{\prime \prime}$. In the simplest case, a clump would occur when a star is observed in 2-4 overlapping frames. In more complicated cases, a multiple star could increase the number of stars in a clump. In pathological cases, a single star might simultaneously merge with two distinct clumps, and so the two separate clumps would be grouped into a greater clump. Star chains could result in long strings of stars being assigned to a meta-clump. (In the absurd case, using a search radius of $1^{\prime}$ instead of $3.6^{\prime \prime}$ would result in a single clump called NGC 2264.) Most clumps only had two or three members, although some had more than ten.

Once the clumps were established, each was examined to determine if all the members of the clump were merely duplicate observations of the same source in overlapping frames. If any two or more stars in a clump originated from the same frame, it was clearly a case of confusion and the clump was labelled as bad (bad clump! bad!). The clump was also flagged as bad if the flux difference between any two stars in the clump was greater than one magnitude-a precaution that prevented mergings between a bad pixel or image artifact with an otherwise fine star. Typically $10 \%$ of the clumps-approximately 50 to 100 in each band-were flagged as bad. These difficult cases were mediated by inspecting the image frames. Some of the clumps were found to contain saturated sources where DAOFIND had detected multiple peaks on the flat top of the point spread function. Others were close or marginally resolved binaries, random star groupings, or cases where DAOFIND mysteriously detected a fine source twice. Finally, other peculiar events occasionally occurred, such as attempted merges with hot pixels or with image artifacts. Saturated stars, multiple stars, and stars in complex clumps obviously
have potentially inaccurate or corrupted magnitudes, so the peculiar status of these stars was retained as a comment in the final survey.

By definition, a good clump consisted of multiple observations of the same star, and could be merged into a single survey entry. Since the magnitude errors were small, it was not necessary to convert the magnitudes into fluxes for these calculations. The averaged magnitude $\bar{m}$ and associated error $\sigma_{\bar{m}}^{2}$ resulting from a combination of $n$ magnitude measurements in a good clump was calculated by

$$
\begin{equation*}
\bar{m}=\frac{\sum_{i=1}^{n} \frac{m_{i}}{\sigma_{m_{i}}^{2}}}{\sum_{i=1}^{n} \frac{1}{\sigma_{m_{i}}^{2}}}, \tag{3.1}
\end{equation*}
$$

where $\sigma_{m_{i}}$ is the statistical uncertainty of the $i^{\text {th }}$ magnitude in the clump, as determined from APPHOT. The uncertainty of $\bar{m}$ was determined by

$$
\begin{equation*}
\sigma_{\bar{m}}^{2}=\frac{1}{\sum_{i=1}^{n} \frac{1}{\sigma_{m_{i}}^{2}}} \tag{3.2}
\end{equation*}
$$

an expression obtained by propagation of errors. The coordinates of the members in each clump were averaged. These merging steps were performed on the data in each of the three bands. Comments peculiar to each of the three bands are noted below.

## $V$ Results

In the $V$ survey, 1281 stars were singly detected while 579 clumps were generated. From the clumps, 530 simple merges were made, while 19 clumps contained close doubles. The remaining clumps were bothersome knots of sources requiring manual merging. After discarding obviously bad sources, a total of 1852 V
stars were obtained from the merging process. The 530 clumps of stars that merged uneventfully provided a useful gauge of the quality of the $V$ magnitudes. Ideally, all the magnitudes in a single clump would be nearly identical. Deviations from this value would be due to variations in sky transparency, vignetting, or errors such as merging problems. Many sources in NGC 2264 are flux-variable (Walker 1956; and others) but all the data in each band were obtained in a single night, so the interval between observations was only a few minutes between overlapping columns and less than an hour between overlapping rows. As a result the magnitude differences in clump members were mostly due to photometric or merging errors. Figure 3.5 shows a histogram of the magnitude differences for multiple measurements of sources within a clump for all 530 clumps. Of the sample of 835 magnitude differences, $50 \%$ were smaller than 0.07 , and $90 \%$ were less than 0.18 . Figure 3.6 shows the magnitude differences plotted as a function of magnitude. It can be seen that most of the large magnitude differences ( $\Delta m_{V}>0.2$ ) occurred for the stars fainter than $m_{V}=18.0$. That very few stars brighter than this showed large magnitude differences indicates very few inappropriate merges between good stars and image artifacts occurred, and that for most stars the photometry were repeatable to better than than 0.1 magnitudes.


Fig. 3.5.- $V$ magnitude differences of 835 merged star pairs from epoch-1 are shown. The sign of the magnitude difference is arbitrary and was set positive. In this sample, $50 \%$ of the magnitude differences were less than 0.07 magnitudes, and $90 \%$ were less than 0.18 magnitudes.


Fig. 3.6.- $V$ magnitude differences of 835 merged star pairs from epoch-1 were plotted against the magnitude of brighter star of the pair. Most mergers involving large magnitude differences ( $\Delta m_{V}>0.2$ ) occurred for the stars fainter than $m_{V}=18.0$. The absence of large magnitude differences for bright stars indicates few faint image artifacts were merged with stars.

R Results

In merging the $R$ survey, 1578 stars were singly detected and 685 clumps were produced. Of these clumps, 660 were trivially merged while the remaining 25 resolved into 39 stars in confused systems. As in Figure 3.5, the $R$ magnitude differences for the 877 pairings generated by the merging process were examined, and $50 \%$ were smaller than 0.08 while $90 \%$ were smaller than 0.20 magnitudes. The merges involving large magnitude differences ( $\Delta m_{R}>0.2$ ) occurred for many stars as bright as $m_{R}=17.0$, but these were still rare events. The photometric repeatability of the data was therefore better than 0.1 magnitudes.

## I Results

In merging the $I$ survey, 1837 singly observed stars were extracted from the list while 1045 clumps were resolved into 997 single stars and 53 stars in multiple systems. The $I$ magnitude differences for 1574 pairings produced by the merging process showed that $50 \%$ of the magnitude differences were smaller than 0.12 , and $90 \%$ were smaller than 0.21 magnitudes. The merges involving large magnitude differences ( $\Delta m_{I}>0.2$ ) occurred for even some stars as bright as $m_{I}=17.0$. The photometric repeatability of the data is therefore not quite as good, and is probably in the range 0.1-0.2 magnitudes.

### 3.5 Band Merging $V, R$, and $I$

After all the machinations of Section 3.4, four lists were produced. The first three were merged lists for the bands, hereafter simply called source lists, and had

1811, 2238, and 2834 entries in each. The last contained a melange of 133 double and clumped stars, hereafter referred to as the doubles list. The next phase of list manipulation was to merge all three source lists into a grand $V-R-I$ survey. This process of band-merging would have been simple if all the stars were widely spaced, if there were no image artifacts, and certainly no instances of multiple stars or clumps of stars. But these complications existed and transformed the simple process into a complicated procedure. Computationally, the challenge was akin to the in-band mergings described in Section 3.4. So the plan of attack was similar-handle the simple cases first, then progress to the increasingly difficult cases. The entire band merging project consisted of six steps.

Step 1) The three source lists were searched for coordinate matches with any stars in the doubles list. In searching for matches among stars of different bands, the $3.6^{\prime \prime}$ search radius was still used, but no magnitude criteria were imposed. Stars that were willing to merge with members from the doubles list were reassigned to the doubles list. Furthermore, any stars remaining on the source lists which would merge with the newly rejected stars were also exiled to the doubles list. This process of rejection was iterated until all the stars that would merge with the doubles list were removed from the source lists.

Step 2) For every $V$ star, the $R$ and $I$ source lists were inspected for stars within the $3.6^{\prime \prime}$ search radius.

Step 3) For the selected $R$ and $I$ matches, the three source lists were searched for any further matches. If found, the additional source or sources indicated a new confused clump. These additional sources were checked for further matches with stars from the three source lists. This process was iterated until no additional sources were culled from the source lists.

Step 4) At this point, each $V$ star was either unmatched with any $R$ or $I$ star, or it had nicely merged with an $R$ or $I$ star (or both), or it was part of a confused clump involving three or more $V, R$, and $I$ entries. Even if a triad of $V, R$, and $I$ stars were matched, it was considered a confused clump if any two stars of the three were separated by more than $3.6^{\prime \prime}$. All the unmerged $V$ stars, as well as merged $V$ stars and their $R$ and $I$ associates, were saved as the first members of the final $V-R-I$ source list. All the confused clumps were appended to the doubles list.

Step 5) All that remained were $R$ and $I$ stars. Matches were sought and if found were added to the $V-R-I$ source list. Any clumps involving more than two stars were ejected to the doubles list. At the end of this step any $R$ or $I$ stars that remained unmerged were appended to the $V-R-I$ source list. This finished the treatment of the well-behaved matches in the band merging.

Step 6) The doubles list was treated manually to combine magnitudes of the confused clump cases. When necessary, the original images were consulted. The consolidated doubles list was saved for future reference.

The result of the band merging was that a master list containing $3304 V-R-I$ stars was produced, and a merged doubles list of 72 stars. As a test of robustness of the merging programs used in this analysis, the source lists and doubles lists were combined in all possible orders, yet the band-merged result was always the same. This concluded the epoch-1 V-R-I mergings.

### 3.6 The $V$ - $R$ Epoch-2 Survey

As noted in 3.3.1, two rows were overlooked in the original epoch-1 $V-R-I$ survey-row two in $V$ and row five in $R$. The gaps in the cluster coverage was
filled by new observations, and the sources from each new band of data required self merging. Then the new data required merging with the epoch-1 survey. Since the $V$ and $R$ grids from these new observations covered different cluster regions, no $V-R$ merging was necessary.

### 3.6.1 Observations

The new CCD data were obtained December 1992 using the Steward 2.3 m telescope. This time a Loral/Fairchild $2048 \times 2048$ chip was used, the output binned $4 \times 4$ to produce frames with a $512 \times 512$ image region at approximately the same plate scale as the epoch-1 data. The integration time for each object-frame was 60 s . Zero-frames were also observed to perform bias subtractions. The weather was only fair, with occasional cirrus. However, when clear the sky was steady, and stellar images in both $V$ and $R$ were measured to have full widths at half maxima of $1.4^{\prime \prime}$. To map the missing regions, a grid of $V$ images six frames wide and three frames tall, and a grid of $24 R$ frames in three rows 7,8 and 9 frames long were observed. In these mappings, each frame overlapped its neighbors by approximately $3^{\prime}$. Because of bad frames and other problems, the new $V$ and $R$ frames did not completely patch the holes of the epoch- 1 survey, but this unsurveyed portion of NGC 2264 is very small (Figures 3.2-3.3).

### 3.6.2 Reductions and Extractions

The reduction of the $V$ and $R$ images followed the same standard steps described in Section 3.3.2. In pixel units, the size of a raw object-frame was $532 \times 512$. Twenty rows of pixels were used in the overscan-correction, so the
overscan-corrected and trimmed images were 512 pixels on a side. These images were debiased using a master zero-frame produced by averaging the zero-frames from each night. The 15 V images and $15 R$ images with the least amount of nebular emission and flares from bright stars were median-filtered to produce sky-frames. These sky-frames were used for sky subtraction and flattening. Using the IRAF tasks DAOFIND and PHOT and appropriate parameters for those programs, sources were extracted from the reduced images as described in Section 3.3.3. The 5-pixel aperture used in the epoch-1 survey was adopted so the data from the two surveys would be as homogeneous as possible. The epoch-2 master lists for $V$ and $R$ contained 1286 and 1938 stars, respectively. Marika Roberson again performed the astrometric calibrations for the frames and found the plate scales and rotation angles for the grids to both be approximately $0.58^{\prime \prime} \mathrm{pix}^{-1}$ and $0.3^{\circ}$.

### 3.6.3 $V$ and $R$ Self-Merging

The $V$ and $R$ master lists were resolved into source lists and a list of 78 problem stars using the software developed for the first epoch of $V, R$, and $I$ data, described in Section 3.4. The resulting $V$ source list had 670 stars. Star clumps which merged easily into single stars were used to gauge the repeatability of the data, as described before. Using the approach illustrated for the epoch-1 data in Figure 3.5 and Figure 3.6, the $V$ magnitude differences for 713 epoch-2 pairings demonstrated that while $50 \%$ of the magnitude differences were 0.07 or less, there was a higher incidence of large magnitude differences-to include $90 \%$ of the epoch-2 data, magnitude differences as large as 0.35 magnitudes must be invoked. While the stars brighter than $\mathrm{m}_{V}=17.0$ had few problems, stars a few magnitudes fainter suffered from large scatter. This was probably due to the light cirrus that
plagued this observing run. (Although the epoch-2 magnitude zero-points had not yet been determined, it is convenient to use them in this discussion.)

The completed $R$ source list contained 1032 well-merged sources. The 1126 R magnitude differences from cluster mergings were comparable in behavior to the $V$ results-while half the magnitude differences were less than 0.06 magnitudes, the $90 \%$ bin occured at a magnitude difference of 0.28 . The large scatter was present mostly in the fainter stars-in this case for stars with $\mathrm{m}_{R}>18.5$.

### 3.6.4 Merging Epoch-1 Observations with Epoch-2

Yet another batch of mergings were required to arnalgamate the new $V$ and $R$ data and the epoch-1 $V-R-I$ survey. Happily all the merging logic had already been developed in the previous work and required only minor modifications. Temporarily shelving the doubles list of 78 stars resulting from the epoch- 2 work, the only files used in this merging were the source lists from the two epochs, and the doubles list from epoch-1. Using a $3.6^{\prime \prime}$ search radius as before but no magnitude-difference restrictions (as the epoch-2 data had not yet been magnitude calibrated) the merging consisted of four steps.

Step 1) Look for and reject any epoch-2 stars that matched with epoch-1 double stars. Furthermore, any epoch-1 stars that matched with the ejected epoch-2 stars were also ejected. This process was repeated until all the stars from the two epochs that were associated with confused clumps were ejected.

Step 2) Generate a list of all the clumps of stars produced when the remaining epoch-1 and epoch-2 surveys were merged. Clumps were classified as either good or bad. A good clump was defined as a single epoch-1 observation that merged
with a single epoch-2 observation using a $3.6^{\prime \prime}$ search radius. (Recall that since the $V$ and $R$ coverage regions for the epoch-2 observations did not overlap, a merge of an epoch-1 star with both a $V$ and an $R$ epoch-2 detection was not possible). Also classified as a good clump were the cases involving no merges at all, because by design the two epochs of data were not completely overlapping. The compendium of bad clumps contained all the pathological cases involving the usual laundry list of double stars, clusters, and image artifacts.

Step 3) Good clumps were merged and the resulting $V$ and $R$ magnitudes and their uncertainties were calculated using the Equations 3.1-3.2.

Step 4) The bad clumps were merged manually.

It has not yet been explained how the magnitude calibrations for the epoch-2 data were obtained. In order to make the combination of the two surveys as seamless as possible, the epoch-2 observations were calibrated using the epoch-1 stars as standards. This was done by using the good merges generated in Step 2 of the epoch-1-epoch-2 merging process. From the 201 V pairings and the 311 $R$ pairings that involved unsaturated flux measurements, zero-point calibrations were calculated for both bands using a modified version of Equation 3.1. The magnitude differences from every $i^{\text {th }}$ pair of unsaturated epoch-1 and epoch-2 measurements $m_{1, i}$ and $m_{2, i}$ of the same star were combined using

$$
\begin{equation*}
\Delta m_{\mathrm{o}}=\frac{\sum_{i=1}^{n} \frac{m_{1, i}-m_{2, i}}{\sigma_{m_{1, i}}^{2}+\sigma_{m_{2, i}}^{2}}}{\sum_{i=1}^{n} \frac{1}{\sigma_{m_{1, i}}^{2}+\sigma_{m_{2, i}}^{2}}} \tag{3.3}
\end{equation*}
$$

where $\sigma_{m_{1, i}}$ is the uncertainty of the epoch-1 magnitude in the $i^{\text {th }}$ pairing, etc. The magnitude zero-points $\Delta m_{0}$ determined this way were applied to the original epoch-2 source lists. Then the surveys from both epochs were remerged, this time with the requirement that for any two stars to merge well, their magnitudes had to


Fig. 3.7.- This displays magnitude differences of 283 star pairs produced by merging the data from the two epochs of $V$ observations. Most of the large magnitude differences $\left(\Delta m_{V}>0.25\right)$ were confined to stars fainter than $\mathrm{m}_{V}>18.5$.
differ by less than one magnitude.

Examining the magnitude differences between 283 unsaturated $V$ measurements from epoch-1 and epoch-2 reveals that $50 \%$ had magnitude differences less than 0.07 magnitudes, and $90 \%$ had a magnitude difference of less than 0.26 magnitudes. Figure 3.7 plots $\Delta m_{V}=m_{1, i}-m_{2, i}$ magnitude differences and demonstrates that the $10 \%$ of stars with $\left|\Delta m_{V}\right|>0.26$ were nearly all at the faint end of the sample.

A dispersion measure indicating the compatibility of the the two epochs of data can be written as

$$
\begin{equation*}
\sigma_{1,2}^{2}=\frac{\sum_{i=1}^{n}\left(m_{1, i}-m_{2, i}\right)^{2}}{n-1} \tag{3.4}
\end{equation*}
$$

where $\sigma_{1,2}^{2}$ is the variance of the scatter in the magnitude differences around


Fig. 3.8. - Merging the data from the two epochs of $R$ observations produced 324 star pairs. Their magnitude differences for $m_{R}<13.0$ drifted toward negative values indicating the epoch- 2 data saturated earlier in this magnitude range than did epoch-1 data.
$\Delta m=0.0$. Using only the 201 unsaturated star-pairs included in the zero-point $V$ band calibration results in $\sigma_{1,2}=0.15$ for the $V$ band. This is comparable to both dispersions obtained when self-merging the $V$ band data of the epoch- 1 and epoch-2 surveys.

Of 324 stars which had unsaturated $R$ measurements from both epochs, $50 \%$ had magnitude differences less than 0.08 magnitudes and $90 \%$ had magnitude differences of less than 0.28 magnitudes. Figure 3.8 shows the distribution of these magnitude differences was markedly assymetrical around the $x$-axis. Since each magnitude difference was $m_{1, i}-m_{2, i}$, where $m_{1, i}$ and $m_{2, i}$ are as in Equation 3.3, it appears that for bright stars epoch-2 data saturated first. The size of the
magnitude differences as calculated with Equation 3.4 for the 311 stars fainter than $m_{R}=12.0$ was 0.27 , somewhat larger than the dispersions from either the epoch-1 or epoch-2 band-merging processes.

In conclusion, since the magnitude-difference dispersions within each epoch were approximately the same size as the dispersions produced when the two epochs were merged, the two data sets blended together well. The $V$ data appeared to merge more smoothly than did the $R$ data. A danger in merging the data from the two epochs lies in the chance, or even certainty, that some of the stars are flux-variable and may have changed in brightness during the three years between the two epochs of observations. With an eye on this caveat, the final multiband survey notes which epoch or epochs of data contributed to the stellar magnitudes recorded. An interesting future study would be to examine the epoch-1 and epoch-2 data in the overlap region, and look for stars with unsaturated magnitudes yet large magnitude differences. Such a study would amount to a blink survey and might provide estimates of the flux-variability of the stars within the cluster.

### 3.7 Merging With a $J-H-K$ Survey

A $J-H-K$ survey was produced for NGC 2264 and described in detail in Lada et al. (1993). In brief, they observed a grid of overlapping frames at the Steward Observatory 1.55 m telescope at Mount Bigelow, using the Rieke $128 \times 128$ infrared camera equipped with Johnson $J, H$, and $K$ filters. With a $J$ and $H$ plate scale of $1.78^{\prime \prime} \mathrm{pix}^{-1}$, their survey covered an area of $21^{\prime} \times 38^{\prime}$, or approximately $60 \%$ of the coverage for the $V-R-I$ survey. The $K$ plate scale was $0.99^{\prime \prime} \mathrm{pix}^{-1}$, and covered approximately $70 \%$ of the region observed in $J$ and $H$. The infrared data from this run suffered from a serious vignetting problem which was largely corrected,
but nonetheless detracted slightly from the quality of the data. They estimated the fluxes in their survey were internally consistent to approximately $10 \%$. However, by cross-referencing the stars in their survey with other surveys (Allen 1973, Warner et al. 1977, Allen et al. 1977, Wynn-Williams \& Becklin 1979, Rydgren \& Vrba 1981, Tapia 1981, Rydgren et al. 1982, Cohen \& Schwartz 1983, Rydgren \& Vrba 1987, Perez et al. 1987, Castelaz \& Grasdalen 1988, Margulis et al. 1990, Mendoza 1990), certain systematic discrepencies were observed between their data and the literature. This was corrected to zeroeth order by biases added to the data. The biases added were $0.14,0.08$, and 0.08 to $J, H$, and $K$, respectively. Their final $J-H-K$ source list contained 2751 stars.

As mentioned in Section 3.6.4, there is a certain danger in merging data from two separate epochs. The $J-H-K$ data was taken during the interval 1990-1991, shortly after the first survey of $V-R-I$ data was obtained, so it is expected that not too many stars varied significantly during this time. After the complex procedure of $V-R-I$ band merging, merging the $V-R-I$ and $J-H-K$ lists was trivial. First all $J-H-K$ stars which merged with stars from the $V-R-I$ doubles list were identified and relocated to the doubles list. Other $V-R-I$ or $J-H-K$ sources which further merged with these rejected stars enlarged the doubles list even more. Then a straightforward merging was performed to combine the two three-band surveys. Any confused star clumps were noted and merged manually. In these merging steps, a $3.6^{\prime \prime}$ search radius was used, and no colour constraints were imposed.

### 3.8 Finishing the Survey

With all the automatic merging steps completed, the last challenge was to contend with the doubles lists. These lists contained a hideous crowd of double
stars, saturated sources, star clumps and chains, and otherwise difficult stars flagged during the merging processes. All such stars were grouped into clumps and merged by hand. Bad detections were discarded and good entries were merged using Equations 3.1-3.2. The photometry of these stars was probably less reliable because of source confusion, so the final survey includes a comment field indicating which sources originated from such clumps.

Finally, the sources were arranged in order of increasing right ascension and declination and assigned survey numbers of the form S0001, S0002, etc. A total of 4900 sources were catalogued in the survey. For easy comparison with the literature, the sources in the finished survey were cross-referenced with a few other standard inventories of NGC 2264 (Herbig 1954; Walker 1956). Although 138 Walker and 68 $\mathrm{LkH} \alpha$ stars are represented in the survey, good photometric measurements were not obtained for many since these usually bright sources were often overexposed in the CCD frames. Some were so saturated they were completely discarded from the survey, producing notable omissions of stars brighter than $m_{V}=12.0$. A future project would be to resurvey the cluster with very short exposures (only a few seconds) so these bright sources could be measured and the gap between the multiband survey and the earlier works could be bridged.

Parameters describing the photometric qualities of the finished multiband survey are presented in Table 3.1.

### 3.9 Survey Quality

In Sections 3.4-3.6 several tests were applied to the survey to gauge its photometric robustness. While the degree to which the survey was infiltrated by field stars is explored in Section 3.10, other questions remain. Is the survey

Table 3.1. Characteristics of the Multiband Survey

| Band | $m_{\min }{ }^{\mathrm{a}}$ | $m_{\max }{ }^{\mathrm{b}}$ | $N_{1}{ }^{\mathrm{c}}$ | $N_{3}{ }^{\mathrm{d}}$ | $N_{\text {tot }}{ }^{e}$ |
| :---: | ---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |
| $V$ | 12.5 | 18.5 | 332 | 1690 | 2235 |
| $R$ | 12.0 | 18.0 | 591 | 2077 | 2980 |
| $I$ | 12.0 | 17.0 | 242 | 2200 | 2868 |
| $J$ | 9.5 | 15.0 | 163 | 1748 | 2095 |
| $H$ | 8.0 | 15.0 | 70 | 1572 | 1835 |
| $K$ |  | 14.5 | 362 | 1156 | 1658 |

aSources brighter than this magnitude have unreliable magnitudes and positions. Occasionally sources show indications of saturation even if they are 0.5 magnitudes fainter than this limit.
${ }^{\text {b }}$ Magnitude limits for the $V, R$, and $I$ surveys were determined during data reduction for a $95 \%$ completeness level, and by looking for roll-overs in magnitudebinned histograms. Limits for the $J, H$, and $K$ surveys are from Lada et al. (1993).
${ }^{\text {c }}$ The number of sources in each band that had no confirming observations in other bands. These are likely to be strongly contaminated with image defects.
${ }^{\mathrm{d}}$ The number of sources in each band that was detected in at least two other bands. These are very reliable sources.
${ }^{\text {e }}$ The total number of detections in each band.
corrupted with many image defects flagged as valid sources? How many objects were missed? How good is the astrometry?

Survey completeness describes the probability that a star in the sky was represented in the survey. The best way to estimate completeness is to map a small region of the survey with greater sensitivity (i.e. longer exposure times or more coadded frames). This sub-survey would include much fainter stars than does the full survey. Comparing the success rate at which stars in the more complete sub-survey were detected by the large survey yields completeness estimates. Since a sub-survey of NGC 2264 was not made, completeness must be estimated differently. Artificial stars were added to a survey image and the success rate of retrieving them by the IRAF tasks DAOFIND and PHOT was monitored. Defining the limiting magnitude of each band to occur at the $95 \%$ completeness level, limiting magnitudes for the $V, R$, and $I$ bands were determined to be 18.6, 18.7, and 17.4. Another way to gauge magnitude limits was to look for roll-overs in the luminosity functions. In Figures 3.9-3.11, these roll-overs occur near magnitudes 18.5, 18.0, and 17.0. Such deviations from power-law distributions could be real results, reflecting a lower luminosity cut-off in the luminosity function. But since they are at approximately the same completeness limits determined by adding artificial stars, such hopeful explanations are unnecessary.

Additional assaults upon completeness are due to spatial, and not photometric, limitations. Since the survey regions of the $V, R$, and $I$ bands are not perfectly overlapping, stars near the edges of the survey regions may not be included in all three surveys. Furthermore, the $J-H-K$ spatial coverage is less than $2 / 3$ the $V-R-I$ spatial coverage, so near-infrared colours are not available for all stars even if they are brighter than the detection limits. Lastly, stars that were very bright ( $m<12.0$ for $V, R$, and $I$ ) are usually saturated. As such, accurate coordinates


Fig. 3.9.- A histogram of apparent magnitudes for the 2235 V detections in the survey is shown. A power-law was fit over the range $m_{V}=13-18$, and the faint magnitude roll-over near $m_{V}=18.5$ reveals the survey magnitude limit. The excess of stars near $m_{V} \leq 12$ is due to all the bright stars in the survey saturating and accumulating at those magnitudes.


Fig. 3.10.- A histogram of apparent magnitudes for the $2980 R$ detections in the survey is shown. A power-law was fit over the range $m_{R}=13-17.5$, and the faint magnitude roll-over near $m_{R}=18.0$ reveals the survey magnitude limit.


Fig. 3.11. - A histogram of apparent magnitudes for the $2868 I$ detections in the survey is shown. A power-law was fit over the range $m_{I}=13-16.5$, and the faint magnitude roll-over near $m_{I}=17.0$ reveals the survey magnitude limit.
and magnitudes were not obtained and these stars were not necessarily included in the survey at all or any bands.

The reliability of the survey is a measure of how likely a single entry in the survey represents a genuine source on the sky. If $N_{g}$ entries in the survey are genuine sources, and $N_{b}$ are bad entries with nonastronomical origins, the reliability of the survey is defined as

$$
\begin{equation*}
\text { Reliability }=\frac{N_{g}}{N_{g}+N_{b}} \tag{3.5}
\end{equation*}
$$

As in completeness estimates, reliability is best gauged by comparing the survey results to a second survey. In the absence of a second survey in each band, two other methods were devised to determine the survey reliability. The first exploited the overlapping nature of the frames in the survey. Define $\mu_{s}$ to be the average sky density of stars in the survey region, and $\mu_{d}$ to be the average sky density of defects misidentified as sources. $N_{\text {tot }}$, the total number of unmerged sources (both good and bad) extracted from the image frames of a survey can be written as

$$
\begin{equation*}
N_{\mathrm{tot}}=J \omega \mu_{d}+J \omega \mu_{s} \tag{3.6}
\end{equation*}
$$

where $J$ and $\omega$ equal the number of frames in the survey and the solid angle in each frame, respectively. The master lists discussed in Section 3.4 contained these $N_{\text {tot }}$ sources. Since nearly every spurious image defect would survive the survey-making project unmerged, the total number of image defects in the completed survey would be $J \omega \mu_{d}$. However, assuming a flawless merging algorithm the number of stellar sources in the final source list would be only $\Omega \mu_{s}$, where $\Omega$ is the solid angle of the entire region surveyed. So the number of entries in a merged source list will be

$$
\begin{equation*}
N=J \omega \mu_{d}+\Omega \mu_{s} \tag{3.7}
\end{equation*}
$$

Eliminating $\mu_{\mathrm{a}}$ from Equations 3.6-3.7 and writing the number of defective sources in the survey as $N_{d}=J \omega \mu_{d}$ yields

$$
\begin{equation*}
N_{d}=\frac{r N-N_{\mathrm{tot}}}{r-1} \tag{3.8}
\end{equation*}
$$

where $r=J \omega / \Omega$. The factor $r$ is the ratio of sky coverage vs. the merged sky coverage. It represents the degree to which the overlapping survey frames were redundant. The values of $N_{d}$ for the epoch-1 $V, R$, and $I$ surveys and the epoch- 2 $V$ and $R$ surveys are $153,503,367,159$, and 377 unreliable detections. If these truly are the numbers of spurious detections (assuming mergings involving these extractions with genuine sources are rare) then approximately 1559 entries in the survey are actually image artifacts and the survey is only $68.2 \%$ reliable. The $J, H$, and $K$ surveys may introduce further unreliable sources. A danger with this calculation was that it was based upon a small difference between two large numbers. For example, to calculate the value of $N_{d}$ for the epoch-1 $V$ band, the values of $r N$ and $N_{\text {tot }}$ were 2692 and 2623, and their difference was only 69 . Furthermore, a star which is so faint that it is detected in only one frame even though it occurs in a region of frame overlap would contribute unnecessarily to the spurious detection list. Repeating this calculation but including only extractions that were brighter than the completeness limits given in Table 3.1 resulted in essentially $100 \%$ reliable sources.

The high spatial density of sources in the cluster made it important to determine how frequently mergings occurred between image defects with good data. While mergings involving defects and sources within a single band would have been flagged as a clump and probably would have resulted in the defect's rejection in the steps of manual merging, a defect in one band might merge with a source in another band, especially if the source had faded to unmeasurable levels
in the band containing the defect. Since there were 4900 entries in the survey area of approximately $4.1 \times 10^{6} \operatorname{arcsec}^{2}$, the average distance between sources in the survey was $29^{\prime \prime}$. Since the search radius used in making merges was only $3.6^{\prime \prime}$, the likelihood of an image defect falling close enough to another star (or defect) to be a merger candidate was only $1.5 \%$. Even if 2000 of the entries were defects, the number that would merge across bands with each other or other genuine sources would only be approximately 30 . So it is clear that merges with image defects are not a matter of concern.

That image defects are rarely involved in multiband mergings is not only reassuring, it was the starting point for the second method of estimating survey reliability. This method is probably more trustworthy than the technique using Equation 3.8 because of the problems noted with that calculation. A $20.6^{\prime} \times 39.0^{\prime}$ area centered upon $6^{h} 38^{m} 3.8^{s}, 9^{\circ} 41^{\prime} 6^{\prime \prime}$ was selected. This region was completely surveyed by each of the three $V, R$, and $I$ bands. This subsurvey area was polled to find all the $V-R-I$ survey sources detected in only one band. In the three bands, 159,310 , and 130 such sources were found. In this region, a total of 2583 sources are listed in the $V-R-I$ survey, so by assuming that all the single-band sources are image defects suggests the reliability of the $V-R-I$ survey is $76.8 \%$. By imposing the magnitude limits in Table 3.1 reduces the numbers of singly detected sources to only 70,35 , and 22 , suggesting a minimum survey reliability of $95 \%$.

Clearly, an excellent way to insure that a subset of stars from the survey consists of real sources and not defects is to simply to require that each source be detected in at least two bands, or is brighter than the limiting magnitude of at least one band. The occasional defect will sneak through this filter, but most will be caught. Some good sources will inevitably be discarded by this filter, especially those that are barely detectable. Indeed, of the three short-wavelength bands,
the $I$ data penetrate less deeply than the others by one magnitude and has so has a smaller number of single-detection entries. But comparatively little can be done with a source with only one magnitude, so losing these unreliable sources is a reasonable cost. Of the full 4900 member multiband survey, 1760 entries represent singly observed objects.

A trick future surveyors could use would be to have grids overlapping to the extent that every location is observed at least twice. Then for every valid source, at least one confirming observation would be anticipated.

Finally, a comment upon the astrometry. Comparing the coordinates of survey stars with the coordinates of stars from other sources (Lapicz 1984; Lada et al. 1993) indicated the survey coordinates were accurate to approximately $0.53^{\prime \prime}$.

### 3.10 Field Stars and Cluster Members

The multiband survey contains thousands of sources. Even when only including sources observed in the $V$ band and at least one other confirming observation in $R$ or $I, 1886$ sources remain. This large ensemble of sources must clearly be contaminated by field stars, both background and foreground. By observing patches of sky near the cluster, Lada et al. (1993) measured the field star density at $K$ and found it was $25 \%$ higher towards NGC 2264 . This implied a cluster population of 230 stars. But since the GMC behind the cluster eliminates many background sources by extinction this is an underestimate of the cluster membership. Correcting for this effect they calculated approximately $360 \pm 130$ members reside in the cluster. Estimates by Adams et al. (1983) were higher ( $\approx 1100$ for the same spatial coverage) but they did not include the essential corrections for noncluster members.

Since the obscuration in the area of NGC 2264 is complicated (Karlsson 1972), the straightforward method of comparing on-cluster star densities with off-cluster star densities that Lada et al. (1993) used at $K$ may not be so easily applicable to NGC 2264 at $V$. So models were used to predict how many stars would one expect to see in the foreground and in the background, using basic principles of galactic star densities, dust extinction from the galactic disk, and extinction from Mon OB1 behind the cluster. This is similar in flavour to the complicated model of Bahcall \& Soneira (1980), although obviously in a highly simplified format. A distance-limited luminosity function (Wielen et al. 1983) measured for a 20 pc sphere centered on the Sun was used to approximate the population density of stars in the galactic disk. This luminosity function was volume-normalized, and by integrating through space towards the cluster the numbers of foreground stars that would be seen were estimated. Integrating beyond the cluster the number of background stars was calculated in the same way. Before being detected at Earth, the light from these background stars must penetrate the murky dust of the Mon OB1 dark cloud and the cluster itself. Converting the 0.5 magnitudes of extinction at $K$ to the visible band results in $A_{G M C}=4.3$ magnitudes (Rieke and Lebofsky 1985). Another consideration for both foreground and background stars is the interstellar extinction due to dust in the galactic disk. The values used by researchers for fields near NGC 2264 typically range through $0.3-1.5 \mathrm{mag} \mathrm{kpc}^{-1}$ (Karlsson 1972). For this study the the vintage value of $\mathrm{A}_{\text {ISM }}=0.7 \mathrm{mag} \mathrm{kpc}{ }^{-1}$ was used. Deviations from this value were not too important since the effects of interstellar extinction were mostly dwarfed by the extinction from the GMC. Since the interstellar medium is almost certainly clumpy, the extinction values for the GMC and interstellar space were only estimates.

Various models were calculated using the extinctions from the GMC and


Fig. 3.12. - The data for $V$ sources confirmed by detections in $R$ or $I$ are displayed along with model estimates of field stars calculated using a solar-neighborhood luminosity function, interstellar extinction of $0.7 \mathrm{mag} \mathrm{kpc}^{-1}$, and the model parameter $A_{G M C}$ which was the $V$ extinction due to the background GMC.
mundane non-cluster dust ( $A_{G M C}$ and $A_{I S M}$ respectively) as free parameters. These models, denoted as $N_{f}\left(A_{G M C}, A_{\text {ISM }}\right)$, produced histograms of anticipated field star counts as a function of apparent magnitude. Figure 3.12 shows a histogram of the 1886 V stars which were confirmed in at least one of the two bands $R$ or $I$. Also shown are the model results for $N_{f}(4.5,0.7)$ and $N_{f}(5.0,0.7)$. If $A_{G M C}$ was set to 4.0 magnitudes or less, the number of background stars shining through the GMC grew so large for $m_{V}=16$ or fainter that more stars were predicted than were observed. If $A_{\text {OMC }}$ was set to more than 5.5 magnitudes, the population of background stars near $m_{V}=18$ dropped so quickly that the number of stars in the the survey which must be attributed to the cluster rocketted up to more than

300 members in just the magnitude bracket $m_{V}=17.75-18.75$. So while $A_{G M C}$ may be clumpy, its average value is probably approximately 4.5-6.0 magnitudes.

The numbers of field stars calculated in the magnitude bins were not strongly dependent upon the extinction values for $m_{V} \leq 17.0$. This is because with that magnitude limit, the majority of the field stars are foreground stars-all the background stars were too extincted to be included. As a result, an estimate of cluster membership can be made. The total number of stars in the cluster brighter than $m_{V}=17.0$ for the various models was calculated as $329,346,364$, and 345 for the four models $N_{f}(4.5,0.7), N_{f}(5.0,0.7), N_{f}(5.5,0.7)$, and $N_{f}(4.5,1.0)$. The numbers of additional field stars (foreground, background) for these four models are $(179,61),(179,34),(179,16)$, and (171,43). Population histograms for the models $N_{f}(4.5,0.7)$ and $N_{f}(5.0,0.7)$ are shown in Figure 3.13. The models were restricted to stars brighter than the limiting magnitude of approximately $m_{V}=18.5$

Lada et al. (1993) posit that the majority of noncluster stars in their $J-H-K$ sample are background stars, mostly G-K dwarfs. Yet because of extinction and our survey magnitude limits, most of the noncluster stars in the $V-R-I$ bands must be foreground stars. So a fast yet effective way to remove the background stars is to require observations in all six bands. To allow for the occasional error and differences in sky coverages for the different bands (especially at $K$ ), this should be relaxed to detections in four or five bands. This results in a foreground star and cluster membership estimate of 815 stars. Subtracting the likely number of foreground stars leaves a cluster population of 636 stars. This is an underestimate for two reasons. First, deeply embedded stars will be missed. Second, the spatial resolution of the survey is such that multiple stars were not likely to be resolved. The search radius of $3.6^{\prime \prime}$ used in the survey would blend any multiples separated by less than $\sim 3000$ a.u., or $10^{-2} \mathrm{pc}$. Even careful inspection of the images would not


Fig. 3.13.- Histograms of cluster stars, determined by subtracting model estimates from the observed numbers of survey stars, are shown for two different models. For stars brighter than $m_{V}=17.0$ the estimated number of stars in the cluster was largely parameter-invariant. The survey limiting magnitude was approximately $m_{V}=18.5$, so the results for this magnitude region were unreliable.
reveal multiplicity in sources closer than several hundred astronomical units. To distinguish foreground stars from cluster stars requires additional information, such as distance measurements, radial velocities, or spectroscopic signatures indicating a youthful nature.

### 3.11 Summary

Images surveying NGC 2264 were reduced and the point sources were extracted to produce source lists of the region in the $V, R$, and $I$ bands. A second set of observations at $V$ and $R$ were reduced to produce another pair of source lists. Together these five surveys provide nearly complete spatial coverage of the cluster. The source lists were merged into a master $V-R-I$ survey which was subsequently merged with the $J-H-K$ survey described by Lada et al. (1993) to produce a multiband survey in 6 bands with 4900 members. The astrometry of this survey is accurate to approximately $0.5^{\prime \prime}$ for unsaturated sources, and the photometry of most of the sources is better than a tenth of a magnitude. The limiting magnitudes and information describing the survey are shown in Table 3.1.

The survey was estimated to have a $95 \%$ completeness for stars within the limiting magnitudes. The completeness drops dramatically for saturated stars which, due to the nature of their flat-topped point spread functions, have inaccurate photometry and coordinates. The reliability of the entire survey is only $68-77 \%$, but by imposing the filter that all sources must be observed in at least two bands, or that at least one magnitude for each source must be brighter than the survey sensitivity limits, the survey reliability is raised to higher than $95 \%$, and still retains 4380 members in the six-band survey.

Models of field star populations and interstellar extinction suggest
approximately 350 stars reside in the cluster. But by combining models of the space density of foreground stars with a few selection criteria applied to the survey stars, a cluster population of 636 stars is estimated. If multiple stars are the norm, the number of stars in the cluster could be much larger.

Creating this survey was a huge project, and the information it contains is just beginning to be assessed. In Chapter 5 the spectra of a subset of sources will be analyzed. Additional analysis is in Chapter 6.

## Chapter 4

## NEAR INFRARED IMAGING POLARIMETRY

### 4.1 Overview

In this chapter the construction and performance of a polarimetry device are discussed. Polarimetric data are presented for two bright nebulae (Sharpless 106 and Sharpless 140) as well as for a fainter clump of nebulosity near the multiband survey source S3321. In these sources polarization levels as high as $50 \%$ are observed in $J$ and $H$, while the results at $K$ are marginal because of the poor performance of the analyzer at long wavelengths. Both centrosymmetric and more complex polarization vector fields are observed around the bright nebulae and the S3321 nebula. Nebular colours allow the illuminating sources to be identified in the S3321 nebula; furthermore these colours argue against single scattering of light as the illumination mechanism for the nebula unless large amounts of extinction were invoked. The variation of fractional polarization as a function of radius from the nebular center is complex and inconsistent with simple geometries and single
scattering models for Sharpless 106 and Sharpless 140, although results for the S3321 nebula are inconclusive.

### 4.2 Introduction

Imaging polarimetry can be used to probe the conditions and geometries in astronomical objects, and especially the dark reflection nebulae associated with star formation. While wispy veils of faint yet polarized nebulosity are most commonly associationed with young stellar objects, they are not restricted to pre-main sequence phenomona (Schmidt et al. 1978; Aspin \& McLean 1984; Heckert \& Smith 1988; and others). The nebulosity often exhibits high levels of linear polarization in the optical and infrared-even surpassing $20-30 \%$ (Joyce \& Simon 1986; Sato et al. 1985; Dyck et al. 1973; and others). Single-beam maps of the infrared polarization structure have often revealed the polarization vectors to be arranged centrosymmetrically around the exciting sources in the nebulae or in aligned fields (Nagata et al. 1983; Aspin et al. 1985; Sato et al. 1985; Ward-Thompson et al. 1985; Joyce \& Simon 1986; Burns et al. 1989; and references contained in Bastien \& Ménard 1988). Some observers have reported a strip of low polarization values at the center of the centrosymmetric pattern. These polarization nodes flank the core source (Warren-Smith et al. 1979; Ward-Thompson et al. 1985; Aspin et al. 1985) and have been convincingly explained as resulting from a collimating disk (Ménard et al. 1988; Bastien \& Ménard 1988). These results fit nicely with other single-beam measurements that indicate that bipolar outflows exhibit cores which are polarized in a direction perpendicular to the flow axis (Sato et al. 1985; Gehrz et al. 1982; Hodapp 1984).

Other work has concentrated on how the fractional polarizations and the
polarization angles of some sources are wavelength dependent (Dyck et al. 1973; Heckert 1988; Heckert \& Zeilik 1981; Heckert \& Smith 1988; Lacasse et al. 1981). These rotations are very large ( $86^{\circ}$ for $\mathrm{W} 33 ; 90^{\circ}$ for $\mathrm{OH} 12.9-03 ; 60^{\circ}$ for Ceph A ) In some cases even the overall polarimetric field structure is wavelength-dependent. The polarization structure of some sources is subject to temporal changes as well (Vrba et al. 1979). Different mechanisms have been advanced to explain these observations, each operating most effectively in different regimes of temperature, density and geometry. They all may be applicable in various astronomical settings, and more than one mechanism may contribute to an object's overall polarization structure. A few of these mechanisms are discussed below.

## The Davis-Greenstein Mechanism

Light can become partially polarized by passing through a cloud of elongated, spinning dust grains situated in the galactic magnetic field (Hildebrand 1988; Martin \& Angel 1976; Savage \& Mathis 1979; Clayton \& Cardelli 1988). Such grains would assume alignments perpendicular to the field and would then extinct light anisotropically-that is light passing through the grains would become polarized perpendicular to the grains (or parallel to the magnetic field). This "Davis-Greenstein mechanism" is compelling, yet difficult to model completely and convincingly. In the literature this is often referred to as dichroic extinction.

Dichroic extinction has been convincingly detected in the outflow source Sharpless 140 (Lonsdale et al. 1980). Furthermore, single-beam polarimetric maps of pre-main sequence infrared sources have suggested that, similar to field star observations, their polarization angles tend to align with the local galactic magnetic field (Heckert \& Zeilik 1981; Dyck \& Lonsdale 1979; and others). Perhaps
these objects have collapsed along the magnetic field lines (Cohen et al. 1984, and sources therein), and the grains aligned in the field produce polarizations parallel to the magnetic field via dichroic extinction (Bastien 1987). A difficulty with this explanation is that high resolution polarimetric maps have shown that often the polarization vectors in these putative disks are aligned perpendicular to the outflow axis, $90^{\circ}$ away from what would be expected (Aspin et al. 1985; Warren-Smith et al. 1987). Never mind, the theorists say-that is just proof that the magnetic fields are wound into toroids in the disks.

It has been observed that for sources polarized by dichroic extinction, the empirical relation $P_{\max }<0.09 E(B-V)$ holds, where $E(B-V)$ is the colour excess (Serkowski et al. 1975). This indicates that unless a source is extremely reddened its polarization is not likely to exceed a few percent. Some of the largest polarization levels ( $15 \%$ at $11.1 \mu \mathrm{~m}$ in the Kleinmann-Low object, Dyck \& Beichman 1974; $15 \%$ at $V$ for stars extincted near M 17, Schulz et al. 1981) indicate the extinction polarization mechanism can be very efficient, producing polarizations at a rate as high as $P / A_{V} \approx 3 \% \mathrm{mag}^{-1}$. Models have matched and exceeded this efficiencies with computed values as high as $P / A_{V} \approx 22 \% \mathrm{mag}^{-1}$ (Mathis 1986).

## Centrosymmetric Scattering Models

While it is clear that reflection nebulae are illuminated by nearby stars, it is not certain how much scattering can be invoked to explain the polarization structure in these nebulae. Careful modelling has shown the beautiful centrosymmetric polarization fields surrounding such sources are due to dust scattering (Elvius \& Hall 1967; Shirt et al. 1983; Bastien \& Ménard 1988; and others). The monotonic increase in polarization levels as a function of radius can be explained using
simple geometries such as the case of a spherical reflection nebula illuminated by a central source. As light leaves the nebula it is scattered and polarized. The fractional polarization of scattered light is maximized when the scattering angle is near $90^{\circ}$ (Greenberg \& Hanner 1970)—this is related to why the daytime sky is most polarized $90^{\circ}$ away from the sun (Shurcliff \& Ballard 1964), although that is an example of Rayleigh scattering. Light from an embedded source that experiences little scattering before being detected on Earth will therefore have little polarization, and this mostly unscathed light will appear to originate from near the nebular core. But consider a photon that leaves the embedded source and just before escaping the nebula is scattered towards the Earth. If the projected distance between the embedded source and the scattering location is large, the photon must have scattered by nearly $90^{\circ}$ to arrive at the terrestrial observer's detector, and will therefore be highly polarized. While the components of the beam with the highest polarizations will be polluted by other photons which scattered by more (or less) than the optimal $90^{\circ}$, the contributions from these diluting photons will decrease the greater the apparent distance from the illuminating core becomes. Astronomical sources which consist of luminous objects embedded in symmetric or spherical reflection nebulae show radial polarization profiles which are monotonically increasing, and even very nearly linear ( $\mathrm{LkH} \alpha 208$ by Shirt et al. 1983; NGC 1999 by Warren-Smith et al. 1980). Planar slab models of dust clouds illuminated by a single source produce results that are strongly geometry dependent, mostly complicated by the angular dependence of Mie scattering (Greenberg \& Roark 1967; Greenberg \& Hanner 1970).

## Linear Scattering Models

The scattered-light model has been invoked in modified form to explain linear polarizations of stars, or even fields of aligned polarization vectors (Elsässer \& Staude 1978). In this model, a young stellar object is surrounded by an optically thick disk with its axis of rotation contained within the plane of the sky. A collimated outflow (possibly but not necessarily bipolar) is also required. Light travelling directly from the source to the observer would be extincted by the disk, but light escaping from the star's polar regions would scatter off the outflow and subsequently be observed at Earth as a highly polarized source. This style of analysis illustrates how polarimetric vector fields can be used to interpret the geometry of illuminating sources. While most astronomical methods measure temperatures, densities, and other physical quantities, polarimetry provides a unique method for probing astronomical settings.

Which of these polarization mechanisms are important in young stellar objects is uncertain. Perhaps they all play roles in determining the many interesting phenomena seen in polarization vector fields: centrosymmetric and linear field patterns, low-polarization nodes, monotonic increases in polarization levels, temporal variability, and changes in wavelength. Further work is necessary to unravel the mysteries of these secretive objects. With the development of infrared arrays new avenues of discovery are accessible. Regions arcminutes in size can be quickly mapped with very high resolution-single-beam observing with its slow mapping rate and beam-smearing is no longer the only option. To exploit the capabilities of the new technologies, it was inviting to augment a high quality infrared camera with a polarimetric analyzer. Such a project could lead to insights about nebular complexes and answer interesting questions about individual
nebulae. It would expose the nature of the polarimetric vector field, indicate which of the many stars in a field were the exciting sources, and might identify the mechanisms responsible for polarizing the light,

The polarimetric structure of many bright sources have been studied (Joyce \& Simon 1986; Heckert 1988; Schmidt et al. 1978; Dyck \& Lonsdale 1979; Sato et al. 1985; Shirt et al. 1983; and others). These sources were excellent subjects to use to test a new polarimetric device's performance. But this dissertation is a study of various aspects of the stars and ISM in NGC 2264 and the polarimeter's mission was to be used there. A review of the $J, H$, and $K$ images of the region obtained by Lada et al. (1993) revealed many regions with clumps of near-infrared nebulosity. Even though the surface brightnesses of these nebulae were low, they were bright enough to suggest the success of polarimetric surveillance.

### 4.3 Building a Polarimeter

In order to construct a working polarimeter for a telescope, three elements are necessary. The first is an infrared camera. The NICMOS $256 \times 256$ infrared array camera (Rieke et al. 1993) was a perfect vehicle for this study. Sensitive to the photometric bands $J, H$, and $K$, its low dark current ( $\approx 40 \mathrm{e}^{-} \mathrm{sec}^{-1}$ ), read noise ( $\approx 50 \mathrm{e}^{-}$), and deep wells ( $\approx 2.4 \times 10^{5} \mathrm{e}^{-}$for linear response) enables it to produce beautiful astronomical images. The large array size allow large pieces of the sky to be recorded with each image. The second necessary element is a polarimetric analyzer suitable for work in the near infrared-this is the component that dissected light into its polarization components. Finally, a housing for the analyzer compatible with the NICMOS array camera had to be designed and built. An important constraint in the design was the need to minimize the disturbance
to the existing camera system. This precluded the use of wire grids and half-wave plates in the cryogenic part of the camera.

### 4.3.1 The Polarimetry Analyzer

An ideal polarimetric analyzer could be described as a device that would be $100 \%$ transparent to radiation that has its electric field vector aligned with the transmission axis of the analyzer while rejecting all the radiation with its electric field vector aligned at an angle $90^{\circ}$ to this axis. Unfortunately, the performance of actual analyzers are not ideal and so their shortcomings must be characterised.

The ability of an analyzer to discriminate between photons with differently oriented electric fields can be measured by the two principal transmittances $k_{1}$ and $k_{2}$. When a $100 \%$ polarized beam strikes a polarimetric analyzer, the intensity fraction transmitted depends upon the orientation of the analyzer's transmission axis. When rotated to allow maximum transmission, this polarizer will transmit a fraction $k_{1}$ of the incident light intensity. At an orientation $90^{\circ}$ from that angle the minimum fraction of light $k_{2}$ will be transmitted. A useful way to express the performance of an analyzer is by its extinction factor $E$, which is the ratio of maximum to minimum transmission when initially unpolarized light passes through two analyzers while one is being rotated;

$$
\begin{equation*}
E=\frac{k_{1}^{2}+k_{2}^{2}}{2 k_{1} k_{2}} \approx \frac{k_{1}}{2 k_{2}} \text { for } k_{1} \gg k_{2} . \tag{4.1}
\end{equation*}
$$

If the objects being studied were arbitrarily bright, the only requirement for a good analyzer would be a large value for $E$. But since in astronomy low light intensities are the norm, an additional requirement is that $k_{1} \approx 1$. This avoids angering the already light-starved astronomer. A large value for $k_{1}$ carries an added
bonus because it implies a smaller overall analyzer emissivity and a corresponding decrease in the amount of blackbody radiation from the analyzer itself. Emission from the analyzer is a significant source of noise since for practical reasons it was necessary to mount the analyzer in the camera guide box where it was at non-cryogenic temperatures.

In choosing an analyzer for this study, $E$ and $k_{1}$ were not the only things that had to be large-the analyzer itself had to be physically big. For even though it was to be mounted very near the field lens, infrared array technology has become so advanced that the useful light beam there is approximately 10 cm in diameter. A large analyzer was required to avoid cropping the field of view.

## Enticing Yet Unsatisfactory Analyzers

Wire grids are one of the best analyzers for the infrared. They work on the principle that light cannot pass though a series of wires if the light's electric field vector and the wires are aligned. This is because electric currents produced in the wire sap energy from the beam (Shurcliff \& Ballard 1964). In order for a wire grid to work be effective at a wavelength $\lambda$, the wires should be spaced by approximately $\lambda / 5$, and the wire's thickness should be approximately $1 / 5$ the width of this interwire spacing (Auton 1967). Making a grid with submicron dimensions for infrared applications is very challenging. Traditionally, wire grids for the near-infrared were made by coating an infrared-transmitting substrate such as $\mathrm{CaFl}_{2}$ with photoresist, exposing this to an interference pattern from an Argon laser, and then chemically etching the surface-leaving equally spaced sinusoidal ridges of photoresist (Auton 1967; Au \& Garvin 1980). By aluminizing the surface at an oblique angle, metal accumulates at the photoresist crests and a
series of wires is generated. Such wires are approximately $0.1 \mu \mathrm{~m}$ thick and are spaced approximately $0.25 \mu \mathrm{~m}$ apart (a frequency of approximately $10^{5} \mathrm{inch}^{-1}$ ). The transmittances of conventional wire grids are approximately $k_{1}=0.85$ and $k_{2}=0.03$ at $\lambda=1.5 \mu \mathrm{~m}$ (Mooney 1989; Molectron 1989). Unfortunately most wire grids are only a few cm in diameter-even the rare giant (and prohibitively expensive) wire grids are approximately 7.5 cm in diameter which would still result in large amounts of the field being lost if used with the NICMOS camera. Very promising for making large wire grids for use in the infrared is a technique in which an infrared transmitting substrate is coated with gold which is in turn coated with photoresist. After exposure to an interference pattern, rows of photoresist are leached away to expose strips of gold which are then removed by an ion beam. When the remaining photoresist is chemically removed the gold strips it protected are exposed, and presto! a wire grid. The extinctions of these wire grids are as high as $E=200$ for $\lambda=1.06 \mu \mathrm{~m}$ (Cowan 1980), but at the time of this project were only commonly available with 2.5 cm diameters. Quotes for 10 cm grids were fabulously expensive (Anderson 1989; Garvin 1989). Equally extraordinarily costly were KRS5 substrate wire grids planned on being produced by ruling engines (Optometrics 1989).

There are still other analyzers available, such as Wollaston prisms which have the advantage of not extincting the second polarization beam (West et al. 1988; Werner \& Gill 1988). This device separates the two beams so both could be simultaneously imaged by the array camera. But since the objects to be studied were extended nebular sources, the two displaced images would overlap resulting in a hybrid sympatric zone that would be impossible to interpret. Furthermore, for noncryogenic use with the NICMOS camera such a prism would be bulky, necessarily custom-made, and very expensive if ever available at all.

## The Low-Tech Compromise

Having eliminated other possibilities, the victorious candidate for the infrared analyzer was a simple Polaroid HR Linear/IR sheet-a descendent of the first J-sheet polarizers. IR Polaroid analyzers consist of an oriented matrix of polyvinyl alcohol/polyvinylene, in sheets $430 \mu \mathrm{~m}$ thick, which are heavily dyed with iodine ink (Polaroid 1990; Trampani 1990). Although it does not have some of the emissivity-related benefits of a metallic wire grid, an IR sheet is an acceptable compromise. It is available in squares approximately 10 cm on a side which covers nearly the entire NICMOS field of view. Its infrared specifications, listed in Table 4.1, are good for $J$ and $H$, but poor at $K$. Other astronomical groups have successfully used HR Linear/IR sheet polarizers with single beam instruments (Castelaz et al. 1985; Burns et al. 1989).

### 4.3.2 Stokes Parameters as Determined by Ideal Analyzers

The polarimetric quantities sought are the normalized Stokes parameters $Q$ and $U$. These are defined as

$$
\begin{equation*}
Q=\frac{I_{0}-I_{90}}{I_{0}+I_{90}} \quad \text { and } \quad U=\frac{I_{45}-I_{135}}{I_{45}+I_{135}} \tag{4.2}
\end{equation*}
$$

where $I_{0}$ indicates the image intensity obtained when the analyzer is in the $90^{\circ}$ orientation, etc. Since this project did not involve measurements of circular polarization, the fractional polarization $P$ was calculated using

$$
\begin{equation*}
P^{2}=U^{2}+Q^{2} \tag{4.3}
\end{equation*}
$$

and the polarization angle $\phi$ was calculated using

$$
\begin{equation*}
\phi=\frac{1}{2} \arctan \left(\frac{U}{Q}\right) \tag{4.4}
\end{equation*}
$$

The normal angle convention was employed in that the polarization angle $\phi$ was measured counter-clockwise from due north.

The uncertainties in the Stokes parameters were calculated from straightforward applications of error propagation to Equations 4.2, producing

$$
\begin{align*}
\sigma_{Q}^{2} & =\frac{4}{\left(I_{0}+I_{90}\right)^{4}}\left(I_{0}^{2} \sigma_{90}^{2}+I_{90}^{2} \sigma_{0}^{2}\right)  \tag{4.5}\\
\sigma_{U}^{2} & =\frac{4}{\left(I_{45}+I_{195}\right)^{4}}\left(I_{45}^{2} \sigma_{135}^{2}+I_{195}^{2} \sigma_{45}^{2}\right) \tag{4.6}
\end{align*}
$$

where $\sigma_{90}$ denotes the intensity and poisson noise in the image at the $90^{\circ}$ analyzer orientation, etc. Error propagation applied to Equation 4.3 yielded

$$
\begin{equation*}
\sigma_{P}^{2}=\frac{1}{Q^{2}+U^{2}}\left(Q^{2} \sigma_{Q}^{2}+U^{2} \sigma_{v}^{2}\right) \tag{4.7}
\end{equation*}
$$

Using the simplification that the uncertainties and intensities in each of the four input images are approximately the same (but not identical or else $Q=U=0!$ ), the uncertainties in $Q$ and $U$ could be estimated as

$$
\begin{equation*}
\sigma_{Q}^{2}=\sigma_{U}^{2}=\frac{\sigma_{I}^{2}}{2 I^{2}}, \tag{4.8}
\end{equation*}
$$

where $\sigma_{I}$ and $I$ represent the parameters of a typical image. This result is interesting but was not used in the computations since it was simple to code Equations 4.5-4.6 into the analysis programs.

The uncertainty of $\phi$ can be elegantly estimated by working within the $Q-U$ plane. In this space, the length of the vector from the origin to the coordinates $(Q, U)$ is $P$. As long as $\sigma_{Q} \approx \sigma_{U}$, the uncertainty of the coordinates of the tip of the polarization vector-and therefore $\sigma_{P}$-is determined by the error circle described by $\sigma_{Q}$ and $\sigma_{U}$. This is also seen in Equation 4.7, where the simplification $\sigma_{Q} \approx \sigma_{U}$ yields $\sigma_{P}=\sigma_{Q}, \sigma_{U}$. As viewed from the origin of the $Q-U$ plane, the radius of the
$\sigma_{Q}-\sigma_{U}$ error circle subtends a small angle $d \psi$ given by $d \psi=\sigma_{P} / P$. Angles in the $Q-U$ plane transform into polarimetry angles by a factor of $1 / 2$ (Equation 4.4), so the uncertainty in $\phi$ can be written in terms of $d \psi$ by $\sigma_{\phi}=d \psi / 2$, and

$$
\begin{align*}
\sigma_{\phi} & =\frac{\sigma_{P}}{2 P} \text { (in radians) }  \tag{4.9}\\
\sigma_{\phi} & =28.65 \frac{\sigma_{P}}{P} \text { (in degrees) }
\end{align*}
$$

As long as $\sigma_{P} / P \ll 1$, Equation 4.9 can be used to calculate $\sigma_{\phi}$. If the uncertainties in the Stokes parameters become too large, the $\sigma_{P}$ error circle in the $Q-U$ plane bloats until it overlaps with the origin, at which point $P, \phi$, and the transformations in Equations 4.3-4.4 become meaningless.

### 4.3.3 Stokes Parameters as Determined by Real Analyzers

Using a non-ideal analyzer like the Polaroid sheet at ambient temperatures has three unfortunate side effects on the image: decreased signal, increased noise, and instrumental effects on the measured polarization.

Because of the insertion of a new filter into the light path, some of the light is blocked. An unpolarized beam is attenuated by the factor $\left(k_{1}+k_{2}\right) / 2 \approx 0.35$ in the near infrared, which applies to radiation from both the source and the sky. This signal decrease could be offset by increasing the integration time by the factor $2 /\left(k_{1}+k_{2}\right)$. But more difficult to amend is the decrease in the signal to noise ratio due to increased background emission from the filter which is most significant at the $K$ band. The results of these effects are discussed more in Section 4.4.2.

When light is reflected by a surface it accumulates a small amount of instrumental polarization. But since the light beam in this study experienced only two (normal) reflections before passing through the analyzer this was not a
significant problem. Also, this and other sources of nonastronomical polarizations were corrected for in the reductions described in Section 4.4.4. Potentially more problematical are errors in polarization values obtained using an analyzer where $k_{1} \neq 1$ and $k_{2} \neq 0$. Consider a light beam consisting of a component $I_{1}$ which is unpolarized and a component $I_{2}$ which is polarized at angle $\phi$. Pass this beam through an analyzer with its axis of maximum transmittance in direction $\theta$, and the intensity $I(\phi)$ transmitted would be

$$
\begin{equation*}
I(\theta)=\frac{1}{2} I_{1}\left(k_{1}+k_{2}\right)+I_{2}\left(k_{1} \cos ^{2}(\phi-\theta)+k_{2} \sin ^{2}(\phi-\theta)\right) \tag{4.10}
\end{equation*}
$$

Substituting Equation 4.10 into the expressions for $Q$ and $U$ in Equations 4.2 produces

$$
\begin{align*}
Q & \left.=\frac{I_{2}}{I_{1}+I_{2}}\left(\frac{k_{1}-k_{2}}{k_{1}+k_{2}}\right)\right) \cos 2 \phi  \tag{4.11}\\
U & =\frac{I_{2}}{I_{1}+I_{2}}\left(\frac{k_{1}-k_{2}}{\left.k_{1}+k_{2}\right)}\right) \sin 2 \phi \tag{4.12}
\end{align*}
$$

The measured polarization $P^{\prime}$ would be

$$
\begin{equation*}
P^{\prime}=P\left(\frac{k_{1}-k_{2}}{k_{1}+k_{2}}\right) \tag{4.13}
\end{equation*}
$$

where $P=I_{2} /\left(I_{1}+I_{2}\right)$ is the polarization that would be measured by a perfect polarimeter (i.e. $k_{1}=1, k_{2}=0$ ). Writing $P^{\prime}$ in terms of the extinction ratio $E$

$$
\begin{equation*}
P^{\prime}=P\left(\frac{2 E-1}{2 E+1}\right) \text { for } k_{1} \gg k_{2} \tag{4.14}
\end{equation*}
$$

illustrates that the polarization value will be underestimated. To insure that the polarization was measured within an accuracy of $1 \%$ (i.e. $\left(P-P^{\prime}\right) / P \leq 0.01$ ), it was important that $E \geq 99.5$. This was clearly exceeded by the values of $E$ in Table 4.1, except for at $K$ where the polarizations would be underestimated by approximately $2 \%$. These errors were smaller than the photometric errors in the study, so corrections for the effect were not important.

In conclusion, in terms of being able to correctly determine the Stokes parameters, the performance of the Polaroid HR linear/IR analyzer was satisfactory at $J$ and $H$ and only slightly degraded at K . But it will be shown that decreased filter transparency and increased thermal emission from the analyzer left it hobbled at $K$.

### 4.3.4 Design and Fabrication

As noted earlier, the polarimetric analyzer was to be mounted inside the camera guide box as close to the field lens as possible. The filter assembly had to meet two design requirements. First, the filter had to be capable of rotating from one filter orientation to the next in a matter of seconds since rapid atmospheric changes could be important in compromising the quality of the polarimetry data (Aspin 1990). Second, it had to conveniently slip in and out of the guide box so images could be taken both with and without the analyzer in place, with a minimum of fuss and telescope down-time during these transitions.

The filter assembly was designed using AUTOCAD programs. The chassis consisted of a rectangular frame that slid through an aperture cut into the guide box and bolted into place immediately above the field lens (Figure 4.1). A ring-shaped bearing mounted on the frame supported a platform which held the analyzer. The platform was rotated by a motor mounted outside the guide box, powered by a Hewlett Packard 6206B DC power supply locatec in the observing room. Eight grooves were inscribed into the platform ring at $45^{\circ}$ intervals. Using the arm of a microswitch to sense them, the analyzer oriented the analyzer to an accuracy greater than $0.45^{\circ}$. By maintaining the power supply at $5-7 \mathrm{~V}$ the filter assembly took only 2 s to advance from one filter location to the next. A control


Fig. 4.1.- A slightly simplified top view of the filter mount. The large box is the guide box. The analyzer (A) is 10 cm on a side and is fastened to the round filter platform by four clips. The perimeter of the filter platform is bound by a large pulley wheel (B). Four brackets on the underside of the pulley wheel (barely seen in this figure) grasp the inner edge of a large circular bearing (C), while the outer edge of the bearing is mounted to the chassis substage by another four brackets (D). A rubber belt ( E ) wrapped around the large pulley wheel communicates with a small pulley wheel ( $F$ ) driven by a DC motor. A small tower ( $G$ ) holds a microswitch $(\mathrm{H})$ which detects the presence of eight grooves, only two of which are labelled (J). When the arm of the switch is not resting in a groove, the DC motor is activated and the platform rotates until the arm falls into the next groove. A control paddle located in the control room is used to command the filter to advance to the next groove.
paddle located in the observing room was used to command the filter to advance to the next orientation. This paddle was embellished with an advisor-pleasing LED to indicate when the filter had advanced and was ready for observing. The completed filter assembly and paddle are shown in Figure 4.2.

### 4.4 The Shakedown Cruise

Its construction complete, two cloudy observing runs had to be endured before data were finally obtained with the polaroid analyzer. During 27-29 June 1991, the Steward Observatory 2.3 m telescope on Kitt Peak was used to observe sources at $J, H$, and $K$. Integration times ranged from 1-300 s. Seeing was fair, with stellar full widths at half maxima measuring approximately $2^{\prime \prime}$. An assortment of calibration frames necessary for the data reduction were also generated.

### 4.4.1 Polarimetry Observations

When observing a new polarimetry source, the first frames were taken without the analyzer in place. These frames were taken to verify that the object had indeed been found and that the nebulosity was bright enough to observe. Also, a good off-source position was sought-such a position was required to be nearby and free of nebulosity and stars. It was not always possible to find locations that were completely free of stars so cosmetically unattractive compromises were sometimes made.

Next, the analyzer was bolted onto the guide box and rotated to the $0^{\circ}$ orientation. Exposure times were adjusted so the nebular regions were well-exposed (or at least long enough so the data were background limited) yet still in the linear


Fig. 4.2.- The analyzer holder and control paddle. The analyzer is not mounted in this photograph. After being modified and rebuilt many times, the analyzer mount is sadly not as shiny as it was originally.
part of the NICMOS camera's response. Once the optimum exposure time was determined the real observing began. An image and its corresponding off-source frame were taken at the $0^{\circ}$ polarizer orientation. Using the paddle in the observing room, the filter was immediately rotated $45^{\circ}$ to the next position and another pair of exposures were taken. This process was repeated until pairs of frames were observed at the $0^{\circ}, 45^{\circ}, 90^{\circ}$, and $135^{\circ}$ positions. Additional observations were usually made at $180^{\circ}, 225^{\circ}, 270^{\circ}$, and $315^{\circ}$. These redundant images were taken because if no useful data were obtained for just one filter orientation, all the frames were useless for polarimetry. At the end of the final integration in a set, the analyzer was checked by the observer to insure that the filter had correctly rotated through all the quadrants. Bias-frames, which are images of extremely short exposure times, were also obtained for data reduction. Dark-current frames were taken but were not used during the reduction.

Just in case the polarizer rotated incorrectly during the night either due to mechanical or human error, an opaque tag was attached to the analyzer near the edge of the image. Since the analyzer was near the field lens this tag was visible on the raw frames in good focus and identified unambiguously the orientation of the filter. This precaution was helpful more than once when, in reducing the data, it was important to understand exactly what mistakes had been made in the early morning hours of a night a few months previous.

### 4.4.2 System Tests

The exposure times used to produce optimal background noise-limited images without the analyzer installed were not the same exposure times used when the analyzer was in place. This is because, as described in Section 4.3.3, the filter
decreased the signal to noise ratio by attenuation and by contributing to the noise via thermal emission. Observations of HD 162208 with and without the filter provided transmission efficiencies $(\eta)$ at all three bands, which are listed in Table 4.2. It can be seen that the values for $\eta$ are in reasonable agreement with $\left(k_{1}+k_{2}\right) / 2$ from Table 4.1. Note, however, that the values of $\eta$ are broadband results while $k_{1}$ and $k_{2}$ are monochromatic quantities.

When observing, integration times were set so the detector wells were not quite filled. Blank sky was observed and the approximate maximum integration times allowed before the wells of the detectors were filled without the analyzer installed $\left(t_{1}\right)$ and with the analyzer installed $\left(t_{2}\right)$ were calculated for each band (Table 4.2). If filter attenuation were the only process occurring, scaling all the exposure times $t_{1}$ by the factor $\eta^{-1}$ would result in properly filled detector wells. But in all bands $t_{1} / \eta>t_{2}$, so the integration times prescribed by $t_{1} / \eta$ would result in saturated detector bins. The reason $t_{1} / \eta>t_{2}$ is that with the analyzer in place, an additional source of noise-thermal emission from the filter-contributed to the rate at which photons were detected by the camera pixels. The changes in limiting magnitudes for $1-\sigma$ signal to noise ratios were calculated for each band by examining images obtained with and without the filter installed, and are listed in Table 4.2. The penalties at $J$ and $H$ are not too bad, but the filter specifications deteriorates at $K$.

### 4.4.3 Standard Reductions

Despite the title of this section, there is no standard recipe for reducing infrared array data. Especially with respect to sky subtraction and flat-field divisions, several methods should be tried and the results of each examined. The

Table 4.1. Specification for the HR Linear/IR Sheet Analyzer

| Band | $k_{1}$ | $k_{2}$ | $E$ |
| :--- | :---: | :---: | :---: |
| $J(1.2 \mu \mathrm{~m})$ | 0.630 | $7.08 \times 10^{-5}$ | 4450 |
| $H(1.6 \mu \mathrm{~m})$ | 0.707 | $9.66 \times 10^{-5}$ | 3660 |
| $K(2.0 \mu \mathrm{~m})^{1}$ | 0.757 | $8.71 \times 10^{-3}$ | 43.5 |

${ }^{1}$ These data is not for the $K$ band center ( $2.2 \mu \mathrm{~m}$ ) since information was not avalailable for the analyzer's performance at wavelengths longer than $2.0 \mu \mathrm{~m}$. Beyond $2.0 \mu \mathrm{~m}$ the performance of the analyzer rapidly degraded (Trampani 1990).

Table 4.2. Noise From the HR Linear/IR Sheet Analyzer

| Band | $\eta$ | $t_{1}$ <br> $(\mathrm{sec})$ | $t_{2}$ <br> $(\mathrm{sec})$ | $\Delta m$ <br> $(\mathrm{mag})$ |
| :---: | :---: | :---: | :---: | :---: |
| $J$ | 0.30 | 630 | 1400 | 0.80 |
| $H$ | 0.35 | 113 | 230 | 0.70 |
| $K$ | 0.30 | 33 | 13 | 1.3 |

method described here was the most successful for this batch of data. The terms sky-frames, object-frames, and bias-frames are defined in Sections 3.3.1-3.3.2. (In infrared astronomy, the word bias-frame is often used instead of zero-frame, and flat-field is used instead of sky-frame.)

First, each sky-frame was subtracted from its object-frame counterpart. This removed additive effects such as pixel bias voltages and sky emission. A collection of 20 bias-frames were observed and median-combined. The resulting bias-frame was subtracted from all the sky-frames and the resulting images were subsequently divided by their integration times and median-combined to produce a normalized master flat-field. The nebulae of interest were often in regions densely populated by stars, so producing a flat-field by this median-filtering process eliminated most of the stellar images. Each sky-subtracted object-frame was flattened by a flat-field division. Flattening removed the effect of differing gains for different pixels. Separate flat-fields were produced for each night and for each wavelength band. Furthermore, frames observed with and without the analyzer were reduced separately, including producing separate flat-fields. The filter and its thermal emission were sufficiently homogeneous that it was unnecessary to produce separate flat-fields for each analyzer orientation. Indeed, because of the decreased number of frames used to make such specialized flat-fields, doing so only increased the image noise and number of spurious star images in the resulting flat-fields.

### 4.4.4 Polarimetric Reduction Arcana

In addition to the mundane image reduction steps, additional calibrations were required to prepare the images for polarimetric analyses. These manipulations were developed to patch subtle cosmetic defects and errors introduced by preceding
reductions. Although each of the following steps had a beneficial result, they were performed with regret since they generally resulted in some loss of potential information.

## Bad Pixel Masking

First it was important to reduce the influences from pixels with unreliable photosensitivities. Since a polarimetry map required at least four input images, a consistently bad pixel would corrupt four pixels in the final map (unless the telescope tracked the sky absolutely perfectly, in which case only one pixel coordinate would be compromised). To correct for these bad pixels they first had to be identified. The majority could be located instantly by their consistently high or low values. In flattened images all the pixel values should be near unity except for those on astronomical sources. Flagging all the pixels several $\sigma$ above or below unity automatically located the bad ones. But unfortunately a large number had to be identified manually. These were the pixels that had little photosensitivity and did not drift much in value. Being nearly the same value in all images, after the sky-subtraction they masqueraded as sky pixels. To identify them the following peculiar but effective technique was devised. If four consecutively observed object-frames were shifted in the $x$-direction by zero, one, two and three pixels respectively and then coadded, a dead and nondrifting pixel would appear as a horizontal line of nearly uniform brightness four pixels long. By adding three more images shifted in the $y$-direction by one, two, and three pixels, a dead pixel would appear as a characteristic L-shaped artifact and the vertex of the artifact would be at the pixel coordinates of the dead pixel. Unfortunately, the array chip used on the first set of observations had a large number of bad pixels, and this process
had to be performed for each of three nights it was used. For the three nights, the total numbers of bad pixels identified were 990, 661, and 1206. Although this was less than a $2 \%$ pixel failure rate for the $256 \times 256$ array, it meant searching for bad pixels was a long and tedious procedure.

Once the bad pixels were identified to a satisfactory level of completeness the images were cleaned. Cleaning consisted of replacing each bad pixel with the weighted sum of all the adjoining and adjacent pixels-adjacent pixels received half the weighting given to adjoining pixels. Neighboring pixels which themselves were bad of course received zero weighting. This method worked well except when several bad pixels formed clusters. There was no way to deal with these regions except to note and lament them.

## Image Alignment

While observing each source, pointing errors accumulated so the telescope did not return to the exact same celestial location for each new integration. This was actually very useful in both identifying bad pixels and in providing a set of sky-frame images at slightly different locations so that a good median-filtered flat-field could be constructed. But before polarimetric calculations could proceed all the images required careful alignment. By using the IRAF tasks DAOFIND and PHOT, pixel coordinates were determined for bright yet unsaturated stars. All the reduced images were shifted by integer pixel values in $x$ and $y$ to coalign them as accurately as possible. The point spread functions of stars in individual frames were measured and compared to the point spread functions of the images in composite frames created by coadding all the coaligned images. The stellar full widths at half maxima increased by only a few percent in the coaddition indicating
the shifts were accurate.

## Final Calibrations

Examining the pixels in blank patches of sky (i.e. free of nebulosity or stellar images) revealed that the median sky pixel values differed between object-frames. These offset values appeared to be spatially invariant over each image, and were probably due to the very light cloud wisps that dogged the observations of even the best night of the run. Correcting for these biases would also help remove both instrumental polarizations and problems due to scattered moonlight which can be strongly polarized (Serkowski 1974). Values (typically equivalent to only a few percent of the average brightness of the nebulae) were subtracted from each image to force the median sky values to zero.

Photometry of the images revealed systematic magnitude differences between stars of the various frames which were probably attributable to the occasional clouds previously mentioned. This problem was addressed by multiplying each frame by gains so the stellar magnitude differences were minimized. Unlike the bias corrections which might introduce only small artificial polarizations of $\approx 1 \%$, the multiplicative corrections were uncomfortably large, nearly $10 \%$ for some images. Such factors could introduce spurious polarization levels as high as $5 \%$ for the strongly polarized sources in this study. The large size of this final correction reaffirmed that polarimetric observations should be obtained on cloud-free, moonless nights.

## Sacrificing Resolution

Since each pixel was smaller than the atmospheric seeing limit the images were degraded in resolution by binning before the Stokes parameters were calculated. As the seeing was approximately $2^{\prime \prime}$ and each pixel subtended approximately $0.6^{\prime \prime}$ on a side, the pixel size could be increased by a factor of $2 / .6 \approx 3$ without a loss of information. Dividing a $256 \times 256$ image into $3 \times 3$ squares and coadding the nine pixels of each $3 \times 3$ region into a new pixel, an $85 \times 85$ image was produced which had the same resolution but $\sqrt{9}=3$ times the signal to noise ratio.

## Finally: Stokes Parameters

After being sky-subtracted, flat-field divided, cleaned of bad pixels, coaligned, corrected for additive and multiplicative effects, and degraded in resolution, the images were finally ready. Frames had been obtained with the analyzer oriented at $0^{\circ}, 45^{\circ}, 90^{\circ}, 135^{\circ}, 180^{\circ}, 225^{\circ}, 270^{\circ}$, and $315^{\circ}$. The differences between images produced by the analyzer oriented at $180^{\circ}$ intervals (e.g. $I_{225}-I_{45}$ ) were examined and no serious differences were noted so all the images were appropriately grouped pairwise and coadded to produce frames at $0^{\circ}, 45^{\circ}, 90^{\circ}$, and $135^{\circ}$. For the Stokes parameters to be calculated at a pixel coordinate, that coordinate was required to have sufficient nebular emission at all four analyzer angles-there was no point in calculating $Q$ and $U$ for blank sky. The dispersion $\sigma_{s k y}$ of pixel values were measured for blank patches of sky. The minimum pixel value to qualify for Stokes parameter calculations was set arbitrarily to $3 \sigma_{s k y}$. The variables $Q, U, P, \phi$, and associated errors were calculated as outlined in Section 4.3.2.

### 4.4.5 Results for Bright Nebulae

Images were obtained of several bright sources, including Sharpless 106 (1950.0: $20^{h} 25^{m} 34^{s}, 37^{\circ} 12^{\prime} 50^{\prime \prime}$ ) and Sharpless 140 (1950.0: $22^{h} 17^{m} 41^{s}, 63^{\circ} 03^{\prime} 49^{\prime \prime}$ ). At 600 pc , Sharpless 106 is a glorious bipolar nebula surrounding a luminous cluster or O star (Allen \& Penston 1975; Sibille et al. 1975; Gehrz et al. 1982). At 910 pc, Sharpless 140 is a compact region of obscuration, probably a bipolar outflow sighted along the outflow axis surrounding a $2 \times 10^{4} \mathrm{~L}_{\odot}$ single object probably similar to a B0 star (Harvey et al. 1978; Blair et al. 1978; Snell et al. 1984). After the reduction procedures were completed, polarimetric maps were calculated for these objects. The maps produced are of high quality, and indicate that the observing and reduction algorithms are successful with these bright sources.

Sharpless 106 (AFGL 2584)

The $H$ images of Sharpless 106 taken at every analyzer orientation were coadded to produce the intensity image in Figure 4.3. Superimposed over that image are the fractional polarization vectors produced by degrading the image dimensions to an $85 \times 85$ grid and calculating the Stokes parameters for pixels with flux levels measuring at least $3 \sigma_{s k y}$ in all four analyzer orientations. The pattern is beautifully centrosymmetric, clearly indicating the location of the illuminating source near the center of the nebula, a source identified variously as \#3 (Sibille et al. 1975) or IRS 4 (Gehrz et al. 1982). None of the other clumps of nebulosity visible in this frame appear to play a significant role in illuminating the nebula. The map faithfully reproduces the $4000 \AA$ centrosymmetric map by Lacasse et al. (1981), yet not their peculiar mapping at $8000 \AA$. (It is interesting to note that


Fig. 4.3.- A double image of Sharpless 106 constructed by coadding all the $H$ band polarimetric frames is displayed at two image stretches. The top image emphasizes the nebular structure while the bottom image shows the polarimetric vectors. Both are shown in logarithmic display with north to the right and east to the top. The image scale is $0.6^{\prime \prime} \mathrm{pix}^{-1}$. The polarizations in this image are typically $10-25 \%$ in the southern half and $20-40 \%$ in the northern half. The inner polarization structure is elongated in the east-west direction and exhibits two nodes of low polarization values just northwest and southeast of IRS 4.
the structure of their $8000 \AA$ polarimetry map could be reconstructed with the infrared data if the order of the images in the $45^{\circ}$ and $135^{\circ}$ pair or the $0^{\circ}$ and $90^{\circ}$ pair were accidentally reversed during data reductions. The values calculated for $P$ would be unaffected but the vector orientations resulting from using either $(-U / Q)$ or $(U /-Q)$ in Equation 4.4 would be arranged as in their $8000 \AA$ map.) Polarization values are approximately $10-25 \%$ in the southern half of the nebula and $20-40 \%$ in the northern half. Polarization errors are typically about $\pm 2-5 \%$ in $P$ and $\pm 5^{\circ}$ for $\phi$. Deviations from a circular centrosymmetric pattern are seen in the inner region of the nebula where the pattern is elliptically distorted. Two nodes of lower polarization flank the core, just to its southeast and especially to its northwest. The major axis of the elliptical distortion and the flanking polarization nodes occur at approximately the same position angle around the illuminating core-perpendicular to the axis of the bipolar nebula and coincident with the plane of a collimating disk proposed by Gehrz et al. (1982). This disk may be altering the local polarization pattern by multiple scattering (Bastien \& Ménard 1988) or by dichroic extinction from elongated grains aligned in a toroidal magnetic field (Aspin et al. 1985). Limitations of the data prevented a further study of this crucial portion of the polarimetry pattern.

Sharpless 140 (AFGL 2884)

The coadded $H$ image of Sharpless 140 is shown in Figure 4.4. Since the seeing was slightly better than it was for Sharpless 106 , the image dimensions were only degraded to $128 \times 128$ when calculating the Stokes parameters. In contrast with the grand centrosymmetric nature of the polarimetry for Sharpless 106, the polarization structure for Sharpless 140 is extremely complicated. Centrosymmetric patterns


Fig. 4.4.- A double image of Sharpless 140 constructed by coadding all the $H$ band polarimetric frames is shown in logarithmic display with north to the top and east to the left. The image scale is $0.6^{\prime \prime}$ pix $^{-1}$. The polarizations in this image are typically $10-20 \%$, with errors of approximately $\pm 2-5 \%$. Polarization angle uncertainties are approximately $\pm 5^{\circ}$. The size of this image fragment is only 100 pixels ( $60^{\prime \prime}$ ) on a side.
exist around two of the nebular clumps, but elsewhere the vectors trace mysterious patterns around and through the nebulosity. This suggests that more than one source plays an important role in illuminating Sharpless 140, or that the light from one or a few sources is being multiply scattered or processed by extended material. The map is similar to the results of Joyce \& Simon (1986), but contains far more spatial detail than their map which was made with a $20^{\prime \prime}$ beam. The polarization values range around $10-20 \%$ with errors comparable to those for Sharpless 106. A few artifacts produced by stars in the off-source frames are visible.

### 4.5 Another Clear Run: NGC 2264

Having used bright nebulae to demonstrate the success of the device, the observing routine, and the reduction method, it was time to look at the faint nebular clumps in NGC 2264. The original $J, H$, and $K$ images taken by Lada et al. (1993) were patrolled to find regions of nebulosity sufficiently bright to enable a reasonable level of polarimetric accuracy. Four promising locations were identified, but four trimesters of cloudy observing runs had to come and go before a single clear night allowed good images to be taken of one clump of nebulosity.

### 4.5.1 Observations

For this run the NICMOS $256 \times 256$ infrared camera was mounted upon the lonely 1.55 m Steward Observatory telescope on Mount Bigelow. In the time since the observations described in Section 4.4, the original detector had been replaced with a new chip which had far fewer bad pixels. The coarse plate scale with the 1.55 m telescope and camera was approximately $0.9^{\prime \prime} \mathrm{pix}^{-1}$. Problems with the
telescope mandated manual tracking for some of the frames, especially when the source was near the meridian. The seeing was approximately $2^{\prime \prime}$, although the point spread functions were slightly elongated by errors in the automatic and manual tracking.

Because of limited observing time between ice storms polarimetry was restricted to only one source-a region of nebulosity associated with several extremely red objects identified in the multiband survey described in Chapter 3. A suitable off-source location (not easy to find in the middle of NGC 2264) had already been found by inspecting the images taken by Lada et al. (1993). Data were obtained in all three bands, both with and without the analyzer installed. The necessary bias-frames and extra sky-frames were also observed. Without the analyzer in place, obejct-frames were taken with integration times set so the images were background limited. With the analyzer installed, integration times were 200 s , 240 s , and 25 s for $J, H$, and $K$. These exposures were long enough so the images were background limited, but short enough to allow for rapid cycling through the analyzer orientations.

### 4.5.2 Reductions

The normal sky subtraction and flattening steps involved in reducing infrared array data were followed as described in Section 4.4.3. The only change was that with the new array, dark-current frames were used instead of bias-frames. Then began the additional reduction steps described in Section 4.4.4. Fortunately the new array chip had fewer bad pixels, so the long and tedious process of identifying bad pixels could be nearly ignored. But because of a new problem with this chip (later repaired) there was a small bias difference between the top and bottom
halves of each image. These bias differences were small-only $20-50 \%$ as large as the dispersion of sky pixel values-but significant enough to merit correction. By adding the correct biases-determined by the differences in median pixel values for blank patches of sky in each image half-to the top half of each image this defect was corrected. The images were coaligned, and images constructed by coadding all the c-aligned frames exhibited only a $5-10 \%$ increase in the stellar full widths at half maxima. Photometry of unsaturated stars and further statistics of blank sky patches revealed bias and gain differences among the images-probably due to the light cirrus that remained in the sky while one ice storm faded and the next developed-which necessitated additive and multiplicative corrections of the type noted in Section 4.4.4. The additive corrections were usually less than $10 \%$ the intensity of the weakest nebular regions where Stokes parameters were calculated, and the multiplicative factors were also within $2-3 \%$ of unity.

Unfortunately, the same bad weather that required the calibration of the images also completely destroyed some of the frames. But this was anticipated and redundant images were observed at each of the analyzer orientations after the nominal four images at $0^{\circ}, 45^{\circ}, 90^{\circ}$, and $135^{\circ}$ were obtained. Because of the redundant images data remained for all analyzer orientations at all bands although the $K$ data were hobbled by a particularly bad set of $0^{\circ}$ frames. The polarimetric images were contracted by a factor of 2 or 3 . This improved the signal to noise substantially while not sacrificing too much resolution (since the pixel size of $0.9^{\prime \prime}$ was smaller than the $2^{\prime \prime}$ seeing). Stokes parameters were calculated for those pixel coordinates with sufficiently high signal in all four analyzer orientations.

### 4.5.3 Masking Images

Figure 4.5 shows the nebulosity at $J$. The image, which was created by coadding the four polarimetry frames, illustrates the complex nature of the region. Many stars were in the field and these complicated attempts to study the nebulosity. Most of these are included in the multiband survey described in Chapter 3, and are schematically represented in Figure 4.6. As it will be shown, the sources S3153, S3218, and S3321 and perhaps S3495 and S3384 are especially significant for this region. The multiband survey results for the stars in this region are listed in Tables 4.3-4.4. Stars in the image were not the only things complicating the polarimetry. Despite efforts to eliminate the stars from the flat-fields some managed to make themselves known as dark artifacts in Figure 4.5. These problems had to be dealt with.

Since the nebulosity is much fainter in these images than in the bright nebulae discussed in Section 4.4.5, it was important to discard from the polarimetric analysis those pixels that contained nebular flux contaminated by stars and artifacts. Pixels to be discarded were those that were too close to stars, or were corrupted by reduction artifacts such as sources in the off-source frames, or were as yet unidentified hot or dead pixels. To facilitate the removal of these corrupted pixels an image mask for each band was produced that was equal to unity for good pixels and zero for bad pixels. In the first stage of creating the image mask for a band only the pixels that were contaminated by stellar images were discarded. Using the astrometric data in Table 4.3, the pixel coordinates of each star were calculated. Then using the photometric data in Table 4.4, a boundary was defined around each stellar pixel location, interior to which the pixels were set equal to zero. The radii of these zones were parameterized as a function of magnitude. The


Fig. 4.5.- The clump of nebulosity near S3321 in NGC 2264 produced by coadding all the $J$ frames from the observing run is shown with north at the top and east to the left. The coverage in this image is $160^{\prime \prime}$ on a side. The point spread functions of stars in this coadded image are approximately $2.2^{\prime \prime} \times 1.8^{\prime \prime}$, the asymmetry being due to tracking errors. The region is filled with nebulosity as well as many stars. Stars in the region of the cluster used to construct a flat-field appear in this image as dark spots. The source S3218 near the nebula center lays immediately southeast of such a spot. Much of the structure which is overexposed with this image stretch is actually nebulosity. The square shaped artifacts just northwest of center are due to a cluster of bad pixels in the image. The long black line visibile in the northeast portion of the image is an artifact apparently due to a meteor.

TABLE 4.3
Coordinates of Stars in the Polarimetry Field

| Source | Walker \# | LkH ${ }^{\text {\# }}$ \# | $\alpha(1950.0)$ | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S2934 | . . . $\cdot$ | . | $6^{h} 38^{m} 10.87^{\text {a }}$ | $9^{\circ} 38^{\prime} 59.11$ | OBS 1 |
| S2935 | . .... | .......... | $6^{\text {h }} 38^{m} 10.92^{3}$ | $9^{\circ} 39^{\prime} 51.11$ | OBS 1 |
| S2936 | ..... | .......... | $6^{\text {h }} 38^{m} 10.94^{\text {a }}$ | $9^{\circ} 40^{\prime} 10.11$ | OBS 1 |
| S2943 | W122 | LkHa 38 | $6^{h} 38^{m} 11.21{ }^{\text {a }}$ | $9^{\circ} 39^{\prime} 23.1$ | OBS $1^{4}$ |
| S2958 | W123 | LkHa 40 | $6^{\text {h }} 38^{m} 11.45^{\prime}$ | $9^{\circ} 38^{\prime} 46.1$ | OBS $1^{\text {a }}$ |
| S2989 | W126 | LkH 41 | $6^{\text {h }} 38^{m} 11.86^{\text {a }}$ | $9^{\circ} 40^{\prime} 41.11$ | OBS $1^{\text {a }}$ |
| S3029 | . $\cdot$. ${ }^{\text {c }}$ | ......... | $6^{h} 38^{m} 12.58{ }^{\text {a }}$ | $9^{\circ} 38^{\prime} 07.11$ | OBS 1 |
| S3033 | $\cdots$ | .......... | $6^{\text {h }} 38^{m} 12.65^{\text {a }}$ | $9^{\circ} 39^{\prime} 59.11$ | OBS 1 |
| S3034 | ..... | - | $6^{\text {h }} 38^{m} 12.67^{8}$ | $9^{\circ} 38^{\prime} 42.11$ | OBS 1 |
| S3039 | $\cdots$ | - | $6^{\text {h }} 38^{m} 12.77^{\circ}$ | $9^{\circ} 39^{\prime} 01.1$ | OBS 1 |
| S3059 | -.... | . ..... | $6^{\text {h }} 38^{m} 13.15{ }^{\text {a }}$ | $9^{\circ} 39^{\prime} 46 .{ }^{\prime \prime}$ | OBS 1 |
| S3095 | ..... | . . . . . | $6^{h} 38^{m} 13.46^{2}$ | $9^{\circ} 40^{\prime} 36.1$ | OBS 1 |
| S3106 | ..... | . . . . . . ${ }^{\text {a }}$ | $6^{\text {h }} 38^{\text {m }} 13.58{ }^{\text {d }}$ | $9^{\circ} 38^{\prime} 39 . ⿱$ | OBS 1 |
| S3112 | . | . . . . . . | $6^{\text {h }} 38^{m} 13.68{ }^{\text {a }}$ | $9^{\circ} 39^{\prime} 33.1$ | OBS 1 |
| S3116 | ..... | LkHa 42 | $6^{h} 38^{m m} 13.73^{\prime \prime}$ | $9^{\circ} 39^{\prime} 06.1$ | OBS 1 |
| S3125 | ..... . | ........... | $6^{\text {h }} 38^{m} 13.87^{\text {d }}$ | $9^{\circ} 39^{\prime} 09 . "$ | OBS 1 |
| S3131 | ..... |  | $6^{\text {h }} 38^{\text {m }} 13.92^{\text {a }}$ | $9^{\circ} 39^{\prime} 40.11$ | $\text { OBS } 1$ |
| S3137 | .. | - | $6^{\text {h }} 38^{m} 14.02^{\prime \prime}$ | $9^{\circ} 38^{\prime} 55 . \prime$ | OBS 1 |
| S3145 | . . | . . . . . | $6^{\text {h }} 38^{\text {m }} 14.18^{\text {a }}$ | $9^{\circ} 39^{\prime} 08.11$ | $\text { OBS } 1$ |
| S3150 | . | ..... | $6^{h} 38^{m} 14.26^{3}$ | $9^{\circ} 40^{\prime} 21 . "$ | OBS 1 |
| S3153 | ..... | .......... | $6^{h} 38^{m} 14.35^{\text {a }}$ | $9^{\circ} 38^{\prime} 45.1$ | OBS $1^{\text {b }}$ |
| S3166 | ..... | ........ | $6^{\text {h }} 38^{m} 14.57^{\text {m }}$ | $9^{\circ} 38^{\prime} 38.1$ | OBS 1 |
| S3169 | ..... | . . . . . | $6^{h} 38^{m} 14.59{ }^{\text {d }}$ | $9^{\circ} 39^{\prime} 04 .^{\prime \prime}$ | OBS 1 |
| S3171 | W136 | .......... | $6^{\text {h }} 38^{\mathrm{m}} 14.61{ }^{\text {d }}$ | $9^{\circ} 38^{\prime} 03.11$ | OBS $1^{4}$ |
| 53178 | ..... | .......... | $6^{h} 38^{m} 14.71^{\text {d }}$ | $9^{\circ} 39^{\prime} 50.1$ | OBS 1 |
| S3183 | ..... | . $\cdot$.... | $6^{h} 38^{m} 14.81^{3}$ | $9^{\circ} 38^{\prime} 52.11$ | OBS 1 |
| S3189 | ..... | . . . . . . | $6^{h} 38^{m} 14.88^{2}$ | $9^{\circ} 39^{\prime} 27.1$ | OBS 1 |
| S3200 | ..... | .... | $6^{h} 38^{m} 15.36^{\text {d }}$ | $9^{\circ} 39^{\prime} 24.1$ | OBS 1 |
| S3202 | .... | .......... | $6^{h} 38^{m} 15.38^{\text {d }}$ | $9^{\circ} 38^{\prime} 44 .^{\prime \prime}$ | OBS $1^{\text {c }}$ |
| S3203 | ..... | . . | $6^{h} 38^{m} 15.38^{\text {a }}$ | $9^{\circ} 38^{\prime} 52.11$ | OBS 1 |
| 53213 | ..... | ........ | $6^{\text {h }} 38^{\text {m }} 15.55^{\text {d }}$ | $9^{\circ} 38^{\prime} 43.11$ | OBS $1^{\text {c }}$ |
| S3218 | ..... | ........ | $6^{h} 38^{m} 15.62^{\text {d }}$ | $9^{\circ} 39^{\prime} 04.1$ | OBS $1^{\text {b }}$ |
| S3240 | ..... | . $\cdot$..... | $6^{h} 38^{m} 16.32^{\text {d }}$ | $9^{\circ} 39^{\prime} 03.11$ | OBS 1 |
| S3254 | $\cdots$ | - | $6^{h} 38^{m} 16.56^{4}$ | $9^{\circ} 39^{\prime} 19.1$ | OBS 1 |
| S3260 | ..... | - | $6^{\text {h }} 38^{m} 16.61{ }^{\text {d }}$ | $9^{\circ} 40^{\prime} 22.11$ | OBS 1 |
| S3275 | ..... | ......... | $6^{\text {h }} 38^{\mathrm{m}} 16.82^{\text {d }}$ | $9^{\circ} 39^{\prime} 23.1$ | $\text { OBS } 1$ |
| S3277 | ..... | ...... | $6^{h} 38^{m} 16.89{ }^{\text {d }}$ | $9^{\circ} 40^{\prime} 07.11$ | $\text { OBS } 1$ |
| S3289 | ..... | .. | $6^{\text {h }} 38^{m} 17.06^{\text {d }}$ | $9^{\circ} 39^{\prime} 03.1$ | OBS 1 |
| S3314 | . | ......... | $6^{\mathrm{h}} 38^{\mathrm{m}} 17.64^{\text {a }}$ | $9^{\circ} 39^{\prime} 33.1$ | OBS 1 |
| S3316 | W150 | ....... | $6^{h} 38^{m} 17.66^{\circ}$ | $9^{\circ} 38^{\prime} 06.1$ | OBS 1 |
| S3321 | - | . . . . . . | $6^{h} 38^{m} 17.78^{\text {d }}$ | $9^{\circ} 39^{\prime} 09.11$ | OBS $1^{\text {b }}$ |
| 53329 | ..... | ......... | $6^{h} 38^{m} 17.93^{\text {d }}$ | $9^{\circ} 38^{\prime} 28.11$ | OBS 1 |
| S3330 | ..... | .......... | $6^{\text {h }} 38^{m} 17.93^{\text {d }}$ | $9^{\circ} 39^{\prime} 02.11$ | OBS 1 |
| S3331 | ..... | . . . . . | $6^{h} 38^{m} 17.95^{\prime}$ | $9^{\circ} 39^{\prime} 15 . "$ | OBS 1 |
| S3336 | ..... | .......... | $6^{\text {h }} 38^{m} 18.05^{\prime}$ | $9^{\circ} 40^{\prime} 29 . ⿱ 1$ | OBS 1 |
| S3344 | ..... | ........ | $6^{h} 38^{m} 18.24{ }^{\text {a }}$ | $9^{\circ} 38^{\prime} 38.1$ | OBS 1 |
| S3356 | . $\cdot$. $\cdot$ | ........ | $6^{h} 38^{\text {m }} 18.43^{\text {a }}$ | $9^{\circ} 38^{\prime} 57.11$ | OBS $1^{\text {c }}$ |
| S3359 | . $\cdot$. | ..... | $6^{h} 38^{\text {m }} 18.45^{\text {d }}$ | $9^{\circ} 38^{\prime} 46 .{ }^{\prime \prime}$ | $\text { OBS } 1$ |
| S3366 | ..... | .......... | $6^{h} 38^{m} 18.62^{\text {a }}$ | $9^{\circ} 38^{\prime} 57 . \prime$ | OBS $1^{\text {c }}$ |
| S3369 | ..... | - | $6^{h} 38^{m} 18.67^{4}$ | $9^{\circ} 40^{\prime} 39.1$ | OBS 1 |
| S3373 | ..... | .......... | $6^{\text {h }} 38^{m} 18.74^{\text {d }}$ | $9^{\circ} 38^{\prime} 38.1$ | OBS 1 |
| S3375 | . $\cdot$. ${ }^{\text {c }}$ | . $\cdot$...... | $6^{\text {h }} 38^{\mathrm{m}} 18.82^{\text {d }}$ | $9^{\circ} 38^{\prime} 55.1$ | OBS $1^{\text {c }}$ |

TABLE 4.3-Continued

| Source | Walker \# | LkH ${ }^{\text {\# }}$ | $\alpha(1950.0)$ | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S3384 | ..... | . $\cdot . .$. | $6^{\text {h }} 38^{m} 18.98{ }^{\text {a }}$ | $9^{\circ} 40^{\prime} 04.1$ | OBS $1^{\text {b }}$ |
| S3390 | ..... | .......... | $6^{h} 38^{m} 19.13^{\text {s }}$ | $9^{\circ} 38^{\prime} 14 .{ }^{\prime \prime}$ | OBS 1 |
| S3391 | ...... | .......... | $6^{\text {h }} 38^{m} 19.13^{\text {a }}$ | $9^{\circ} 38^{\prime} 32.1$ | OBS 1 |
| S3400 | ..... | . | $6^{\text {h }} 38^{m} 19.22^{\text {d }}$ | $9^{\circ} 39^{\prime} 49.1$ | OBS 1 |
| S3412 | ..... | .......... | $6^{\text {h }} 38^{m} 19.37^{\text {a }}$ | $9^{\circ} 38^{\prime} 27 . \prime$ | OBS 1 |
| S3413 | ..... | .......... | $6^{\text {h }} 38^{m} 19.37^{\text {a }}$ | $9^{\circ} 38^{\prime} 41.11$ | OBS 1 |
| S3419 | ..... | .......... | $6^{h} 38^{m} 19.46^{\text {a }}$ | $9^{\circ} 39^{\prime} 36.1$ | OBS 1 |
| S3420 | ..... | .......... | $6^{h} 38^{m} 19.49^{\text {a }}$ | $9^{\circ} 39^{\prime} 17.1$ | OBS 1 |
| S3431 | ..... | .......... | $6^{h} 38^{m} 19.70^{\text {a }}$ | $9^{\circ} 39^{\prime} 12.1$ | OBS 1 |
| S3438 | W159 | . $\cdot$........ | $6^{\text {h }} 38^{m} 19.75^{\text {a }}$ | $9^{\circ} 39^{\prime} 21.1$ | OBS $1^{*}$ |
| S3466 | ..... | .......... | $6^{\text {h }} 38^{\mathrm{m}} 20.23^{\text {d }}$ | $9^{\circ} 38^{\prime} 43.1$ | OBS 1 |
| S3467 | ..... | ....... | $6^{\text {h }} 38^{\text {m }}$ 20.31* | $9^{\circ} 38^{\prime} 30.1$ | OBS 1 |
| S3482 | ..... | ...... | $6^{h} 38^{m} 20.71^{\text {a }}$ | $9^{\circ} 38^{\prime} 38.1$ ' | OBS 1 |
| S3485 | . . . . | . | $6^{\text {h }} 38^{m}$ m $20.76^{3}$ | $9^{\circ} 40^{\prime} 36.1$ | OBS 1 |
| S3489 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 20.81^{\text {a }}$ | $9^{\circ} 39^{\prime} 25.1$ ' | OBS 1 |
| S3495 | ..... | .......... | $6^{h} 38^{m} 20.88^{3}$ | $9^{\circ} 38^{\prime} 23.1$ ' | OBS $1^{\text {b }}$ |
| S3505 | . $\cdot$. ${ }^{\text {c }}$ | . . . . . ${ }^{\text {a }}$ | $6^{\text {h }} 38^{\mathrm{m}} 21.07^{\text {a }}$ | $9^{\circ} 38^{\prime} 45.1$ | OBS $1^{\text {a }}$ |
| S3514 | W164 | LkHa 53 | $6^{\text {h }} 38^{\mathrm{m}} 21.24^{\text {a }}$ | $9^{\circ} 39^{\prime} 17.1$ ' | OBS $1^{\text {a }}$ |
| S3525 | ..... | - | $6^{h} 38^{m} 21.43{ }^{\text {a }}$ | $9^{\circ} 40^{\prime} 02.1$ | OBS 1 |
| S3532 | ..... | ......... | $6^{h} 38^{m} 21.55^{\text {a }}$ | $9^{\circ} 38^{\prime} 59.1$ | OBS 1 |
| S3536 | ..... | .......... | $6^{h} 38^{m} 21.63^{3}$ | $9^{\circ} 38^{\prime} 38.1$ | OBS $1^{\text {a }}$ |

${ }^{\text {a }}$ Spectral information in Chapter 3.
${ }^{b}$ Notable for a very red SED
${ }^{\text {c }}$ Possibly a multiple source
Note.-The source numbers and coordinstes are listed for 73 stars in the region atudied because of the reflection nebulosity. Where applicable, Walker designations and $\mathrm{LkH} \alpha$ numbers are given for the stars.

TABLE 4.4
Photometry of Stars in the Polarimetry Field

| Source | $V$ | $R$ | $I$ | $J$ | H | $K$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S2934 | . . . ${ }^{\text {a }}$ | . . . ${ }^{\text {. }}$ | . .... | ..... | . $\cdot$. ${ }^{\text {. }}$ | $14.36 \pm 0.11$ |
| S2935 | 19.53土 0.09 | $18.24 \pm 0.08$ | $16.72 \pm 0.04$ | $15.96 \pm 0.15$ | . $\cdot$. | ..... |
| S2936 | $19.70 \pm 0.11$ | $17.98 \pm 0.07$ | $15.92 \pm 0.02$ | $14.34 \pm 0.08$ | $13.83 \pm 0.12$ | . $\cdot$. |
| S2943 | $15.55 \pm 0.00$ | $14.33 \pm 0.01$ | $13.58 \pm 0.00$ | $11.96 \pm 0.06$ | $10.76 \pm 0.12$ | $9.87 \pm 0.10$ |
| S2958 | $16.49 \pm 0.01$ | $15.36 \pm 0.01$ | $14.19 \pm 0.01$ | $12.89 \pm 0.08$ | $12.00 \pm 0.12$ | $11.34 \pm 0.06$ |
| S2989 | 15.31 $\pm 0.00$ | $14.12 \pm 0.00$ | $13.06 \pm 0.00$ | $12.08 \pm 0.08$ | $11.45 \pm 0.12$ | $11.30 \pm 0.06$ |
| S3029 | ..... | ..... | ..... | $15.56 \pm 0.09$ | $14.66 \pm 0.12$ | $14.20 \pm 0.07$ |
| S3033 | ..... | $18.85 \pm 0.09$ | $16.55 \pm 0.03$ | $14.97 \pm 0.08$ | $14.34 \pm 0.12$ | $13.81 \pm 0.10$ |
| S3034 | ..... | . | ..... | $16.91 \pm 0.42$ | ... | ..... |
| S3039 | . | ..... | ..... | ..... | $14.64 \pm 0.17$ | $12.66 \pm 0.07$ |
| S3059 | $18.92 \pm 0.05$ | $17.34 \pm 0.03$ | $14.79 \pm 0.01$ | $13.16 \pm 0.08$ | $12.36 \pm 0.12$ | $11.95 \pm 0.06$ |
| S3095 | ..... | ..... | $16.37 \pm 0.03$ | $14.00 \pm 0.08$ | $13.35 \pm 0.12$ | $12.88 \pm 0.07$ |
| S3106 | ..... | ..... | ..... | ..... | ..... | $13.86 \pm 0.07$ |
| S3112 | ..... | . . | ..... | ..... | ..... | $16.01 \pm 0.56$ |
| S3116 | $17.48 \pm 0.01$ | $16.00 \pm 0.01$ | $13.84 \pm 0.00$ | $12.45 \pm 0.06$ | $11.75 \pm 0.12$ | $11.04 \pm 0.07$ |
| S3125 | ..... | ..... | ..... | ..... | ..... | $11.91 \pm 0.10$ |
| S3131 | . . . . | ..... | ..... | . $\cdot$... | ..... | $13.90 \pm 0.07$ |
| S3137 | . | ..... | ..... | . $\cdot .$. | ..... | $13.89 \pm 0.09$ |
| S3145 | . . | ..... | ..... | . $\cdot .$. | . $\cdot$ | $13.46 \pm 0.10$ |
| S3150 | . | . | . . | . $\cdot$... | $15.74 \pm 0.27$ | $14.66 \pm 0.16$ |
| S3153 | . . . | ..... | $16.77 \pm 0.06$ | 11.73 $\pm 0.08$ | $9.25 \pm 0.12$ | $7.94 \pm 0.10$ |
| S3166 | ..... | ..... | ..... | ..... | ..... | $13.21 \pm 0.07$ |
| S3169 | . . | . | . . | ..... | ..... | $12.80 \pm 0.10$ |
| S3171 | $15.35 \pm 0.01$ | $14.09 \pm 0.01$ | $12.83 \pm 0.01$ | $11.46 \pm 0.08$ | $10.79 \pm 0.17$ | $10.17 \pm 0.10$ |
| S3178 | ..... | ..... | ..... | $15.03 \pm 0.11$ | $14.11 \pm 0.17$ | 13.61 $\pm 0.10$ |
| S3183 | . $\cdot$ | ..... | ..... | 15.01 $\pm 0.11$ | 13.15 $\pm 0.17$ | $11.76 \pm 0.07$ |
| S3189 | ..... | ..... | ..... | .... | ..... | $14.89 \pm 0.14$ |
| S3200 | ..... | ..... | ..... | . | $14.14 \pm 0.17$ | $13.17 \pm 0.10$ |
| S3202 | . . | ..... | ..... | . | - | $14.47 \pm 0.13$ |
| S3203 | . . | ..... | ..... | ..... | $13.27 \pm 0.17$ | 11.57 $\pm 0.10$ |
| S3213 | . . | ..... | …' | . | ..... | $13.14 \pm 0.12$ |
| S3218 | ..... | $18.92 \pm 0.11$ | $16.28 \pm 0.03$ | $13.72 \pm 0.08$ | $12.39 \pm 0.17$ | $11.66 \pm 0.07$ |
| S3240 | . . . | ..... | ..... | ..... | 14.65 $\pm 0.19$ | $12.99 \pm 0.07$ |
| S3254 | . | …' | . | . | ... | 15.04 $\pm 0.21$ |
| S3260 | $18.95 \pm 0.05$ | $17.38 \pm 0.03$ | $15.78 \pm 0.02$ | $14.46 \pm 0.08$ | $13.84 \pm 0.12$ | $13.15 \pm 0.07$ |
| S3275 | ..... | ..... | ..... | ..... | 14.99 $\pm 0.20$ | $13.35 \pm 0.07$ |
| S3277 | ..... | . | ..... | ..... | .... | $14.37 \pm 0.08$ |
| S3289 | . | . $\cdot$ | $\cdots$ | . | ..... | 13.88 $\pm 0.07$ |
| S3314 | $20.16 \pm 0.15$ | $18.32 \pm 0.09$ | $16.02 \pm 0.02$ | $14.29 \pm 0.08$ | $13.67 \pm 0.12$ | $13.02 \pm 0.05$ |
| S3316 | $15.39 \pm 0.01$ | $14.38 \pm 0.01$ | $13.46 \pm 0.01$ | $12.78 \pm 0.08$ | $12.22 \pm 0.12$ | $12.03 \pm 0.07$ |
| S3321 | ..... | ..... | $17.79 \pm 0.11$ | 12.83土0.06 | $10.48 \pm 0.17$ | $8.88 \pm 0.07$ |
| S3329 | ..... | . $\cdot$... | ..... | ..... | $14.72 \pm 0.33$ | $13.38 \pm 0.06$ |
| S3330 | ..... | ..... | ..... | ..... | . | $13.67 \pm 0.10$ |
| S3331 | ..... | . . . . | ..... | ..... | ..... | $11.91 \pm 0.10$ |
| S3336 | $19.09 \pm 0.06$ | $17.20 \pm 0.02$ | $15.14 \pm 0.01$ | $12.94 \pm 0.08$ | $11.74 \pm 0.12$ | $10.99 \pm 0.06$ |
| S3344 | ..... | ..... | ..... | ..... | $13.42 \pm 0.12$ | $11.57 \pm 0.07$ |
| S3356 | . . . $\cdot$ | $17.25 \pm 0.04$ | 15.15 $\pm 0.01$ | $13.23 \pm 0.08$ | $12.00 \pm 0.12$ | $11.60 \pm 0.10$ |
| S3359 | ..... | ..... | ..... | ..... | ..... | $13.18 \pm 0.10$ |
| S3366 | . $\cdot$. ${ }^{\text {c }}$ | $17.71 \pm 0.05$ | $15.39 \pm 0.01$ | . $\cdot$. | $11.85 \pm 0.17$ | $11.93 \pm 0.10$ |
| S3369 | . | ..... | ..... | $16.19 \pm 0.21$ | ..... | $14.79 \pm 0.09$ |
| S3373 | ..... | . . | . | . | ..... | $13.21 \pm 0.07$ |
| S3375 | . $\cdot$. | ..... | . . . . | . $\cdot$... | ..... | $12.56 \pm 0.10$ |

TABLE 4.4-Continued

| Source | $V$ | $R$ | $I$ | $J$ | H | $K$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S3384 | ..... | $19.10 \pm 0.11$ | $16.77 \pm 0.04$ | $13.83 \pm 0.08$ | $12.28 \pm 0.17$ | $11.51 \pm 0.10$ |
| S3390 | $16.65 \pm 0.01$ | $15.44 \pm 0.01$ | $13.91 \pm 0.01$ | $12.96 \pm 0.08$ | $12.28 \pm 0.12$ | $11.95 \pm 0.10$ |
| S3391 | ..... | ..... | ..... | ..... | $15.00 \pm 0.21$ | $13.08 \pm 0.07$ |
| S3400 | $19.64 \pm 0.11$ | $18.02 \pm 0.05$ | $15.92 \pm 0.02$ | $14.63 \pm 0.11$ | $14.47 \pm 0.17$ | $13.83 \pm 0.07$ |
| S3412 | ..... | ..... | ..... | ..... | $15.24 \pm 0.42$ | $14.41 \pm 0.10$ |
| S3413 | $18.63 \pm 0.06$ | $17.33 \pm 0.04$ | $15.35 \pm 0.02$ | $14.34 \pm 0.08$ | 13.69 ${ }^{\text { }} 0.12$ | $13.32 \pm 0.07$ |
| S3419 | $17.63 \pm 0.02$ | $16.58 \pm 0.02$ | $15.05 \pm 0.01$ | $13.96 \pm 0.08$ | $13.21 \pm 0.12$ | $12.59 \pm 0.07$ |
| S3420 | ..... | ..... | ..... | ..... | - | $13.03 \pm 0.10$ |
| S3431 | . . | . | ..... | .... | ..... | $14.10 \pm 0.08$ |
| S3438 | $11.66 \pm 0.00$ | ..... | $10.56 \pm 0.00$ | $10.78 \pm 0.06$ | $10.55 \pm 0.17$ | $10.36 \pm 0.07$ |
| S3466 | ..... | . | ..... | 14.56 $\pm 0.08$ | $15.09 \pm 0.23$ | ..... |
| S3467 | . . . | ..... | ..... | ..... | ..... | $14.94 \pm 0.11$ |
| S3482 | -•... | $\ldots$ | $\ldots$ | $\ldots$ | . | $13.98 \pm 0.05$ |
| S3485 | $\cdots$ | ..... | $\cdots$ | ..... | $14.89 \pm 0.17$ | $14.40 \pm 0.06$ |
| S3489 | $18.61 \pm 0.07$ | $17.65 \pm 0.08$ | $16.06 \pm 0.03$ | $14.79 \pm 0.08$ | $14.03 \pm 0.17$ | $13.90 \pm 0.06$ |
| S3495 | -•••• | . . . ${ }^{\text {c }}$ | ..... | $16.25 \pm 0.22$ | $12.61 \pm 0.12$ | $10.28 \pm 0.05$ |
| S3505 | $13.94 \pm 0.01$ | $13.14 \pm 0.01$ | $12.54 \pm 0.01$ | 12.36 $\pm 0.08$ | $11.92 \pm 0.12$ | $11.73 \pm 0.05$ |
| S3514 | $13.51 \pm 0.00$ | $12.68 \pm 0.01$ | $12.06 \pm 0.00$ | $11.76 \pm 0.06$ | $11.11 \pm 0.12$ | $10.60 \pm 0.07$ |
| S3525 | ..... | ..... | ..... |  | ..... | $14.73 \pm 0.11$ |
| S3532 | ..... | . | ..... | ..... | ..... | $14.17 \pm 0.07$ |
| S3536 | $14.16 \pm 0.02$ | $13.47 \pm 0.01$ | $12.95 \pm 0.01$ | $12.85 \pm 0.08$ | $12.53 \pm 0.12$ | $12.38 \pm 0.05$ |

Note.-The source numbers and photometry for 73 stars in the region studied with the polarimeter.
resulting image masks looked like slices of swiss cheese. Next, mask pixels were set equal to zero if they were affected by artifacts from the image reduction (i.e. stars in the off-source frames). These corrupted pixels appeared as negative sources and were flagged by looking for pixels more than $3 \sigma_{s k y}$ below zero. Finally, the few bad pixels remaining were identified manually. A $256 \times 256$ mask was constructed for each band. Since the polarimetric images were to be contracted to $128 \times 128$ or $85 \times 85$ in size to improve signal to noise (see Section 4.4.4), similar contractions were performed upon the masks. In contracting a $2 \times 2$ or $3 \times 3$ block of mask pixels, the output pixel was set to zero if any of the pixels in the input block was zero. The Stokes parameter maps developed in Section 4.5 .2 were multiplied by the appropriate image masks and then total fractional polarizations and polarization angles were calculated. Details regarding the reduction and mask generation peculiar to each band of data are described in the next section.

### 4.5.4 NGC 2264 Polarimetric Maps

The reduction steps described in Sections 4.4.3-4.4.4 were ultimately justified by the high quality of the resulting polarimetry for Sharpless 106 and Sharpless 140. The same steps, slightly modified for the nebula near S3321 in NGC 2264, again produced good results even though the surface brightness of this nebula was much lower. Only a portion of the $256 \times 256$ images was subtended by the nebula, so a region approximately $2.1^{\prime}$ square centered on $6^{h} 38^{m} 16^{s}, 9^{\circ} 39^{\prime} 22^{\prime \prime}$ (1950.0) was selected for study. This area contains all the strong nebulosity and 53 stars ranging from 13th to 19 th magnitude in $J$.


Fig. 4.6.- A schematic of the stars from Figure 4.5 are shown. The sizes of the circles scale with $K$ magnitude, but if no $K$ magnitude was available then it was estimated by $K \approx J-2.0$. The five sources labelled with a single letter are discussed in the text, and are notable for having very red spectral energy distributions: $\mathrm{A}=\mathrm{S} 3153, \mathrm{~B}=\mathrm{S} 3218, \mathrm{C}=\mathrm{S} 3321, \mathrm{D}=\mathrm{S} 3384, \mathrm{E}=\mathrm{S} 3495$. The eight stars labelled with a single digit number are observed in the spectroscopic survey discussed in Chapter 5: $1=$ S2943, $2=$ S2958, 3=S2989, 4=S3171, 5=S3438, 6=S3505, 7=S3514, 8=S3536.

## $J$-band Images

A mask was defined so that pixels within $5.4^{\prime \prime}$ ( 6 pixels) of a 14 th magnitude star were set to zero, and this radius shrank $0.9^{\prime \prime}$ ( 1 pixel) for each magnitude the central star dimmed. After bad pixel removal, $61 \%$ of the pixels remained. The masked nebula is shown in Figure 4.7. The stellar full widths at half maxima ae approximately $2.2^{\prime \prime} \times 1.8^{\prime \prime}$-the asymmetry due to tracking errors. The bulk of the nebulosity is associated with S3321, although S3153 is surrounded by an intense glowing halo (mostly masked in Figure 4.7) as well as a bright spur of light that dangled to the south. The integrated $J$ magnitude of the ebular region is approximately $10.58 \pm 0.05$, and the $J$ surface brightness ranges from 20.0 to $18.5 \mathrm{mag} \operatorname{arcsec}^{-2}$.

Stokes parameters were obtained by first contracting the images and image mask covering the area in Figure 4.7 by a factor of three in both dimensions, as described in Section 4.4.4. Calculations proceeded at every pixel (now 2.7" on a side) at which the flux was greater than $3 \sigma_{s k y}$. A total of 769 pixels passed these tests, or approximately $33 \%$ of the area in Figure 4.7. The polarization ranges from 5-20\% near S3321 to greater than $30 \%$ in the southern regions of nebulosity and $50 \%$ in the nebular outskirts to the north. It drops to very small values within a few pixels of some of the stellar images, probably due to dilution from residual stellar flux. Overall photometry of the masked stars yielded zero polarization values for them (within photometry errors)-indeed part of the image reduction forced this to be the case. The polarization pattern is clearly centrosymmetric around S3321, identifying it as the source responsible for illuminating the nebula.

Typical errors in the polarimetry are $\pm 2-4 \%$ in the brightest nebular regions and increase to as high as $\pm 11 \%$ in the faintest regions near the north. The errors


Fig. 4.7.- A double image is displayed of the inner region of $J$ nebulosity which had the stellar sources and image artifacts removed by a masking. The majority of the nebulosity is associated with S3321 (east of center), although the bright source S3153 also has a large amount of nebulosity around it, which is mostly masked in the image. The roughly triangular black patch south and slightly east (left) of S3321 is a masked image artifact. The polarization pattern is centrosymmetric around S3321, and the percent polarization ranges from approximately $5-20 \%$ near the source, to greater than $30 \%$ in the southern regions of nebulosity, and $50 \%$ in the nebular outskirts to the north. Typical errors in percent polarization are $\pm 2-4 \%$ in the bright nebular regions and $\pm 11 \%$ near the north. The errors in polarization angle are about $\pm 8-11^{\circ}$ in the inner portions of the nebula and drop to approximately $\pm 4^{\circ}$ at the nebular extremities.
in polarization angle are about $\pm 8-11^{\circ}$ in the inner portions of the nebula and drop to approximately $\pm 4^{\circ}$ at the nebular extremities. Despite the low errors in $P$ and $\phi$ for the northern portion of the nebula these vectors should be viewed with caution. The nebular surface brightness there is relatively low and the fluxes in these pixels may have been influenced or even dominated by the calibration steps. In essence, the calculated polarimetry errors may reflect the precision but not accuracy of the $Q$ and $U$ measurements in this region.

There is a strip approximately $13.5^{\prime \prime}$ (5 pixels) long that extends from S3321 to the west-northwest, which contains pixels of peculiarly low polarizations. If real, this structure may be analogous to the nodes of low polarization flanking Sharpless 106 indicating the presence of a dense disk (Gehrz et al. 1982). In this context, the brightest nebulosity in the field could be interpreted as a lobe of emission extending from S3321 towards the southwest, perpendicular to the low-polarization strip. This is discussed in more detail in Section 4.8. Since the polarizations in the area of the node are low, the uncertainties in $\phi$ climb to meaningless values in excess of $30^{\circ}$.

## H-band Images

The procedure used in making the $J$ image mask was repeated for the $H$ frames. Pixels within $5.4^{\prime \prime}$ ( 6 pixels) of a 12.5 magnitude star were masked and this threshold radius decreased by $0.9^{\prime \prime}$ ( 1 pixel) for every $3 / 4$ magnitude difference of the central star. The masking process eliminated $28 \%$ of the image, which is shown in Figure 4.8. The stellar full widths at half maxima are approximately $2.2^{\prime \prime} \times 1.9^{\prime \prime}$. Instead of being so strongly dominated by structure around S3321 as in the $J$ data, an increased fraction of nebular flux is associated with S3153. Knots on the south


Fig. 4.8.- A double image of the region of $H$ nebulosity is shown in which the stellar sources and artifacts removed by masking. The nebulosity is distributed around several sources, especially S3321 and S3153. The polarization pattern is very complex, and is not exclusively centrosymmetric around S3321 as in the $J$ data. This may be real, indicating a complex interaction of sources and dust, or could be a result of low signal to noise in the polarimetry. Small fragments of centrosymmetric structure are seen around S3321 and S3153. The percent polarization ranges from approximately $5-15 \%$ near the source to $35 \%$ at the edges of the nebula. The errors are approximately $\pm 5-11 \%$, and the uncertainties in $\phi$ are as large as $\pm 20^{\circ}$.
and east sides of this source are very bright. The integrated $H$ magnitude of the nebula is approximately $9.39 \pm 0.13$, and the $H$ surface brightness ranges from 19.5 to $17.7 \mathrm{mag} \operatorname{arcsec}^{-2}$.

Contracting the images and image mask by a factor of three in both dimensions, Stokes parameters were calculated for each pixel which was brighter than $2 \sigma_{s k y}$. Polarization vectors were determined for $35 \%$ of the area in Figure 4.8. In contrast with the results from the $J$ data, the $H$ polarization pattern is not strongly centrosymmetric around a single source. Instead it is very complex with an overall box-like shape around the whole nebula. It is unclear how much of this large-scale structure i affected by instrumental effects but the small fragments of centrosymmetric structure near S3321 and S3153 are probably real.

The polarization in the nebula is typically $5-15 \%$ and occasionally reaches as high as $35 \%$. The errors are approximately $\pm 4-6 \%$, and near $\pm 11 \%$ at the nebular boundaries. Since $\sigma_{P} / P$ is large, $\phi$ is uncertain by as much as $\pm 20^{\circ}$. This is another indicator that the polarimetry for this source is not too reliable and with longer integrations the vector field may resolve itself into centrosymmetric patterns around S3321 and S3153.

## K-band Images

As discussed in Section 4.4.2, the analyzer's performance was dreadful in the $K$ band. Yet images were taken and reduced to see what might be found. The results were as expected. An image mask was made by excluding pixels less than 6 pixels distant from stars with $m_{K}=10.5$, and this threshold radius decreased by one pixel for every magnitude fainter the central star became. After removing the bad pixels, $78 \%$ of the region remained intact (Figure 4.9). The full widths at half


Fig. 4.9.- An image of the $K$ nebulosity is displayed in which the stellar sources and artifacts have been eliminated. The nebulosity is very weak but is mostly associated with S3321 and S3153. A bright spur of nebulosity extends south from S3153.
maxima of the stars in the $0^{\circ}$ and $45^{\circ}$ images are approximately $1.8^{\prime \prime} \times 1.5^{\prime \prime}$, but in the $90^{\circ}$ and $135^{\circ}$ images they are approximately $2.2^{\prime \prime} \times 1.5^{\prime \prime}$. The distribution of nebular light is not too different from the $H$ nebulosity. While the nebulosity surrounding S3321 had faded, the emission near S3153-and especially the spur to its immediate south-continues to grow in relative importance. The integrated $K$ magnitude of the nebular region is approximately $8.55 \pm 0.21$, and the $K$ surface brightness ranges from 17.6 to $16.3 \mathrm{mag} \operatorname{arcsec}^{-2}$. The images are too noisy to calculate polarization vectors-even after invoking all the image calibration and signal to noise enhancement steps, the signal to noise ratio is $P / \sigma_{P} \approx 1$, or even lower, so polarization maps at $K$ are not presented.

### 4.6 Radial Dependence of Fractional Polarization

In the discussion of the polarization maps in Section 4.5.4 an emphasis was placed upon the directions of the vectors. The magnitude of the fractional polarization is also interesting, and in this section its radial variation is investigated.

### 4.6.1 Sharpless 106

The large region over which the centrosymmetric polarization structure in Sharpless 106 is established (Figure 4.3) makes it an interesting source for further study. Since the nebula is clearly illuminated by a single object (IRS 4), the radial variation of the magnitude of centrosymmetric polarizations could be examined. But before proceeding with this analysis some image cleaning was required. When studying NGC 2264 masks were made to eliminate the spurious polarizations from stars in the field. But such masks were not created for Sharpless 106. As a result the polarization map was peppered with vectors not representative of the nebular polarization vector field. These pixels were mostly removed from further analysis by a simple test-it was required that for inclusion in this analysis, a line perpendicular to each pixel's polarization vector had to point in a direction less than $25^{\circ}$ away from the nebular center. This criterion quickly eliminated nearly all the bad polarization pixels from the $85 \times 85$ image and retained 1072 pixels for study. The scientific purity of this step is slightly questionable, since such a requirement would produce a centrosymmetric pattern out of a sample of randomly oriented vectors. But the point of this part of the analysis was not to study the centrosymmetric nature of the pattern (which was unquestioned) but rather the radial variation in polarization magnitude.

For each remaining pixel the radial distance from IRS 4 was computed. The pixels were ordered from nearest to farthest from IRS 4, and then binned into groups. All the pixels in a group were those confined to an annulus 1 pixel wide (1.8") centered upon IRS 4. The polarizations of the pixels in the bins were added by

$$
\begin{equation*}
\bar{P}=\frac{\sum_{i=1}^{n} \frac{P_{i}}{\sigma_{P_{i}}^{2}}}{\sum_{i=1}^{n} \frac{1}{\sigma_{P_{i}}^{2}}} \tag{4.15}
\end{equation*}
$$

where $\sigma_{P_{i}}^{2}$ is the estimated error of the $i^{\text {th }}$ measurement of $P$. Since the nebula was clearly bipolar in form this was performed on its north and south halves separately and the results are shown in Figure 4.10. Errors were calculated using

$$
\begin{equation*}
\sigma_{\bar{P}}^{2}=\frac{1}{\sum_{i=1}^{n} \frac{1}{\sigma_{P_{i}}^{2}}} \tag{4.16}
\end{equation*}
$$

It might be argued that this error estimate is of limited value since it is a sum of individual photometry errors combined with the implicit assumption that all the polarizations at a certain distance from IRS 4 are converging to the same value. But as can be seen in Figure 4.10, genuine coherent structure does exist in the radial polarimetry profiles so perhaps this implicit assumption has some validity. Plots of the radial variations in intensity for the two nebular halves are shown in Figure 4.11. The intensity maps showed large azimuthal variations around IRS 4, so the errorbars shown in that figure were estimated from the scatter around the average values, and not from photometric uncertainties.

Recall that simplified scattering models and observations of astronomical sources embedded in scattering nebulae produce monotonically increasing polarization vs. radius profiles (Section 4.2). The polarization structure of the southern half of the nebula was not a simple linear function or even a power law. A


Fig. 4.10.- This plot shows the radial dependence of the polarization levels in Sharpless 106. Separate analyses were performed for the northern and southern halves. A complicated combination of linear regimes and roll-overs are seen.


Fig. 4.11.- This plot shows the radial dependence of the nebular intensity in Sharpless 106, similar to Figure 4.10.
linear region for the inner $15^{\prime \prime}(0.044 \mathrm{pc})$ is followed by a plateau and then another linear region $70-85^{\prime \prime}$ ( $0.20-0.25 \mathrm{pc}$ ) from the source. The northern half is smaller in spatial extent but no less complicated. A linear region which peaked near $20^{\prime \prime}$ $(0.058 \mathrm{pc})$ rolled over and declined to low levels at which point it appeared to reach a plateau level, although this region of the plot was very noisy. Within the context of a scattering model there are two explanations for the polarization roll-over in the north lobe and the various dips in the south lobe. The drops in polarization could be caused by multiple scattering which would dilute the polarization levels produced by single scattering. Or it is possible that a particular dusty cloudlet is scattering light more than the local less-dense nebular environment so the polarimetry for that projected region of the nebula is elevated. The polarization maximum in the northern lobe near $20^{\prime \prime}$ is particularly interesting and can be traced on intensity and polarization maps as a broad swath of nebulosity arcing around IRS 4.

Apparently a phenomenon more complex than single scattering in a uniform medium is occurring in this nebula. Model results indicate that radial profiles are strongly geometry dependent (Greenberg \& Hanner 1970; Bastien \& Ménard 1988). Additional observations, especially of the fainter outer regions of the nebula and in other bands would be helpful in exploring these interesting features further.

### 4.6.2 The NGC 2264 Clump

In the $J$ band, the polarization pattern is dominated by the single source S3321 so radial profiles of the polarization could be studied. In order to be used in this analysis the polarization angles in the masked $J$ map described in Section 4.5.4 were required to be within $45^{\circ}$ of centrosymmetric around S3321. This very loose


Fig. 4.12. - This plot shows the radial dependence of the polarization levels in the nebulosity associated with S3321 in NGC 2264.
restriction eliminated a few bad pixels in the southern portion of the nebula. A total of 351 pixels were grouped into annular regions 2 -pixels wide, and combined using Equations 4.15-4.16. The results (Figure 4.12) are less compelling than those of Sharpless 106.

Even at small distances from S3321 the polarization values remains near $10 \%$ so there may be a very steep rise in polarization values from $0 \%$ near the center of this nebula. Or perhaps more likely, the presence of a circumstellar disk could produce a residual overall polarization that is not well-resolved in in these observations (Bastien \& Ménard 1988). After the slowly varying region 15-50" from the center, the polarization values increase dramatically once again. This is similar to the results for Sharpless 106, perhaps an indication of a unifying syndrome.

Since the $H$ polarization pattern for the nebulosity in NGC 2264 is complicated and without a clear central source it was not possible to reproduce this analysis for
that band. The quality of the $K$ polarimetry is so low there is no point in working with it further.

### 4.7 Nebular Colours

The colours of the S3321 nebulosity were examined as a final analysis. Thirteen circular regions $9^{\prime \prime}$ in diameter were selected as being representative of the nebula. These regions were free from defects, have reasonably uniform $J$ polarization values throughout, and span the ranges of nebular surface brightness and fractional polarization. The images were masked by a master-mask created by multiplying the three masks from the $J, H$, and $K$ images (Section 4.5.3). This insured identical spatial coverage for all three colours. Integrated magnitudes for these regions were measured and $J-H$ and $H-K$ colours calculated (Figure 4.13). Four sources from the multiband survey with very red $J-H$ and $H-K$ colours were also plotted on this figure-the colours of the source S3495 (3.58 $\pm 0.25,2.32 \pm 0.13$ ) locate it well off the diagram.

Reflection nebulae are bluer than the sources illuminating them because of the wavelength dependence of Mie-scattering. It is obvious from Figure 4.13 that the only sources redder than essentially all the nebular colours obtained are S3153 and S3321, strongly suggesting these are the sources inspiring the nebulosity. This is not a surprise, considering the polarization patterns. But the colours of the nebulosity reveal more information about the scattering in the cloud. Modelling colours of reflection nebulae is a frightening quest because of the complicated angular dependence of the scattering efficiency in Mie theory. However, the situation is ameliorated by a few observations. Consider the simplified case of a radially symmetric reflection nebula with a central source emitting light with an


Fig. 4.13.- The infrared colours of different regions of the S3321 nebula are shown as well as the integrated colour of the nebula. Also plotted are four of the highly reddened objects in the nebula. The dashed lines indicate the blueing colour shifts predicted by a very simple model of a reflection nebula. Considering the simplicity of the model, the model results were considered consistent with the data. The normal reddening vector from dust is shown for $A_{V}=5$.
intensity $I_{0}$. The scattered intensity the observer sees an angular distance $\phi$ from the embedded source (in an optically thin approximation) is given by

$$
\begin{equation*}
I(\phi)=\iint I_{0} \sigma_{s}(\theta, x) N(x, r) \delta R d x d \theta \tag{4.17}
\end{equation*}
$$

where $\sigma_{s}(\theta, x)$ is the scattering cross-section, $\theta$ is the scattering angle in the plane that contains the source, scatterer, and observer, $x$ is the ratio of scatterer radius to light wavelength, $N$ is the number density of dust grains, $r$ is the distance from the source to the scatterer, and $\delta R$ is a radial distance element. If this integration were to be performed, both $r$ and $\delta R$ would have to be written as a function of $\theta$ and $\phi$ (scaled by the distance to the nebula), and $\delta R$ for $\theta=90^{\circ}$ would be determined by the resolution of the mapping of the nebula. The integration is made complicated because the scattering cross-section is a sensitive function of both $\theta$ and $x$. But two observations simplify the situation. First, the grain radii of astronomical dust are considered to occur in power-law distributions, and not just a single size. This and grain shapes deviating from perfect spheres should dampen most of the wild functional variations in $\sigma_{s}(\theta, x)$ to a reasonable behavior (Greenberg \& Hanner 1970). Second, and most importantly, the $\theta$ and $x$ dependences of the scattering efficiency are separable-that is the scattering cross-section can be written as a product of a function of $x$ and a function of $\theta$ (van de Hulst 1957):

$$
\begin{equation*}
\sigma_{s}(\theta, x)=f(\theta) \overline{\sigma_{s}(x)} \tag{4.18}
\end{equation*}
$$

Consequently, as long as only flux ratios (i.e. colours) are being considered, most of the subtleties from the $\theta$ dependencies will cancel (and even assumptions such as optical thinness are unnecesary), so geometrical effects can be separated from wavelength dependencies.

With these simplifications in hand, consider a beam of light ( $I_{0}$ ) incident upon a scattering cloudlet. Part of the beam will be transmitted $\left(I_{t}\right)$, and the difference
between the incident and transmitted beams comprises the energy extincted from the incident beam by both absorption and scattering. The fraction of light scattered $I_{s}$ can be written as

$$
\begin{equation*}
I_{s}=\left(I_{0}-I_{t}\right) \frac{\sigma_{s}}{\sigma_{T}} \tag{4.19}
\end{equation*}
$$

where $\sigma_{s}$ and $\sigma_{T}$ are the scattering and total extinction cross-sections. The $J-H$ colour of a reflection nebula could be written as

$$
\begin{align*}
(J-H)_{r f} & =2.5 \log _{10}\left(\frac{I_{s, H}}{I_{s, J}}\right) \\
& =2.5 \log _{10}\left(\frac{\left(I_{0, H}-I_{t, H}\right) \frac{\sigma_{s, H}}{\sigma_{T, H}}}{\left(I_{0, J}-I_{t, J}\right) \frac{\sigma_{s, J}}{\sigma_{T, J}}}\right) \tag{4.20}
\end{align*}
$$

where the subscripts $J$ and $H$ indicate the bands for the various intensities and cross-sections. The extincted portion of the beam can be written in terms of optical $\operatorname{depth} \tau$,

$$
\begin{equation*}
I_{0}-I_{t}=I_{0}\left(1-e^{-\tau}\right) \tag{4.21}
\end{equation*}
$$

and so Equation 4.20 can be rewritten as

$$
\begin{equation*}
(J-H)_{r f}=2.5 \log _{10}\left(\frac{I_{0, H}\left(1-e^{-\tau_{H}}\right)\left(\frac{\vec{\sigma}_{\alpha, H}}{\sigma_{T, H}}\right)}{I_{0, J}\left(1-e^{-\tau_{J}}\right)\left(\frac{\bar{\sigma}_{A, J}}{\sigma_{T, J}}\right)}\right), \tag{4.22}
\end{equation*}
$$

where the angular dependence of Mie-scattering has been separated and cancelled from the scattering cross-sections. Identifying the intensity ratio $I_{\mathrm{o}, H} / I_{\mathrm{o}, J}$ as the colour of the illuminating source $(J-H)_{\mathrm{o}}$, and assuming the ratio $\bar{\sigma}_{s} / \sigma_{T}$ should at most be only slowly varying for adjacent photometric bands, the nebular colour can be written as

$$
\begin{equation*}
(J-H)_{r f}=(J-H)_{\circ}+2.5 \log _{10}\left(\frac{1-e^{-\tau_{H}}}{1-e^{-\tau_{J}}}\right) \tag{4.23}
\end{equation*}
$$

Compared to the transmitted beam, the incident beam of light is attenuated by the factor $e^{-\tau}$, which for the $J$ band produces an extinction of

$$
\begin{equation*}
A_{J}=2.5 \log _{10} \frac{I_{0, J}}{I_{t, J}}=2.5 \log _{10} e^{\tau_{J}}=1.0857 \tau_{J} \tag{4.24}
\end{equation*}
$$

It is common practice to express such infrared extinctions in terms of the extinction in the $V$ band using conversion equations such as $\Delta m_{J}=A_{V}\left(A_{J} / A_{V}\right)$. So casting Equation 4.24 in terms of $A_{V}$ yields

$$
\begin{equation*}
\tau_{J}=A_{V}\left(\frac{1}{1.0857} \frac{A_{J}}{A_{V}}\right) \tag{4.25}
\end{equation*}
$$

Using equations of this form, the $J-H$ and $H-K$ blue excesses anticipated for the nebula are

$$
\begin{align*}
(J-H)_{r f}-(J-H)_{0} & =2.5 \log _{10}\left(\frac{1-e^{-a_{H} A_{V}}}{1-e^{-a_{J} A_{V}}}\right)  \tag{4.26}\\
(H-K)_{r f}-(H-K)_{0} & =2.5 \log _{10}\left(\frac{1-e^{-a_{K} A_{V}}}{1-e^{-a_{H} A_{V}}}\right) \tag{4.27}
\end{align*}
$$

$$
\begin{equation*}
\text { where } a_{J}=\frac{1}{1.0857} \frac{A_{J}}{A_{V}}, \quad \text { etc. } \tag{4.28}
\end{equation*}
$$

In the limiting case of an extremely optically thick reflecting cloud, Equations 4.264.27 predict the logarithmic terms will vanish and the nebular colours will approach the colours of the illuminating source. For a thin cloud where $A_{V}$ approaches zero, the colour excess of the nebula will be at a maximum, specifically

$$
\lim _{A_{V} \rightarrow 0}\left\{\begin{array}{l}
(J-H)_{r f}-(J-H)_{0}=2.5 \log _{10} \frac{A_{J} / A_{V}}{A_{H} / A_{V}}=-0.518  \tag{4.29}\\
(H-K)_{r f}-(H-K)_{0}=2.5 \log _{10} \frac{A_{H} / A_{V}}{A_{K} / A_{V}}=-0.485
\end{array}\right.
$$

These results indicate that from single scattering the maximum blueing that a nebula can exhibit compared to the illuminating source is $\Delta(J-H)=-0.518$ and $\Delta(H-K)=-0.485$. Blueing lines, with tick marks at 0.518 and 0.485 intervals, are shown in Figure 4.13. Since the nebulosity is certainly more blue than the maximum allowable colour shift for a single scattering, this provides evidence that a situation more complicated than single-scattering is occurring in the nebula. In fact, in units of blueing, double or even triple scattering in the nebula would be
necessary to account for the rich blue colours seen. Interpreting this too strictly as evidence for double or triple scattering is of course nonsense because additional scattering would come at the cost of more long-wavelength light being scattered, which would result in less blueing. The very high levels of polarization in the reflection nebula are also inconsistent with these multiple scattering scenarios. It can be seen in Figure 4.13 that while this analysis calculates the general direction of the blueing vectors, neither S3321 or S3153 really seemed to have the correct colour to account for the colour of the nebula. An explanation for this quandary may lie in extinction. If the geometry of the system is such that light from S3321 is being extincted by a disk, the source would be reddened. Light exiting S3321 in polar directions could illuminate the reflection nebula after suffering less extinction. A difference in line-of-sight and polar extinctions equivalent to $A_{V}=5$ magnitudes would shift the source the length of the reddening vector shown on Figure 4.13. If this were the case, dereddening the effect of this cloud from S3321 would place it in a position where it could nicely account for the nebular colours. This would also explain why the integrated nebular flux is greater than that of S3321 and S3153 combined. As it will be noted in the next section, a polar vs. equatorial difference in visual extinctions of 5 magnitudes is small compared to the total extinction experienced by S3321. On the other hand, this entire scenario might be destroyed by careful modelling which handled scattering theory appropriately.

### 4.8 S3321, RNO, and Outflow D

The source S 3321 was discussed in Castelaz \& Grasdalen (1988), who refer to it as RNO-the Red Nebulous Object. They discovered that it is a double source experiencing 18-21 magnitudes of extinction at $V$. The duplicitous nature of S3321
was verified by careful inspection of the $J, H$, and $K$ images of Chapter 3. Castelaz \& Grasdalen (1988) found that RNO-West is apparently a $5-8 \mathrm{M}_{\odot}, 10^{4} \mathrm{~K}$ source less than $3 \times 10^{5} \mathrm{yr}$ old, and RNO-East is only 3000 K and is younger than $10^{5} \mathrm{yr}$. This pair of sources is also coincident with the most massive ( $16-30 \mathrm{M}_{\odot}$ ) molecular outflow detected in the cluster (Margulis 1987). This object, which Margulis called Outflow D, is a bipolar outflow oriented with its lobes in a southwest-northeast arrangement, in good agreement with the orientation that would be produced by a disk as proposed in Section 4.5.4. The lobe of bright luminosity extending from S3321 towards the southwest corresponds to the the red-shifted jet of emission. This outflow has a dynamical age of only $6.9 \times 10^{4} \mathrm{yr}$, similar to the estimates for the components of RNO. Using IRAS point source data, Margulis estimated the infrared luminosity of Outflow D as $330 \mathrm{~L}_{\odot}$. RNO/Outflow D/S3321 is clearly an extremely young source in a cluster consisting of members with ages usually a few million years old. This nebular region is clearly an interesting area needing further study.

### 4.9 Summary

A working infrared imaging polarimeter was created by augmenting an infrared array camera with a simple Polaroid sheet analyzer. This arrangement was successful with bright sources at the infrared bands $J$ and $H$, and marginally useful at $K$. By using a variety of reduction tricks, good results were obtained for sources with high polarization levels $(P>5-10 \%)$. Centrosymmetric polarization patterns are confirmed for Sharpless 106, while Sharpless 140 has a more complicated polarization pattern. A strip of low polarization is found in Sharpless 106, spatially coincident with a collimating disk suspected to be in the system. The
degree of polarization as a function of the distance from the illuminating source is investigated for Sharpless 106, and was found to be complicated and not just monotonically increasing as expected if single scattering and a simple geometry were responsible for the observed polarization levels.

Faint nebulosity surrounding S3321 in NGC 2264 was studied with the imaging polarimeter. At $J$ the polarization pattern is strongly centrosymmetric around S3321, identifying it as the illuminating source in the region. A strip of low polarization pixels is found extending from the source, roughly perpendicular to the long axis of the nebular region. The radial dependence of the fractional polarization is not convincingly linear, although the data are so noisy it was dangerous to draw many conclusions. At $H$ the pattern is more complex, no longer centered exclusively around S3321, but also apparently influenced by S3153. By $K$, the nebular emission is too faint for polarimetric work. Although the nebula was too faint for reliable polarimetry at all bands, integrated colours could be obtained. Colour information in the nebula verify that while it is illuminated by one or both of the sources S3321 and S3153, the colours of the reflection nebula can not be explained by a cartoon model unless S3321 is highly extincted, as from a disk. Observations of S3321 by previous workers have revealed large amounts of long-wavelength emission, a duplicitious nature, and an associated molecular outflow.

## Chapter 5

## THE MX SPECTRAL SURVEY

### 5.1 Overview

In this chapter a spectroscopic atlas of 361 bright stars $(V \leq 17)$ selected from the multiband survey is discussed. Spectral classification criteria for the stars are developed and the stars are classified to an accuracy of a few spectral subtypes. The nature of the sources in the spectral survey is examined, and from the background sources it is estimated the GMC behind NGC 2264 provides approximately 4 magnitudes of visual extinction for these stars. Emission line activity is measured for the stars and is used to group the stars into broad categories. Spectral veiling is observed in many of the stars, and 54 T Tauri stars are noted.

### 5.2 Introduction and Motivation

In Chapter 3 the development of a multiband survey for NGC 2264 was described. The entries in that survey could be categorized into five classes. The
first class contains the foreground stars. As it was discussed in Section 3.10, approximately $1 / 3$ of the survey stars brighter than $V \approx 17.0$ are probably foreground stars. The extinctions these stars suffer should be at most only a few tenths of magnitude at $V$. The second class of stars includes the background sources. The GMC behind NGC 2264 helps decrease contamination from these by providing extinction and so these stars probably only represent $10 \%$ of the stars with $V<17.0$. The third population of the survey contains all the cluster stars that have managed to extricate themselves from the majority of the dust that was involved in their formations. These stars will still suffer small to moderate amounts of interstellar extinction. The fourth class contains cluster stars with large amounts of extinction due to the clumpy interstellar medium in the complex. The dust extincting these stars is not associated with disks, but rather just intracluster clouds. There is probably a continuum of extinctions experienced by the stars in the cluster so the distinction between this group of stars and the unreddened stars in the previous category is somewhat artificial. The last category contains those cluster objects with large amounts of extinction and reddening-not merely of interstellar or intracluster origin, but rather due to circumstellar disks or dust clouds intimately associated with the sources. Anomalous infrared colours due to thermal excesses are expected from this crowd (Lada et al. 1993), which presumably would contain the youngest stars of all the classes. A sixth category could be listed which would contain all the spurious entries of a nonstellar nature, but it is assumed in this chapter they have been eliminated by requiring detections in at least two bands.

The magnitudes and resulting colours in the multiband survey contain a great deal of information but they do not unambiguously identify the nature of the stars in the sample. A star in any of the five categories listed above could
easily be mistaken for a star in at least one other category. For example, consider the problems involved in trying to use colours to distinguish cluster stars from foreground stars. Foreground stars should be easily differentiated from cluster members by their positions well above the main-sequence on a colour-magnitude plot. But problems arise even in this simple case. The magnitude limits of the survey were such that the photometry of foreground stars earlier than type A0 were saturated and unusable, so a foreground early-type star could not be distinguished from a cluster star. This is not too much of a problem since the brightest stars have been examined already (Walker 1956; Adams et al. 1983; Warner et al. 1977). But what about the fainter stars? Walker showed that due to the youth of the cluster, later than A0 the cluster stars were located well above the main-sequence on a colour-magnitude diagram, mimicking the higher flux anticipated from a foreground star. It would be difficult to distinguish a foreground K star from a pre-main-sequence K star on the basis of a few magnitudes alone. Trying to differentiate a foreground star from an unreddened cluster star by colours alone could not be done.

It is little easier to photometrically distinguish background stars from cluster stars. The background stars must peer through the murky dust of the GMC behind NGC 2264, and so will be strongly extincted. For a main sequence background star just behind the GMC to pierce through 5 magnitudes of extinction to be detected in a survey which had a limiting magnitude of $m_{V}=18.6$, its absolute magnitude must be at least $M_{V}=18.6-5-9.7=3.9$, requiring an $F$ or earlier star. So suppose such an A0 background star were included in the survey. Its reddened colours would be $J-H=0.54, H-K=0.32$ (Rieke and Lebofsky 1985), which could be mistaken for an unreddened pre-main sequence K star which would have infrared colours $J-H=0.37$, and $H-K=0.10$ and $m_{V} \approx 15.5$ (Johnson 1966;

Koornneef 1983). The colours are in some disagreement, certainly enough to merit suspicion, but if the photometry were in doubt by $10-15 \%$ in each band the disagreement could be explained by the errorbars. It might even be postulated that the odd colours were due to variability by this " K " star, as often seen with T Tauri stars (Rydgren \& Vrba 1981; Mendoza 1968). These problems are compounded by the fact that young stars exhibit strong infrared excesses (Lada et al. 1993; Strom et al. 1971; Warner et al. 1977). It is very difficult to determine the nature of sources by their colours alone-the simultaneous effects of stellar distances, the unpredictable characteristics of pre-main sequence stars, intracluster and circumstellar extinction, and intrinsic infrared excesses cannot be securely disentangled.

In the last several years, various disk models have been promoted which can fit the near-IR colours of young stellar objects (for example, Hillenbrand et al. 1992; Lada \& Adams 1992). Unfortunately, the solutions from these models are not unique, and to constrain them sufficiently information about the central sources such as temperature and luminosity are required which cannot be obtained from photometry. Spectroscopy of young stellar objects can be used with the photometry to produce this much needed information. Additionally, there are a number of recent research projects in which entire star-forming clusters are being surveyed in the near infrared (Lada et al. 1993; Greene \& Young 1993; Carpenter et al. 1993; Lada 1992; Eiroa \& Casali 1992; Barsony et al. 1991; and others). These studies use colour-colour diagrams to interpret the nature of the stars in the clusters. But while this is a time-effective way to study large numbers of stars, a spectroscopic follow-up study of the stars of at least one of the clusters is a useful way to verify the accuracy of the colour interpretations.

To understand more about the stars in NGC 2264, spectroscopic data for
a large sample of stars in the cluster were desired. Since the cluster contains a very large number of stars in a small region of the sky, the spectroscopic project was ideally suited to a multiplexing instrument like the Steward MX (Hill 1984). The heart of this instrument consists of 32 remote-controlled probes which are commanded to positions in the telescope focal plane so a fiber-optic filament near the tip of each probe can catch the light from a star for spectral analysis. A second filament on each probe collects light for a sky spectrum. In order for the MX to work, the coordinates fed to the software controlling the probe positions had to be accurate to approximately $1^{\prime \prime}$, the radius of a fiber-optic filament. The astrometry in the photometric survey easily met this requirement.

### 5.3 Processing MX Data

In this section the preprocessing, observing, and reduction of MX data is discussed. The main point to working with the MX instrument was to maximize the acquisition rate of data, and to optimize this extensive pre-observing work was required. After the observing run the CCD images needed to be reduced using standard methods as well as techniques unique to working with the MX.

### 5.3.1 Source Selection

Prior to the MX observing run a great deal of preparation was needed because a large number of coordinates had to be processed. In addition to coordinates for program stars, a group of center stars had to be selected. Center stars are used as coordinate references for the telescope to guide upon while the probes gather data. Since it is crucial that the center stars have excellent coordinates, 22 Walker stars
with astrometry in excellent agreement with published values (Lapicz 1984) were chosen.

To maximize the efficiency of the spectrometer, the coordinates of as many potential observing targets as possible had to be made available to the MX. With too few targets the instrument became starved of sources and would start to reobserve stars. Worse still, in order to collect data on sources not yet observed, the MX software might assign probes in such a way that the other probes were prevented from operating, and so they would be inactive for that integration. The more sources that were available to the MX the fewer bad choices it was forced to make and the more data it could collect.

To generate a list of potential program stars, sources detected in at least five bands were culled from the photometric survey. This insured that the core of the MX sample would include stars accompanied by plenty of photometric data. Also, Walker stars and $\mathrm{LkH} \alpha$ stars that did not merge into the survey were included (this contained very bright stars which were saturated in the photometric survey or for other reasons did not have detections in all bands). Stars with anomalous infrared colours were also flagged for MX analysis. These were the stars with either $J-H$ or $H-K>1.5$, and especially those sources with $(J-H) /(H-K)<1.0$. This latter criterion was used because infrared colours due exclusively to normal reddening should result in $(J-H) /(H-K) \approx 1.7$ (Rieke and Lebofsky 1985), so a value below 1.0 suggests significant long wavelength emission. Using these criteria, approximately 900 potential program stars were selected. Six additional stars of known spectral types were picked from bright star catalogues for later use as spectral comparisons.

Because the sources spanned a wide range of brightnesses, they were grouped
into bins by $V$ magnitude. For those stars lacking full photometric coverage, $V$ magnitudes were estimated as $m_{V}=m_{I}+1.5$ or $m_{V}=m_{J}+2.5$. The four magnitude bins used were $m_{V}=10-13,13-15,15-17$, and 17-19, which contained $78,84,201$, and 538 stars respectively. All the infrared anomaly stars fell into the two faint bins (32 into the $m_{V}=15-17$ list, 138 into the $m_{V}=17-19$ list). Each program star required an observation priority to help the MX software determine which sources were more important to observe. Stars with peculiar infrared properties were given highest priorities.

For each center star, the celestial coordinates for the program stars that would lie in the telescope's field of view were converted into $(x, y)$ coordinates in the focal plane. These $(x, y)$ coordinates were dependent upon factors such as telescope flexure and atmospheric aberration, so they had to be recalculated for every few hours of observing. Then the $(x, y)$ coordinates were transformed by the MX software into target files. These contained the locations to which the probes would be commanded to move for each integration. If a source was selected for observation, its priority was lowered to discourage the MX software from selecting it for future observations, although it was always better to observe a source an additional time than to let a probe sit idle. Figure 5.1 shows a map of the focal plane for a typical integration, and indicates the locations of the 32 probes groping for sources. Since the lists involving the fainter stars had so many entries, the target files created for them had all or nearly all the probes assigned to sources. But when creating the target files for the brightest stars, often as many as $1 / 3$ of the probes were inactive so as to allow the other probes to service hard to reach but as yet unobserved stars. While this reduced the multiplex advantage of the MX, the exposures were so short for these stars it was well worth it. MXPACKAGE, written by John Hill for the IRAF environment, contains all the MX software


Fig. 5.1.- The image plane of the 2.3 m telescope with 32 probes seeking sources in the cluster is shown. In this example, four of the probes (numbered 04, 08, 0A, and 0 E ) are not assigned sources. The large dashed circle represents the approximate field of view of the telescope. The dot at the tip of each probe indicates the location of the fiber-optic filament. This figure was produced by MXPACKAGE.
needed to transform source lists into $(x, y)$ coordinates and target files.
Overall, with more than 900 program stars, twenty-two center stars, and additional offset and alignment stars required for telescope navigation, producing target files for every few hours of a five night observing run resulted in more than 500,000 coordinates being processed. As a comparison, some observers have claimed that with the naked eye stars as faint as $m_{V} \approx 7.5$ can be detected-approximately 32,000 stars in both hemispheres of the night sky are brighter than this.

### 5.3.2 Observations

The spectroscopic data were obtained during the four good nights of a five night observing run in January 1993. The Steward 2.3 m telescope was used with the $B \& C$ spectrograph which provided a wavelength coverage of approximately $3700 \AA$ to $7000 \AA$ at a resolution of $10 \AA$. The $12 \times 8$ Bok Loral CCD chip was used which had a full size of $1200 \times 800$ pixels. Its readout was binned to dimensions $1200 \times 400$, of which 315 rows were read out. At sunset and sunrise, 300 s twilight flats, 60 s chip flats, 0 s bias frames, and 1 hour dark current frames were taken. After focusing the spectroscope, $120 \mathrm{~s} \mathrm{He}-\mathrm{Ne}-\mathrm{Ar}$ comparison lamp spectra and 20 s fiber flats were taken every few hours. A chip flat is the frame produced by illuminating the chip with a quartz lamp, while a fiber flat is produced when light from a quartz lamp is carried to the chip by the individual MX fiber-optic filaments. Integration times for the stellar spectra ranged from 300 s for stars with $m_{V}=10-13$ to 1 hour for stars with $m_{V}=17-19$.

### 5.3.3 CCD Reduction

The first steps of the CCD reduction were accomplished using the IRAF tasks in CCDRED. The object, fiber flat, chip flat, and comparison lamp frames were overscan corrected and trimmed (see Section 3.3.2) to pixel dimensions $1197 \times 285$. The bias frames were found to be unusable so the object frames were debiased by fitting unilluminated portions of each with a polynomial surface. For example, rows $1-15,53,162,213-214$, and $260-285$ were unused in the first night's observations. These regions were fit with a chebyshev surface of orders 5 and 2 in the ( $x, y$ ) coordinates. Subtracting these surfaces from the images resulted in debiased frames. Bias corrections were so small they were significant for only the faintest sources observed. In order to account for the way the chip was illuminated by the spectrograph, the images needed flattening. To make a flat-field image, all the chip flats were averaged and then smoothed with a $50 \times 100$ pixel box to remove small scale effects. The flat-field divisions corrected for multiplicative factors and finished the standard CCD reductions.

For the next series of reduction steps the IRAF tasks in MXPACKAGE were used. A fiber flat was chosen from each night of data, and its sixty-four continuum spectra were traced using interactive fitting routines. These traces were used as initial guesses to trace the continuum spectra of all the other fiber flats which in turn were used to trace and extract the stellar, sky, and comparison spectra.

By identifying the emission lines in the comparison lamp spectra and fitting their locations with fourth order legendre polynomials, fits to the dispersion relations were made. The stellar and sky spectra were linearized using the dispersion relations for the comparison lamp that was observed most recently in the past or nearest in the future. Since nearly all the stellar spectra had recognizable
features such as hydrogen or calcium lines any bad dispersion relations would have been obvious in the reduced spectra but no such errors were observed. The linearized spectra were trimmed to the spectral range of $3690-6960 \AA$ and a pixel size of $3 \AA$. Fits to unsaturated comparison spectra as well as nebular emission lines indicated that the resolutions (full widths at half maxima) of the spectra were about $10 \AA$. The usable blue end of the spectra was set by the degrading efficiency of the instrument combined with the low amounts of short wavelength fluxes from most of the program stars. The red end of the spectra was terminated by telluric $\mathrm{O}_{2}$ bands near $6800 \AA$. Because of these limitations, the usable spectral coverage of most of the spectra was approximately $3880-6750 \AA$.

Sky subtraction posed special challenges for the spectra in the sample. Along with the stellar spectra, sky spectra were obtained by separate fibers on each MX probe located 40 " from the star fiber. The sky spectra in each frame were scaled by their median values, then were median-filtered into a final spectrum. All the median-filtered sky spectra were checked for contamination from errant cluster stars, and if they were tainted then the corrupted input sky spectra were discarded and the median-filtering was repeated. The averaged spectra were iteratively subtracted from each stellar spectrum on the same image until the airglow line [O I] $5577 \AA$ was removed. These steps were usually well perfomed by MXPACKAGE tasks, but noise spikes near $5577 \AA$ corrupted the results for 42 spectra and in these cases non-automated sky subtraction was necessary. For these spectra if the $5577 \AA$ line could not be fit manually, the atmospheric/nebular lines [OI] $6300 \AA$ or [OII] $3727 \AA$ were used instead.

In the sky subtracted stellar spectra, the nebular line [N II] $6583 \AA$ is visible in emission in 129 stars and in absorption in 16 stars. This line is not seen in normal stellar or T Tauri spectra (Joy 1945) and its presence in stellar spectra
indicates that while the contributions of airglow were accurately subtracted from those spectra, flux from cluster nebulosity was not. A continuum subtracted, median-average of all the sky spectra is shown in Figure 5.2. The strongest nebular lines were Balmer lines and a variety of forbidden lines, especially [N II] $6583 \AA$. Clearly the stars that have nebular forbidden lines in their spectra will also have their hydrogen lines modified to some degree by a nebular contribution. The degree to which the stellar spectra are contaminated is explored further in Section 5.5.2.

During the run, 33 target files were used to observe a total of 978 spectra. Many of these were multiply observed while 185 were stars that were too faint to be detected. Coadding all the good spectra resulted in spectra for 361 stars. It was seen that the spectral continua were strongly modulated by an instrumental effect. This effect was seen, not in the twilight flats or sky spectra, but in sources smaller than the fiber diameters; the modulation was probably related to refraction of the stellar images (Young \& Rottler 1991) and the angle at which the starlight entered the fibers. The outcome of this unpredictable effect was that while individual spectral features were unaffected, continuum information such as reddening effects or the location of broadband spectral maxima was lost. Because of this problem and for ease of comparison with spectral standards, all 361 spectra were flattened by divisions with continuum fits. The continua for $K$ and especially $M$ stars were difficult to define and somewhat arbitrarily chosen but flattening was still useful. So these spectra are primarily useful for spectral classification, while they are of more limited utility for optical spectral energy distribution determinations. The coordinates for the 346 spectral survey stars that are included in the survey discussed in Chapter 3 are listed in Table 5.3. The photometry for these sources are given in Table 5.4. Data for cluster sources which are not in the photometric survey, yet for which spectra were obtained, are listed in Table 5.5.


Fig. 5.2.- Displayed is a normalized spectrum produced by median-filtering all the sky spectra from the MX cluster data. Strong telluric airglow features are identified with a "T", the most important of which is [O I] $5577 \AA$. The other features are nebular Balmer and forbidden lines.


Fig. 5.3.- A histogram is shown for the 329 program stars observed in the spectroscopic survey for which accurate $V$ magnitudes are available. The data for stars with $m_{V}<12.5$ are replaced with Walker's magnitudes, otherwise data from the photometric survey are used.

A histogram of the $V$ magnitudes for the stars observed is shown in Figure 5.3. The fluxes from the faintest stars were barely detected, so they were very sensitive to the sky and bias subtraction steps. As a result the equivalent widths for some of these sources were exaggerated and the useful wavelength ranges were not as large, especially at the blue end of the spectra.

### 5.4 Spectral Classification

The 361 stars in the spectroscopic sample consist of a heterogenous ensemble of background and foreground stars, cluster members with varying degrees of reddening, Herbig Ae stars, T Tauri stars, and other objects of a very young nature. A way to establish a foothold in understanding the sample was to determine their MK spectral classes. The literature of MK classification is huge and the techniques used can become deeply involved. So to be efficient and since high accuracy spectral typing was not required (and probably not possible with the MX data) devising a partly or completely automated method was attractive. Core to the philosophy of MK classification is matching new spectra to the spectra of classified standard stars, and one way of doing this is by using prominent temperature-dependent or luminosity-sensitive features. It is important to use simultaneously as many of these features as possible; if the general impetus from most of these spectral features drive the classification of a star towards a certain MK type, the fact that another feature or two suggest a different classification is not cause for alarm. It is the overall spectral gestalt which is important. This nature of the MK philosophy eases its automation-by developing a set of classification features, a weighted or median-filtered numerical estimate of its spectral type can be generated. Even if a spectrum were very noisy, several tentative estimates of the star's spectral type could be used to produce a reasonably reliable classification. However, the automated approach is somewhat heretical, as the masters themselves wrote: "There appears to be, in a sense, a sort of indefiniteness connected with the determination of spectral type and luminosity from a simple inspection of a spectrogram. Nothing is measured; no quantitative value is put on any spectral feature" (Morgan et al. 1943). The goal for this
section was straightforward-spectral classifications accurate to a few subtypes for all the stars. Luminosity classifications were difficult to execute with the spectral resolution of the MX data, so for most stars either a giant or dwarf classification was sufficient.

A few words on terminology. In this dissertation the letter+number designation relating to a star's temperature (i.e. B7) is called its spectral type or spectral class, and the single digit number (" 7 " in the case of B7) is called the subtype or subclass. The roman numeral denoting a star's luminosity (I, II, III etc.) is called its luminosity class. In some quarters more careful definitions are applied to the terms spectral type and spectral class, but since these are not universally followed no distinction will be made here. When possible, stars were classed as either giants or dwarfs. In this paper, a giant star is defined as a star of luminosity class I-II, while a dwarf star is a member of luminosity class III, IV or V.

### 5.4.1 Selecting Classification Criteria

When performing spectral class determinations, the usual approach is to compare the spectra of the program stars to a library of spectral standards observed with the same or similar observing arrangement. Unfortunately no such library exists for MX data and while six standard stars were observed during the run they did not constitute an adequate reference library. The atlas of Jacoby, Hunter, \& Christian (1984)—hereafter JHC-contains 161 spectra of stars from type $O$ to M in luminosity classes $\mathrm{I}-\mathrm{V}$, spanning the spectral region $3510-7427 \AA$ at $4.5 \AA$ resolution. Fifty-seven spectra are of class V stars (solar metallicity), so the JHC library provided excellent coverage of the temperature and luminosity ranges for stars expected in the MX survey. The JHC data were obtained in electronic
format and the spectra were smoothed and trimmed to match the MX data's $10 \AA$ resolution and $3690-6960 \AA$ coverage. Finally they were continuum fitted and divided for easy comparison to the MX data. In Figure 5.4 seven processed spectra from the JHC library are shown as examples.

In its original formulation (Morgan et al. 1943), MK classification was performed on data that have a much higher spectral resolution than the MX's $10 \AA$. Furthermore, to match the sensitivity of photographic emulsions the classification features used were in the spectral range $3920-4900 \AA$. This is bluer than the bulk of the MX data and a poor choice for the survey sources since most produced the preponderance of their fluxes at much longer wavelengths. For the MX data new spectral features were required for classification. In order to be a useful taxonomic aide, a spectral feature-either a line, line blend, absorption band, or bandhead-was required to vary in a predictable and quantifiable way over at least five spectral subtypes. Also, the most cherished temperature features were independent of luminosity, and the most treasured luminosity features were independent of temperature. The literature was searched for hints on useful classification criteria (Morgan et al. 1943; Abt et al. 1968; Seitter 1970; Morgan \& Keenan 1973; Seitter 1975; Keenan \& McNeil 1976; Pritchet \& van den Bergh 1977; Cohen \& Kuhi 1979; Turnshek et al. 1985; Torres-Dodgen \& Weaver 1993; and others). Promising possibilities were tested using the JHC library. Other useful classification features were found by directly inspecting the JHC spectra. Since many of the survey stars were expected to show emission lines characteristic of T Tauri stars (especially the Balmer and calcium doublet lines), line ratios involving those features were not useful for this study.

A variety of suitable classification features were found. The simplest were line ratios, such as $\mathrm{Ca} \mathrm{K} /(\mathrm{H} \epsilon+\mathrm{Ca} \mathrm{H})$ for early-type stars where Ca II K was not likely


Fig. 5.4.- Spectra of seven main sequence stars from Jacoby, Hunter, \& Christian (1984) are shown. These spectra were smoothed, trimmed, and flattened to match the MX survey data.
to be in emission. More complicated or broad features were also used, such as the "G band" (produced by CH), the "Mg b" feature at $5177-5184 \AA$, or a $300 \AA$ wide absorption feature near $5211 \AA$ produced by MgH , which is prominent in late G to early $M$ stars and is particularly enhanced in dwarfs. Also occasionally useful were blends of lines, such as a group of metal lines near 4019-4084 $\AA$ or a temperature sensitive region near 4090-4250 $\AA$. When measuring these somewhat ill-defined or diffuse features, great care was taken to always measure them over the same wavelength ranges to be as objective as possible. The behavior of each feature with respect to spectral subtype or luminosity class was fit with a curve which was nearly always first order. The results for each spectral type are described below. The criteria most commonly used for spectral taxonomy are listed in Table 5.1.

Table 5.1. Spectral Classification Criteria

| Stellar Type | Temperature Indicator | Luminosity Indicator |
| :---: | :---: | :---: |
| O | He I lines: $4471 \AA$, He II lines: $4686 \AA, 5412 \AA$ |  |
| B | He I lines: $4388 \AA, 4471 \AA, 5876 \AA$ | ........ |
| A | $\mathrm{Ca} \mathrm{K}{ }^{\text {a }}$ | ......... |
| F | Ca K ${ }_{\text {a }}^{\text {a }}$ G band, ${ }^{\text {b }} \mathrm{Mg}$ b 4019-4084 $\AA$ metal blend ${ }^{\text {d }}$ | $\mathrm{Mg} \mathrm{b}^{\text {c }}$ |
| G | Mg b c G band, $\mathrm{MgH} 5211 \AA$, 4019-4084 $\AA$ metal blend ${ }^{\text {d }}$ | Fe $6495 \AA, \mathrm{MgH} 5211 \AA$, $\mathrm{Mg} \mathrm{b}^{\mathrm{c}}$ |
| K | 4090-4250 $\AA$ CN blende $\mathrm{MgH} 5211 \AA$, TiO bands: $6159 \AA, 6187 \AA, 6255 \AA$ | 4090-4250 $\AA$ CN blende <br> $\mathrm{MgH} 4780 \AA, \mathrm{MgH} 5211 \AA$ |
| M | $\mathrm{MgH} 5211 \AA, \mathrm{TiO}$ bands: $4584 \AA$, $4626 \AA, 4804 \AA, 4848 \AA, 5448 \AA$, $5497 \AA, 5598 \AA, 5629 \AA, 5661 \AA$; VO $5737 \AA$ | $\mathrm{MgH}: 4780 \AA, 5211 \AA ; \mathrm{Mg} \mathrm{b}$; Ca I lines: $6103 \AA, 6122 \AA$; $\mathrm{CaH} 6385 \AA$ |

${ }^{\mathrm{a}} \mathrm{Ca}$ II K occurs at $3934 \AA, \mathrm{Ca}$ II H is at $3968 \AA$ and blends with $\mathrm{H} \epsilon$.
${ }^{\text {b }}$ The $G$ band occurs near $4300 \AA$ and is produced by CH .
${ }^{c}$ The Mg b feature is a narrow absorption feature, a blend dominated by a cluster of Mg I lines at $5167 \AA, 5173 \AA$, and $5184 \AA$.
${ }^{\mathrm{d}} \mathrm{A}$ blend of lines including $\mathrm{Mn} \mathrm{I}, \mathrm{Fe} \mathrm{I}$, and Sr II.
${ }^{\mathrm{e}} \mathrm{A}$ region with a temperature-sensitive continuum shape. This is also luminosity sensitive.


Fig. 5.5.- Three He features are indicated in two main sequence O star spectra from the JHC library. For later O stars, the He I $4471 \AA$ feature grows, while the He II lines at $4686 \AA$ and $5412 \AA$ shrink. The $\mathrm{H} \beta$ and $\mathrm{H} \gamma$ lines were truncated in this figure.

## O Stars

All the hydrogen lines are of fairly invariant strength, but the helium lines are good temperature indicators. The He I lines at $4388 \AA, 4471 \AA, 5876 \AA$, and the He II lines at $4542 \AA, 4686 \AA$, and $5412 \AA$ were measured in ratio with $H \beta$ and also $\mathrm{H} \gamma$ (two hydrogen lines were used in case the datum in one line was corrupted). The best results were from ratios involving He I $4471 \AA$, and He II $4686 \AA$ and $5412 \AA$, because the other lines were either too weak or were blended with other features. Figure 5.5 shows the relevent spectral regions of two $O$ stars. In Figure 5.6 the trends of the He I lines vs. O subclass are shown. The feature with the least scatter, He I $4471 \AA$, is an MK classification feature. Even though individually


Fig. 5.6.- The equivalent width ratios for He I lines $/ \mathrm{H} \gamma$ and He II lines $/ \mathrm{H} \gamma$ are shown as functions of $O$ subtype.
fits are not too compelling, using the three simultaneously is an effective way to classify 0 stars.

## B Stars

The He I lines at $4922 \AA$ and $6678 \AA$ are helpful for classifying B stars but the most important are at $4388 \AA, 4471 \AA$, and $5876 \AA$ (Figure 5.7). Deblending the He I lines from the surrounding spectral features was a delicate process. For example, to be consistent, the $4388 \AA$ line was defined as always being from 4366-4399 $\AA$, while the $5876 \AA$ feature was defined as being bound by $5860-5881 \AA$. The complex of telluric sodium lines, especially the Na I 5890-5896 $\AA$ doublet, did not cause too many problems because all the B star fluxes were so high the effects from atmospheric lines were relatively small. As a check, ratios of the lines with both $\mathrm{H} \beta$ and $\mathrm{H} \gamma$ were calculated and compared (while this redundant calculation could be interpreted as just being careful, it was also an echo of the MK philosophy of using multiple features in spectral classification). Much of the variation in He vs. H line ratios results from the increasing strength of the hydrogen lines. Figure 5.8 shows the fits to the He I line variations.


Fig. 5.7.- Portions of two B star spectra from the JHC library showing temperature sensitive He I lines are displayed. The Balmer lines continue to strengthen and are shown here truncated to fit within the figure.


Fig. 5.8.- The equivalent width ratios for three He I lines $/ \mathrm{H} \gamma$ are shown vs. B subtype. Difficult deblending introduced much of the scatter.


Fig. 5.9.- Portions of two A star spectra from the JHC library are displayed to show the temperature sensitive Ca II K line. The He line at $3968 \AA$ is actually a blend of $\mathrm{H} \epsilon$ and Ca II H .

## A Stars

The spectra of A stars are notable for their lack of many features except strong hydrogen lines. However, the Ca II K line appears near A0 and grows continuously through later subtypes (Figure 5.9). The Ca II K line was used in classifications in ratio with $\mathrm{H} \epsilon$, which is actually a blend of $\mathrm{H} \epsilon$ and Ca II H (Figure 5.10). Although this was the only feature found for A stars, it was very reliable.


Fig. 5.10.- The equivalent width ratio for $\mathrm{Ca} \mathrm{II} \mathrm{K} /(\mathrm{H} \epsilon+\mathrm{Ca}$ II H$)$ is plotted vs. A spectral subtype.

## F Stars

These spectra are more eventful than any of the preceding types (Figure 5.11). The Ca II features continue to strengthen and the G band makes its appearance near $\mathrm{H} \gamma$ as a tiny nub at F 0 , but by F ( dwarfs its neighboring H line. The Mg I b feature is a blend of lines that first appears near $5167 \AA$. The G band and the Mg b features are good examples of the complex blends used in some of the spectral typing. For these features the equivalent widths were calculated by drawing a line across the appropriate wavelength interval (4239-4330 $\AA$ for the $G$ band, 5111-5250 $\AA$ for the Mg b feature) so its endpoints touched the continuum on either side. The flux deficit under the straight line was computed and divided by the average continuum level. A line blend including Sr II $4077 \AA$ and a host of Mn I and Fe I lines dwells in the interval 4019-4084 $\AA$. This blend is strong only for late F stars and was used to distinguish them from early F stars. The classification relations developed for F stars are shown in Figures 5.12 and 5.13. Tentative luminosity classifications were possible with some F stars. There was an uncertain luminosity class dependence with Fe I $6495 \AA$ and more importantly Mg b. This latter feature is much stronger in class V stars than in III and IV stars, and it is nearly absent in luminosity class I and II stars.


Fig. 5.11. - Portions of two F star spectra from the JHC library are displayed to show four temperature sensitive features, all of which increased in strength with spectral subtype.


Fig. 5.12.- The increase with spectral subtype of three features is shown for $F$ stars


Fig. 5.13. - A metal blend including Strontium abruptly appears for later F subtypes.

## G Stars

G stars were challenging to classify with the MX data. The features used for doing so are shown in Figure 5.14.

The $\mathrm{Ca} \mathrm{K} / \mathrm{H} \epsilon$ ratio reaches a maximum of 1.2 for late F stars and since it remains saturated at this level it was no longer useful. Furthermore, it is subject to distortion from emission activity. The G band changes shape in a complicated way through the $G$ stars but sadly the equivalent width of the entire structure did not vary too much and the fits to it or its components were dominated by scatter. The metal blend at 4019-4084 $\AA$ has a slightly believable temperature dependence (Figure 5.15), although the scatter for this fit was large-partly due to some of its components (especially [S II] $4069 \AA$ ) sporadically occurring in emission. In tandem with the metal blend and the changing shape of the $G$ band the classifications were


Fig. 5.14. - Two G star spectra show four temperature and luminosity sensitive features. The metal blend and to a lesser degree the Mg b feature change in size while the other structures are helpful in how they change in shape.


Fig. 5.15.- In G stars, the metal blend have a noisy correleation with temperature and the equivalent width of the Fe I $6495 \AA$ line demonstrates a weak luminosity dependence.
executed using the shape of the Mg b feature and the broad MgH feature, which appears as a wide pedestal at the base of the Mg b stars for later G stars.

Luminosity classifications were marginally possible for $G$ stars, albeit it even more difficult than spectral subtype classification. A weak luminosity dependence for Fe I $6495 \AA$ equivalent widths was used to separate class I-II stars from III-V, as shown in Figure 5.15. The two temperature-sensitive features Mg b and $\mathrm{MgH} 5211 \AA$ were helpful in luminosity classifications as well, since Mg b is absent in class I and the MgH feature is enhanced in giants.

## $K$ Stars

K stars were classified into three groups-early, mid, and late. Comparing these groups to the JHC library and cool star spectral catalogues (Pritchet \& van den Bergh 1977; Turnshek et al. 1985) the three were found to correspond with spectral types K1, K4, and K7. As with the G stars numerical methods were not reliable, and many of the classifications were performed by looking at the nature of various features (in true MK fashion). The two most important regions for K classification were the MgH feature, and a CN band red of the G band (Figures 5.16-5.17). The area of interest ( $4090-4250 \AA$ ) near the $G$ band is notable for how a line touching the tops of spectral bumps changes in curvature (note: this is not the continuum!), although it is sensitive to both temperature and luminosity. This line is convex upwards for K1, straight or sagging slightly downwards for K4, and dramatically concave by K7. In fitting the shapes to this region, the bump from Ca I $4227 \AA$ was disregarded since it has an erratic behavior (it may be particularly sensitive to luminosity). The MgH region short of $5211 \AA(4950-5170 \AA$ ) was the second area of importance for K classification. In early K stars it appears as a


Fig. 5.16.- Portions of three $K$ star spectra show the temperature sensitivity of the complex CN absorption feature between the G band ( $4304 \AA$ ) and the metal blend (4019-4084 $\AA$ ). For early K stars (K0-K1) an envelope line drawn over this region was slightly convex upwards. For mid $K$ stars this region was linear or slightly convex downwards. For late stars ( $\sim \mathrm{K} 7$ ) this region was strongly convex downwards. This region is also sensitive to luminosity.


Fig. 5.17.- Two $K$ star spectra show the strong temperature dependence of the MgH band. It is nearly nonexistent for early K but is a broad well for mid to late K stars. This well is also a luminosity sensitive feature, being more pronounced in dwarfs than in giants. The strong and obvious absorption hole at $4780 \AA$ is produced by MgH , and is an excellent dwarf indicator for mid and late K stars.
very small absorption dip dominated by Mg b , and if any broadband absorption is present in the $4950-5170 \AA$ region its envelope is convex upward. By mid K a tremendous absorption valley appears. This hole stays enormous for later K stars or decreases somewhat, but it never fades to the tiny presence it has in the K1 stars. Some additional weak but useful features occur longward of $6100 \AA$. With careful continuum removal this area is flat for K 1 stars. But mid to late K stars exhibit broad yet weak beginnings of TiO bandhead absorption near $6159 \AA$, $6187 \AA$, and $6255 \AA$. Another TiO band starts to appear under the Na I doublet (5890-5896 $\AA$ ) for late K stars. The Na I doublet itself appeared attractive for classification but telluric sodium emission lines produced too much pollution. Luminosity class IV-V stars were identified by a hole at $4780 \AA$, a gift from MgH which is strong in mid to late K stars. Also the enormous $5211 \AA$ feature in mid to late K stars is accentuated in dwarfs and smaller in giants. Both these luminosity discriminants are distinctive and were among the most reliable of all the luminosity criteria in any spectral type.

## M Stars

While TiO could occasionally be detected in K spectra, a strong set of bandheads indicate an $M$ star. $M$ stars were grouped into categories-very early, early, mid, and late-which by comparison to the JHC library and various late star atlases were found to compare well with the classes M1, M3, M5, and M7. The general trend with $M$ stars is that as stars became cooler the bandheads become deeper and craggier until late $M$ spectra resemble the teeth on a ripsaw (Figure 5.18). So M star temperature classification was executed by looking for bandheads corresponding to later and later subtypes. For example, in order


Fig. 5.18. - A late $M$ star's spectra is instantly recognizable. Spectral fragments from two M stars demonstrate how the TiO bandheads transform into an assortment of jagged peaks and deep crevices.
for a spectrum to be classified as an M5 star, first features seen in the M1 and M3 subtypes had to be detected. The various TiO bandheads are identified in Figure 5.19. It was sadly ironic that since stars of progressively later subtypes produce more of their fluxes at progressively longer wavelengths, the features used for M-subtype classification were arranged in an optimally bad manner. That is, the diagnostic M1 features appear near 6000-7000 $\AA$, the M3 features develop near $4800-5700 \AA$, and the M5 features occur near 4600-5000 $\AA$. The coolest and faintest objects in the survey were classified in the blue region of the spectra, exactly where the spectra were weakest.

To differentiate late K stars from M stars the TiO bandhead at $6233 \AA$ had to be very deep. Also sought were the minor bandheads at $6652 \AA, 6681 \AA$, and $6714 \AA$ which appear as notches in the telluric $\mathrm{O}_{2}$ absorption. The Na I 5890-5896 $\AA$ doublet sits in a bandhead at $5862 \AA$ that becomes visible at M0 or M1. The $5810 \AA$ bandhead is occasionally seen in very early M spectra, although this feature usually did not appear until M2 or M3. Stars that showed three or more of these features were clearly M1 stars or later.

To graduate to the ranks of an M3 star, additional TiO bandheads had to be visible. The first to appear are at $5448 \AA, 5497 \AA, 5598 \AA, 5629 \AA$, and $5661 \AA$, followed by the $4804 \AA$ bandhead. Of these features, the most unambiguous are the $4804 \AA, 5497 \AA$ and $5661 \AA$ bandheads. A bandhead at $5003 \AA$ was not too useful, since it is spoiled by a nebular forbiden line ([O III] $5007 \AA$ ) which was strong and not always subtracted well from the spectra. The $5448 \AA$ bandhead is significantly deeper at M3 than at M1. A CaOH feature at $5530-5570 \AA$ was used by Turnshek et al. (1985), since it appeared with a distinctive square-shaped profile for some stars with their instruments but this blend was not so characteristic in the NGC 2264 stars.


Fig. 5.19. - The spectral region $4440-6820 \AA$ of an M5 V star shows all the TiO bandheads used in temperature classification. The VO $5737 \AA$ bandhead is marked although not visible on this spectrum. Six features used in luminosity classifications are indicated with dotted lines.

Stars as late as M5 are indicated by the development of bandheads at $4584 \AA$, $4626 \AA, 4848 \AA, 4954 \AA$-although the $4848 \AA$ bandhead was sometimes confused by stellar or incompletely subtracted nebular $\mathrm{H} \beta$ emission. The latest stars of the samples showed some evidence of being M7 stars. These stars were flagged by the initiation of VO bandheads, the first and most prominent being VO $5737 \AA$.

Once an M star's subtype was determined, its luminosity class was estimated. For M1 stars the MgH $4780 \AA$ feature was used the same way as for K stars. The $\mathrm{MgH} 5211 \AA$ feature (especially in the area $4950-5250 \AA$ ) is large and campanulate for dwarfs, but in giants is disrupted by bandheads into dentate fragments. Three Ca I lines at $6103 \AA, 6122 \AA$, and $6162 \AA$ were useful-for although Ca I $6162 \AA$ are strong for all luminosity classes, the other two are greatly enhanced in dwarfs. The best M1 dwarf indicator is $\mathrm{CaH} 6385 \AA$, a strong and easily seen absorption feature. For stars later than M1, these discriminants were still good dwarf indicators, although after M3 the $\mathrm{MgH} 4780 \AA$ dip is destroyed by a bandhead. This loss is partially offset by a useful development in the Mg b complex: in dwarfs, an Mg b line at $5167 \AA$ dominates the complex but in giants this part of the spectrum is dominated by a TiO bandhead. All these features, except the $\mathrm{MgH} 5211 \AA$ bowl (which can be seen in Figure 5.17) are illustrated in Figure 5.19.

### 5.4.2 Classifying Survey Stars

Each star was grouped into the categories $\mathrm{O}-\mathrm{B}, \mathrm{A}, \mathrm{F}, \mathrm{G}, \mathrm{K}$, and M , and then classified using the automated and manual methods described in the previous section. For stars classified using automatic methods, the weights of the various criteria are given in Table 5.2. To insure no stars were incorrectly binned from the first round of classifications, the stars were also classified using the criteria of the

Table 5.2. Spectral Classification Weights

| Stellar | Feature | Weight |
| :--- | :--- | :--- |
| O | He I 4471 $\AA$ | 4.0 |
|  | He II 4686 $\AA$ | 2.0 |
|  | He II $5412 \AA$ | 4.0 |
|  |  |  |
| Be I 4388 $\AA$ | 2.0 |  |
|  | He I 4471 $\AA$ | 4.0 |
|  | He I 5876 $\AA$ | 4.0 |
|  | Ca K | 4.0 |
| F | G band | 2.0 |
|  | Mg b | 4.0 |
|  | $4019-4084 \AA$ metal blend | 1.0 |

Note. - Multiple criteria were used to calculate spectral types for O, B, and F stars-these are the weights used. For A stars only one feature was used (Ca K). For the other spectral types subjective features were used; normally all such features were given the same subjective weight.
adjoining spectral types. Some stars had spectra so noisy they required smoothing. After all the survey stars were classified the spectra of six reference stars observed during the MX run were also classified using the same methods. Without prior knowledge of their published spectral types, the classifications produced for these standard stars were A0, A3, F8, G5, K1, and M5 which compared nicely with their published spectral types-A3, A2, F7, G2, K2, and M2 III. The reference spectra are shown in Figure 5.20.

### 5.4.3 Classification Results

The spectral classifications for all 361 cluster stars are listed in Table 5.6 at the end of this chapter. When available, spectral classifications by Walker (1956) and Trumpler (1956) are also tabulated. With one exception (S1947) all the classifications agreed well with Walker's, the average difference being only 1.2 subtypes. The Trumpler classifications differed by an average 2.3 subtypes from the calculated classifications (Trumpler's classifications differ from Walker's by 2.0 subtypes). As with the photometry in Chapter 3, the classifications blended nearly seamlessly with Walker's work. All the spectra are displayed in a spectral atlas in the appendix.

While no O stars were found ( S Mon was not observed), fourteen were classified as ranging from $\mathrm{B} 0-\mathrm{B} 9$. In performing these classifications the Helium line at $5876 \AA$ was given only $1 / 2$ the weight of the other criteria because of possible contamination from the nearby sodium doublet. Although it was not possible to parameterise well, He I $4922 \AA$ was seen in all the B stars. The deep sharp absorption features seen in the B star spectra near $4050 \AA, 4260 \AA$, and $5265 \AA$ were not stellar in origin. These artifacts were apparently due to slightly bad rows


Fig. 5.20.- The reduced spectra of six standard stars observed and classified using the methods developed in Section 5.4.1 are shown. After each of the star's catalogue designation, its estimated spectral class is listed, followed by its published spectral class. All the classification errors were small and acceptable for the purposes of this study.
in the CCD chip and are visible in the spectra of the brightest stars, regardless of spectral type.

Twenty-four stars were classified as ranging from A0 to A8. Two additional late A stars (perhaps A6-A7?) were also observed but even after smoothings their spectra were too noisy to classify well. Five of the twenty-six A stars exhibited $\mathrm{H} \alpha$ in emission or reversal in the line core.

Thirty F stars were observed including one star which showed faint TiO features suggesting it may be a double star. Of the F stars three were possibly giants and five could not be luminosity classed convincingly. Four showed $\mathrm{H} \alpha$ in emission.

Because of uncertainties and difficulties in classifying G stars the accuracy of their classifications were probably only good to approximately $\pm 3$ subtypes, instead of $\pm 1$ or 2 subtypes for the earlier stars, so only odd integer subtypes were used for G stars. The distinction between late G and early K was often difficult to discern and some misidentifications involving these two groups may have transpired. A TiO bandhead at $6159 \AA$ was occasionally present in G9 stars, although these G stars may actually have otherwise undetected K or M companions. Twenty-four Of the thirty-four G stars were clearly dwarfs while three of the remainder exhibited symptoms which suggested, with varying degrees of conviction, that they were giants. $\mathrm{H} \alpha$ emission was present in thirteen G stars, and $\mathrm{H} \alpha$ linewidths for the other main sequence stars were consistently smaller than normal. This is probably due to the lines being partially filled in and is discussed more fully in Sections 5.5 and 6.3.

A total of 125 K stars were found: thirty-two K1, sixty-eight K4, and twenty-five K 7 stars. A single additional noisy spectrum was reduced that may
be a T Tauri K star. That the numbers of the stars in the three bins were not monotonically increasing suggests the classification criteria were overly restrictive against the K7 categorization. The dwarf nature of the K stars were confident for eleven K1, fifty-four K4, and nineteen K7 stars. The main sequence status of a relatively small percentage of K1 stars was probably due to the paucity of good giant indicators for this temperature regime (the $\mathrm{MgH} 4780 \AA$ and $5211 \AA$ features did not become useful luminosity indicators until mid to late K ). Balmer and Ca II H, K emission lines were seen in 107 K stars but the hydrogen line emission may be in part due to nebular contributions.

The 130 M stars classified were biased towards early subtypes: fifty-five M1 stars, fifty M3 stars, seventeen M5 stars, and eight M7 stars. Most were clearly dwarfs-only seven M1, twelve M3, one M5, and two M7 stars showed any indications they might be giant stars while the rest, except for eleven particularly noisy and inconclusive spectra, were dwarf stars. That so few M5 and M7 stars were found compared to the well populated M1 and M3 categories was a result of the magnitude limit of the survey sample. The apparent $V$ magnitude of an unreddened M5 V cluster star is approximately 21.7 (Johnson 1966), and although the M stars in NGC 2264 are expected to be a few to several magnitudes more luminous than this main sequence brightness, they will still be under-represented in the survey because the population of stars in the spectroscopic survey rolls over near $m_{V}=16-17.0$ (Figure 5.3). Balmer and Ca II emission lines were seen in 102 M stars. Two objects, S2173 and S3895, are continuum stars that might also be best classified as $M$ stars.

It was mentioned that the spectra of forty-two $A, K$, and $M$ stars were very noisy and required smoothing to increase their signal to noise ratios. This was done using a normalized boxcar which slid across the data. For each star the boxcar
width was chosen to be as narrow as possible yet wide enough to decrease the noise sufficiently. The boxcar sizes ranged from 3 to 10 pixels wide, and are noted in Table 5.6. The smoothed spectra are shown last in the appendix, along with the unsmoothed spectra of two stars, S2173 and S3920, which were difficult to classify. Comments on individual sources are made in Section 5.6.

### 5.5 Emission Features

Young stars like those in NGC 2264 can be anticipated to show anomalous line profiles. In addition to emission lines or reversals in line cores, some may have absorption lines which appear normal but are actually partly filled in by emission, a phenomenon known as spectral veiling or incipient emission (Strom 1983; Finkenzeller \& Basri 1987). While emission lines and line reversals are easily recognized this last effect is more subtle; yet by comparing the linewidths of the survey stars to those of the JHC data it can be identified. Because of the instrumental problem noted in Section 5.3 .3 which required normalizations of the spectra, meaningful fluxes in the lines could not be measured. But equivalent widths defined as

$$
\begin{equation*}
W=\int \frac{F_{c}-F_{\lambda}}{F_{c}} d \lambda \tag{5.1}
\end{equation*}
$$

where $F_{\lambda}$ is the intensity of the spectrum and $F_{c}$ is the continuum level, are insensitive to slowly varying multiplicative modifications to the spectra such as normalizations. This also means that equivalent widths are unaffected by extinction. This is very satisfying since dereddening youthful stars is a contentious and problematical area (Lada \& Adams 1992; Cohen \& Kuhi 1979).

Is it possible that the spectral classifications were effected by spectral veiling? It will be seen that the Balmer and calcium lines are clearly subject to veiling,
especially for stars of spectral types $\mathrm{K}-\mathrm{M}$. But since the spectral classifications of the G-M stars were mostly performed without using spectral features normalized by hydrogen linewidths, it is unlikely their spectral classifications were altered too much by spectral veiling effects. Earlier stars (B-F) were classified by the equivalent widths of features which were normalized by hydrogen lines. If these hydrogen lines were corrupted by spectral veiling the spectral classifications would be modified, usually resulting in a star classified as cooler than it actually was. But since the hydrogen lines used were always near the classification features and their strengths were of the same order of magnitude, effects from the component of spectral veiling that appears as an additional source of continuum emission would mostly be eliminated. Veiling manifested as selective emission in the hydrogen line profiles would modify the classifications, but as it was noted in Section 5.4.3, the spectral classifications obtained agreed well with those of Walker and Trumpler.

### 5.5.1 JHC Equivalent Widths

The 130 luminosity class I, III, and V stars of spectral type B0-M5 in the JHC atlas were again called into service as spectral references. The equivalent widths of their Ca II K and Balmer lines were measured. To do this, the $\mathrm{H} \alpha, \mathrm{H} \beta$, and $\mathrm{H} \delta$ lines were fitted with gaussians, while both the $\mathrm{H} \epsilon$ and Ca II K line pair, and the $\mathrm{H} \gamma$ line and G band were deblended. Converting spectral types into numerical values, where the spectral type determined the ten's value (i.e. $\mathrm{B} \rightarrow 10, \mathrm{~A} \rightarrow 20$ ) and the subtype determined the one's value (i.e. $\mathrm{A} 3 \rightarrow 23, \mathrm{M} 3 \rightarrow 63$ ) allowed the results to be fit numerically. This was a strange choice for an independent variable but it enabled a comparison between the MX and JHC data. The data and fits to the temperature dependence of the $\mathrm{H} \alpha, \mathrm{H} \beta$, and calcium lines for the class III and
class V JHC stars-which were similar in size and so grouped together-are shown in Figures 5.21-5.22. Giant stars, with smaller surface pressures, have narrower lines. Their lines were also measured and fit, and the results for $\mathrm{H} \alpha$ are shown in Figure 5.23.

### 5.5.2 Survey Star Widths

The Balmer and calcium line equivalent widths for the NGC 2264 stars were measured. The presence of the nebular forbidden line [ N II] $6583 \AA$ was noted in 145 spectra and its equivalent widths measured. The survey stars were decomposed into two categories. The first category contained stars with no measurable [ N II] $6583 \AA$ feature, the second contained all the stars with this line either in emission or absorption. The second category clearly contained those stars with questionable nebular emission subtraction, and the Balmer lines for this sample have probably been corrupted by some unknown amount. The equivalent width data for all the spectral survey stars are given in Table 5.7 at the end of the chapter. Normal convention was followed, where a negative equivalent width indicates an emission feature.

To estimate the complications introduced by nebular emission tainting the stellar spectra, the raw $\mathrm{H} \alpha$ and [ N II] $6583 \AA$ fluxes (in units of counts) were measured at a moderately bright location in the nebula. The flux continuum level near $\mathrm{H} \alpha$ for the B 1 star S 2289 ( W 88) was also measured. S 2289 is so bright its $R$ magnitude was not reliably measured by the survey, so it was estimated using Walker's $m_{V}=9.02$ measurement. The apparent $J-H$ colour for this star suggested it was moderately extincted ( $A_{V}=2.1$ magnitudes), so correcting for reddening and the star's intrinsic colour converted Walker's value to $m_{R} \approx 8.6$.


Fig. 5.21.- The $\mathrm{H} \alpha$ and $\mathrm{H} \delta$ equivalent widths of 40 class III and 47 class V stars are shown. The nonzero measurements were fit with 5th to 9 th order legendre polynomials. The two luminosity classes had similar widths.


Fig. 5.22.- The equivalent widths of the calcium H and K lines are shown, as in Figure 5.21.


Fig. 5.23.- The $\mathrm{H} \alpha$ equivalent widths of 43 JHC luminosity class I stars were measured and fit as described in Figure 5.21. As expected the line was narrower for $\mathrm{B}, \mathrm{A}$, and F giants, but was as strong as those of dwarf stars for later spectral types.

This magnitude was used to estimate the $\mathrm{H} \alpha$ equivalent width the nebular flux would produce if added to stellar spectra. This relation is shown as a function of $m_{R}$ in Figure 5.24. The equivalent width that might be measured for the [N II] $6583 \AA$ feature in those conditions is also shown (its line flux was $20-35 \%$ that of $\mathrm{H} \alpha$ ). Indicated on this line are the apparent $R$ magnitudes of unreddened main sequence stars assuming an apparent distance modulus of 9.7. This figure is just an estimate of the problems nebular contamination could introduce-a bright clump of nebulosity could make the situation much worse for a star. Furthermore, if the continuum modulation that affected MX spectra (Section 5.3.3) reduced the star's flux particularly severely, the relative effect of nebular emission would be enhanced. It is clear from Figure 5.24 that as early as A0 the linewidth contamination from the nebula could be a problem. So in this study, it is explicity noted when data for stars with nebular contamination are used.

In Figures 5.25-5.26 the MX $\mathrm{H} \alpha$ equivalent widths were compared to those from the JHC sample. Several early-type stars showed unusually small equivalent widths. Some were stars with obvious emission reversals in the line cores, for others the anemic nature of their $\mathrm{H} \alpha$ lines was not so obvious. These linewidths were consistent with some of the early stars being giants, as shown in Figure 5.21, but this explanation cannot be used for the later stars, many of which exhibited spectral features indicating dwarfness. That some stars near A0 lie well above the JHC fit was not alarming considering the scatter in Figure 5.21 for stars in the range A0-A3. Mid-F stars showed no peculiarity in $\mathrm{H} \alpha$, but in later stars the line was often anemic. Three stars in the interval A6-F4 lie well above the JHC fit. The spectra for these stars are slightly noisy but appear otherwise normal-the enhanced equivalent widths are apparently due to a slight errors in both the sky subtraction and continuum line fits. The $\mathrm{H} \alpha$ equivalent widths for stars with


Fig. 5.24.- Some of the stars in the survey exhibited forbidden lines in their spectra, indicating inaccurate nebular subtraction in the data reduction. This figure presents an estimate of the degree to which a star's $\mathrm{H} \alpha$ equivalent width (the solid line) might be effected by nebular emission, using the [ N II ] 6583 equivalent width (the dashed line) as an indicator as to the extent of the subtraction problem. The estimates are plotted as a function of the star's apparent $R$ magnitude, and the locations of unreddened main sequence stars are shown assuming an apparent distance modulus of 9.7.


Fig. 5.25.- H $\alpha$ equivalent widths for the survey stars are shown with main sequence fits to the JHC data. The early stars (B0-F0) generally followed the JHC fit well, although the linewidths of some A stars were partially filled in, while a few were seen to exhibit emission or reversals in their line profiles. The line widths of F0-K0 stars were partially filled in, while the late stars (K0-M5) were often in emission, although many exhibited entirely normal linewidths. Stars with strong emission lines are shown in Figure 5.26. Stars with forbidden lines in their spectra were excluded from this plot.


Fig. 5.26. - The plot in Figure 5.25 is redrawn over the entire range of measured linewidths. Stars with forbidden lines are plotted in the lower graph, and appear to be similar to the emission-line population of stars in the uncontaminated sample. Just how strongly they were affected by nebular emission cannot be determined, so these stars were not included in later analyses of $\mathrm{H} \alpha$ line strengths.


Fig. 5.27.- $\mathrm{H} \delta$ equivalent widths for survey stars were compared to the fit to the JHC atlas. The data for only stars without forbidden lines in their spectra are shown, even though the nebular contribution to $\mathrm{H} \delta$ was probably very small for all but the faintest stars. The anemic condition of the absorption lines for early stars was apparent even for $\mathrm{H} \delta$ lines, which indicated the effect could not be explained by nearby nebular emission or sky subtraction artifacts.
forbidden lines are also shown in Figure 5.26. Stars later than G2 were most prone to being infected with forbidden lines because they were fainter and more sensitive to the errors in trying to subtract a clumpy nebular background from a stellar spectrum. The abnormally large positive equivalent widths for stars in this range can also be explained by the effects of bad sky subtraction. It was unfortunate that stars in this interesting spectral range had contaminated spectra, yet a large population of uncorrupted stars remained in the sample. The equivalent width plots in Figures 5.27-5.28 are restricted to the sample uncontaminated by forbidden lines and showed the same trends of anemic equivalent widths for early stars and emission lines for stars mostly later than K0. Since the sky spectrum in


Fig. 5.28.- The widths of the $\mathrm{H} \epsilon+\mathrm{Ca}$ II H line blend agree well with the fit to the JHC atlas for early stars, although a population with anemic lines is visible. The mid to late stars nearly all showed anemic absorption lines, which for stars later than K0 developed into emission lines. The lower graph redraws the data on a different scale to show the group of emission line stars.

Figure 5.2 shows that by $\mathrm{H} \delta$ the nebular emission was quite weak, maintaining the separation between stars with forbidden lines and those without was probably unnecessary for such hydrogen lines. The results for the $H \epsilon$ line blend were very nice--for the early spectra the hump in the JHC fit was traced with some delicacy but after F4-G0 the lines became anemic, and by K4 most were in emission. The sample of stars plotted was significantly smaller than for the $\mathrm{H} \alpha$ plots because many of the later stars had too much noise in this portion of the spectrum. Finally, the results for the Ca II K line are shown in Figure 5.29. Since Ca II K cannot be infected with nebular emission it was irrelevant whether nebular forbidden lines were found in its spectrum and so the entire sample of stars was plotted. Fifty-four of the stars in the sample exhibited Ca II K in emission. These all had $\mathrm{H} \alpha$ emission lines too, practically insuring they were T Tauri stars (other criteria outlined by Herbig (1962), such as Fe I $4063 \AA, 4132 \AA$, or Li I $6707 \AA$ were unmeasurable because of signal to noise limitations in the spectra). Furthermore, 35 of these T Tauri stars had no forbidden lines so the $\mathrm{H} \alpha$ equivalent widths are probably uncontaminated by nebular emission.

The anemic nature of the Balmer and calcium lines in a star could be due to one of three causes. The first could be that the star was actually a giant star mistaken for a main-sequence star. This could explain some of the early-type anemic stars in the sample, but not the majority of them. The second cause was possible contamination from nebular emission which could produce the appearance of anemic lines for stars as faint as G0. This explanation does not apply to the anemic calcium lines, and even after using the nebular emission lines as a criterion for eliminating the tainted spectra from the sample, a large number of stars with anemic Balmer lines remained. Therefore the effect being seen in this sample of stars was real and is what has been referred to as spectral veiling or incipient


Fig. 5.29.- Ca II K equivalent widths for survey stars were compared to the fit to the JHC atlas. Since forbidden line emission would not contaminate this line, the entire set of data was plotted. Emission lines infested 54 stars, all later than K0. Of these stars, all exhibited $\mathrm{H} \alpha$ emission and are almost certainly T Tauri stars. Thirty-five of the fifty-four stars had no forbidden line emission, making them excellent candidates for further study.
emission (Cohen \& Kuhi 1979; Strom 1983). This is discussed more in Section 6.3.

### 5.6 Notes on Stars

In this section comments on individual stars are presented. Some of these stars exhibited anomalous spectral features, others were just interesting for various reasons. Stars which appeared to be background stars were selected. They were assumed to have normal main-sequence colours, and if deviations from these colours were consistent with dust reddening, extinction estimates through the cluster and GMC were obtained. The stars with strong intrinsic infrared excesses were modelled in Section 6.5. Stars were also examined for emission lines from He I $5876 \AA$, Fe II $4924 \AA$, [O I] $6300 \AA$, and Na I $5893 \AA$. These are commonly observed in emission in young stars (Cohen \& Kuhi 1979). The latter two emission lines were visible in the night sky and nebular spectra, and so may be modified, destroyed, or created by sky subtractions. The first two lines were not subject to this interference.

## Stars

S1316: The exceedingly deep Balmer lines are probably due to a slightly bad nebular subtraction in this spectrum.

S1665-W 59: The $J-H$ and $V-R$ colours of this A6 star imply 2.4-4.3 magnitudes of extinction. Assuming $A_{v}=3$ magnitudes places this star in the cluster.

S1896-LkH $\alpha$ 15: In addition to Balmer and CaH and K lines, this K 4 T Tauri star exhibits emission from He I $5876 \AA$, Fe II $4924 \AA$, and [O I] $6300 \AA$.

S1901-W 66: The photometry of this B0 star is mostly saturated, but Walker's $B-V$ colour indicates this star is extincted by $A_{V}=3.1$ magnitudes, placing it approximately 2200 pc distant.

S1939-W 67: The photometry of this B0 star is mostly saturated but Walker's $B-V$ colour indicates it is a cluster star with $A_{v}=2.8$ magnitudes.

S1947-W 68: The classification of S1947 (B2) is in stark contrast with Walker's classification (G0 IV-V). The spectrum of S1947 is clearly that of a B star. The spectrum Walker published was equally clearly that of a $G$ star. There were no stars near W 68 on his finding chart, and the closest source to S1947 was S1944, an $m_{V}=16$ star $24^{\prime \prime}$ to the north. The $V$ magnitude of S 1947 was saturated so the survey value $m_{V}=12.11$ was an upper limit while Walker listed $m_{V}=11.72$. On the basis of these magnitudes, confusion with S1944 can be eliminated as a resolution to the conflict. The only survey data for S1947 that were unsaturated were the $J$ and $H$ measurements: $m_{J}=10.29 \pm 0.11, m_{H}=10.10 \pm 0.17$. The unextincted magnitudes of a B2 star with a distance modulus of 9.7 are $m_{J}=7.95$, and $m_{H}=8.04$ (Johnson 1966, Koornneef 1983). To explain the apparent $J$ and $H$ magnitudes as being due to approximately 2 mag of extinction in each band would imply $A_{v}>8$ magnitudes and result in $J-H>0.77$, inconsistent with the observed $J-H=0.19 \pm 0.20$. So this star must be a background star peering through the GMC. The infrared colour suggests the star is experiencing 2.6 magnitudes of extinction at $V$, placing it at a distance of $1730-1930 \mathrm{pc}$. The survey $J$ and $H$ magnitudes and $J-H$ colour were inconsistent with a G0 star ( $m_{J}=13.19, J-H=0.24$ ) unless it were several magnitudes above the main sequence. So it appears that by a spurious clerical error, the spectrum Walker published for the star at the coordinates of $W 68$ must actually be data for some other star.

S2079: The lines from He I $5876 \AA$, Fe II $4924 \AA$, and [O I] $6300 \AA$ are in emission for this K1 star.

S2173-W 79, LkH $\alpha$ 22: Although it was grouped with the M stars, the spectrum of this extraordinary continuum star defied a photospheric spectral classification. Among the emission lines are He I $5876 \AA$, Fe II $4924 \AA$, and NaI $5893 \AA$.

S2163-LkH $\alpha$ 21: The huge $\mathrm{H} \alpha$ line in this G3 star is real.
S2230: The $J-H$ and $V-R$ colours suggest this A2 star is suffering approximately 3-3.9 magnitudes of extinction, and is at a distance of approximately 2000 pc.

S2234-W 84: The H $\alpha$ line in this F8 spectrum appears to be real.
S2313: This star displays the features of an F spectrum, but with TiO features best explained by an $M$ companion. In order to be apparent in this spectrum, the M star must be a giant or serendipitious foreground object.

S2364-W 90, LkH $\alpha$ 25: The increasing flux at longer wavelengths cannot be explained by emission; the $V-R, J-H$, and $H-K$ colours would imply $0.59,8.2$, and 17.14 magnitudes of extinction respectively for this A2 spectrum.

S2418: The large $\mathrm{H} \alpha$ line in this G9 star is real.

S2510: This F4 cluster star is experiencing approximately 3.5 magnitudes of extinction.

S2515-W 95, LkH $\alpha$ 26: This M1 star shows tiny emission features from He I $5876 \AA$ and Fe II $4924 \AA$.

S2563-LkH $\alpha$ 28: This M1 star shows emission features from He I $5876 \AA$ and Fe II $4924 \AA$.

S2579-W 100: The reversal in $\mathrm{H} \alpha$ is not the only thing strange with this A2 star:
the $J-H$ and $H-K$ colours imply an infrared excess. The $V$ magnitude is normal for a cluster member.

S2716-W 108: The colours are irregular for this F8 star. It is sufficiently bright at $R$ that the $\mathrm{H} \alpha$ emission must be genuine.

S2763: The extinctions for this star are approximately 3-5 magnitudes, and this is probably a background A7 star. The $\mathrm{H} \alpha$ emission and [N II] emission are probably from nebular contamination and fall within the estimates of Figure 5.24.

S2809: A K4 star exhibiting He I $5876 \AA$ and Fe II $4924 \AA$ emission. The lines [O I] $6300 \AA$ and Na I $5893 \AA$ are in absorption, but this is due to sky subtraction errors.

S2958-W 123, LkH $\alpha$ 40: A K4 star with small emission features from He I $5876 \AA$ and Fe II $4924 \AA$.

S3048: The magnitudes of this A0 star are very irregular and suggest this is a flux variable.

S3323-W 151: This F2 star shows nearly no reddening. The absent $\mathrm{H} \alpha$ line has apparently been filled by nebular emission.

S3381: This background A0 star is extincted by approximately 4 magnitudes of extinction, and is at a distance of $\approx 2100 \mathrm{pc}$.

S3511-W 165: The same comments for S2579 apply to this A4 star.
S3514-W 164, LkH $\alpha$ 53: The $\mathrm{H} \alpha$ line in this G3 star is small but unlikely to be due to nebular emission.

S3552-LkH $\alpha$ 54: A K4 star showing emission from Fe II $4924 \AA$.
S3692: A foreground A4 star.

S4392-W 213: A foreground A1 star.

S3895: Another " M " continuum star, although not as extreme as S2173. Visible in emission are He I $5876 \AA$, Fe II $4924 \AA$, and [O I] $6300 \AA$.

S3920-W 197, $\mathrm{LkH} \alpha$ 66: A spectrum vaguely resembling a K star, showing emission from Fe II $4924 \AA$.

S4433-W 217, LkH $\alpha$ 72: A K1 star with emission from Fe II $4924 \AA$ and He I $5876 \AA$.
$\mathrm{LkH} \alpha$ 6: A K7 star with huge hydrogen emission lines and a small He I $5876 \AA$ emission line.

### 5.7 Summary

A set of stars from the multiband survey of Chapter 3 was observed with a multiplexing spectrometer. Data were reduced and presented. The 361 stars represented a reasonably unbiased and random sample of the bright cluster stars in the magnitude range $m_{V} \approx 12-17$. A set of spectral classification criteria were devised using a published database as spectral references. These criteria were parameterised when possible, and the resulting classification relations were used to automate the classification procedure for many of the stars. The resulting spectral types agreed closely with published values. Equivalent widths of the stars were measured and it was shown that in addition to the T Tauri stars and Ae stars, a population of stars with anemic absorption lines exists in the cluster. This was identified as an indication of spectral veiling. The nature of individual stars was discussed. Background stars shining through the GMC were identified, and for these a visual extinction of 2.5-4 magnitudes was inferred.

TABLE 5.3
Survey Coordinate Data

| Source | Walker \# | LkH $\alpha$ \# | $\alpha$ (1950.0) | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S0131 | W033 | .......... | $6^{\text {h }} 37^{m} 10.78^{\text {a }}$ | $9^{\circ} 37{ }^{18}{ }^{\prime \prime}$ | OBS |
| S0422 | W035 | ......... | $6^{\text {h }} 37^{\text {m }} 19.30^{\text {s }}$ | $9^{\circ} 25^{\prime} 31.1$ | OBS |
| S0445 | W036 | ......... | $6^{h} 37^{m} 19.87^{\text {a }}$ | $9^{\circ} 37^{\prime} 36.11$ | OBS |
| S0710 | W038 | . | $6^{\text {h }} 37^{\text {m }} 26.09^{\text {a }}$ | $10^{\circ} 03^{\prime} 25.11$ | OBS |
| S0921 | W039 | ........ | $6^{\text {h }} 37^{\text {m }} 31.61{ }^{\text {d }}$ | $9^{\circ} 20^{\prime} 03.1$ | OBS |
| S0967 | W040 | ......... | $6^{h} 37^{m} 32.66^{\circ}$ | $9^{\circ} 35^{\prime} 10.11$ | OBS |
| S1066 | W041 | ......... | $6^{\text {h }} 37^{\text {m }} 34.99^{\text {a }}$ | $9^{\circ} 38^{\prime} 34.1$ " | OBS |
| S1117 | W042 | ......... | $6^{\text {h }} 37^{\text {m }} 36.07^{\text {a }}$ | $9^{\circ} 39^{\prime 23.1}$ | OBS 1 |
| S1129 | W043 | .......... | $6^{\text {h }} 37^{\mathrm{m}} 36.34^{\text {s }}$ | $9^{\circ} 44^{\prime \prime} 40.1$ | OBS12 |
| S1212 | ..... | LkHa 09 | $6^{\text {h }} 37^{\text {m }} 38.30^{\text {a }}$ | $9^{\circ} 30^{\prime} 32.1$ | OBS 1 |
| S1270 | W045 | - | $6^{\text {h }} 37^{\text {m }} 39.50^{\text {a }}$ | $9^{\circ} 38^{\prime} 36.11$ | OBS 1 |
| S1276 | W046 | .......... | $6^{\text {h }} 37^{\text {m }} 39.60^{\text {d }}$ | $9^{\circ} 48^{\prime \prime} 58.11$ | OBS12 |
| S1309 | . | ......... | $6^{\text {h }} 37^{m} 40.17^{\text {a }}$ | $9^{\circ} 34^{\prime} 58.11$ | OBS 1 |
| S1315 | ..... | ......... | $6^{h} 37^{m} 40.27^{\text {s }}$ | $9^{\circ} 51^{\prime} 16.1$ | OBS12 |
| S1316 | ..... | .......... | $6^{\text {h }} 37^{m} 40.27^{\text {a }}$ | $9^{\circ} 51^{\prime} 21 .{ }^{\prime \prime}$ | OBS12 |
| S1364 | $\cdots$ | ......... | $6^{\text {h }} 37^{m} 41.21^{\text {a }}$ | $9^{\circ} 40^{\prime} 00.1$ " | OBS 1 |
| S1369 | W048 | ........ | $6^{\text {h }} 37^{m} 41.28^{1}$ | $9^{\circ} 40^{\prime} 53.1$ | OBS 1 |
| S1382 | . | . | $6^{h} 37^{m} 41.59^{4}$ | $9^{\circ} 38^{\prime} 12.1{ }^{\prime \prime}$ | OBS 1 |
| S1389 | W049 | ......... | $6^{\text {h }} 37^{m}{ }^{\text {4 }} 41.69^{4}$ | $9^{\circ} 36^{\prime} 15.11$ | OBS 1 |
| S1407 | ..... | ......... | $6^{h} 37^{m} 42.12^{\text {a }}$ | $9^{\circ} 42^{\prime} 15.11$ | OBS12 |
| S1447 | ..... | ......... | $6^{\text {h }} 37^{m} 42.86{ }^{\text {a }}$ | $9^{\circ} 34^{\prime} 50.1$ " | OBS 1 |
| S1478 | W050 | . | $6^{\text {h }} 37{ }^{\text {m }} 43.32^{1}$ | $9^{\circ} 51^{\prime} 56.11$ | OBS 12 |
| S1499 | . | . | $6^{\text {h }} 37^{m}{ }^{43.63}{ }^{\text {a }}$ | $9^{\circ} 51^{\prime} 14.11$ | OBS12 |
| S1500 | W051 | ......... | $6^{h} 37^{m} 43.66^{8}$ | $9^{\circ} 38^{\prime} 38.11$ | OBS 1 |
| S1513 | ..... | .......... | $6^{h} 37^{m} 43.87^{4}$ | $9^{\circ} 45^{\prime} 07.11$ | OBS12 |
| S1518 | ..... | .......... | $6^{\text {h }} 37^{\text {m }}$ 43.99 ${ }^{\text {a }}$ | $9^{\circ} 35^{\prime} 56.11$ | OBS 1 |
| S1529 | . | . | $6^{\text {c }} 37^{m} 44.14{ }^{\text {a }}$ | $9^{\circ} 46^{\prime} 58.11$ | OBS12 |
| S1562 | W054 | ......... | $6^{\text {h }} 37^{m} 44.64{ }^{\text {a }}$ | $9^{\circ} 53^{\prime} 01.1$ | OBS 1 |
| S1566 | W053 | ......... | $6^{\text {h }} 37^{m}{ }^{\text {m }}$ 44.69 ${ }^{\text {a }}$ | $9^{\circ} 45^{\prime} 11 .{ }^{\prime \prime}$ | OBS12 |
| S1590 | ..... | .......... | $6^{\text {h }} 37^{m}{ }^{\text {m }}$ 45.14* | $9^{\circ} 37^{\prime} 34.1$ " | OBS 1 |
| S1598 | ... | ......... | $6^{\text {h }} 37^{m} 45.36{ }^{\text {a }}$ | $9^{\circ} 53^{\prime} 05.11$ | OBS 1 |
| S1606 | ..... | ......... | $6^{h} 37^{m} 45.46{ }^{\text {a }}$ | $9^{\circ} 49^{\prime} 01.1$ | OBS12 |
| S1621 | ..... | ......... | $6^{h} 37^{m} 45.89{ }^{\text {a }}$ | $9^{\circ} 38^{\prime} 28.1$ " | OBS 1 |
| S1629 | W055 | LkH 12 | $6^{\text {h }} 37^{m} 45.96^{\text {a }}$ | $9^{\circ} 37^{\prime} 31.11$ | OBS 1 |
| S1637 | W057 | ......... | $6^{h} 37^{m} 46.27^{4}$ | $9^{\circ} 44^{\prime} 19.1$ | OBS12 |
| S1645 | W056 | . | $6^{\text {h }} 37^{m} 46.42{ }^{\text {a }}$ | $9^{\circ} 33^{\prime} 58.1$ " | OBS 1 |
| S1648 | W058 | LkHa 13 | $6^{\text {h }} 37^{m}{ }^{46.464}$ | $9^{\circ} 51^{\prime} 14.1$ " | OBS12 |
| S1665 | W059 | ......... | $6^{\text {h }} 37^{m}{ }^{46.75}{ }^{\text {a }}$ | $9^{\circ} 46^{\prime} 06.1$ | OBS12* |
| S1675 | , | ......... | $6^{\text {h }} 37^{m} 46.89{ }^{\text {a }}$ | $9^{\circ} 38^{\prime} 52.11$ | OBS 1 |
| S1702 | ..... | ......... | $6^{h} 37^{m} 47.52{ }^{\text {a }}$ | $9^{\circ} 54^{\prime} 20.1$ | OBS 1 |
| S1734 | ..... | ......... | $6^{\text {h }} 37^{m}{ }^{\text {4 }} 48.24^{\text {a }}$ | $9^{\circ} 26^{\prime} 03.1$ " | OBS 1 |
| S1758 | ..... | . | $6^{\text {h }} 37{ }^{\text {m }} 48.60{ }^{\text {a }}$ | $9^{\circ} 37^{\prime} 49.11$ | OBS 1 |
| S1760 | ..... | . | $6^{\text {h }} 37{ }^{m} 48.60{ }^{\text {a }}$ | $9^{\circ} 51^{\prime} 35.11$ | OBS12 |
| S1769 | W061 | .. | $6^{\text {h }} 37^{m} 48.74{ }^{\text {a }}$ | $9^{\circ} 44^{\prime} 06.1$ | OBS12 |
| S1776 | W062 | ......... |  | $9^{\circ} 35^{\prime} 47.11$ | OBS 1 |
| S1796 | ..... | ......... | $6^{\text {h }} 37^{m}{ }^{\text {4 }}$ 49.27 ${ }^{\text {a }}$ | $9^{\circ} 28^{\prime} 53.1{ }^{\prime \prime}$ | OBS 1 |
| S1804 | W063 | .......... | $6^{\text {h }} 37^{m} 49.34^{\prime}$ | $9^{\circ} 41^{\prime} 43.1$ " | OBS12 |
| S1806 | W064 | ...... | $6^{\text {h }} 37^{m}{ }^{\text {4 }}$ 49.37 ${ }^{\text {d }}$ | $10^{\circ} 00^{\prime} 33.1$ ' | OBS 1 |
| S1820 |  | ......... | $6^{h} 37^{m} 49.56^{3}$ | $9^{\circ} 38^{\prime} 09.1$ | OBS 1 |
| S1829 | W065 | ......... | $6^{\text {h }} 37^{\text {m }} 49.70^{4}$ | $9^{\circ} 22^{\prime} 02.1$ | OBS 1 |
| S1896 | ..... | LkHa 15 | $6^{\text {h }} 37^{m}{ }^{\text {m }}$ 51.39 ${ }^{\text {a }}$ | $9^{\circ} 54^{\prime} 54.1$ " | OBS 1 |
| S1898 | ... | .......... | $6^{\text {h }} 37^{m} 51.43^{4}$ | $9^{\circ} 51^{\prime} 14.1$ ' | OBS12 |

TABLE 5.3-Continued

| Source | Walker \# | LkH $\alpha$ \# | $\alpha$ (1950.0) | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S1901 | W066 | ......... | $6^{\text {h }} 37^{m} 51.48{ }^{\text {a }}$ | $9^{\circ} 50^{\prime} 14.1$ | OBS12 |
| S1932 |  | ......... | $6^{\text {h }} 37^{m} 52.01^{3}$ | $9^{\circ} 42^{\prime} 01.1$ | OBS12 |
| S1937 |  | ........ | $6^{\text {h }} 37{ }^{\text {m }} 52.06^{\text {a }}$ | $9^{\circ} 50^{\prime} 04.1$ | OBS 1 |
| S1939 | W067 | ........ | $6^{\text {h }} 37^{m} 52.08{ }^{\text {a }}$ | $9^{\circ} 50^{\prime} 21.1$ | OBS12 |
| S1947 | W068 | .......... | $6^{\text {h }} 37^{\text {m }} 52.18{ }^{\text {a }}$ | $9^{\circ} 57^{\prime} 48.1$ | OBS 1 |
| S1950 | W069 | ......... | $6^{\text {h }} 37^{\text {m }} 52.25^{\text {a }}$ | $9^{\circ} 38^{\prime} 34.11$ | OBS |
| S1960 | W070 | ......... | $6^{\text {h }} 37^{m} 52.46{ }^{\text {a }}$ | $9^{\circ} 29^{\prime} 42.1$ | OBS 1 |
| S1973 | ..... | ....... | $6^{\mathrm{h}} 37^{\mathrm{m}} 52.70^{\text {a }}$ | $9^{\circ} 42^{\prime} 31.1$ | OBS12 |
| S1976 | ..... | ......... | $6^{\text {h }} 37^{m} 52.75{ }^{\text {a }}$ | $9^{\circ} 43^{\prime} 01.1$ | OBS12 |
| S1996 | ..... | LkHa 16 | $6^{\text {h }} 37^{m} 52.97^{3}$ | $9^{\circ} 37^{\prime} 45 . \prime$ | OBS 1 |
| S2006 | W073 |  | $6^{\text {h }} 37^{m} 53.11^{\text {a }}$ | $10^{\circ} 00^{\prime} 37.1$ | OBS 1 |
| S2007 | . | ......... | $6^{\boldsymbol{h}} 37^{m} 53.13^{\text {a }}$ | $9^{\circ} 29^{\prime} 13.1$ | OBS 1 |
| S2008 | ... | ......... | $6^{\text {h }} 37^{\text {m }} 53.16^{\text {a }}$ | $9^{\circ} 35^{\prime} 41.1$ | OBS 1 |
| S2009 | W074 | ......... | $6^{\text {h }} 37^{\mathrm{m}} 53.18^{\text {a }}$ | $9^{\circ} 50{ }^{\prime} 07.1$ | OBS12 ${ }^{\text {a }}$ |
| S2022 | , | ......... | $6^{\mathrm{h}} 37^{\mathrm{m}} 53.40^{\text {d }}$ | $9^{\circ} 32^{\prime} 44.1$ | OBS 1 |
| S2038 | ..... | ......... | $6^{\text {h }} 37^{\text {m }} 53.74{ }^{\text {a }}$ | $9^{\circ} 39^{\prime} 49.1$ | OBS 1 |
| S2055 | ..... |  | $6^{\text {h }} 37^{\text {m }} 54.10^{\text {a }}$ | $9^{\circ} 38^{\prime} 51.1$ | OBS 1 |
| S2068 | W076 | ......... | $6^{\text {h }} 37^{\text {m }} 54.26^{\prime}$ | $9^{\circ} 51^{\prime} 32.1$ | OBS12 |
| S2079 | . | ......... | $6^{\text {h }} 37^{m} 54.45^{\circ}$ | $9^{\circ} 37^{\prime} 37.1$ | OBS 1 |
| S2104 | ..... | ......... | $6^{\text {h }} 37^{\text {m }} 55.03^{\text {a }}$ | $9^{\circ} 46^{\prime} 32.1$ | OBS12 |
| S2113 | W077 | LkH 18 | $6^{h} 37^{m} 55.15{ }^{\text {a }}$ | $9^{\circ} 37^{\prime} 55.1$ | OBS 1 |
| S2116 | . | .......... | $6^{\text {h }} 37^{\text {m }} 55.18^{\prime}$ | $9^{\circ} 53^{\prime} 42 . "$ | OBS 1 |
| S2117 | ..... | ......... | $6^{\text {h }} 37^{m} 55.18^{\text {d }}$ | $9^{\circ} 53^{\prime} 54 . "$ | OBS 1 |
| S2146 | ..... | ......... | $6^{h} 37^{\text {m }} 55.82^{\prime}$ | $9^{\circ} 50^{\prime} 48.1$ | OBS12 |
| S2162 | W078 | LkH ${ }^{20}$ | $6^{\text {h }} 37^{m} 56.06^{\circ}$ | $9^{\circ} 53^{\prime} 54.11$ | OBS 1 |
| S2163 |  | LkHa 21 | $6^{\text {h }} 37^{m} 56.06^{\prime}$ | $9^{\circ} 57^{\prime} 05.11$ | OBS 1 |
| S2167 | ..... | ......... | $6^{\text {h }} 37^{\text {m }} 56.16^{*}$ | $9^{\circ} 30^{\prime} 51 .{ }^{\prime \prime}$ | OBS 1 |
| S2171 | ..... | ......... | $6^{\text {h }} 37^{\text {m }} 56.23^{\text {a }}$ | $9^{\circ} 51^{\prime} 01.1$ | OBS12 |
| S2173 | W079 | LkHa 22 | $6^{\text {h }} 37^{m} 56.26^{\circ}$ | $9^{\circ} 36^{\prime} 49.1$ | OBS 1 |
| S2190 | W081 | ... | $6^{\text {h }} 37^{m} 56.54{ }^{\text {a }}$ | $9^{\circ} 52^{\prime} 44.11$ | OBS 1 |
| S2191 | W080 | ......... | $6^{h} 37^{m} 56.57^{\text {d }}$ | $9^{\circ} 54^{\prime} 36.1$ | OBS 1 |
| S2228 | ..... | LkHa 23 | $6^{h} 37^{m} 57.19^{\circ}$ | $9^{\circ} 43^{\prime} 02.1$ | OBS12 |
| S2230 | ..... | .......... | $6^{\text {h }} 37^{\text {m }} 57.22^{\text {d }}$ | $9^{\circ} 25^{\prime} 48.11$ | OBS 1 |
| S2234 | W084 | ......... | $6^{\text {h }} 37^{m} 57.29^{\circ}$ | $9^{\circ} 36^{\prime} 30.1$ | OBS 1 |
| S2253 | ..... | ......... | $6^{\text {h }} 37^{m} 57.53^{\circ}$ | $9^{\circ} 35^{\prime} 12.1$ | OBS 1 |
| S2268 | ..... | ......... | $6^{\text {h }} 37^{\text {m }} 57.84^{\text {a }}$ | $9^{\circ} 36^{\prime} 27.1$ | OBS 1 |
| S2279 | $\ldots$ | ......... | $6^{\text {h }} 37^{m} 58.01^{\prime}$ | $9^{\circ} 26^{\prime} 41.1$ | OBS 1 |
| S2280 | ..... | LkH $\alpha 24$ | $6^{\text {h }} 37^{\text {m }} 58.01^{\text {a }}$ | $9^{\circ} 49^{\prime \prime} 59.1$ | OBS 12 |
| S2284 | ..... | .......... | $6^{h} 37^{m} 58.08^{\prime}$ | $9^{\circ} 53^{\prime} 51.1$ | OBS 1 |
| S2289 | W088 | ......... | $6^{h} 37^{m} 58.20^{\circ}$ | $9^{\circ} 48^{\prime} 53.11$ | OBS12 |
| S2313 | ..... | ......... | $6^{\text {c }} 37^{m} 58.59^{\circ}$ | $9^{\circ} 31^{\prime} 32.1$ | OBS 1 |
| S2322 | ..... | ......... | $6^{\kappa} 37^{m} 58.66{ }^{\text {a }}$ | $9^{\circ} 51^{\prime} 22.1$ | OBS 12 |
| S2325 | $\ldots$ | ......... | $6^{6} 37^{m} 58.70^{\circ}$ | $9^{\circ} 38^{\prime} 02.1$ | OBS 1 |
| S2359 | $\cdots$ | ......... | $6^{\text {h }} 37^{m} 59.38{ }^{\text {a }}$ | $9^{\circ} 26^{\prime} 47.1$ | OBS 1 |
| S2364 | W090 | LkHa 25 | $6^{h} 37^{m} 59.42{ }^{\circ}$ | $9^{\circ} 50^{\prime} 54.1$ | OBS12 |
| S2374 | , | Lhat | $6^{h} 37^{m} 59.57^{\prime}$ | $9^{\circ} 26^{\prime} 10.1$ | OBS 1 |
| S2377 | ... | ...... | $6^{\text {h }} 37^{m} 59.66{ }^{\text {a }}$ | $9^{\circ} 49^{\prime} 30.1$ | OBS 12 |
| S2387 | ..... | ......... | $6^{h} 37^{m} 59.81{ }^{\text {a }}$ | $9^{\circ} 54^{\prime} 19.1$ | OBS 1 |
| S2390 | ..... | ......... | $6^{\text {¢ }} 37^{m} 59.88{ }^{\text {a }}$ | $9^{\circ} 48{ }^{\prime} 33.1$ | OBS 12 |
| S2395 | ..... | .......... | $6^{h} 37^{m} 59.98{ }^{\text {a }}$ | $9^{\circ} 36^{\prime} 15 . \prime \prime$ | OBS 1 |
| S2405 | ..... | ........ | $6^{h} 38^{m} 00.17^{\text {a }}$ | $9^{\circ} 51^{\prime} 17.1$ | OBS 12 |
| S2418 | .... | $\cdots$ | $6^{h} 38^{m} 00.34^{\circ}$ | $9^{\circ} 31^{\prime} 35.1$ | OBS 1 |

TABLE 5.3-Continued

| Source | Walker \# | LkH $\chi_{\text {\# }}$ | $\alpha$ (1950.0) | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S2424 | $\ldots$ | ......... | $6^{\text {h }} 38^{m} 00.41^{\text {a }}$ | $9^{\circ} 40^{\prime} 43.4$ | OBS 1 |
| S2448 | W092 | .......... | $6^{\text {h }} 38^{m} 00.86^{\prime \prime}$ | $9^{\circ} 52^{\prime} 09.11$ | OBS 1 |
| S2449 |  | ......... | $6^{\text {h }} 38^{m} 00.89^{\circ}$ | $9^{\circ} 50^{\prime} 42.11$ | OBS12 |
| S2495 | ..... |  | $6^{\text {h }} 38^{m} 01.82{ }^{\text {a }}$ | $9^{\circ} 48^{\prime} 59.1$ | OBS12 |
| S2506 | $\ldots$ |  | $6^{\text {h }} 388^{\text {m }} 02.04{ }^{\text {s }}$ | $9^{\circ} 44^{\prime} 59.1$ | OBS12 |
| S2510 | ..... | ......... | $6^{\text {c }} 388^{\text {m }} 02.09^{3}$ | $9^{\circ} 28^{\prime} 44.11$ | OBS 1 |
| S2514 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 02.16^{3}$ | $9^{\circ} 51^{\prime} 41.11$ | OBS12 |
| S2515 | W095 | LkHa 26 | $6^{\text {h }} 38^{m} 02.21{ }^{\text {a }}$ | $9^{\circ} 35^{\prime} 32.1$ | OBS 1 |
| S2521 | W096 | LkH 27 | $6^{\text {h }} 38^{m} 02.28{ }^{\text {a }}$ | $9^{\circ} 52^{\prime} 21.11$ | OBS 1 |
| S2525 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 02.35^{\text {a }}$ | $9^{\circ} 31^{\prime} 42.1$ | OBS 1 |
| S2534 | ..... | ......... | $6^{\text {h }} 38^{m} 02.52^{\text {a }}$ | $9^{\circ} 43^{\prime} 24.11$ | OBS12 |
| S2563 | $\ldots$ | LkHa 28 | $6^{\text {h }} 38^{m} 03.19^{\prime}$ | $9^{\circ} 51^{\prime} 30.11$ | OBS12 |
| S2565 | W097 | ......... | $6^{\text {h }} 38^{\text {m }} 03.31^{*}$ | $9^{\circ} 39^{\prime} 30.11$ | OBS 1 |
| S2566 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 03.43^{\text {s }}$ | $9^{\circ} 29^{\prime} 51.11$ | OBS 1 |
| S2569 | W099 | ......... | $6^{\text {h }} 38^{m} 03.46{ }^{\text {a }}$ | $9^{\circ} 27^{\prime} 04 . "$ | OBS 1 |
| S2579 | W100 | ......... | $6^{\text {h }} 38^{\text {m }} 03.62^{\text {d }}$ | $9^{\circ} 54^{\prime} 37.11$ | OBS 1 |
| S2586 |  | ......... | $6^{\text {h }} 38^{\text {m }} 03.72^{\text {d }}$ | $9^{\circ} 35^{\prime} 44 .{ }^{\prime \prime}$ | OBS 1 |
| S2593 | W101 | ......... | $6^{h} 38^{m} 03.86^{\text {a }}$ | $9^{\circ} 35^{\prime} 34 .{ }^{\prime \prime}$ | OBS 1 |
| S2612 | W104 | ......... | $6^{\text {h }} 38^{\text {m }} 04.22^{\text {d }}$ | $9^{\circ} 56^{\prime} 15.11$ | OBS 1 |
| S2634 | ..... | LkH $\alpha 29$ | $6^{\text {h }} 38^{m} 04.58^{\text {d }}$ | $9^{\circ} 26^{\prime} 42.11$ | OBS 1 |
| S2636 | ..... | ......... | $6^{\text {h }} 38^{m} 04.66^{\prime}$ | $9^{\circ} 50^{\prime} 23.11$ | OBS12 |
| S2644 |  |  | $6^{\text {h }} 38^{m} 04.80^{\text {d }}$ | $9^{\circ} 55^{\prime} 19.11$ | OBS 1 |
| S2652 | W105 | LkH $\alpha 30$ | $6^{\text {h }} 38^{m} 04.94^{\text {a }}$ | $9^{\circ} 39^{\prime} 41 .{ }^{\prime \prime}$ | OBS 1 |
| S2659 | ..... | , | $6^{\text {h }} 38^{m} 05.11^{\text {d }}$ | $9^{\circ} 533^{\prime} 31.11$ | OBS 1 |
| S2662 | W106 | . | $6^{\text {h }} 38^{m} 05.21^{\text {a }}$ | $9^{\circ} 40^{\prime} 18.1$ " | OBS 1 |
| S2664 |  | ......... | $6^{\text {h }} 38^{\text {m }} 05.23^{\text {d }}$ | $9^{\circ} 51^{\prime} 43.11$ | OBS 12 |
| S2666 | ..... | LkHa 31 | $6^{\text {h }} 38^{\text {m }} 05.26^{\text {a }}$ | $9^{\circ} 57^{\prime} 49.11$ | OBS 1 |
| S2716 | W108 |  | $6^{\text {h }} 38^{m} 06.07^{\text {a }}$ | $9^{\circ} 47^{\prime} 38.11$ | OBS 12 |
| S2743 | ...... | LkH $\alpha 33$ | $6^{\text {h }} 38^{\mathrm{m}} 06.46^{\text {a }}$ | $9^{\circ} 46^{\prime} 17.11$ | OBS12 |
| S2753 | ..... | LkH $\alpha 34$ | $6^{\text {h }} 38^{\text {m }} 06.77^{\text {a }}$ | $9^{\circ} 31^{\prime} 36 . "$ | OBS 1 |
| S2756 | ..... | ... | $6^{\text {h }} 38^{\text {m }} 06.811^{\text {a }}$ | $9^{\circ} 55^{\prime} 06 . "$ | OBS 1 |
| S2760 | W112 | ......... | $6^{\text {h }} 38^{\text {m }} 06.89^{\text {a }}$ | $9^{\circ} 41^{\prime} 60.1$ | OBS $1^{\text {a }}$ |
| S2761 | ..... | ......... | $6^{\text {h }} 38^{m} 06.89{ }^{\text {a }}$ | $9^{\circ} 47^{\prime} 56 . "$ | OBS12 |
| S2763 | ..... | .......... | $6^{\text {h }} 38^{m} 06.94{ }^{\text {a }}$ | $9^{\circ} 40^{\prime} 48.11$ | OBS 1 |
| S2764 | $\ldots$ | ......... | $6^{\text {h }} 38^{m} 06.94{ }^{\text {a }}$ | $9^{\circ} 55^{\prime} 23.11$ | OBS 1 |
| S2777 | ..... | . | $6^{\text {h }} 38^{m} 07.30^{\text {d }}$ | $9^{\circ} 54^{\prime} 58 . "$ | OBS 1 |
| S2809 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 07.80^{\circ}$ | $9^{\circ} 47^{\prime} 46.11$ | OBS12 |
| S2827 | $\ldots$ | ......... | $6^{\text {h }} 38^{m} 08.18^{\text {d }}$ | $9^{\circ} 29^{\prime} 16.11$ | OBS 1 |
| S2843 | W115 | LkH $\alpha 35$ | $6^{\text {h }} 38^{m} 08.74{ }^{\text {d }}$ | $9^{\circ} 36^{\prime} 17.11$ | OBS 1 |
| S2854 | W116 | ... | $6^{\text {h }} 38^{\mathrm{mm}} 08.90^{\text {a }}$ | $9^{\circ} 33^{\prime} 30.11$ | OBS 1 |
| S2861 | ..... | ......... | $6^{\text {h }} 38^{m} 09.00^{\text {d }}$ | $9^{\circ} 53^{\prime} 46.11$ | OBS 1 |
| S2862 | W117 | ......... | $6^{\text {h }} 38^{\text {m }} 09.10^{\text {d }}$ | $9^{\circ} 50^{\prime} 04 .{ }^{\prime \prime}$ | OBS12 |
| S2892 | W118 | ......... | $6^{\text {h }} 38^{m} 09.74{ }^{\text {a }}$ | $9^{\circ} 22^{\prime} 56 . "$ | OBS 1 |
| S2898 | ..... | ......... | $6^{\text {h }} 388^{\text {m }} 09.96{ }^{\text {a }}$ | $9^{\circ} 53^{\prime} 42.11$ | OBS 1 |
| S2920 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 10.49^{\text {a }}$ | $9^{\circ} 54^{\prime} 06 . "$ | OBS 1 |
| S2926 | W120 |  | $6^{\text {h }} 38^{\text {m }} 10.63^{\text {a }}$ | $9^{\circ} 34^{\prime} 15.11$ | OBS 1 |
| S2943 | W122 | LkHa 38 | $6^{\text {h }} 38^{m} 11.21^{\text {d }}$ | $9^{\circ} 39^{\prime} 23.11$ | OBS 1 |
| S2944 | W121 | ......... | $6^{\text {h }} 38^{\mathrm{m}} 11.23^{\text {a }}$ | $9^{\circ} 57^{\prime} 04 . "$ | OBS 1 |
| S2945 | ..... | LkH ${ }^{\text {c }} 39$ | $6^{\text {h }} 38^{\text {m }} 11.26^{\text {a }}$ | $9^{\circ} 42^{\prime} 25.11$ | OBS12 |
| S2958 | W123 | LkH\% 40 | $6^{\text {h }} 38^{\text {m }} 11.45^{\text {d }}$ | $9^{\circ} 38^{\prime} 46.11$ | OBS 1 |
| S2969 | W124 | ......... | $6^{\mathrm{h}} 38^{\text {m }} 11.59^{\text {a }}$ | $9^{\circ} 42^{\prime} 36.11$ | OBS12 |
| S2971 |  |  | $6^{\text {h }} 38^{\text {m }} 11.59^{\text {a }}$ | $9^{\circ} 54^{\prime} 49.11$ | OBS 1 |

TABLE 5.3-Continued

| Source | Walker \# | LkH $\alpha$ \# | $\alpha$ (1950.0) | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S2984 | W125 | .......... | $6^{\text {h }} 38^{m} 11.78{ }^{\text {d }}$ | $9^{\circ} 51^{\prime} 34 . "$ | OBS12 * |
| S2989 | W126 | LkH 41 | $6^{h} 38^{m} 11.86{ }^{\text {a }}$ | $9^{\circ} 40^{\prime} 41 .{ }^{\prime \prime}$ | OBS 1 |
| S2993 | W127 |  | $6^{\text {h }} 38^{m} 11.93{ }^{\text {a }}$ | $9^{\circ} 33^{\prime} 08.11$ | OBS 1 |
| S3031 |  | $\ldots . .$. | $6^{\text {h }} 38^{\text {m }} 12.62^{\text {a }}$ | $9^{\circ} 54^{\prime} 01.11$ | OBS 1 |
| S3044 | W129 | ......... | $6^{h} 38^{m} 12.82{ }^{\text {a }}$ | $9^{\circ} 44^{\prime} 12.1$ | OBS12 |
| S3048 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 12.86{ }^{\text {a }}$ | $9^{\circ} 54^{\prime} 06 . "$ | OBS 1 |
| S3052 | ..... | .......... | $6^{\text {h }} 38^{\text {m }} 12.91^{\text {a }}$ | $9^{\circ} 33^{\prime} 43.1$ | OBS 1 |
| S3077 | ..... | .......... | $6^{\text {h }} 38^{m} 13.29^{\text {a }}$ | $9^{\circ} 27^{\prime} 28 . /$ | OBS 1 |
| S3102 | ..... | .......... | $6^{\text {h }} 38^{\text {m }} 13.51^{\text {a }}$ | $9^{\circ} 48^{\prime} 47 .{ }^{\prime \prime}$ | OBS12 |
| S3108 | W132 | ......... | $6^{\text {h }} 38^{\text {m }} 13.61^{\text {a }}$ | $9^{\circ} 36^{\prime} 25 . /$ | OBS 1 |
| S3110 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 13.63^{\prime}$ | $9^{\circ} 30^{\prime} 17.1$ | OBS 1 |
| S3122 | ..... |  | $6^{\text {h }} 38^{m} 13.85{ }^{\text {a }}$ | $9^{\circ} 42^{\prime} 11.11$ | OBS12 |
| S3135 | ..... | LkHa 43 | $6^{\text {h }} 38^{\text {m }} 13.99^{\text {a }}$ | $9^{\circ} 33^{\prime} 51 .{ }^{\prime \prime}$ | OBS 1 |
| S3141 | ..... | .......... | $6^{\text {h }} 38^{\text {m }} 14.11^{\text {s }}$ | $9^{\circ} 31^{\prime} 45.11$ | OBS 1 |
| S3160 | ..... | .......... | $6^{\text {h }} 38^{m} 14.47^{\text {m }}$ | $9^{\circ} 36^{\prime} 26 . "$ | OBS 1 |
| S3170 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 14.59^{\text {a }}$ | $9^{\circ} 54^{\prime} 41.11$ | OBS 1 |
| S3171 | W136 | .......... | $6^{\text {h }} 38^{\text {m }} 14.61^{\text {a }}$ | $9^{\circ} 38^{\prime} 03.1$ | OBS 1 |
| S3174 |  | ......... | $6^{\text {h }} 38^{\text {m }} 14.66^{\circ}$ | $9^{\circ} 32^{\prime} 45.1$ | OBS 1 |
| S3184 | W137 | ......... | $6^{\text {h }} 38^{\text {m }} 14.81^{\text {d }}$ | $9^{\circ} 55^{\prime} 11 .{ }^{\prime \prime}$ | OBS 1 |
| 53197 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 15.19^{\text {a }}$ | $9^{\circ} 31^{\prime} 43.1$ | OBS 1 |
| S3205 | ..... | ......... | $6^{\text {h }} 38^{m} 15.38^{\text {a }}$ | $9^{\circ} 47^{\prime} 55 . "$ | OBS 12 |
| S3214 | ..... | .......... | $6^{\text {h }} 38^{m} 15.55^{\text {d }}$ | $9^{\circ} 54^{\prime} 15 .{ }^{\prime \prime}$ | OBS 1 |
| S3221 | ..... | ....... | $6^{\text {h }} 38^{m} 15.70^{\prime}$ | $9^{\circ} 32^{\prime} 09 . "$ | OBS 1 |
| S3225 | W138 | ......... | $6^{\text {h }} 38^{\text {m }} 15.98{ }^{\text {d }}$ | $9^{\circ} 27^{\prime} 05 . "$ | OBS 1 |
| S3232 | W139 | LkH $\alpha 4$ | $6^{\text {h }} 38^{\text {m }} 16.10^{\text {d }}$ | $9^{\circ} 35{ }^{\prime} 38.11$ | OBS 1 |
| S3251 | ..... | ......... | $6^{\text {h }} 38^{m} 16.51{ }^{\text {d }}$ | $9^{\circ} 37^{\prime} 01.1$ | OBS 1 |
| S3252 | ..... | ......... | $6^{\text {h }} 38^{m}{ }^{\text {m }} 16.511^{\text {d }}$ | $9^{\circ} 51^{\prime} 16.11$ | OBS 12 |
| S3268 | ..... | ......... | $6^{\text {h }} 38^{m} 16.68{ }^{\text {d }}$ | $9^{\circ} 37^{\prime} 26.1$ | OBS 1 |
| S3272 | $\ldots$ | ......... | $6^{\text {h }} 38^{m} 16.75^{4}$ | $9^{\circ} 31^{\prime} 06.11$ | OBS 1 |
| S3276 | W146 | .......... | $6^{\text {h }} 38^{m} 16.85{ }^{\text {d }}$ | $9^{\circ} 41^{\prime} 34.1$ | OBS12 |
| S3282 | ..... | . | $6^{\text {h }} 38^{m} 16.97^{4}$ | $9^{\circ} 54^{\prime} 45.11$ | OBS 1 |
| S3308 | ..... | ......... | $6^{\text {h }} 38^{m} 17.54^{\text {a }}$ | $9^{\circ} 30^{\prime} 16.1$ | OBS 1 |
| S3312 | W149 | ......... | $6^{\text {h }} 388^{\text {m }} 17.62^{\text {d }}$ | $9^{\circ} 37^{\prime} 49.11$ | OBS 1 |
| S3317 | W148 | ......... | $6^{\text {h }} 38^{\text {m }} 17.69^{4}$ | $9^{\circ} 37^{\prime} 12.11$ | OBS 1 |
| S3323 | W151 | ......... | $6^{\text {h }} 38^{m} 17.81{ }^{\text {a }}$ | $9^{\circ} 50^{\prime} 48.11$ | OBS12 |
| S3351 | W153 | LkH $\alpha 48$ | $6^{\text {h }} 38^{\text {m }} 18.36^{\prime}$ | $9^{\circ} 43^{\prime} 38.11$ | OBS12 |
| S3358 | ..... | ....... | $6^{\text {h }} 38^{\text {m }} 18.45^{\text {a }}$ | $9^{\circ} 28^{\prime} 56.1$ | OBS 1 |
| S3363 | ..... | ......... | $6^{\text {h }} 38^{m} 18.58{ }^{\text {a }}$ | $9^{\circ} 32^{\prime} 58.11$ | OBS 1 |
| S3365 | ..... | ......... | $6^{\text {h }} 38^{m} 18.62^{\text {a }}$ | $9^{\circ} 34^{\prime} 12.11$ | OBS 1 |
| S3376 | $\ldots$ | ......... | $6^{\text {h }} 38^{\text {m }} 18.84^{4}$ | $9^{\circ} 52^{\prime} 02.1$ | OBS 1 |
| S3381 | ..... | ......... | $6^{\text {h }} 38^{m}{ }^{\text {m }} 18.94^{4}$ | $9^{\circ} 30^{\prime} 18.11$ | OBS $1^{\text {a }}$ |
| S3392 | W156 | ......... | $6^{\text {h }} 38^{m} 19.15{ }^{\text {a }}$ | $9^{\circ} 51^{\prime} 15.11$ | OBS12 |
| S3393 |  | ......... | $6^{\text {h }} 38^{m} 19.15{ }^{\text {a }}$ | $9^{\circ} 54^{\prime} 44.11$ | OBS 1 |
| S3395 | $\cdots$ | ......... | $6^{\text {h }} 38^{\text {m }} 19.20^{\text {a }}$ | $9^{\circ} 31^{\prime} 17.11$ | OBS |
| S3396 | W157 | ......... | $6^{\text {h }} 38^{\text {m }} 19.20^{\text {a }}$ | $9^{\circ} 35^{\prime} 55.11$ | OBS |
| S3398 |  | ......... | $6^{\text {h }} 38^{\text {m }} 19.20^{4}$ | $9^{\circ} 54^{\prime} 19.1$ | OBS 1 |
| S3402 | W158 | ......... | $6^{\text {h }} 38^{m}{ }^{\text {m }} 19.25^{\text {a }}$ | $9^{\circ} 57^{\prime} 37.1$ | OBS 1 |
| S3408 | ..... | ......... | $6^{\text {h }} 38^{\text {m }} 19.34^{\text {a }}$ | $9^{\circ} 26^{\prime} 26 . "$ | OBS |
| S3425 | ..... | LkH¢ 49 | $6^{\text {h }} 38^{m} 19.58^{\text {a }}$ | $9^{\circ} 27^{\prime} 45.11$ | OBS 1 |
| S3435 | ..... | ......... | $6^{\text {h }} 38^{m} 19.73^{\text {a }}$ | $9^{\circ} 53^{\prime} 39.1$ | OBS 1 |
| S3438 | W159 | .......... | $6^{\text {h }} 38^{\text {m }} 19.75^{\text {a }}$ | $9^{\circ} 39^{\prime} 21.1$ | OBS |
| S3441 |  | .......... | $6^{\text {h }} 38^{m} 19.80^{\circ}$ | $9^{\circ} 299^{\prime} 02.1$ | OBS 1 |

TABLE 5.3-Continued

| Source | Walker \# | LkHa \# | $\alpha(1950.0)$ | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S3442 | -.... | .......... | $6^{\text {h }} 38^{m} 19.82^{\text {d }}$ | $9^{\circ} 28^{\prime} 11.1$ | OBS 1 |
| S3443 | . $\cdot$. | . $\cdot$ | $6^{h} 38^{m} 19.85{ }^{\text {a }}$ | $9^{\circ} 54^{\prime} 37.1$ | OBS 1 |
| S3448 | . | .... | $6^{\text {h }} 38^{\mathrm{m}} 19.90^{\text {s }}$ | $9^{\circ} 51^{\prime} 41.1$ ' | OBS12 |
| S3452 |  | ......... | $6^{\text {h }} 38^{m} 19.99^{\text {a }}$ | $9^{\circ} 28^{\prime} 00.1$ | OBS 1 |
| S3470 | W160 | .......... | $6^{h} 38^{m} 20.47^{\text {d }}$ | $9^{\circ} 36^{\prime} 06.1$ | OBS 1 |
| S3475 | ..... | LkHa 51 | $6^{h} 38^{m} 20.59^{3}$ | $9^{\circ} 51^{\prime} 10.11$ | OBS12 |
| S3496 | W162 | ......... | $6^{h} 38^{m} 20.90^{3}$ | $9^{\circ} 33^{\prime} 54.1$ | OBS 1 |
| S3505 | ..... | . | $6^{h} 38^{m} 21.07^{3}$ | $9^{\circ} 38^{\prime} 45.1$ | OBS 1 |
| S3510 | ..... | . | $6^{h} 38^{m} 21.17^{3}$ | $9^{\circ} 30^{\prime} 10.11$ | OBS 1 |
| S3511 | W165 | ......... | $6^{h} 38^{m} 21.19^{\text {d }}$ | $9^{\circ} 25^{\prime} 49.11$ | OBS 1 |
| S3514 | W164 | LkH ${ }^{53}$ | $6^{h} 38^{m} 21.24^{\text {a }}$ | $9^{\circ} 39^{\prime} 17.11$ | OBS 1 |
| S3529 | ..... | .......... | $6^{h} 38^{m} 21.50^{\text {a }}$ | $9^{\circ} 27^{\prime} 57.1$ | OBS 1 |
| S3535 | ..... | LkHa 55 | $6^{h} 38^{m} 21.63^{3}$ | $9^{\circ} 31^{\prime} 31.1$ | OBS 1 |
| S3536 | ..... | ......... | $6^{\mathrm{h}} 38^{\mathrm{m}} 21.63^{\text {a }}$ | $9^{\circ} 38^{\prime} 38.1$ " | OBS 1 |
| S3537 | ..... | .......... | $6^{h} 38^{m} 21.65^{4}$ | $9^{\circ} 48^{\prime} 26.1$ | OBS12 |
| S3546 | W168 | . | $6^{h} 38^{\mathrm{m}} 21.84^{\text {d }}$ | $10^{\circ} 01^{\prime} 24 .{ }^{\prime \prime}$ | OBS 1 |
| S3552 | ..... | LkHa 54 | $6^{h} 38^{m} 22.06^{\text {d }}$ | $9^{\circ} 30^{\prime} 26.1$ ' | OBS 1 |
| S3556 | ..... | .......... | $6^{h} 38^{m} 22.15{ }^{\text {d }}$ | $9^{\circ} 26^{\prime} 16.11$ | OBS 1 |
| S3568 | ..... | .......... | $6^{h} 38^{m} 22.39^{2}$ | $9^{\circ} 30^{\prime} 41.11$ | OBS 1 |
| S3579 | ..... | . . | $6^{h} 38^{m} 22.59^{\text {a }}$ | $9^{\circ} 36^{\prime} 30.11$ | OBS 1 |
| S3580 | ..... | . | $6^{h} 38^{m} 22.61 *$ | $9^{\circ} 28^{\prime} 48.11$ | OBS 1 |
| S3583 | W170 | . . . . . . | $6^{h} 38^{m} 22.68{ }^{\text {a }}$ | $9^{\circ} 44^{\prime} 09.1$ | OBS12 |
| S3584 | W169 | . $\cdot$ | $6^{h} 38^{m} 22.68{ }^{\text {d }}$ | $9^{\circ} 46^{\prime} 56.11$ | OBS12 |
| S3592 | ..... | - | $6^{h} 38^{m} 22.94{ }^{\text {a }}$ | $9^{\circ} 31^{\prime} 06.1$ ' | OBS 1 |
| S3602 | W175 |  | $6^{h} 38^{m} 23.16^{\text {a }}$ | $9^{\circ} 33^{\prime} 33.1$ ' | OBS 1 |
| S3607 | W171 |  | $6^{h} 38^{m} 23.30^{\prime}$ | $9^{\circ} 41^{\prime} 08.1$ ' | OBS 1 |
| S3611 | ..... | . ...... | $6^{\text {h }} 38^{\mathrm{m}} 23.37^{\text {a }}$ | $9^{\circ} 26^{\prime} 16.1$ ' | OBS 1 |
| S3618 | W173 | . | $6^{\mathrm{h}} 38^{\mathrm{m}} 23.50^{\text {a }}$ | $9^{\circ} 45^{\prime} 45.1$ | OBS12 |
| S3628 | ..... | - | $6^{\text {h }} 38^{m} 23.71^{\text {a }}$ | $9^{\circ} 48^{\prime} 54.11$ | OBS12 |
| S3636 | W174 | ......... | $6^{h} 38^{m} 23.83^{\text {a }}$ | $9^{\circ} 44^{\prime} 09.11$ | OBS12 |
| S3646 | ..... | .......... | $6^{\text {h }} 38^{m} 24.02^{\text {a }}$ | $9^{\circ} 36^{\prime} 39.11$ | OBS 1 |
| S3650 | ..... | . ......... | $6^{h} 38^{m} 24.10^{3}$ | $9^{\circ} 26^{\prime} 37.11$ | OBS 1 |
| S3659 | ..... | .......... | $6^{\text {h }} 38^{\mathrm{m}} 24.24^{\text {a }}$ | $9^{\circ} 54^{\prime} 43.1$ | OBS 1 |
| S3666 | -...' | . | $6^{h} 38^{m} 24.55^{\text {a }}$ | $9^{\circ} 38^{\prime} 19.1$ ' | OBS 1 |
| S3679 | ..... | ......... | $6^{h} 38^{m} 24.96{ }^{\text {d }}$ | $9^{\circ} 27^{\prime} 48.1$ " | OBS 1 |
| S3683 | W179 | . $\cdot$........ | $6^{h} 38^{m} 25.03^{\text {d }}$ | $9^{\circ} 55^{\prime} 53.1$ | OBS 1 |
| S3686 | -•... | ........ | $6^{h} 38^{m} 25.08{ }^{\text {a }}$ | $9^{\circ} 30^{\prime} 06.11$ | OBS 1 |
| S3690 | ..... | ........ | $6^{h} 38^{m} 25.15^{\text {a }}$ | $9^{\circ} 44^{\prime} 03.11$ | OBS12 |
| S3692 | .... | . $\cdot$..... | $6^{h} 38^{m} 25.23{ }^{\text {a }}$ | $9^{\circ} 30^{\prime} 40.1$ | OBS 1 |
| S3693 | ..... | ...... | $6^{\text {h }} 38^{\mathrm{m}} 25.27^{\text {a }}$ | $9^{\circ} 34^{\prime} 21.11$ | OBS 1 |
| S3698 | ..... | . . . . ${ }^{\text {a }}$ | $6^{h} 38^{\text {m }} 25.37^{3}$ | $9^{\circ} 36^{\prime} 18.1$ " | OBS 1 |
| S3702 | ..... | ....... | $6^{h} 38^{m} 25.51{ }^{\text {d }}$ | $9^{\circ} 31^{\prime} 26.11$ | OBS 1 |
| S3712 | - | ......... | $6^{h} 38^{m} 25.63^{4}$ | $9^{\circ} 49^{\prime} 34.1$ | OBS12 |
| S3719 | W181 | .......... | $6^{h} 38^{m} 25.94{ }^{\text {d }}$ | $9^{\circ} 55^{\prime} 49.11$ | OBS 1 |
| S3725 | , | . . . . . | $6^{h} 38^{m} 26.04{ }^{\text {d }}$ | $9^{\circ} 38^{\prime} 49.1$ | OBS 1 |
| S3761 | ..... | ....... | $6^{h} 38^{m} 27.12^{\text {d }}$ | $9^{\circ} 26^{\prime} 27.1$ | OBS 1 |
| S3767 | W184 | LkHa 60 | $6^{h} 38^{m} 27.29{ }^{\text {d }}$ | $9^{\circ} 55^{\prime} 25.1$ | OBS 1 |
| S3772 | W185 | ......... | $6^{\text {h }} 38^{m} 27.36^{\text {d }}$ | $9^{\circ} 42^{\prime} 20.1$ | OBS12 |
| S3776 |  | .... | $6^{\text {h }} 38^{m} 27.55^{*}$ | $9^{\circ} 55^{\prime} 37 . \prime$ | OBS 1 |
| S3790 | W186 | ........ | $6^{h} 38^{m} 27.91 *$ | $9^{\circ} 58^{\prime} 02.1$ | OBS 1 |
| S3792 | , | . $\cdot$ | $6^{h} 38^{m} 28.01{ }^{\text {m }}$ | $9^{\circ} 38^{\prime} 25.1$ | OBS 1 |
| S3796 | -.... | . $\cdot$........ | $6^{h} 38^{m} 28.06^{3}$ | $9^{\circ} 54^{\prime} 48.1$ | OBS 1 |

TABLE 5.3-Continued

| Source | Walker \# | LkH $\alpha$ \# | $\alpha$ (1950.0) | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S3799 |  | LkH $\alpha 61$ | $6^{h} 38^{m} 28.13^{\text {a }}$ | $9^{\circ} 29^{\prime} 09.1$ | OBS 1 |
| S3802 | W189 |  | $6^{\text {h }} 38^{m} 28.25{ }^{\text {a }}$ | $9^{\circ} 30^{\prime} 26.1$ | OBS |
| S3806 | ..... | .......... | $6^{\text {h }} 38^{m} 28.37^{\text {a }}$ | $9^{\circ} 25^{\prime} 58.1$ | OBS |
| S3810 | ..... | ......... | $6^{h} 38^{m} 28.42{ }^{\text {d }}$ | $9^{\circ} 27^{\prime} 30.11$ | OBS |
| S3811 | ..... | ......... | $6^{h} 38^{m} 28.44^{4}$ | $9^{\circ} 34^{\prime} 43.1$ | OBS |
| S3812 | ..... | LkH $\mathrm{Cl}^{2}$ | $6^{\text {h }} 38^{\text {m }} 28.46^{\text {a }}$ | $9^{\circ} 29^{\prime} 04.11$ | OBS |
| S3813 | W190 | .......... | $6^{h} 38^{m} 28.46^{\text {a }}$ | $9^{\circ} 58{ }^{\prime} 38.11$ | OBS |
| S3815 | W100 | ......... | $6^{h} 38^{m} 28.53^{\text {a }}$ | $9^{\circ} 31^{\prime} 00.11$ | OBS |
| S3834 | $\ldots$ | .......... | $6^{\text {h }} 38^{m} 29.35^{\text {a }}$ | $9^{\circ} 29^{\prime} 34.1$ " | OBS |
| S3844 | W191 | ......... | $6^{\text {h }} 38{ }^{\text {m }} 29.57^{\text {a }}$ | $9^{\circ} 36{ }^{\prime} 14.1$ | OBS |
| S3861 | .... | ......... | $6^{h} 38^{m} 29.98{ }^{\text {a }}$ | $9^{\circ} 35^{\prime} 29.1$ | OBS |
| S3866 | ..... | .......... | $6^{\text {h }} 38^{m} 30.12{ }^{\text {a }}$ | $9^{\circ} 29^{\prime} 07.1$ | OBS 1 |
| S3869 | ..... | ......... | $6^{h} 38^{m} 30.22^{\text {a }}$ | $9^{\circ} 40{ }^{\prime} 51.1$ | OBS 1 |
| S3871 | ..... | ......... | $6^{\text {h }} 388^{m} 30.31^{3}$ | $9^{\circ} 49^{\prime} 34.1$ | OBS 12 |
| S3872 | ..... | LkHa 64 | $6^{h} 38{ }^{m} 30.36^{4}$ | $9^{\circ} 29^{\prime} 38.1$ | OBS 1 |
| S3873 | W193 | ......... | $6^{\text {h }} 388^{\text {m }} 30.43^{\text {a }}$ | $9^{\circ} 34^{\prime} 12.11$ | OBS 1 |
| S3875 | ..... | ......... | $6^{\text {h }} 38^{m} 30.46^{\text {a }}$ | $9^{\circ} 43^{\prime} 07.1$ | OBS 12 |
| S3878 | ..... | ......... | $6^{\text {h }} 38{ }^{\text {m }} 30.62^{\text {a }}$ | $9^{\circ} 28^{\prime} 10.1$ | OBS 1 |
| S3880 | W194 | .......... | $6^{\text {h }} 38{ }^{\text {m }} 30.72^{\text {a }}$ | $9^{\circ} 41^{\prime} 12.1$ | OBS 12 |
| S3884 | ..... | ......... | $6^{\text {h }} 388^{m} 30.89^{\circ}$ | $9^{\circ} 29^{\prime} 27.1$ | OBS 1 |
| S3889 | $\ldots$ | .......... | $6^{h} 38{ }^{\text {m }} 31.01^{\text {a }}$ | $9^{\circ} 29^{\prime} 11.1$ | OBS 1 |
| S3895 | ..... | ......... | $6^{\text {h }} 38{ }^{m} 31.22^{\text {a }}$ | $9^{\circ} 29^{\prime} 03.1$ | OBS 1 |
| S3897 | W195 |  | $6^{\text {h }} 38{ }^{\text {m }} 31.27^{\text {a }}$ | $9^{\circ} 55^{\prime} 07.1$ | OBS 1 |
| S3913 | ..... | . | $6^{h} 38^{m} 31.85^{\prime}$ | $9^{\circ} 55^{\prime} 34.1$ | OBS 1 |
| S3915 | ..... | ......... | $6^{h} 38^{m} 31.87^{\circ}$ | $9^{\circ} 32^{\prime} 46.1$ | OBS 1 |
| S3917 | ..... |  | $6^{h} 38{ }^{\text {m }} 31.90^{\circ}$ | $9^{\circ} 39^{\prime} 14.1$ " | OBS 1 |
| S3920 | W197 | LkHa 66 | $6^{h} 38{ }^{\text {m }} 31.97{ }^{\text {a }}$ | $9^{\circ} 57^{\prime} 27.1$ | OBS 1 |
| S3923 | ..... | LkH\% 65 | $6^{h} 38^{m} 32.02^{\text {a }}$ | $9^{\circ} 30^{\prime} 24.1$ " | OBS 1 |
| S3947 | $\cdots$ | ......... | $6^{h} 38^{m} 32.62^{\circ}$ | $9^{\circ} 52^{\prime} 11.1$ | OBS 1 |
| S3956 | ..... | ......... | $6^{h} 38^{m} 32.88{ }^{\text {a }}$ | $9^{\circ} 32^{\prime} 20.1$ | OBS 1 |
| S3963 | ..... | .......... | $6^{\text {h }} 38{ }^{\text {m }} 33.10^{\text {a }}$ | $9^{\circ} 41^{\prime} 19.1$ | OBS12 |
| S3964 | ..... | ......... | $6^{h} 38^{\text {m }} 33.12^{\prime \prime}$ | $9^{\circ} 31^{\prime} 54.11$ | OBS 1 |
| S3969 | ..... | .......... | $6^{h} 38{ }^{\text {m }} 33.24{ }^{\circ}$ | $9^{\circ} 47^{\prime} 00.1$ | OBS12 |
| S3973 | ..... | LkH\% 67 | $6^{h} 38^{m} 33.36^{\text {a }}$ | $9^{\circ} 42^{\prime} 35.1$ | OBS12 |
| S3974 | W199 | LkHa 68 | $6^{h} 38^{m} 33.388^{\text {a }}$ | $9^{\circ} 36^{\prime} 47.11$ | OBS 1 |
| S3979 | $\ldots$ | .......... | $6^{h} 38{ }^{\text {m }} 33.50^{\text {a }}$ | $9^{\circ} 31^{\prime} 26.11$ | OBS 1 |
| S3982 | .... | .......... | $6^{h} 38^{m} 33.55^{\text {m }}$ | $9^{\circ} 34^{\prime} 23.1$ " | OBS 1 |
| S3990 | ..... | ......... | $6^{h} 38{ }^{m} 33.89{ }^{\text {d }}$ | $9^{\circ} 42^{\prime} 38.1$ | OBS12 |
| S3995 | ... | ... | $6^{h} 38^{m} 34.15^{\text {d }}$ | $9^{\circ} 30^{\prime} 10.11$ | OBS 1 |
| S4003 | . | LkH 69 | $6^{h} 38^{m} 34.37^{\circ}$ | $9^{\circ} 29^{\prime} 23.1$ " | OBS 1 |
| S4005 | ..... | Lka | $6^{h} 38^{m} 34.42^{\text {a }}$ | $9^{\circ} 33^{\prime} 42.1$ | OBS 1 |
| S4011 | ..... | ......... | $6^{h} 38^{m} 34.63^{\circ}$ | $9^{\circ} 33^{\prime} 23.1$ | OBS 1 |
| S4015 | W203 | ......... | $6^{h} 38^{m} 34.80^{\circ}$ | $9^{\circ} 30^{\prime} 19.1$ | OBS 1 |
| 54016 | ..... | ...... | $6^{h} 38^{m} 34.80^{\circ}$ | $9^{\circ} 34^{\prime} 38.1$ | OBS 1 |
| S4037 | ..... | ......... | $6^{h} 38^{m} 35.40^{\circ}$ | $9^{\circ} 50^{\prime} 24.1$ | OBS12 |
| S4038 | ..... | ......... | $6^{h} 38^{m} 35.45^{\circ}$ | $9^{\circ} 48^{\prime} 30.11$ | OBS12 |
| S4053 | ..... | . | $6^{h} 38^{m} 35.93^{8}$ | $9^{\circ} 33^{\prime} 06.1$ | OBS 1 |
| S4062 | W204 | LkH $<70$ | $6^{h} 38^{m} 36.14{ }^{4}$ | $9^{\circ} 36^{\prime} 30.1$ | OBS 1 |
| S4073 |  |  | $6^{h} 38^{m} 36.33^{\prime}$ | $9^{\circ} 35^{\prime} 08.11$ | OBS 1 |
| S4078 | ... | . | $6^{h} 38^{m} 36.70^{\prime}$ | $9^{\circ} 48^{\prime} 25.11$ | OBS12 |
| S4082 | ... | ... | $6^{h} 38^{m} 36.84^{\text {a }}$ | $9^{\circ} 54^{\prime} 07.11$ | OBS 1 |
| S4087 | ..... |  | $6^{h} 38^{m} 36.96{ }^{\text {a }}$ | $9^{\circ} 46^{\prime} 07.1$ | OBS12 |

TABLE 5.3-Continued

| Source | Walker \# | LkHa \# | $\alpha(1950.0)$ | $\delta(1950.0)$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S4090 | W206 | .......... | $6^{h} 38^{m} 37.01 *$ | $9^{\circ} 46^{\prime} 45.1$ | OBS12 |
| S4112 | ..... | .......... | $6^{\text {h }} 38^{\text {m }} 37.70^{\text {s }}$ | $9^{\circ} 32^{\prime} 07.1$ | OBS 1 |
| S4121 | ..... | LkH ${ }^{1} 1$ | $6^{h} 38^{m} 37.99^{\text {a }}$ | $9^{\circ} 32^{\prime} 33.1$ | OBS 1 |
| S4124 | ..... | .......... | $6^{h} 38^{\text {m }} 38.02^{s}$ | $9^{\circ} 46^{\prime} 21.1$ | OBS12 |
| S4126 | ..... | .......... | $6^{h} 38^{m} 38.04^{\text {a }}$ | $9^{\circ} 46^{\prime} 59.1$ | OBS12 |
| S4133 | -•... | . $\cdot . . . . .$. | $6^{h} 38^{m} 38.19^{\prime \prime}$ | $9^{\circ} 40^{\prime} 28.1$ | OBS 1 |
| S4136 | W208 | ....... | $6^{h} 38^{m} 38.26^{\text {a }}$ | $9^{\circ} 30^{\prime} 22.1$ | OBS 1 |
| S4146 | ..... | ........ | $6^{h} 38^{m} 38.35^{\text {a }}$ | $9^{\circ} 48^{\prime} 53 . \prime$ | OBS12 |
| S4176 | W209 | .......... | $6^{h} 38^{\text {m }} 38.90^{\text {a }}$ | $9^{\circ} 36^{\prime} 51 . "$ | OBS 1 |
| S4194 | ..... | .......... | $6^{h} 38^{m} 39.41^{3}$ | $9^{\circ} 34^{\prime} 48.1$ | OBS 1 |
| S4200 |  | ... | $6^{h} 38^{m} 39.58{ }^{\text {a }}$ | $9^{\circ} 40^{\prime} 30.1$ | OBS 1 |
| S4201 | ..... |  | $6^{h} 38^{m} 39.60^{\text {a }}$ | $9^{\circ} 35^{\prime} 39.11$ | OBS I |
| S4210 | ..... |  | $6^{h} 38^{m} 39.91^{\text {d }}$ | $9^{\circ} 48^{\prime} 17.1$ | OBS12 |
| S4212 | W210 | .......... | $6^{h} 38^{\text {m }} 39.98^{\text {d }}$ | $9^{\circ} 29^{\prime} 18.11$ | OBS 1 |
| S4214 |  | .......... | $6^{h} 38^{m} 39.98{ }^{\text {m }}$ | $9^{\circ} 45^{\prime} 36 . \prime$ | OBS12 |
| S4220 |  | .......... | $6^{h} 38^{m} 40.15^{s}$ | $9^{\circ} 38^{\prime} 55.11$ | OBS 1 |
| S4229 |  | .......... | $6^{\text {h }} 38^{\mathrm{m}} 40.56^{\text {a }}$ | $9^{\circ} 46^{\prime} 58.11$ | OBS12 |
| S4236 |  |  | $6^{\text {h }} 38^{m} 40.70^{\text {a }}$ | $9^{\circ} 37^{\prime} 38.1$ " | OBS 1 |
| S4238 | W211 | ....... | $6^{h} 38^{m} 40.75^{\text {a }}$ | $9^{\circ} 39^{\prime} 35.11$ | OBS 1 |
| S4281 | ..... |  | $6^{h} 38^{\mathrm{m}} 41.95^{\text {a }}$ | $9^{\circ} 55^{\prime} 04.1$ | OBS 1 |
| S4282 | ..... | ......... | $6^{h} 38^{m} 41.98{ }^{\text {a }}$ | $9^{\circ} 26^{\prime} 50.11$ | OBS 1 |
| S4292 | ..... |  | $6^{h} 38^{m} 42.17^{\prime}$ | $9^{\circ} 33^{\prime} 08.11$ | OBS 1 |
| S4296 | ..... |  | $6^{h} 38^{m} 42.24^{\text {a }}$ | $9^{\circ} 38^{\prime} 01.11$ | OBS 1 |
| S4307 | ..... | .... | $6^{h} 38^{m} 42.46^{\text {a }}$ | $9^{\circ} 35^{\prime} 01.11$ | OBS 1 |
| S4314 | . $\cdot$. ${ }^{\text {a }}$ | ....... | $6^{h} 38^{m} 42.70^{\circ}$ | $9^{\circ} 34^{\prime} 50.11$ | OBS 1 |
| S4363 | ..... | . | $6^{\text {h }} 38^{m} 44.02^{\text {m }}$ | $9^{\circ} 29^{\prime} 06.1$ | OBS 1 |
| S4365 | W214 | .......... | $6^{h} 38^{m} 44.18^{\text {a }}$ | $9^{\circ} 42^{\prime} 31.11$ | OBS12 |
| S4392 | W213 | -••....... | $6^{h} 38^{m} 44.95{ }^{\text {a }}$ | $9^{\circ} 52^{\prime} 42.1$ | OBS 1 |
| S4433 | W217 | LkH ${ }^{72}$ | $6^{h} 38^{m} 46.37^{*}$ | $9^{\circ} 29^{\prime} 54.1$ " | OBS 1 |
| S4473 | ..... | .......... | $6^{h} 38^{m} 47.33^{*}$ | $9^{\circ} 30^{\prime} 59.1$ ' | OBS 1 |
| S4494 | W218 |  | $6^{h} 38^{m} 47.98^{\circ}$ | $9^{\circ} 46^{\prime} 31.11$ | OBS12 |
| S4508 | W219 |  | $6^{h} 38{ }^{m} 48.41^{\text {s }}$ | $9^{\circ} 43^{\prime} 08.11$ | OBS12 |
| S4675 | W223 |  | $6^{h} 388^{m} 52.44^{\prime}$ | $9^{\circ} 46^{\prime} 36.11$ | OBS12 |
| S4737 | W225 | . ${ }^{\text {c...... }}$ | $6^{h} 38{ }^{m} 54.05^{*}$ | $10^{\circ} 02^{\prime} 57.1$ ' | OBS 1 |

## ${ }^{4}$ Possibly a multiple source.

Note.-The source numbers and coordinates are listed for 346 stars selected from the 4900 stars in the the completed survey from Chapter 3. Where applicable, Walker designations and LkHa numbers are given for the stars. The last column notes whether the data result from first epoch of observations or a merging of data from both the first and second epochs of observations ("OBS 1' or "OBS12').

TABLE 5.4
Survey Photometric Data

| Source | $\underset{(\mathrm{mag})}{V}$ | $\begin{gathered} R \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} I \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} J \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} H \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} K \\ (\mathrm{mag}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S0131 | $11.87 \pm 0.01$ |  | $9.65 \pm 0.01$ | . $\cdot .$. | ............ | -........... |
| S0422 | $11.22 \pm 0.01$ | $10.60 \pm 0.01$ | $10.15 \pm 0.01$ |  |  |  |
| S0445 |  | $10.92 \pm 0.01$ | $10.69 \pm 0.01$ |  |  |  |
| S0710 |  | $15.72 \pm 0.01$ | ........... |  |  |  |
| S0921 | $11.69 \pm 0.00$ | $11.06 \pm 0.00$ | $10.86 \pm 0.00$ |  |  |  |
| S0967 | $14.52 \pm 0.00$ | $13.67 \pm 0.00$ | $12.97 \pm 0.00$ | $12.58 \pm 0.11$ |  |  |
| S1066 | 14.06 $\pm 0.02$ | $13.35 \pm 0.01$ | $12.91 \pm 0.02$ | $12.59 \pm 0.11$ | $12.27 \pm 0.17$ |  |
| S1117 | $13.31 \pm 0.01$ | 12.61 $\pm 0.01$ | $12.01 \pm 0.01$ | $11.66 \pm 0.11$ | $11.20 \pm 0.17$ |  |
| S1129 | $11.34 \pm 0.00$ | $11.97 \pm 0.00$ | $10.18 \pm 0.02$ | $10.14 \pm 0.11$ | $10.05 \pm 0.12$ |  |
| S1212 | $16.18 \pm 0.01$ | $15.43 \pm 0.01$ | $14.36 \pm 0.01$ | $13.25 \pm 0.11$ | $12.20 \pm 0.12$ | $11.70 \pm 0.10$ |
| S1270 | $15.23 \pm 0.02$ | $14.45 \pm 0.01$ | $13.97 \pm 0.02$ | $13.65 \pm 0.08$ | $13.12 \pm 0.17$ | $13.03 \pm 0.07$ |
| S1276 | 11.21 0.01 | $11.65 \pm 0.00$ |  | $8.51 \pm 0.06$ | $8.95 \pm 0.12$ | $7.59 \pm 0.10$ |
| S1309 |  | $18.91 \pm 0.09$ | $16.79 \pm 0.04$ | $15.23 \pm 0.08$ | $14.52 \pm 0.17$ | $14.36 \pm 0.11$ |
| S1315 | $15.73 \pm 0.00$ | $14.71 \pm 0.02$ | $13.72 \pm 0.01$ | 13.05 $\pm 0.11$ | $12.58 \pm 0.17$ | $12.28 \pm 0.07$ |
| S1316 | $16.81 \pm 0.01$ | $15.67 \pm 0.02$ | $14.50 \pm 0.01$ | $13.15 \pm 0.08$ | $12.91 \pm 0.12$ | $12.65 \pm 0.10$ |
| S1364 | $18.17 \pm 0.03$ | $16.94 \pm 0.03$ | $15.23 \pm 0.01$ | $14.07 \pm 0.08$ | $13.42 \pm 0.12$ | $13.20 \pm 0.10$ |
| S1369 | $14.86 \pm 0.00$ | $13.82 \pm 0.01$ | $12.81 \pm 0.01$ | $11.82 \pm 0.08$ | $11.19 \pm 0.12$ | $11.02 \pm 0.07$ |
| S1382 | $17.65 \pm 0.02$ | $16.49 \pm 0.03$ | $15.21 \pm 0.02$ | $14.22 \pm 0.08$ | $13.69 \pm 0.17$ | $13.31 \pm 0.10$ |
| S1389 | 15.36士0.00 | $14.59 \pm 0.01$ | $14.00 \pm 0.01$ | $13.63 \pm 0.08$ | $13.28 \pm 0.17$ | 12.93士0.10 |
| S1407 | $18.89 \pm 0.05$ | 17.77 $\pm 0.09$ | $16.27 \pm 0.02$ | $15.15 \pm 0.06$ | $15.10 \pm 0.15$ | 14.57 $\pm 0.15$ |
| S1447 | $17.92 \pm 0.02$ | $16.68 \pm 0.02$ | $15.17 \pm 0.01$ | $14.21 \pm 0.08$ | $13.56 \pm 0.17$ | $13.34 \pm 0.07$ |
| S1478 | $10.85 \pm 0.04$ | $11.59 \pm 0.00$ | $9.95 \pm 0.00$ | $8.60 \pm 0.08$ | $8.79 \pm 0.17$ | $8.45 \pm 0.07$ |
| S1499 | $13.10 \pm 0.00$ | $13.77 \pm 0.02$ | $13.73 \pm 0.00$ | 12.94 $\pm 0.11$ | $12.35 \pm 0.17$ | $12.08 \pm 0.05$ |
| S1500 | $16.03 \pm 0.01$ | $14.97 \pm 0.02$ | $13.77 \pm 0.01$ | $12.81 \pm 0.08$ | $12.21 \pm 0.17$ | $11.89 \pm 0.05$ |
| S1513 | $15.68 \pm 0.00$ | $14.60 \pm 0.02$ | $13.51 \pm 0.00$ | $12.89 \pm 0.08$ | $12.35 \pm 0.17$ | $12.02 \pm 0.07$ |
| S1518 | $17.59 \pm 0.01$ | 16.36 $\pm 0.02$ | $14.78 \pm 0.01$ | $13.69 \pm 0.08$ | $13.09 \pm 0.17$ | $12.84 \pm 0.05$ |
| S1529 | $17.72 \pm 0.02$ | $16.84 \pm 0.01$ | $15.05 \pm 0.01$ | $13.90 \pm 0.11$ | $13.29 \pm 0.17$ | $13.00 \pm 0.10$ |
| S1562 | ........... | $13.49 \pm 0.01$ | $12.69 \pm 0.00$ | $12.35 \pm 0.11$ | $11.70 \pm 0.17$ | $11.46 \pm 0.06$ |
| S1566 | $16.41 \pm 0.01$ | $15.86 \pm 0.03$ | $14.78 \pm 0.01$ | $13.50 \pm 0.11$ | $12.62 \pm 0.12$ | $12.45 \pm 0.06$ |
| S1590 | $18.82 \pm 0.06$ | $17.58 \pm 0.07$ | $16.20 \pm 0.04$ | $15.12 \pm 0.11$ | $14.57 \pm 0.17$ | $14.59 \pm 0.09$ |
| S1598 | $17.44 \pm 0.02$ | $16.01 \pm 0.01$ | $14.06 \pm 0.00$ | $12.63 \pm 0.08$ | $11.62 \pm 0.12$ | $11.14 \pm 0.07$ |
| S1606 | $15.37 \pm 0.01$ | $14.72 \pm 0.01$ | $13.47 \pm 0.01$ | $13.01 \pm 0.06$ | 12.56 $\pm 0.17$ | $12.06 \pm 0.10$ |
| S1621 | ............ | ............ | , | $13.59 \pm 0.11$ | $11.62 \pm 0.12$ | $10.47 \pm 0.06$ |
| S1629 | $15.70 \pm 0.01$ | $14.60 \pm 0.02$ | $12.66 \pm 0.01$ | $12.12 \pm 0.08$ |  | $10.63 \pm 0.07$ |
| S1637 | $15.88 \pm 0.01$ | $13.99 \pm 0.02$ | $12.23 \pm 0.01$ | $10.22 \pm 0.08$ | $9.22 \pm 0.12$ | $8.52 \pm 0.10$ |
| S1645 | $15.34 \pm 0.01$ | $14.25 \pm 0.01$ | $13.20 \pm 0.00$ | $12.12 \pm 0.08$ | $11.59 \pm 0.12$ | $11.53 \pm 0.07$ |
| S1648 | $15.61 \pm 0.00$ | $14.47 \pm 0.01$ | $13.55 \pm 0.00$ | $12.91 \pm 0.08$ | $12.52 \pm 0.17$ | 12.07 $\pm 0.07$ |
| S1665 | $15.30 \pm 0.00$ | $13.98 \pm 0.00$ | $13.21 \pm 0.00$ | $12.49 \pm 0.08$ | $12.11 \pm 0.12$ | $11.75 \pm 0.10$ |
| S1675 | $17.06 \pm 0.02$ | $15.89 \pm 0.01$ | $14.20 \pm 0.01$ | $13.21 \pm 0.08$ | $12.15 \pm 0.17$ | $12.28 \pm 0.07$ |
| S1702 | $15.81 \pm 0.00$ | $14.71 \pm 0.00$ | $13.34 \pm 0.00$ | $12.56 \pm 0.08$ | $12.05 \pm 0.12$ | $11.73 \pm 0.05$ |
| S1734 | $17.59 \pm 0.02$ | $16.55 \pm 0.02$ | $14.88 \pm 0.01$ | $14.05 \pm 0.06$ | $13.42 \pm 0.12$ | $13.21 \pm 0.07$ |
| S1758 | 18.22 $\pm 0.04$ | $17.00 \pm 0.03$ | $15.45 \pm 0.02$ | $14.30 \pm 0.08$ | $13.77 \pm 0.12$ | $13.62 \pm 0.05$ |
| S1760 | $17.34 \pm 0.01$ | $15.98 \pm 0.01$ | $14.27 \pm 0.00$ | 13.36 $\pm 0.08$ | $12.67 \pm 0.12$ | $12.28 \pm 0.07$ |
| S1769 | 14.98 $\pm 0.01$ | $14.22 \pm 0.01$ | $13.51 \pm 0.01$ | $12.99 \pm 0.08$ | $12.71 \pm 0.12$ | $12.55 \pm 0.07$ |
| S1776 | ........... | $11.81 \pm 0.00$ | $11.34 \pm 0.00$ | $11.50 \pm 0.06$ | $11.33 \pm 0.17$ | $11.14 \pm 0.06$ |
| S1796 | $18.35 \pm 0.02$ | $17.25 \pm 0.02$ | $15.68 \pm 0.01$ | $15.04 \pm 0.08$ | $14.31 \pm 0.12$ | $14.10 \pm 0.07$ |
| S1804 | $14.72 \pm 0.00$ | $14.00 \pm 0.01$ | $13.32 \pm 0.00$ | $13.15 \pm 0.08$ | $12.83 \pm 0.12$ | $12.67 \pm 0.07$ |
| S1806 | $15.35 \pm 0.00$ | $14.50 \pm 0.00$ | $13.75 \pm 0.00$ | ............ | ............ | ............ |
| S1820 | $17.39 \pm 0.02$ | $16.13 \pm 0.02$ | $14.56 \pm 0.01$ | $13.45 \pm 0.08$ | $13.08 \pm 0.17$ | $12.56 \pm 0.10$ |
| S1829 | $11.99 \pm 0.00$ | ............ | $10.91 \pm 0.00$ | ............. | ............ | ........... |
| S1896 | $16.50 \pm 0.01$ | $15.19 \pm 0.00$ | $13.90 \pm 0.01$ | $12.59 \pm 0.08$ | $11.88 \pm 0.17$ | $11.15 \pm 0.07$ |
| S1898 | $15.79 \pm 0.01$ | $14.71 \pm 0.02$ | $13.63 \pm 0.00$ | $13.04 \pm 0.11$ | $12.60 \pm 0.17$ | $12.29 \pm 0.05$ |

TABLE 5．4－Continued

| Source | $\underset{(\mathrm{mag})}{V}$ | $\begin{gathered} R \\ (\mathrm{mag}) \end{gathered}$ | $\underset{(\mathrm{mag})}{I}$ | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} K \\ (\mathrm{mag}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S1901 | $12.56 \pm 0.01$ | $11.90 \pm 0.01$ | $10.72 \pm 0.01$ | $9.55 \pm 0.11$ | $9.26 \pm 0.17$ | $8.53 \pm 0.05$ |
| S1932 | $17.76 \pm 0.02$ | $16.31 \pm 0.02$ | $14.73 \pm 0.01$ | $13.82 \pm 0.08$ | $13.12 \pm 0.17$ | $12.64 \pm 0.07$ |
| S1937 | $17.05 \pm 0.03$ | $15.55 \pm 0.02$ | $15.45 \pm 0.03$ | $13.77 \pm 0.08$ | $13.61 \pm 0.17$ | $13.00 \pm 0.05$ |
| S1939 | $11.61 \pm 0.00$ | $11.89 \pm 0.00$ |  | $8.49 \pm 0.08$ | $8.58 \pm 0.17$ | $7.63 \pm 0.05$ |
| S1947 | $12.11 \pm 0.00$ |  |  | $10.43 \pm 0.11$ | $10.18 \pm 0.17$ |  |
| S1950 |  |  | $9.56 \pm 0.01$ | $7.70 \pm 0.06$ | $7.64 \pm 0.17$ | $6.32 \pm 0.05$ |
| S1960 | $11.56 \pm 0.00$ |  |  | $10.30 \pm 0.11$ | $9.99 \pm 0.12$ | $9.86 \pm 0.06$ |
| S1973 | $16.83 \pm 0.01$ | $15.72 \pm 0.02$ | $14.56 \pm 0.01$ | $14.03 \pm 0.11$ | $13.40 \pm 0.12$ | $12.99 \pm 0.06$ |
| S1976 | $17.37 \pm 0.02$ | $16.04 \pm 0.02$ | $14.73 \pm 0.01$ | $13.40 \pm 0.08$ | $12.97 \pm 0.12$ | $12.54 \pm 0.07$ |
| S1996 | $16.84 \pm 0.01$ | $15.54 \pm 0.01$ | $14.06 \pm 0.01$ | $12.65 \pm 0.11$ | $12.13 \pm 0.12$ | $11.81 \pm 0.06$ |
| S2006 |  |  | $9.93 \pm 0.00$ |  |  |  |
| S2007 | $18.06 \pm 0.04$ | $16.82 \pm 0.02$ | $15.21 \pm 0.01$ | $14.50 \pm 0.11$ | $14.03 \pm 0.12$ | $13.65 \pm 0.07$ |
| S2008 | $17.41 \pm 0.01$ | $16.18 \pm 0.01$ | $14.90 \pm 0.01$ | $14.28 \pm 0.08$ | $13.48 \pm 0.12$ | $13.36 \pm 0.07$ |
| S2009 | $11.39 \pm 0.00$ | $10.06 \pm 0.00$ |  | $8.78 \pm 0.06$ | $8.92 \pm 0.12$ | $8.61 \pm 0.06$ |
| S2022 | $17.43 \pm 0.02$ | $16.19 \pm 0.01$ | $14.76 \pm 0.01$ | $13.93 \pm 0.08$ | 13．26 $\pm 0.12$ | $12.87 \pm 0.07$ |
| S2038 | $17.39 \pm 0.01$ | $16.17 \pm 0.01$ | $14.35 \pm 0.01$ | $13.29 \pm 0.08$ | 12．77 $\pm 0.12$ | $12.45 \pm 0.06$ |
| S2055 | $16.37 \pm 0.02$ | $15.21 \pm 0.01$ | $14.10 \pm 0.01$ | $13.34 \pm 0.11$ | $12.56 \pm 0.12$ | $12.40 \pm 0.07$ |
| S2068 | $14.38 \pm 0.00$ | $13.49 \pm 0.02$ | $12.81 \pm 0.00$ | 12．59 $\pm 0.08$ | $12.23 \pm 0.12$ | $12.15 \pm 0.06$ |
| S2079 | $17.97 \pm 0.03$ | $16.56 \pm 0.03$ | $15.57 \pm 0.02$ | $12.42 \pm 0.08$ | 11．54土 0.12 | $9.60 \pm 0.07$ |
| S2104 | $17.48 \pm 0.02$ | $16.71 \pm 0.01$ | $15.26 \pm 0.01$ | $14.73 \pm 0.08$ | $14.24 \pm 0.12$ | $14.00 \pm 0.06$ |
| S2113 | $14.60 \pm 0.01$ | $13.66 \pm 0.01$ | $12.84 \pm 0.01$ | $12.10 \pm 0.11$ | $11.55 \pm 0.12$ | $11.20 \pm 0.10$ |
| S2116 | $15.39 \pm 0.00$ | $14.11 \pm 0.00$ | $12.54 \pm 0.00$ | $11.50 \pm 0.08$ | $10.69 \pm 0.12$ | $10.54 \pm 0.07$ |
| S2117 | $17.44 \pm 0.02$ | $16.22 \pm 0.01$ | $14.77 \pm 0.01$ | $13.81 \pm 0.08$ | $13.14 \pm 0.17$ | $13.06 \pm 0.07$ |
| S2146 | $15.88 \pm 0.01$ | $14.72 \pm 0.02$ | $13.68 \pm 0.01$ | $12.89 \pm 0.08$ | $12.31 \pm 0.12$ | $12.04 \pm 0.07$ |
| S2162 | $16.06 \pm 0.01$ | 14．97士0．00 | $13.51 \pm 0.00$ | $12.66 \pm 0.08$ | $11.87 \pm 0.12$ | $11.36 \pm 0.07$ |
| S2163 | $13.74 \pm 0.00$ | $12.86 \pm 0.01$ | $12.10 \pm 0.00$ | $11.59 \pm 0.08$ | $10.85 \pm 0.12$ |  |
| S2167 | 17．93士0．04 | $16.47 \pm 0.01$ | $14.73 \pm 0.01$ | $13.43 \pm 0.08$ | $12.95 \pm 0.12$ | $12.85 \pm 0.05$ |
| S2171 | $15.59 \pm 0.00$ | $14.47 \pm 0.02$ | $13.46 \pm 0.00$ | $12.78 \pm 0.08$ | $12.28 \pm 0.12$ | $11.95 \pm 0.06$ |
| S2173 | $16.52 \pm 0.01$ | $15.40 \pm 0.01$ | $14.54 \pm 0.01$ | $13.46 \pm 0.08$ | $12.86 \pm 0.17$ | $11.62 \pm 0.06$ |
| S2190 | 16．37 $\pm 0.01$ | $15.15 \pm 0.01$ | $13.96 \pm 0.00$ | $13.41 \pm 0.11$ | $12.57 \pm 0.12$ | $12.33 \pm 0.07$ |
| S2191 | $15.70 \pm 0.00$ | $14.60 \pm 0.00$ | $13.09 \pm 0.00$ | $11.69 \pm 0.08$ | $11.18 \pm 0.12$ | $10.76 \pm 0.06$ |
| S2228 | $15.90 \pm 0.01$ | $15.00 \pm 0.01$ | $13.67 \pm 0.01$ | $12.90 \pm 0.08$ | $11.89 \pm 0.17$ | $11.84 \pm 0.10$ |
| S2230 | $15.98 \pm 0.02$ | $15.15 \pm 0.01$ | $14.17 \pm 0.01$ | $13.65 \pm 0.06$ | $13.24 \pm 0.12$ | $12.94 \pm 0.10$ |
| S2234 |  |  | $10.92 \pm 0.00$ | $10.73 \pm 0.08$ | $10.18 \pm 0.12$ | $9.79 \pm 0.06$ |
| S2253 | $15.18 \pm 0.01$ | $14.23 \pm 0.00$ | $13.42 \pm 0.00$ | $13.11 \pm 0.08$ | $12.54 \pm 0.17$ | $12.32 \pm 0.07$ |
| S2268 | $16.56 \pm 0.01$ | $15.55 \pm 0.01$ | $15.09 \pm 0.01$ | $13.47 \pm 0.08$ | $12.71 \pm 0.12$ | $12.35 \pm 0.07$ |
| S2279 | $14.21 \pm 0.02$ | $13.61 \pm 0.01$ | $13.08 \pm 0.01$ | $12.92 \pm 0.08$ | $12.71 \pm 0.17$ | $12.64 \pm 0.07$ |
| S2280 | $15.71 \pm 0.02$ | $14.74 \pm 0.01$ | $13.55 \pm 0.01$ | $12.71 \pm 0.08$ | $11.97 \pm 0.12$ | $11.77 \pm 0.10$ |
| S2284 | $15.02 \pm 0.01$ | $13.98 \pm 0.00$ | $13.23 \pm 0.00$ | $12.56 \pm 0.08$ | $11.81 \pm 0.12$ | $11.81 \pm 0.10$ |
| S2289 | $11.23 \pm 0.01$ | $11.58 \pm 0.00$ | ．．．．．．．．．．．． | $9.16 \pm 0.08$ | $8.97 \pm 0.09$ | $8.94 \pm 0.10$ |
| S2313 | $16.65 \pm 0.01$ | $15.53 \pm 0.01$ | $14.10 \pm 0.01$ | $13.16 \pm 0.08$ | $12.60 \pm 0.17$ | $12.24 \pm 0.06$ |
| S2322 | $17.13 \pm 0.02$ | $15.90 \pm 0.01$ | $14.39 \pm 0.00$ | $13.53 \pm 0.08$ | $12.98 \pm 0.17$ | $12.60 \pm 0.06$ |
| S2325 |  | $18.35 \pm 0.06$ | $16.36 \pm 0.04$ | $14.72 \pm 0.08$ | $14.52 \pm 0.17$ | $13.58 \pm 0.10$ |
| S2359 | $15.25 \pm 0.02$ | 14．37士0．01 | $13.68 \pm 0.02$ | $13.02 \pm 0.08$ | $12.57 \pm 0.17$ | $12.52 \pm 0.05$ |
| S2364 | $12.79 \pm 0.02$ | $12.47 \pm 0.01$ | $12.05 \pm 0.02$ | $11.37 \pm 0.11$ | $10.43 \pm 0.17$ | $9.33 \pm 0.07$ |
| S2374 | $16.82 \pm 0.01$ | $15.91 \pm 0.01$ | $15.02 \pm 0.02$ | $14.17 \pm 0.08$ | $13.68 \pm 0.17$ | $13.55 \pm 0.07$ |
| S2377 | $14.89 \pm 0.02$ | $14.15 \pm 0.01$ | $13.50 \pm 0.02$ | $13.10 \pm 0.08$ | $12.71 \pm 0.17$ | $12.59 \pm 0.05$ |
| S2387 | $17.72 \pm 0.03$ | $16.43 \pm 0.01$ | $15.00 \pm 0.01$ | $14.03 \pm 0.08$ | $13.53 \pm 0.17$ | $13.18 \pm 0.06$ |
| S2390 | $15.93 \pm 0.01$ | $15.41 \pm 0.01$ | $14.13 \pm 0.01$ | $13.09 \pm 0.11$ | $12.54 \pm 0.17$ | $12.24 \pm 0.05$ |
| S2395 | $17.05 \pm 0.01$ | $15.99 \pm 0.01$ | $15.23 \pm 0.02$ | $14.64 \pm 0.11$ | $14.13 \pm 0.17$ | $13.80 \pm 0.07$ |
| S2405 | $14.69 \pm 0.01$ | $13.95 \pm 0.01$ | $13.29 \pm 0.01$ | $12.85 \pm 0.08$ | $12.54 \pm 0.17$ | $12.32 \pm 0.05$ |
| S2418 | $14.18 \pm 0.01$ | $13.23 \pm 0.01$ | $13.08 \pm 0.02$ | $12.18 \pm 0.08$ | $11.54 \pm 0.12$ | $11.10 \pm 0.05$ |

TABLE 5．4－Continued

| Source | $\begin{gathered} V \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} R \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} I \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} J \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} H \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} K \\ (\mathrm{mag}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S2424 | $17.54 \pm 0.02$ | $16.38 \pm 0.01$ | $15.37 \pm 0.02$ | $14.53 \pm 0.11$ | $14.09 \pm 0.17$ | $13.76 \pm 0.06$ |
| S2448 | $11.87 \pm 0.00$ |  | $10.56 \pm 0.01$ | $10.30 \pm 0.08$ | $9.55 \pm 0.12$ | $9.48 \pm 0.06$ |
| S2449 | $17.58 \pm 0.04$ | $16.28 \pm 0.01$ | $14.86 \pm 0.02$ | $13.75 \pm 0.08$ | $13.03 \pm 0.12$ | $12.97 \pm 0.06$ |
| S2495 | $13.32 \pm 0.02$ | $13.04 \pm 0.00$ | $12.08 \pm 0.02$ | $11.92 \pm 0.06$ | $11.60 \pm 0.12$ | $11.32 \pm 0.10$ |
| S2506 | $17.39 \pm 0.02$ | $16.04 \pm 0.02$ | $14.77 \pm 0.02$ | $13.70 \pm 0.08$ | $13.14 \pm 0.12$ | $12.52 \pm 0.10$ |
| S2510 | $15.59 \pm 0.00$ | $14.41 \pm 0.00$ | $13.26 \pm 0.01$ | $12.30 \pm 0.11$ | $11.70 \pm 0.12$ | $11.48 \pm 0.10$ |
| S2514 | $15.95 \pm 0.01$ | $14.84 \pm 0.01$ | $13.66 \pm 0.01$ | $12.82 \pm 0.08$ | $12.11 \pm 0.12$ | $11.93 \pm 0.10$ |
| S2515 | $16.04 \pm 0.01$ | $14.89 \pm 0.00$ | $13.77 \pm 0.01$ | $12.96 \pm 0.08$ | $11.96 \pm 0.12$ | $11.81 \pm 0.07$ |
| S2521 | $13.98 \pm 0.01$ | $13.03 \pm 0.00$ | $12.25 \pm 0.01$ | $11.71 \pm 0.08$ | $10.88 \pm 0.12$ | 10．14 $\pm 0.07$ |
| S2525 | $12.30 \pm 0.01$ | $11.58 \pm 0.01$ | $11.09 \pm 0.02$ | $10.71 \pm 0.08$ | $10.43 \pm 0.12$ | $10.24 \pm 0.06$ |
| S2534 |  | $18.70 \pm 0.09$ | $16.58 \pm 0.07$ | $14.93 \pm 0.08$ | $14.36 \pm 0.17$ | $14.15 \pm 0.07$ |
| S2563 | $16.43 \pm 0.01$ | $15.45 \pm 0.02$ | $14.64 \pm 0.01$ | $13.62 \pm 0.08$ | $12.31 \pm 0.12$ | $11.63 \pm 0.05$ |
| S2565 | $16.59 \pm 0.01$ | $15.41 \pm 0.01$ | $14.02 \pm 0.01$ | $12.94 \pm 0.08$ | $12.37 \pm 0.17$ | $11.96 \pm 0.07$ |
| S2566 | $17.97 \pm 0.03$ | $16.63 \pm 0.01$ | $14.94 \pm 0.01$ | $13.74 \pm 0.08$ | $13.15 \pm 0.12$ | $13.05 \pm 0.07$ |
| S2569 | $11.62 \pm 0.00$ |  | $10.24 \pm 0.02$ | $9.93 \pm 0.08$ | $9.74 \pm 0.12$ | $9.85 \pm 0.05$ |
| S2579 | ．．．． |  | $9.97 \pm 0.01$ | $9.54 \pm 0.08$ | $9.21 \pm 0.12$ | $8.48 \pm 0.06$ |
| S2586 | $16.94 \pm 0.01$ | $15.72 \pm 0.01$ | $14.57 \pm 0.01$ | $13.74 \pm 0.06$ | $13.13 \pm 0.12$ | $12.82 \pm 0.05$ |
| S2593 | $16.11 \pm 0.01$ | $14.98 \pm 0.00$ | $13.92 \pm 0.01$ | $13.23 \pm 0.08$ | $12.49 \pm 0.12$ | $12.30 \pm 0.05$ |
| S2612 | $11.67 \pm 0.01$ | $11.17 \pm 0.01$ | $10.84 \pm 0.02$ | $11.05 \pm 0.06$ | $10.81 \pm 0.12$ | ．．． |
| S2634 | $16.17 \pm 0.02$ | $14.93 \pm 0.02$ | $13.90 \pm 0.02$ | $12.99 \pm 0.08$ | $12.35 \pm 0.12$ | $12.06 \pm 0.06$ |
| S2636 | $16.80 \pm 0.02$ | 15．37 $\pm 0.02$ | $13.49 \pm 0.02$ | $12.19 \pm 0.08$ | $11.67 \pm 0.12$ | $11.38 \pm 0.05$ |
| S2644 | $18.14 \pm 0.05$ | $16.77 \pm 0.03$ | $14.74 \pm 0.02$ | $13.54 \pm 0.08$ | $13.01 \pm 0.12$ | 12．57士0．07 |
| S2652 | $15.24 \pm 0.00$ | 14．27 $\pm 0.01$ | $13.41 \pm 0.01$ | $12.40 \pm 0.08$ | $11.63 \pm 0.17$ | $11.14 \pm 0.05$ |
| S2659 | ．．．．．．．．．．．． | $18.93 \pm 0.10$ | $16.70 \pm 0.05$ | $15.22 \pm 0.08$ | $14.40 \pm 0.17$ | $14.41 \pm 0.09$ |
| S2662 | $13.21 \pm 0.00$ | $12.60 \pm 0.01$ | $12.08 \pm 0.01$ | $11.74 \pm 0.08$ | $11.40 \pm 0.12$ | $11.29 \pm 0.07$ |
| S2664 | $14.74 \pm 0.00$ | $13.86 \pm 0.02$ | $13.17 \pm 0.01$ | $12.80 \pm 0.08$ | $12.23 \pm 0.12$ | $12.09 \pm 0.10$ |
| S2666 | $14.97 \pm 0.00$ | $14.03 \pm 0.01$ | $14.03 \pm 0.01$ | $12.38 \pm 0.08$ | $11.74 \pm 0.12$ |  |
| S2716 | $12.13 \pm 0.00$ | $12.30 \pm 0.00$ | $10.98 \pm 0.00$ | $10.61 \pm 0.08$ | $10.01 \pm 0.12$ | $9.61 \pm 0.07$ |
| S2743 | $14.38 \pm 0.00$ | $13.98 \pm 0.01$ | $12.85 \pm 0.00$ | $12.15 \pm 0.11$ | $11.44 \pm 0.17$ | $11.00 \pm 0.06$ |
| S2753 | $15.96 \pm 0.02$ | $14.88 \pm 0.02$ | $14.00 \pm 0.01$ | $13.02 \pm 0.08$ | $12.37 \pm 0.17$ | $11.76 \pm 0.07$ |
| S2756 | $16.17 \pm 0.02$ | $15.03 \pm 0.01$ | $13.96 \pm 0.01$ | $13.15 \pm 0.08$ | $12.41 \pm 0.17$ | $12.19 \pm 0.10$ |
| S2760 | ．．．．．．．．．．． | $10.91 \pm 0.00$ |  | $10.87 \pm 0.08$ | $10.89 \pm 0.17$ | $10.90 \pm 0.06$ |
| S2761 | $16.18 \pm 0.01$ | 15．31 $\pm 0.02$ | $13.62 \pm 0.00$ | $12.50 \pm 0.11$ | $11.84 \pm 0.17$ | $11.65 \pm 0.07$ |
| S2763 | $15.94 \pm 0.00$ | $15.35 \pm 0.01$ | $14.83 \pm 0.01$ | $14.52 \pm 0.08$ | $13.81 \pm 0.17$ | $13.02 \pm 0.06$ |
| S2764 | $17.34 \pm 0.03$ | $16.11 \pm 0.02$ | $14.73 \pm 0.01$ | 13．76土0．08 | $12.99 \pm 0.17$ | $12.70 \pm 0.10$ |
| S2777 | $16.14 \pm 0.01$ | $14.96 \pm 0.01$ | $13.61 \pm 0.01$ | 12．76 $\pm 0.08$ | $12.16 \pm 0.17$ | $11.79 \pm 0.07$ |
| S2809 | $15.43 \pm 0.00$ | 14．69 ${ }^{\text {土 }} 0.02$ | $13.38 \pm 0.00$ | $12.29 \pm 0.11$ | $11.79 \pm 0.17$ | $11.23 \pm 0.07$ |
| S2827 | $19.13 \pm 0.10$ | 17．67 $\pm 0.05$ | $15.51 \pm 0.01$ | $13.95 \pm 0.11$ | $13.48 \pm 0.17$ | $12.83 \pm 0.10$ |
| S2843 | $14.64 \pm 0.00$ | $13.77 \pm 0.01$ | $12.93 \pm 0.00$ | $12.15 \pm 0.11$ | $11.98 \pm 0.17$ | $11.33 \pm 0.06$ |
| S2854 | $11.92 \pm 0.02$ | $11.24 \pm 0.01$ | $10.72 \pm 0.00$ | $10.47 \pm 0.08$ | $10.44 \pm 0.17$ | $10.23 \pm 0.05$ |
| S2861 | $15.56 \pm 0.00$ | $14.38 \pm 0.01$ | $13.19 \pm 0.00$ | $12.41 \pm 0.08$ | 11．87 $\pm 0.12$ | $11.67 \pm 0.07$ |
| S2862 | $13.60 \pm 0.01$ | $12.97 \pm 0.02$ | $12.39 \pm 0.01$ | $11.91 \pm 0.08$ | $11.62 \pm 0.12$ | $11.38 \pm 0.05$ |
| S2892 |  | $11.30 \pm 0.01$ | $10.76 \pm 0.00$ | $10.47 \pm 0.11$ | $10.57 \pm 0.12$ |  |
| S2898 | $15.79 \pm 0.00$ | $14.75 \pm 0.01$ | $13.70 \pm 0.00$ | $12.97 \pm 0.08$ | $12.38 \pm 0.12$ | $12.20 \pm 0.10$ |
| S2920 | $15.56 \pm 0.00$ | $14.49 \pm 0.01$ | $13.48 \pm 0.00$ | $12.74 \pm 0.08$ | 12．19 $\pm 0.12$ | $11.89 \pm 0.07$ |
| S2926 | $14.31 \pm 0.00$ | $13.11 \pm 0.01$ | $12.05 \pm 0.00$ | $11.26 \pm 0.08$ | $10.69 \pm 0.12$ | $10.58 \pm 0.10$ |
| S2943 | $15.55 \pm 0.00$ | $14.33 \pm 0.01$ | $13.58 \pm 0.00$ | $11.96 \pm 0.06$ | $10.76 \pm 0.12$ | $9.87 \pm 0.10$ |
| S2944 | $12.49 \pm 0.00$ | $11.88 \pm 0.01$ | $11.07 \pm 0.00$ | $10.88 \pm 0.08$ | $10.26 \pm 0.12$ | ．．．．．．．．．．．． |
| S2945 | $17.35 \pm 0.01$ | $16.63 \pm 0.01$ | $14.49 \pm 0.01$ | $13.34 \pm 0.06$ | $12.58 \pm 0.12$ | $12.05 \pm 0.06$ |
| S2958 | $16.49 \pm 0.01$ | $15.36 \pm 0.01$ | $14.19 \pm 0.01$ | $12.89 \pm 0.08$ | $12.00 \pm 0.12$ | $11.34 \pm 0.06$ |
| S2969 | $16.65 \pm 0.01$ | 15．81 $\pm 0.01$ | $14.93 \pm 0.01$ | $14.47 \pm 0.06$ | $13.91 \pm 0.12$ | $13.66 \pm 0.05$ |
| S2971 | $17.70 \pm 0.03$ | $16.43 \pm 0.01$ | $14.86 \pm 0.01$ | $13.86 \pm 0.08$ | $13.38 \pm 0.12$ | $13.03 \pm 0.07$ |

TABLE 5.4-Continued

| Source | $\underset{(\mathrm{mag})}{V}$ | $\begin{gathered} R \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} I \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} J \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} H \\ (\operatorname{mag}) \end{gathered}$ | $\begin{gathered} K \\ (\mathrm{mag}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S2984 | $12.43 \pm 0.00$ | $11.44 \pm 0.00$ | $11.20 \pm 0.00$ | $11.16 \pm 0.08$ | $10.92 \pm 0.12$ | $10.85 \pm 0.05$ |
| S2989 | $15.31 \pm 0.00$ | $14.12 \pm 0.00$ | $13.06 \pm 0.00$ | $12.08 \pm 0.08$ | $11.45 \pm 0.12$ | $11.30 \pm 0.06$ |
| S2993 | $15.97 \pm 0.01$ | $14.67 \pm 0.01$ | $13.06 \pm 0.00$ | $12.00 \pm 0.08$ | $11.33 \pm 0.12$ | $11.11 \pm 0.07$ |
| S3031 | $16.98 \pm 0.02$ | $15.74 \pm 0.01$ | $14.12 \pm 0.00$ | $13.01 \pm 0.08$ | $12.26 \pm 0.12$ | $11.94 \pm 0.07$ |
| S3044 | $16.25 \pm 0.01$ | $15.07 \pm 0.02$ | 14.20 $\pm 0.01$ | $12.68 \pm 0.08$ | $11.91 \pm 0.12$ | $11.22 \pm 0.07$ |
| S3048 | $12.35 \pm 0.14$ | $11.50 \pm 0.14$ | $14.74 \pm 0.01$ | $13.32 \pm 0.08$ | $13.05 \pm 0.12$ | $12.78 \pm 0.05$ |
| S3052 | $16.64 \pm 0.01$ | $15.37 \pm 0.01$ | $14.01 \pm 0.00$ | $12.74 \pm 0.08$ | $12.03 \pm 0.12$ | $11.78 \pm 0.05$ |
| S3077 | $19.57 \pm 0.10$ | $18.56 \pm 0.08$ | $16.64 \pm 0.04$ | $15.41 \pm 0.08$ | $15.44 \pm 0.30$ | $14.44 \pm 0.14$ |
| S3102 | $16.15 \pm 0.01$ | $15.34 \pm 0.01$ | $13.88 \pm 0.00$ | $13.30 \pm 0.08$ | $12.59 \pm 0.12$ | $12.34 \pm 0.07$ |
| S3108 |  |  | $10.18 \pm 0.00$ | $10.25 \pm 0.08$ | $10.23 \pm 0.12$ | $10.11 \pm 0.07$ |
| S3110 | ............ | $16.76 \pm 0.02$ | $14.83 \pm 0.01$ | $13.47 \pm 0.08$ | $12.90 \pm 0.17$ | $12.68 \pm 0.07$ |
| S3122 | $17.09 \pm 0.01$ | $16.01 \pm 0.01$ | $14.59 \pm 0.01$ | $13.69 \pm 0.08$ | $13.13 \pm 0.12$ | $12.67 \pm 0.10$ |
| S3135 | $13.98 \pm 0.01$ | $12.87 \pm 0.00$ | $12.32 \pm 0.00$ | $11.49 \pm 0.08$ | $10.80 \pm 0.17$ | $10.32 \pm 0.06$ |
| S3141 | $16.94 \pm 0.01$ | $15.66 \pm 0.01$ | $14.01 \pm 0.01$ | $12.97 \pm 0.08$ | $12.44 \pm 0.17$ | $11.96 \pm 0.07$ |
| S3160 | $16.32 \pm 0.01$ | $15.43 \pm 0.01$ | $14.50 \pm 0.01$ | $13.14 \pm 0.08$ | $12.09 \pm 0.17$ | $11.34 \pm 0.07$ |
| S3170 | $16.77 \pm 0.01$ | $15.61 \pm 0.01$ | $14.23 \pm 0.00$ | $13.39 \pm 0.08$ | $12.91 \pm 0.17$ | $12.65 \pm 0.10$ |
| S3171 | $15.35 \pm 0.01$ | $14.09 \pm 0.01$ | $12.83 \pm 0.01$ | $11.46 \pm 0.08$ | $10.79 \pm 0.17$ | $10.17 \pm 0.10$ |
| S3174 | $17.07 \pm 0.01$ | $15.80 \pm 0.01$ | $14.19 \pm 0.01$ | $13.23 \pm 0.08$ | $12.52 \pm 0.17$ | $12.05 \pm 0.07$ |
| S3184 | $11.24 \pm 0.00$ | ............ |  | $10.21 \pm 0.08$ | $10.01 \pm 0.17$ | $9.93 \pm 0.10$ |
| S3197 | $15.90 \pm 0.01$ | $14.91 \pm 0.01$ | 13.73 $\pm 0.01$ | $13.00 \pm 0.08$ | $12.57 \pm 0.17$ | $12.30 \pm 0.05$ |
| S3205 | $15.41 \pm 0.00$ | $14.73 \pm 0.02$ | $13.47 \pm 0.00$ | $12.65 \pm 0.11$ | $12.34 \pm 0.17$ | $11.76 \pm 0.07$ |
| S3214 | $14.67 \pm 0.00$ | $13.67 \pm 0.00$ | $12.75 \pm 0.00$ | $11.97 \pm 0.11$ | $11.53 \pm 0.17$ | $11.29 \pm 0.06$ |
| S3221 | $14.98 \pm 0.01$ | $13.82 \pm 0.01$ | $12.90 \pm 0.01$ | $13.06 \pm 0.08$ | $11.65 \pm 0.17$ | $11.28 \pm 0.07$ |
| S3225 | $11.37 \pm 0.00$ | $10.58 \pm 0.01$ | $9.93 \pm 0.01$ | $9.88 \pm 0.11$ | $9.92 \pm 0.17$ | $10.03 \pm 0.05$ |
| S3232 | $13.74 \pm 0.00$ | $12.62 \pm 0.00$ | $11.42 \pm 0.00$ | $10.73 \pm 0.08$ | $9.81 \pm 0.17$ | $9.18 \pm 0.05$ |
| S3251 | $14.66 \pm 0.01$ | $13.69 \pm 0.00$ | $12.90 \pm 0.01$ | $12.05 \pm 0.08$ | $11.61 \pm 0.12$ | $11.44 \pm 0.07$ |
| S3252 | $14.15 \pm 0.00$ | 12.87士0.02 | $11.92 \pm 0.00$ | $11.17 \pm 0.08$ | $10.61 \pm 0.12$ | $10.35 \pm 0.06$ |
| S3268 | - | .... | . | $14.28 \pm 0.08$ | $12.20 \pm 0.12$ | $11.12 \pm 0.05$ |
| S3272 | $11.38 \pm 0.00$ | ............ | $10.34 \pm 0.01$ | $10.40 \pm 0.11$ | $10.34 \pm 0.12$ | $10.40 \pm 0.06$ |
| S3276 | $14.75 \pm 0.00$ | $13.85 \pm 0.02$ | $12.77 \pm 0.00$ | $12.23 \pm 0.08$ | $11.54 \pm 0.12$ | $11.28 \pm 0.06$ |
| S3282 | $12.89 \pm 0.00$ | $12.13 \pm 0.00$ | $11.47 \pm 0.00$ | $11.10 \pm 0.08$ | $10.75 \pm 0.12$ | $10.60 \pm 0.07$ |
| S3308 |  | $11.36 \pm 0.11$ | $13.36 \pm 0.00$ | $12.72 \pm 0.08$ | $12.34 \pm 0.12$ | $12.29 \pm 0.07$ |
| S3312 | $14.27 \pm 0.01$ | $13.41 \pm 0.01$ | $12.66 \pm 0.01$ | $12.10 \pm 0.08$ | $11.67 \pm 0.12$ | $11.56 \pm 0.06$ |
| S3317 | $13.66 \pm 0.01$ | $12.96 \pm 0.00$ | $12.51 \pm 0.01$ | $12.23 \pm 0.08$ | $12.02 \pm 0.12$ | $11.96 \pm 0.10$ |
| S3323 | $12.72 \pm 0.01$ | $12.10 \pm 0.02$ | $11.59 \pm 0.01$ | $11.52 \pm 0.08$ | $11.37 \pm 0.12$ | $11.35 \pm 0.10$ |
| S3351 | $15.83 \pm 0.01$ | $14.68 \pm 0.02$ | $13.65 \pm 0.01$ | $12.77 \pm 0.08$ | $12.18 \pm 0.12$ | $11.96 \pm 0.07$ |
| S3358 | $17.65 \pm 0.01$ | $16.73 \pm 0.02$ | $15.16 \pm 0.01$ | $14.32 \pm 0.08$ | $13.44 \pm 0.12$ | $13.49 \pm 0.07$ |
| S3363 | $17.01 \pm 0.01$ | $15.79 \pm 0.01$ | $14.05 \pm 0.01$ | $12.86 \pm 0.08$ | $12.30 \pm 0.12$ | $11.97 \pm 0.07$ |
| S3365 | $12.83 \pm 0.00$ | $12.13 \pm 0.00$ | $11.45 \pm 0.00$ | $11.26 \pm 0.08$ | $10.92 \pm 0.12$ | $10.92 \pm 0.10$ |
| S3376 | $15.22 \pm 0.00$ | $14.15 \pm 0.00$ | $13.12 \pm 0.00$ | $12.60 \pm 0.08$ | $11.83 \pm 0.12$ | $11.66 \pm 0.07$ |
| S3381 | $16.71 \pm 0.02$ | 15.88 $\pm 0.01$ | $15.41 \pm 0.02$ | $14.10 \pm 0.08$ | $13.57 \pm 0.17$ | $14.27 \pm 0.13$ |
| S3392 | $14.89 \pm 0.00$ | $13.85 \pm 0.02$ | $13.01 \pm 0.00$ | $12.50 \pm 0.08$ | $12.04 \pm 0.12$ | $11.84 \pm 0.05$ |
| S3393 | $12.53 \pm 0.00$ | ........... | $11.04 \pm 0.00$ | $10.69 \pm 0.08$ | $10.27 \pm 0.12$ | $10.17 \pm 0.10$ |
| S3395 | $19.17 \pm 0.07$ | $17.84 \pm 0.04$ | $15.72 \pm 0.02$ | $14.28 \pm 0.11$ | $13.91 \pm 0.12$ | $13.45 \pm 0.07$ |
| S3396 | .......... | ............ | $10.20 \pm 0.00$ | $10.39 \pm 0.08$ | $10.32 \pm 0.12$ | 10.27 $\pm 0.06$ |
| S3398 | $14.87 \pm 0.00$ | $13.90 \pm 0.00$ | $12.96 \pm 0.00$ | $12.34 \pm 0.08$ | $11.86 \pm 0.12$ | $11.72 \pm 0.06$ |
| S3402 | ............ | ............. | $10.29 \pm 0.00$ | $9.45 \pm 0.08$ | $9.28 \pm 0.12$ | ............. |
| S3408 | $14.17 \pm 0.02$ | $13.75 \pm 0.01$ | $13.19 \pm 0.01$ | $12.76 \pm 0.08$ | $12.15 \pm 0.12$ | $11.78 \pm 0.06$ |
| S3425 | $15.31 \pm 0.01$ | $14.80 \pm 0.00$ | $13.52 \pm 0.00$ | $12.45 \pm 0.08$ | $12.06 \pm 0.12$ | $11.50 \pm 0.07$ |
| S3435 | $14.22 \pm 0.00$ | $13.36 \pm 0.00$ | $12.56 \pm 0.00$ | $11.99 \pm 0.08$ | $11.27 \pm 0.12$ | $11.19 \pm 0.06$ |
| S3438 | $11.66 \pm 0.00$ | ........... | $10.56 \pm 0.00$ | $10.78 \pm 0.06$ | $10.55 \pm 0.17$ | $10.36 \pm 0.07$ |
| S3441 | $18.65 \pm 0.03$ | $17.39 \pm 0.03$ | $15.54 \pm 0.01$ | $14.62 \pm 0.06$ | $13.97 \pm 0.12$ | $13.76 \pm 0.10$ |

TABLE 5．4－Continued

| Source | $\underset{(\mathrm{mag})}{V}$ | $\underset{\text { (mag) }}{R}$ | $\begin{gathered} I \\ (\text { mag }) \end{gathered}$ | $\begin{gathered} J \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} H \\ \text { (mag) } \end{gathered}$ | $\underset{(\mathrm{mag})}{K}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S3442 | $17.15 \pm 0.01$ | $16.01 \pm 0.01$ | $13.97 \pm 0.00$ | $12.79 \pm 0.08$ | $12.25 \pm 0.12$ | $11.98 \pm 0.10$ |
| S3443 | $15.46 \pm 0.00$ | $14.41 \pm 0.00$ | $13.41 \pm 0.00$ | $12.66 \pm 0.08$ | $12.14 \pm 0.12$ | $11.97 \pm 0.06$ |
| S3448 | $16.33 \pm 0.01$ | $15.01 \pm 0.02$ | $13.71 \pm 0.00$ | $12.91 \pm 0.08$ | $12.27 \pm 0.12$ | $11.90 \pm 0.07$ |
| S3452 | $18.81 \pm 0.04$ | $17.65 \pm 0.04$ | $15.67 \pm 0.02$ | $14.51 \pm 0.08$ | $14.02 \pm 0.12$ | $13.78 \pm 0.07$ |
| S3470 | $15.36 \pm 0.00$ | $14.30 \pm 0.00$ | $13.13 \pm 0.00$ | $12.55 \pm 0.08$ | $11.90 \pm 0.12$ | $11.65 \pm 0.07$ |
| S3475 | $15.52 \pm 0.00$ | $14.06 \pm 0.02$ | $12.92 \pm 0.00$ | $11.94 \pm 0.08$ | $11.24 \pm 0.12$ | $10.66 \pm 0.05$ |
| S3496 | $15.60 \pm 0.01$ | $14.39 \pm 0.00$ | $13.09 \pm 0.00$ | $12.21 \pm 0.08$ | $11.43 \pm 0.12$ | $11.28 \pm 0.05$ |
| S3505 | $13.94 \pm 0.01$ | $13.14 \pm 0.01$ | $12.54 \pm 0.01$ | $12.36 \pm 0.08$ | $11.92 \pm 0.12$ | $11.73 \pm 0.05$ |
| S3510 | $16.43 \pm 0.01$ | $15.23 \pm 0.01$ | $13.38 \pm 0.00$ | $12.15 \pm 0.08$ | $11.48 \pm 0.17$ | $11.35 \pm 0.07$ |
| S3511 | $11.63 \pm 0.00$ | $10.85 \pm 0.00$ | $10.53 \pm 0.01$ | $10.70 \pm 0.08$ | $10.31 \pm 0.12$ | $9.53 \pm 0.10$ |
| S3514 | $13.51 \pm 0.00$ | $12.68 \pm 0.01$ | $12.06 \pm 0.00$ | $11.76 \pm 0.06$ | $11.11 \pm 0.12$ | $10.60 \pm 0.07$ |
| S3529 | $17.96 \pm 0.03$ | $16.75 \pm 0.02$ | $14.49 \pm 0.01$ | $13.03 \pm 0.08$ | $12.49 \pm 0.12$ | $12.18 \pm 0.10$ |
| S3535 | $17.31 \pm 0.02$ | 16．03士 0.01 | $14.70 \pm 0.01$ | 13．82 $\pm 0.08$ | $13.18 \pm 0.12$ | $12.91 \pm 0.10$ |
| S3536 | $14.16 \pm 0.02$ | $13.47 \pm 0.01$ | $12.95 \pm 0.01$ | $12.85 \pm 0.08$ | $12.53 \pm 0.12$ | $12.38 \pm 0.05$ |
| S3537 | $15.95 \pm 0.01$ | $15.30 \pm 0.03$ | $14.08 \pm 0.00$ | $13.62 \pm 0.08$ | $13.27 \pm 0.12$ | $12.81 \pm 0.07$ |
| S3546 | $15.20 \pm 0.01$ | $14.09 \pm 0.00$ | $13.07 \pm 0.00$ | ．．．．．．．．．．．． |  |  |
| S3552 | 12．87 $\pm 0.00$ | 11．97士0．00 | $11.22 \pm 0.00$ | $10.45 \pm 0.08$ | $9.49 \pm 0.17$ | $8.77 \pm 0.07$ |
| S3556 | $12.54 \pm 0.01$ | $11.77 \pm 0.01$ | $11.19 \pm 0.01$ | $10.93 \pm 0.08$ | $10.56 \pm 0.17$ | $10.38 \pm 0.10$ |
| S3568 | ． | $13.86 \pm 0.00$ | $12.81 \pm 0.00$ | $12.01 \pm 0.08$ | $11.55 \pm 0.17$ | $11.28 \pm 0.06$ |
| S3579 |  | $18.88 \pm 0.09$ | $16.20 \pm 0.02$ | 14．43土 0.08 | $13.73 \pm 0.17$ | $13.35 \pm 0.07$ |
| S3580 |  | $14.33 \pm 0.00$ | $13.15 \pm 0.00$ | $12.38 \pm 0.08$ | $11.77 \pm 0.17$ | $11.51 \pm 0.07$ |
| S3583 | $15.86 \pm 0.02$ | $14.71 \pm 0.01$ | $13.57 \pm 0.01$ | $12.57 \pm 0.11$ | $12.00 \pm 0.17$ | 11．76 $\pm 0.10$ |
| S3584 | $13.46 \pm 0.01$ | $13.07 \pm 0.00$ | $12.09 \pm 0.00$ | $11.81 \pm 0.11$ | $11.39 \pm 0.17$ | $11.41 \pm 0.07$ |
| S3592 | $16.38 \pm 0.03$ | $15.27 \pm 0.01$ | $13.96 \pm 0.01$ | $12.97 \pm 0.08$ | $12.44 \pm 0.17$ | $12.16 \pm 0.07$ |
| S3602 | $15.64 \pm 0.01$ | $14.72 \pm 0.01$ | $13.73 \pm 0.00$ | $13.12 \pm 0.11$ |  | $12.38 \pm 0.07$ |
| S3607 | $13.84 \pm 0.01$ | $13.13 \pm 0.00$ | $12.64 \pm 0.00$ | $12.37 \pm 0.11$ | $12.24 \pm 0.17$ | $12.19 \pm 0.07$ |
| S3611 | $16.82 \pm 0.01$ | $15.66 \pm 0.01$ | $14.29 \pm 0.01$ | 13．53土 0.11 | $13.08 \pm 0.17$ | $12.61 \pm 0.07$ |
| S3618 | $16.28 \pm 0.01$ | $15.48 \pm 0.03$ | $14.07 \pm 0.01$ | $13.16 \pm 0.08$ | $12.62 \pm 0.17$ | $12.33 \pm 0.06$ |
| S3628 | $13.02 \pm 0.02$ | $12.76 \pm 0.01$ | $11.93 \pm 0.02$ | $11.86 \pm 0.11$ | $11.45 \pm 0.12$ | $11.39 \pm 0.07$ |
| S3636 | $15.11 \pm 0.02$ | $14.19 \pm 0.01$ | $13.51 \pm 0.02$ | $12.87 \pm 0.08$ | $12.24 \pm 0.17$ | $12.18 \pm 0.07$ |
| S3646 | $17.60 \pm 0.02$ | $16.20 \pm 0.01$ | $14.31 \pm 0.01$ | $12.83 \pm 0.08$ | $12.04 \pm 0.17$ | $11.73 \pm 0.05$ |
| S3650 | $14.68 \pm 0.01$ | $13.51 \pm 0.01$ | $12.69 \pm 0.02$ | $11.61 \pm 0.11$ | $11.09 \pm 0.17$ | $10.86 \pm 0.05$ |
| S3659 | $15.93 \pm 0.01$ | $14.69 \pm 0.00$ | $13.25 \pm 0.01$ | 12．16 $\pm 0.11$ | $11.59 \pm 0.17$ | $11.41 \pm 0.07$ |
| S3666 | $15.94 \pm 0.02$ | $14.71 \pm 0.01$ | $13.47 \pm 0.02$ | $12.40 \pm 0.11$ | $11.73 \pm 0.12$ | $11.45 \pm 0.06$ |
| S3679 | ， | 16．25 $\pm 0.02$ | $14.98 \pm 0.01$ | $13.89 \pm 0.11$ | $13.31 \pm 0.12$ | $13.22 \pm 0.07$ |
| S3683 | $11.26 \pm 0.00$ | ， | $10.07 \pm 0.01$ | $10.08 \pm 0.08$ | $9.95 \pm 0.12$ |  |
| S3686 | ．．．．．．．．．．．． | $11.90 \pm 0.00$ | $12.51 \pm 0.01$ | $11.39 \pm 0.08$ | $10.93 \pm 0.12$ | $10.71 \pm 0.07$ |
| S3690 | $16.98 \pm 0.02$ | $15.93 \pm 0.01$ | $15.11 \pm 0.02$ | $14.23 \pm 0.11$ | $13.78 \pm 0.12$ | $13.55 \pm 0.07$ |
| S3692 |  | ．．．．．．．．．．． | $10.03 \pm 0.01$ | $9.54 \pm 0.08$ | $9.51 \pm 0.12$ | $9.33 \pm 0.05$ |
| S3693 | $17.88 \pm 0.03$ | $16.60 \pm 0.01$ | $14.70 \pm 0.01$ | $13.34 \pm 0.08$ | $12.73 \pm 0.12$ | $12.53 \pm 0.07$ |
| S3698 | $17.56 \pm 0.02$ | $16.23 \pm 0.01$ | $14.58 \pm 0.01$ | $13.49 \pm 0.08$ | $12.80 \pm 0.12$ | $12.60 \pm 0.07$ |
| S3702 | $16.06 \pm 0.02$ | $14.99 \pm 0.01$ | $13.35 \pm 0.02$ | $13.50 \pm 0.08$ | $12.00 \pm 0.12$ | $12.28 \pm 0.10$ |
| S3712 | $17.75 \pm 0.04$ | $16.40 \pm 0.01$ | $14.69 \pm 0.02$ | $13.47 \pm 0.08$ | $12.88 \pm 0.12$ | $12.57 \pm 0.06$ |
| S3719 | $11.27 \pm 0.00$ | $10.64 \pm 0.00$ | $10.10 \pm 0.02$ | $10.35 \pm 0.08$ | $10.36 \pm 0.12$ |  |
| S3725 | $17.70 \pm 0.07$ | $16.40 \pm 0.02$ | $14.88 \pm 0.02$ | $13.33 \pm 0.08$ | $12.30 \pm 0.12$ | $11.15 \pm 0.06$ |
| S3761 | $18.00 \pm 0.03$ | $16.77 \pm 0.02$ | $15.17 \pm 0.02$ | $13.97 \pm 0.08$ | $13.45 \pm 0.12$ | $13.17 \pm 0.07$ |
| S3767 | $14.23 \pm 0.02$ | $13.23 \pm 0.01$ | $12.45 \pm 0.02$ | $11.56 \pm 0.08$ | $10.81 \pm 0.12$ | $10.20 \pm 0.10$ |
| S3772 | $15.92 \pm 0.01$ | $15.05 \pm 0.02$ | $14.47 \pm 0.01$ | $14.09 \pm 0.06$ | $13.55 \pm 0.10$ | $13.34 \pm 0.07$ |
| S3776 | $15.36 \pm 0.02$ | $14.34 \pm 0.01$ | $13.55 \pm 0.02$ | $12.89 \pm 0.08$ | $12.23 \pm 0.12$ | $12.19 \pm 0.10$ |
| S3790 | $15.66 \pm 0.01$ | $14.40 \pm 0.00$ | $13.07 \pm 0.01$ | $12.08 \pm 0.08$ | $11.50 \pm 0.12$ | ．．．．．．．．．．．． |
| S3792 | ．．．．．．．．．．．． | ．．．．．．．．．．． | $14.14 \pm 0.02$ | $13.17 \pm 0.08$ | $12.50 \pm 0.12$ | $12.22 \pm 0.06$ |
| S3796 | $17.18 \pm 0.02$ | $15.96 \pm 0.01$ | $14.73 \pm 0.01$ | $13.78 \pm 0.08$ | $13.26 \pm 0.12$ | $12.95 \pm 0.07$ |

TABLE 5．4—Continued

| Source | $\begin{gathered} V \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} R \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} I \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} K \\ (\mathrm{mag}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S3799 |  | $12.56 \pm 0.00$ | $11.90 \pm 0.01$ | $11.18 \pm 0.06$ | $10.35 \pm 0.12$ | $9.68 \pm 0.10$ |
| S3802 |  |  | $10.49 \pm 0.01$ | $10.27 \pm 0.08$ | $9.98 \pm 0.12$ | $9.93 \pm 0.10$ |
| S3806 | $18.66 \pm 0.05$ | $17.44 \pm 0.04$ | $15.70 \pm 0.03$ | $14.56 \pm 0.08$ | $14.00 \pm 0.12$ | $13.65 \pm 0.07$ |
| S3810 |  | 18．05 $\pm 0.07$ | $16.09 \pm 0.03$ | $14.79 \pm 0.08$ | $14.42 \pm 0.17$ | $14.18 \pm 0.07$ |
| S3811 | $17.38 \pm 0.02$ | $16.05 \pm 0.01$ | $14.35 \pm 0.01$ | $12.71 \pm 0.08$ | $12.11 \pm 0.12$ | $11.50 \pm 0.06$ |
| S3812 |  | $13.30 \pm 0.00$ | $12.39 \pm 0.01$ | $11.57 \pm 0.06$ | $10.93 \pm 0.12$ | $10.35 \pm 0.07$ |
| S3813 | $12.38 \pm 0.00$ | $11.81 \pm 0.00$ | $11.22 \pm 0.01$ | $11.22 \pm 0.08$ | $10.92 \pm 0.12$ |  |
| S3815 | $16.57 \pm 0.02$ | $15.42 \pm 0.01$ | $14.33 \pm 0.02$ | $13.46 \pm 0.08$ | $12.81 \pm 0.12$ | $12.59 \pm 0.05$ |
| S3834 |  | $15.53 \pm 0.01$ | $14.07 \pm 0.01$ | $13.08 \pm 0.08$ | $12.55 \pm 0.12$ | $12.25 \pm 0.10$ |
| S3844 | $15.42 \pm 0.00$ | $14.42 \pm 0.01$ | $13.35 \pm 0.01$ | $12.52 \pm 0.08$ | $12.07 \pm 0.17$ | $11.62 \pm 0.10$ |
| S3861 | $16.94 \pm 0.01$ | $15.63 \pm 0.01$ | 13．81 $\pm 0.01$ | $12.54 \pm 0.08$ | $11.79 \pm 0.12$ | 11．37士0．06 |
| S3866 |  | $17.30 \pm 0.07$ | $15.62 \pm 0.03$ | $14.39 \pm 0.08$ | $14.12 \pm 0.17$ | $13.51 \pm 0.07$ |
| S3869 | $16.58 \pm 0.01$ | $15.61 \pm 0.01$ | $14.69 \pm 0.01$ | $13.67 \pm 0.08$ | $13.07 \pm 0.17$ | $12.72 \pm 0.06$ |
| S3871 | $14.04 \pm 0.01$ | $13.23 \pm 0.02$ | $12.62 \pm 0.02$ | $11.84 \pm 0.11$ | $11.60 \pm 0.17$ | $11.37 \pm 0.07$ |
| S3872 |  | $16.30 \pm 0.02$ | $14.05 \pm 0.01$ | $13.26 \pm 0.08$ | $12.01 \pm 0.17$ | $11.63 \pm 0.07$ |
| S3873 | $11.30 \pm 0.00$ | $10.59 \pm 0.00$ | $9.92 \pm 0.01$ | $9.35 \pm 0.08$ | $9.22 \pm 0.17$ | $9.22 \pm 0.10$ |
| S3875 | $13.74 \pm 0.01$ | $13.13 \pm 0.02$ | $12.80 \pm 0.02$ | $12.60 \pm 0.11$ | $12.37 \pm 0.17$ | $12.32 \pm 0.10$ |
| S3878 |  | $18.57 \pm 0.15$ | $16.22 \pm 0.03$ | $14.79 \pm 0.08$ | 14．22 $\pm 0.17$ | $13.86 \pm 0.07$ |
| S3880 | $13.02 \pm 0.00$ | $12.40 \pm 0.02$ | $12.01 \pm 0.00$ | 11．69士0．11 | － | $11.56 \pm 0.07$ |
| S3884 |  | 15．44 $\pm 0.01$ | $13.96 \pm 0.00$ | 12．59 $\pm 0.11$ | $11.87 \pm 0.17$ | $11.55 \pm 0.10$ |
| S3889 |  | $13.01 \pm 0.01$ | $12.11 \pm 0.00$ | $11.36 \pm 0.08$ | $10.84 \pm 0.17$ | $10.47 \pm 0.07$ |
| S3895 |  | $15.36 \pm 0.01$ | $13.96 \pm 0.00$ | $12.80 \pm 0.11$ | $12.14 \pm 0.17$ | $11.42 \pm 0.07$ |
| S3897 | $12.75 \pm 0.01$ | $12.19 \pm 0.01$ | $11.71 \pm 0.01$ | $11.63 \pm 0.11$ | $11.47 \pm 0.17$ | $11.30 \pm 0.10$ |
| S3913 | $17.37 \pm 0.02$ | $16.23 \pm 0.02$ | $14.91 \pm 0.01$ | 14．10 $\pm 0.11$ | $13.00 \pm 0.12$ | $13.17 \pm 0.10$ |
| S3915 | $14.88 \pm 0.00$ | $13.82 \pm 0.02$ | $12.33 \pm 0.01$ | 11．28 $\pm 0.08$ | $10.53 \pm 0.17$ | $10.00 \pm 0.06$ |
| S3917 | $17.68 \pm 0.02$ | $16.45 \pm 0.03$ | $14.59 \pm 0.01$ | $13.70 \pm 0.08$ | $12.96 \pm 0.17$ | $12.56 \pm 0.07$ |
| S3920 | $15.43 \pm 0.00$ | $14.65 \pm 0.02$ | $13.43 \pm 0.00$ | $12.77 \pm 0.08$ | $12.04 \pm 0.17$ |  |
| S3923 |  | $14.08 \pm 0.01$ | 13．26 $\pm 0.00$ | $12.33 \pm 0.11$ | $11.76 \pm 0.17$ | $11.44 \pm 0.10$ |
| S3947 | $16.72 \pm 0.01$ | $15.69 \pm 0.01$ | $14.66 \pm 0.01$ | 14．04 $\pm 0.08$ | $13.26 \pm 0.12$ | $13.06 \pm 0.05$ |
| S3956 | $15.79 \pm 0.00$ | $14.67 \pm 0.02$ | $13.24 \pm 0.01$ | $12.22 \pm 0.11$ | $11.24 \pm 0.09$ | $11.05 \pm 0.07$ |
| S3963 | $18.76 \pm 0.04$ | $17.25 \pm 0.03$ | $15.12 \pm 0.01$ | $13.78 \pm 0.08$ | $13.26 \pm 0.12$ | $13.07 \pm 0.09$ |
| S3964 | $18.36 \pm 0.03$ | $16.74 \pm 0.04$ | $14.89 \pm 0.01$ | $13.19 \pm 0.08$ | $12.07 \pm 0.12$ | $11.46 \pm 0.05$ |
| S3969 | $17.71 \pm 0.02$ | $16.68 \pm 0.08$ | $14.99 \pm 0.01$ | $13.89 \pm 0.08$ | $13.24 \pm 0.12$ | $12.93 \pm 0.10$ |
| S3973 | $16.58 \pm 0.01$ | $15.50 \pm 0.02$ | $14.34 \pm 0.00$ | $13.50 \pm 0.08$ | $12.78 \pm 0.12$ | $12.37 \pm 0.06$ |
| S3974 | 15．11 $\pm 0.00$ | $14.13 \pm 0.01$ | $13.29 \pm 0.00$ | $12.45 \pm 0.08$ | $11.92 \pm 0.12$ | $11.71 \pm 0.06$ |
| S3979 | $18.27 \pm 0.03$ | $17.04 \pm 0.04$ | $15.38 \pm 0.02$ | $14.18 \pm 0.08$ | $13.64 \pm 0.12$ | $13.21 \pm 0.10$ |
| S3982 | $18.45 \pm 0.03$ | $17.17 \pm 0.03$ | $15.30 \pm 0.01$ | $14.13 \pm 0.08$ | $13.60 \pm 0.12$ | $13.35 \pm 0.07$ |
| S3990 | $15.66 \pm 0.00$ | $14.90 \pm 0.01$ | $14.21 \pm 0.00$ | 13．94 $\pm 0.06$ | $13.47 \pm 0.12$ | $13.15 \pm 0.07$ |
| S3995 |  | $16.28 \pm 0.02$ | $14.30 \pm 0.01$ | 12．99 $\pm 0.08$ | $12.50 \pm 0.12$ | $12.23 \pm 0.07$ |
| S4003 | ．．．．．．．．．．． | $16.08 \pm 0.01$ | $14.47 \pm 0.01$ | 13．37 $\pm 0.06$ | $12.63 \pm 0.12$ | $12.34 \pm 0.10$ |
| S4005 |  | $18.42 \pm 0.10$ | $16.09 \pm 0.02$ | $15.06 \pm 0.18$ | $14.07 \pm 0.12$ | $13.87 \pm 0.06$ |
| S4011 | $13.94 \pm 0.00$ | $13.20 \pm 0.02$ | $12.59 \pm 0.00$ | 12．19士0．08 | $11.76 \pm 0.12$ | $11.63 \pm 0.10$ |
| S4015 |  | $12.38 \pm 0.01$ | $11.86 \pm 0.00$ | $11.69 \pm 0.11$ | $11.41 \pm 0.12$ | $11.45 \pm 0.10$ |
| S4016 | $14.43 \pm 0.00$ | $13.42 \pm 0.01$ | $12.49 \pm 0.00$ | $11.80 \pm 0.08$ | $11.33 \pm 0.12$ | $11.09 \pm 0.06$ |
| S4037 | $17.26 \pm 0.02$ | $15.96 \pm 0.01$ | $14.48 \pm 0.01$ | $13.57 \pm 0.08$ | $12.80 \pm 0.12$ | $12.77 \pm 0.07$ |
| S4038 | $14.71 \pm 0.00$ | $14.38 \pm 0.01$ | $13.10 \pm 0.00$ | $12.72 \pm 0.08$ | $12.20 \pm 0.12$ | $11.96 \pm 0.06$ |
| S4053 | $17.13 \pm 0.01$ | $15.94 \pm 0.01$ | $14.49 \pm 0.01$ | $13.54 \pm 0.08$ | $12.87 \pm 0.12$ | $12.67 \pm 0.10$ |
| S4062 | $15.05 \pm 0.00$ | $14.10 \pm 0.00$ | $13.06 \pm 0.00$ | $12.20 \pm 0.08$ | $11.59 \pm 0.12$ | $11.15 \pm 0.05$ |
| S4073 | $17.92 \pm 0.02$ | $16.56 \pm 0.01$ | $15.01 \pm 0.01$ | $14.00 \pm 0.08$ | $13.38 \pm 0.12$ | $13.17 \pm 0.10$ |
| S4078 | $15.44 \pm 0.00$ | $14.79 \pm 0.01$ | $13.51 \pm 0.00$ | $13.01 \pm 0.08$ | $12.53 \pm 0.12$ | $12.17 \pm 0.05$ |
| S4082 | $16.40 \pm 0.01$ | $15.32 \pm 0.01$ | $14.20 \pm 0.00$ | $13.41 \pm 0.08$ | $12.79 \pm 0.12$ | $12.54 \pm 0.06$ |
| S4087 | － | $15.13 \pm 0.01$ | $13.68 \pm 0.00$ | $13.45 \pm 0.11$ | $12.59 \pm 0.12$ | $12.35 \pm 0.07$ |

TABLE 5．4－Continued

| Source | $\begin{gathered} V \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} R \\ \text { (mag) } \end{gathered}$ | $\underset{\text { (mag) }}{I}$ | $\begin{gathered} J \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} H \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} K \\ (\text { mag }) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S4090 | $10.92 \pm 0.04$ | $10.31 \pm 0.00$ |  | $8.61 \pm 0.08$ | $9.03 \pm 0.12$ | $8.85 \pm 0.07$ |
| S4112 | $13.99 \pm 0.00$ | $13.00 \pm 0.01$ | $12.25 \pm 0.01$ | $11.86 \pm 0.08$ | $11.32 \pm 0.12$ | $11.17 \pm 0.10$ |
| S4121 | $15.87 \pm 0.00$ | $14.93 \pm 0.01$ | $14.15 \pm 0.01$ | $13.69 \pm 0.08$ | $13.21 \pm 0.12$ | $12.93 \pm 0.07$ |
| S4124 | $17.25 \pm 0.03$ | $16.37 \pm 0.02$ | $14.41 \pm 0.01$ | $13.40 \pm 0.11$ | $12.82 \pm 0.12$ | $12.51 \pm 0.07$ |
| S4126 | $17.96 \pm 0.05$ | $17.60 \pm 0.07$ | $15.51 \pm 0.02$ | $14.52 \pm 0.11$ | 13．99 $\pm 0.12$ | $13.67 \pm 0.10$ |
| S4133 | $17.72 \pm 0.02$ | $16.47 \pm 0.01$ | $14.51 \pm 0.01$ | $13.27 \pm 0.11$ | $12.63 \pm 0.12$ | $12.15 \pm 0.07$ |
| S4136 |  | 11．97士0．00 | 11．32 $\pm 0.00$ | 10．99士0．08 | $10.76 \pm 0.17$ | $10.62 \pm 0.07$ |
| S4146 | $16.73 \pm 0.01$ | $15.90 \pm 0.02$ | $14.31 \pm 0.01$ | $13.59 \pm 0.11$ | $12.72 \pm 0.12$ | $12.61 \pm 0.10$ |
| S4176 | $11.56 \pm 0.00$ | $11.10 \pm 0.00$ | $10.54 \pm 0.00$ | $10.55 \pm 0.11$ | $10.40 \pm 0.17$ | $10.41 \pm 0.07$ |
| S4194 | 15．41 $\pm 0.00$ | 14．40 $\pm 0.00$ | 13．55 $\pm 0.00$ | 12．79 $\pm 0.11$ | 12．50 $\pm 0.17$ | $12.14 \pm 0.07$ |
| S4200 | $17.47 \pm 0.01$ | $16.13 \pm 0.01$ | $14.36 \pm 0.00$ | $13.21 \pm 0.08$ | $12.72 \pm 0.17$ | $12.39 \pm 0.10$ |
| S4201 | $16.77 \pm 0.01$ | $15.51 \pm 0.01$ | $13.85 \pm 0.00$ | $13.02 \pm 0.11$ | $12.08 \pm 0.12$ | $12.02 \pm 0.07$ |
| S4210 | $18.48 \pm 0.03$ | $17.75 \pm 0.06$ | $15.84 \pm 0.02$ | 14．96士0．08 | $14.73 \pm 0.17$ | $14.30 \pm 0.07$ |
| S4212 | ．．．．．．．．．．．． | $12.72 \pm 0.00$ | $12.09 \pm 0.00$ | $12.19 \pm 0.11$ | $11.83 \pm 0.17$ | $11.65 \pm 0.08$ |
| S4214 | $18.11 \pm 0.02$ | $17.02 \pm 0.04$ | $15.11 \pm 0.01$ | $14.29 \pm 0.08$ | $13.76 \pm 0.12$ | $13.41 \pm 0.07$ |
| S4220 | 18．56士 0.05 | $17.21 \pm 0.03$ | $15.16 \pm 0.01$ | 14．13土 0.11 | $13.48 \pm 0.17$ | $13.20 \pm 0.07$ |
| S4229 | $17.44 \pm 0.02$ | $16.40 \pm 0.02$ | $14.34 \pm 0.00$ | $13.40 \pm 0.08$ | $12.80 \pm 0.12$ | 12．57 $\pm 0.10$ |
| S4236 | $16.04 \pm 0.01$ | $14.97 \pm 0.01$ | $13.84 \pm 0.01$ | $13.03 \pm 0.08$ | $12.23 \pm 0.12$ | $12.00 \pm 0.10$ |
| 54238 | $16.09 \pm 0.00$ | $14.79 \pm 0.01$ | $13.38 \pm 0.00$ | $12.25 \pm 0.08$ | $12.73 \pm 0.17$ | $11.37 \pm 0.07$ |
| S4281 | $17.44 \pm 0.02$ | ．．．．．．．．．．．． | $14.72 \pm 0.01$ | $13.85 \pm 0.08$ | $13.19 \pm 0.12$ | $12.79 \pm 0.10$ |
| S4282 | $12.63 \pm 0.00$ | $12.20 \pm 0.01$ | $11.75 \pm 0.01$ | $11.69 \pm 0.08$ | $11.55 \pm 0.12$ | $11.57 \pm 0.10$ |
| S4292 | $17.65 \pm 0.01$ | $16.26 \pm 0.02$ | $14.79 \pm 0.01$ | $13.75 \pm 0.08$ | $13.19 \pm 0.12$ | $12.93 \pm 0.10$ |
| S4296 | $14.36 \pm 0.01$ | $13.52 \pm 0.01$ | $12.76 \pm 0.01$ | $12.18 \pm 0.08$ | $11.89 \pm 0.17$ | $11.52 \pm 0.10$ |
| S4307 | $18.83 \pm 0.05$ | $17.34 \pm 0.03$ | $15.15 \pm 0.01$ | $13.98 \pm 0.08$ | $13.50 \pm 0.17$ | $13.22 \pm 0.10$ |
| S4314 | $14.94 \pm 0.00$ | $13.90 \pm 0.00$ | $12.96 \pm 0.00$ | $12.46 \pm 0.08$ | $11.99 \pm 0.12$ | 11．83 $\pm 0.10$ |
| S4363 | ． | $15.37 \pm 0.01$ | $14.55 \pm 0.01$ | $14.36 \pm 0.08$ | $13.86 \pm 0.12$ | $13.73 \pm 0.10$ |
| S4365 | $13.02 \pm 0.00$ | $12.29 \pm 0.02$ | $11.66 \pm 0.00$ | 11．47士 0.08 | $11.06 \pm 0.12$ | ．．．．．．．．．．． |
| S4392 | ．．．．．．．．．．． | ． | ．．．．．．．．．．．． | $8.86 \pm 0.11$ | $9.22 \pm 0.12$ | ． |
| S4433 | ．．．．．．．．．．．． | $13.53 \pm 0.00$ | $12.34 \pm 0.00$ | $11.33 \pm 0.11$ | $10.55 \pm 0.17$ | $9.86 \pm 0.14$ |
| S4473 | $18.13 \pm 0.03$ | $16.78 \pm 0.01$ | $15.14 \pm 0.01$ | $13.87 \pm 0.11$ | $13.46 \pm 0.17$ | $13.08 \pm 0.14$ |
| S4494 | $15.84 \pm 0.00$ | $15.24 \pm 0.00$ | $13.99 \pm 0.00$ | $13.57 \pm 0.11$ | $12.96 \pm 0.17$ | ．．．．．．．．．．． |
| S4508 | $15.62 \pm 0.01$ | $14.69 \pm 0.01$ | $13.92 \pm 0.01$ | $13.49 \pm 0.11$ | $12.89 \pm 0.17$ |  |
| S4675 | ． | $11.49 \pm 0.00$ | ． | $10.19 \pm 0.11$ | $10.04 \pm 0.17$ | ．．．．．．．．．．．． |
| S4737 | ．．．．．．．．．．． | $12.59 \pm 0.00$ | $12.17 \pm 0.00$ | ．．．．．． | ．．．．．．．．．．．． | ． |

NOTE．－The source numbers and photometry are listed for 346 stars selected from the 4900 stars in the completed survey．The $J, H$ ，and $K$ data have slight biases added as discussed in the text．

Table 5.5. Additional Stars

| Name | $\alpha(1950.0)$ | $\delta(1950.0)$ | $m_{V}$ |
| :--- | :--- | ---: | :--- |
| LkH $\alpha$ | $6^{h} 37^{m} 27.00^{s}$ | $10^{\circ} 08^{\prime} 30 . \prime$ | 17.00 |
| W032 | $6^{h} 37^{m} 10.43^{s}$ | $10^{\circ} 07^{\prime} 41 . .^{\prime \prime}$ | 12.99 |
| W034 | $6^{h} 37^{m} 12.06^{s}$ | $10^{\circ} 08^{\prime} 32 . .^{\prime \prime}$ | 10.91 |
| W060 | $6^{h} 37^{m} 47.00^{s}$ | $10^{\circ} 04^{\prime} 43 . .^{\prime \prime}$ | 12.46 |
| W087 | $6^{h} 37^{m} 57.73^{s}$ | $10^{\circ} 11^{\prime} 22 . .^{\prime \prime}$ | 10.74 |
| W091 | $6^{h} 38^{m} 38.51^{s}$ | $10^{\circ} 11^{\prime} 36 .^{\prime \prime}$ | 12.32 |
| W094 | $6^{h} 38^{m} 01.91^{s}$ | $10^{\circ} 14^{\prime} 20 .^{\prime \prime}$ | 10.42 |
| W098 | $6^{h} 38^{m} 03.15^{s}$ | $10^{\circ} 12^{\prime} 41 . .^{\prime \prime}$ | 11.75 |
| W114 | $6^{h} 38^{m} 07.62^{s}$ | $9^{\circ} 16^{\prime} 46 . .^{\prime \prime}$ | 11.54 |
| W128 | $6^{h} 38^{m} 12.07^{s}$ | $9^{\circ} 14^{\prime} 31 . .^{\prime \prime}$ | 10.99 |
| W172 | $6^{h} 38^{m} 23.08^{s}$ | $10^{\circ} 11^{\prime} 18 .^{\prime \prime}$ | 10.04 |
| W180 | $6^{h} 38^{m} 25.48^{s}$ | $10^{\circ} 03^{\prime} 34 . \prime$ | 12.86 |
| W182 | $6^{h} 38^{m} 26.84^{s}$ | $9^{\circ} 14^{\prime} 09 . .^{\prime \prime}$ | 10.31 |
| W196 | $6^{h} 38^{m} 31.67^{s}$ | $10^{\circ} 37^{\prime} 07 . \prime$ | 11.46 |
| W221 | $6^{h} 38^{m} 48.96^{s}$ | $10^{\circ} 05^{\prime} 20 . .^{\prime \prime}$ | 12.12 |
|  |  |  |  |

Note. - Data (Lapicz 1984; Walker 1956; Herbig 1954) for stars observed in the spectroscopic survey, but which were not represented in the photometric survey of Chapter 3.

TABLE 5.6
The Spectral Survey

| Source | Walker \# | LkH ${ }^{\text {\# }}$ | Type ${ }^{\text {a,b }}$ | Lines ${ }^{\text {c }}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S0131 | W033 | ............ | K4 | ........... | $\mathrm{M}^{\text {e }}$ |
| S0422 | W035 | . | A1 | ........... |  |
| S0445 | W036 |  | A1 | ........... | ................ |
| S0710 | W038 | . | F7d | ........... | ...... |
| S0921 | W039 | ........... | A2 | ........... | ...... |
| S0967 | W040 | ........... | K1 | $\boldsymbol{r}$ | . |
| S1066 | W041 | ........ | G5d | $f$ | .............. |
| S1117 | W042 | ........... | K1 | H ${ }^{\text {r }}$ |  |
| S1129 | W043 |  | A6 | ............ | A7III ${ }^{\text {e }}$ |
| S1212 | ..... | LkH $\alpha 09$ | M1d | Ca, $\mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\varepsilon}$ |  |
| S1270 | W045 |  | K1 |  | CaI 4227A in emission? |
| S1276 | W046 | ........... | A5 | ............ | A5III; A1 ${ }^{\text {i }}$ |
| S1309 | ..... | ........... | M5d | $\mathrm{H} \alpha$ | 5-pixel boxcar ${ }^{\text {k }}$ |
| S1315 | ..... | ...... | K4d | f | ................ |
| S1316 | ..... | ........... | G7 | f |  |
| S1364 | .... | ......... | M5d | $f$ | ........... |
| S1369 | W048 | ........ | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \mathrm{e}$ | h |
| S1382 | ..... | ........... | M1?d |  | 5-pixel boxcar ${ }^{\text {k }}$ |
| S1389 | W049 | ....... | K4 | f | ................ |
| S1407 | ..... | ........... | M3? | H ${ }^{\text {a }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S1447 | ..... | ... | M3d | ! |  |
| S1478 | W050 | ... | B1 | ........... | B3V ${ }^{\text {e }} \mathrm{Br}^{\text {i }}$ |
| S1499 | ..... | ......... | K7d | H $\alpha$ | .......... |
| S1500 | W051 | ........ | M1d | 1 | .......... |
| S1513 |  | ........ | K7d | H ${ }^{\text {a }}$ | ............ |
| S1518 | ... | ......... | M5g |  | ...................... |
| S1529 | ..... | ....... | M3d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \epsilon$ |  |
| S1562 | W054 | ........ | G7d | $\mathrm{H}^{\mathbf{f}}$ | ....................... |
| S1566 | W053 | ........... | K7d | Ca, $\mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ |  |
| S1590 | ..... | ........... | M1?d? | H $\alpha \beta^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S1598 | ..... | ........... | M3g? | $\mathrm{Ha}^{\text {f }}$ | ................ |
| S1606 | ..... | - | K4d | H $\alpha \beta$ | ............. |
| S1621 | ..... | . | M3g | H $\alpha \beta$ | . ${ }^{\text {a }}$.......... |
| S1629 | W055 | LkH 12 | K1 | $\mathrm{Ca}, \mathrm{H} \alpha \beta \boldsymbol{\gamma \varepsilon}$ | j |
| S1637 | W057 | ............ | K7 | ............ | ...... |
| S1645 | W056 | ............ | K7d | Ha | ...... |
| S1648 | W058 | LkH $\alpha^{13}$ | K4 | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta}$ | .......... |
| S1665 | W059 |  | A6 | ............ | .... |
| S1675 | ..... | ........... | M3d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \epsilon^{f}$ | ............ |
| S1702 | .... | ........ | K7d | $\mathrm{H} \alpha$ | ......... |
| S1734 | ..... | .... | M5d |  | ................ |
| S1758 | ..... | ........... | M3? ${ }^{\text {g }}$ | Ha ${ }^{\text {f }}$ | 5-pixel boxcar ${ }^{\text {k }}$ |
| S1760 | ..... | ........... | M3 | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma 6 \epsilon^{\text {f }}$ | j |
| S1769 | W061 | ........ | F9d | Ha | ................ |
| S1776 | W062 | .... | F6g? | ............ | ............... |
| S1796 | ..... | ........ | M1d |  | ..................... |
| S1804 | W063 | .... | G9d? | Ha ${ }^{\text {f }}$ | ............. |
| S1806 | W064 | . | K1d | . |  |
| S1820 | ..... | ... | M1d | He | 3 -pixel boxcar ${ }^{\text {k }}$ |

TABLE 5.6-Continued

| Source | Walker \# | LkH ${ }^{\text {\# }}$ | Type ${ }^{\text {a }}$ b | Lines ${ }^{\text {c }}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S1829 | W065 | .......... | F4d | . ...... | ........................................ |
| S1896 | ..... | LkHa 15 | K4 | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\epsilon}$ | h |
| S1898 | . | ............ | K4d | $\mathrm{H} \alpha \beta^{\text {f }}$ | . |
| S1901 | W066 |  | B0 | ... |  |
| S1932 | ..... | ............ | M1d | $\mathrm{H} \alpha \boldsymbol{\beta}^{\mathbf{f}}$ |  |
| S1937 | ..... | . | M3?g? | H $\alpha^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S1939 | W067 | ............ | B0 | $\cdots$ | B2V ${ }^{\text {c }}$ |
| S1947 | W068 | . | B2 | ............ | GOIV--Ve,m |
| S1950 | W069 | ............ | K4d | ............ | K3II-III, TiO 5862 ${ }^{\text {e }}$ present? |
| S1960 | W070 | ........... | F8d | ............ |  |
| S1973 | ..... | . . . . . . . . | K7d | $H \alpha \beta \boldsymbol{\gamma} \boldsymbol{\delta}$ | . ...................................... |
| S1976 | ..... | - | A7? |  | Ha reversal, 3-pixel boxcar ${ }^{\text {k }}$ |
| S1996 | ..... | LkH 16 | M3d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ | $j$ j |
| S2006 | W073 | ........... | G5g? | ............ | Luminosity class III?, G5III ${ }^{\text {e }}$ |
| S2007 | ..... | ............ | M5d | ............. | ...................................... |
| S2008 | ... | . . | M1d | ............. | . |
| S2009 | W074 | ........... | B4 | -.......... | B5 spectroscopic binary ${ }^{\text {i }}$ |
| S2022 | ..... | ............ | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \boldsymbol{\beta} \boldsymbol{\gamma} \delta \epsilon^{\text {f }}$ | . . . . . . . . . . . . . . . . . . . . . . . . . . . . |
| S2038 | ..... | . . . . . . | M3d | $\mathrm{H} \alpha$ | . |
| S2055 | ..... | ... | K4d | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta} \boldsymbol{\gamma}^{\text {f }}$ | - |
| S2068 | W076 | . $\cdot$........ | K1 | $\mathrm{Ha}^{\mathbf{f}}$ |  |
| S2079 | ..... | . | K1d | Ca, H $\alpha \beta \gamma \delta \delta \epsilon^{\text {f }}$ | h |
| S2104 | ..... | ....... | K4 | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta} \boldsymbol{\gamma}^{\text {f }}$ | . |
| S2113 | W077 | LkHa 18 | K4d | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta}^{\text {f }}$ | ..................................... |
| S2116 |  |  | K7?g? | .............. | 3-pixel boxcark |
| S2117 | ..... | .......... | K7d | Ho | ..................................... |
| S2146 | ..... | ........... | K4d | $H \alpha^{f}$ | ...................................... |
| S2162 | W078 | LkH 20 | M1d | Ca, H $\alpha \beta \gamma \delta$ c | h |
| S2163 | ..... | LkH 21 | G3d | $\mathrm{H} \alpha$ | ..................................... |
| S2167 | ..... | ............ | M5d | $t$ | ................................... |
| S2171 | ..... | ....... | K4d | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta} \boldsymbol{\gamma}^{\boldsymbol{f}}$ | .................................. |
| S2173 | W079 | LkHa 22 | M? | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{e}$ | $\mathrm{j}, \mathrm{n}$ |
| S2190 | W081 | ............ | K4? | $\mathrm{Ha}^{\mathbf{f}}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S2191 | W080 | ............. | M1d | $\mathrm{H} \alpha$ | ...................................... |
| S2228 | ..... | LkHa 23 | K4d | Ca, Has\% 6 e | j ${ }^{\text {d }}$ |
| S2230 | ..... | ............. | A2 | ............. | .................................... |
| S2234 | W084 | ............ | F8d | $\mathrm{H} \alpha$ | - |
| S2253 | ..... | ............ | K4 | $\mathrm{Ha}^{\text {f }}$ | - |
| S2268 | ..... | ............ | K7 | 1 | . .................................... |
| S2279 | *.... | ........... | G3d |  | .................................... |
| S2280 | ..... | LkH 24 | K4? | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {h,k }}$ |
| S2284 | ..... | ........... | K4d | Ha | ..................................... |
| S2289 | W088 | ............. | B1 | ............ | B5V: B6 spectroscopic binary ${ }^{\text {i }}$ |
| S2313 | ..... | ........... | F? | $\mathrm{H} \alpha$ | p |
| S2322 | ..... | ............ | M1d | Ha ${ }^{\text {f }}$ | .......................................... |
| S2325 | ..... | ............ | M3? | Ha ${ }^{\text {f }}$ | 10-pixel boxcar ${ }^{\text {k }}$ |
| S2359 | ..... | ............ | K4 | $\mathrm{H} \alpha$ | ...................................... |
| S2364 | W090 | LkHa 25 | A2 | $\mathrm{H} \boldsymbol{\alpha}$ |  |
| S2374 | ..... | ........... | F1 | ............ | ................................... |

TABLE 5.6-Continued

| Source | Walker \# | LkH $\alpha$ \# | Type ${ }^{\text {a }}$, | Lines ${ }^{\text {c }}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S2377 | ... | $\cdot$ | K1d | H ${ }^{\text {f }}$ | ...................... |
| S2387 | ..... | ........... | M3d | .... | ..................... |
| S2390 | ..... | ........... | K7a | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta} \boldsymbol{\gamma}^{\text {f }}$ |  |
| S2395 | $\ldots$ | ............ | K7d | ........... |  |
| S2405 | ..... | ............ | G9d | H ${ }^{\text {f }}$ |  |
| S2418 | ..... | ........... | G9d | H $\alpha \beta$ | Fe I 6495A emission? |
| S2424 | ..... | ........... | M1d | $\mathrm{H} \alpha \beta^{\boldsymbol{r}}$ |  |
| S2448 | W092 | ........... | K1 | $\mathrm{H}^{\text {f }}$ | KoIV ${ }^{\text {e }}$ |
| S2449 | ... | ........... | M3d | $\mathrm{H} \alpha \beta^{\text {f }}$ | ............... |
| S2495 | ..... | ........... | G9d | $\mathrm{H} \alpha$ |  |
| S2506 | ... | ........... | M3d | H $\alpha \beta \boldsymbol{\beta} \boldsymbol{\gamma}$ |  |
| S2510 | ..... | ............ | F4g? | ....... |  |
| S2514 | ..... | ........... | M1d | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta}^{\mathbf{1}}$ |  |
| S2515 | W095 | LkHL 26 | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{e}$ | h |
| S2521 | W096 | LkH\& 27 | K1 | $\mathrm{H} \alpha \beta \gamma$ | ........ |
| S2525 | ..... |  | G5d |  |  |
| S2534 | ..... | ........... | M3?g | H ${ }^{\text {d }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S2563 | ..... | LkHa 28 | M1g? |  |  |
| S2565 | W097 | ........... | M3d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \varepsilon^{\text {f }}$ | ..................... |
| S2566 | ..... | ........... | M5d | $\mathrm{H} \alpha \boldsymbol{\beta}^{\text {f }}$ | ................... |
| S2569 | W099 | ........... | F6d | ........... | ....................... |
| S2579 | W100 | ........... | A2 | . | A2IV' Ha reversal |
| S2586 | ..... | ........... | K7d | Ha |  |
| S2593 | W101 | ............ | M1d | H $\alpha$ | $\cdots$ |
| S2612 | W104 | - | A6 | ............ | A5IV ${ }^{\text {e }}$ |
| S2634 | ..... | LkHa 29 | K7d | H $\alpha$ | ..... |
| S2636 | ..... | ......... | M5d | Ho |  |
| S2644 | ..... | - | M3d | ............ |  |
| S2652 | W105 | LkH $\alpha 30$ | K4d | $\mathrm{Ca}, \mathrm{H} \alpha \boldsymbol{\beta} \boldsymbol{\gamma} \boldsymbol{6}$ e | ${ }^{\mathrm{h}}$, |
| S2659 | ..... | ........... | M3? | Ha ${ }^{\text {f }}$ | 5-pixel boxcar ${ }^{\text {k }}$ |
| S2662 | W106 | ........... | G9d |  |  |
| S2664 | . | ........... | K4d | H2 ${ }^{\text {f }}$ |  |
| S2666 | $\cdots$ | LkHa 31 | K4d | H $\alpha \boldsymbol{\beta} \boldsymbol{\gamma} \boldsymbol{\delta} \epsilon^{\boldsymbol{f}}$ | j |
| S2716 | W108 | ........... | F8d | $\mathrm{H} \boldsymbol{\alpha}$ | GOIII-IV ${ }^{\text {a }}$ |
| 52743 | ..... | LkHa 33 | K4 | Ca, $\mathrm{H} \alpha \beta \boldsymbol{\gamma \epsilon}$ | $j$ |
| S2753 | $\ldots$ | LkH $\alpha 34$ | K4d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\epsilon}$ | h |
| 52756 | .. | ........... | M1d | H $\alpha \beta^{\text {f }}$ |  |
| S2760 | W112 | ............ | A0 | ............ | $\mathrm{AOV}^{\text {e }}$ |
| S2761 | ... | ........... | M1d | Ca, $\mathrm{H} \alpha \beta \gamma \epsilon^{\text {f }}$ | ................... |
| S2763 | ..... | ......... | A7 | $\mathrm{Ha}^{\text {f }}$ | ................ |
| S2764 | ..... | ... | M3d | H $\alpha$ | , |
| 52777 | ... | ........... | K7?d | ..... | 3 -pixel boxcar ${ }^{\mathbf{k}}$ |
| S2809 | $\ldots$ | ........... | K4?d? | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {h, }}$, |
| S2827 | $\ldots$ | - | M5d |  | 9 |
| S2843 | W115 | LkHa 35 | K1d | $\mathrm{H} \alpha \beta$ | .......... |
| S2854 | W116 | ........... | F6d? | ............ | F5III-IV ${ }^{\text {e }}$ |
| S2861 | ..... | ........... | K7 | ............ | ..................... |
| S2862 | W117 | . | G3 | Ha ${ }^{\text {f }}$ |  |
| S2892 | W118 | .......... | F8d | ........... | . |

TABLE 5.6-Continued

| Source | Walker \# | LkH $\alpha$ \# | Type ${ }^{\text {a }}$ b | Lines ${ }^{\text {c }}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S2898 | ..... | ........... | K4d | H $\alpha \beta$ | .............. |
| S2920 | ..... | ........... | K4d | H $\alpha$ |  |
| S2926 | W120 | ............ | M1d | .... |  |
| S2943 | W122 | LkHa 38 | K1 | H $\alpha \beta^{\text {r }}$ | j |
| S2944 | W121 | ..... | G7d |  |  |
| S2945 | ... | LkH ${ }^{\text {c }} 39$ | M1d | ${ }^{\mathbf{H} \alpha \beta} \boldsymbol{\gamma}^{\boldsymbol{\delta}}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S2958 | W123 | LkHa 40 | K4d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{1}$ |  |
| S2969 | W124 |  | K4d | H $\alpha \beta^{\text {f }}$ |  |
| S2971 | ..... | ........... | M5d | ...... |  |
| S2984 | W125 | ........... | F7d | ........... | F6-G0; $\mathrm{III}-\mathrm{V}^{\text {e }}$ |
| S2989 | W126 | LkH 41 | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\varepsilon}$ | $\mathrm{h}^{\text {a }}$ |
| S2993 | W127 |  | M3d | $\mathrm{H} \boldsymbol{\alpha}$ |  |
| S3031 | ..... | ..... | M3d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\varepsilon}$ | j |
| S3044 | W129 | ........... | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ | h |
| S3048 | ..... | ........... | A0 | ............ | ...................... |
| S3052 | ..... | ........... | K1d | $\mathrm{H} \alpha$ | .................... |
| S3077 | ..... | ........... | M3d | $\mathrm{H}^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S3102 | ..... | ........... | M1d | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta} \boldsymbol{\gamma}^{\mathbf{r}}$ |  |
| S3108 | W132 | ............ | B8 |  |  |
| S3110 | ..... | ....... | M3d | $\mathrm{Ha}^{\text {r }}$ |  |
| S3122 | ..... | ...... | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \boldsymbol{\beta} \boldsymbol{\gamma} \boldsymbol{\sigma} \boldsymbol{\epsilon}$ | h |
| S3135 | ..... | LkH $\alpha 3$ | K1 | $\mathrm{H} \boldsymbol{\alpha}$ |  |
| S3141 | ..... | LkHa | M3d | Ho |  |
| S3160 | ..... | ....... | K4d | H $\alpha \beta \gamma \delta$ |  |
| S3170 | $\ldots$ | ........... | M1d | $\mathrm{H} \alpha \beta_{\gamma}$ |  |
| S3171 | W136 | ..... | K4 | $\mathrm{Ha}^{\text {f }}$ |  |
| S3174 | ..... | ......... | M3d |  |  |
| S3184 | W137 | ......... | B7 | ............ | B9 ${ }^{\text {i }}$ |
| S3197 | ..... | . | K7d | $\mathrm{H}^{\text {f }}$ |  |
| S3205 | $\ldots$ | ............ | K4d | $\mathrm{H} \alpha \boldsymbol{\beta} \boldsymbol{\gamma} \boldsymbol{\delta} \epsilon^{\text {f }}$ | ..................... |
| S3214 | $\ldots$ | ........... | K1 | $\mathrm{Ha}^{\text {f }}$ | ..................... |
| S3221 | ... | ........... | K4d | Ha | ..................... |
| S3225 | W138 | . | B9 |  | .................... |
| S3232 | W139 | LkH ${ }^{47}$ | K1 | Ha | ....................... |
| S3251 | ..... | .......... | G9d? | $\mathrm{H} \alpha \boldsymbol{\beta}^{\text {f }}$ | Luminosity class III-V |
| S3252 | ..... | ........... | K4d | $\mathrm{Ha}^{\text {f }}$ | ...................... |
| S3268 | ..... | ........... | K1 | Ha | .... |
| S3272 | ..... | ............ | A1 | ............ | ......... |
| S3276 | W146 | ......... | K1d | Ha ${ }^{\text {f }}$ | ..................... |
| S3282 | . | ........ | G5d | ..... | .................... |
| S3308 | ..... | ........... | K1d? | Ha ${ }^{\text {f }}$ | .................... |
| S3312 | W149 | ........... | G7 | . | ............... |
| S3317 | W148 | ... | G5d | Ha ${ }^{\text {f }}$ |  |
| S3323 | W151 | ........... | F2d? | $\mathrm{Ha}^{\text {f }}$ |  |
| S3351 | W153 | LkH $\alpha 4$ | K7d | $\mathrm{H} \alpha \boldsymbol{\beta}_{\boldsymbol{\gamma}}$ | j |
| S3358 | W. | ........... | M3d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma^{i}$ |  |
| S3363 | ..... | ... | M5d | $H \alpha \beta$ | h,q |
| S3365 | $\cdots$ | . ........ | G7?d? | ........... |  |
| S3376 | .... | ... | K4d | H ${ }^{\text {f }}$ | ................... |

TABLE 5.6-Continued

| Source | Walker \# | LkH ${ }^{\text {\# }}$ | Type ${ }^{\text {a,b }}$ | Lines ${ }^{\text {c }}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S3381 | ..... | ........... | A0 | ............ | .............. |
| S3392 | W156 | ........... | K1d | H ${ }^{\text {f }}$ | ........... |
| S3393 | W150 | ........... | K1 |  |  |
| S3395 | ..... | ........... | M5g? | ${ }_{\sim} \boldsymbol{\alpha} \beta_{\gamma}{ }^{\text {r }}$ | 3-pixel boxcar ${ }^{\text {k }}$, 9 |
| S3396 | W157 | - | B8 | ....... |  |
| S3398 | .... | ........... | K4d | H $\alpha$ | ............... |
| S3402 | W158 | ........... | F2d | ........... | A7-F0; IV-V' |
| S3408 | ..... | ........... | G7d | ............ |  |
| S3425 | $\ldots$ | LkH 49 | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\rho}$ | h |
| S3435 | $\ldots$ | ........... | K1 | $\mathrm{H}^{\mathbf{r}}$ |  |
| S3438 | W159 | - | B8 | Ha | AOV ${ }^{\text {e }}$ |
| S3441 | ..... | ........... | M3g | H ${ }^{\text {f }}$ |  |
| S3442 | ..... | ............ | M5d | H ${ }^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S3443 | ..... | ........... | K4d | H ${ }^{\text {f }}$ |  |
| S3448 | ... | ........... | M1d | $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta}^{\boldsymbol{r}}$ |  |
| S3452 | ..... | ......... | M5d | $\mathrm{H}^{\mathbf{r}}$ | 3-pixel boxcar ${ }^{\text {k }}$ ¢ 9 |
| S3470 | W160 |  | K4d | ${ }_{H} \alpha^{\boldsymbol{\beta}}$ |  |
| S3475 | ..... | LkH ${ }^{\text {c }} 51$ | K4d | $\mathrm{Ca}, \mathrm{H} \alpha \beta_{\boldsymbol{\gamma} \boldsymbol{\gamma} \boldsymbol{\delta}}$ | h |
| S3496 | W162 | ........... | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \boldsymbol{\gamma} \boldsymbol{e}$ | ..... |
| S3505 | ..... | . | K1 | ........... |  |
| S3510 | ... | ........... | M5d | H ${ }^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S3511 | W165 |  | A4 | Ho | Ho reversal |
| S3514 | W164 | LkH ${ }^{\text {c }} 3$ | G3d | $\mathrm{H} \boldsymbol{\alpha}$ |  |
| S3529 | ..... |  | M5g | $\mathrm{H} \alpha \beta \boldsymbol{\gamma} \delta^{\text {f }}$ |  |
| S3535 | ..... | LkH ${ }^{5} 5$ | M5d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \boldsymbol{\gamma} \boldsymbol{e}$ | h,q |
| S3536 | . $\cdot$ | ........... | G7d | $\mathrm{Ha}^{\mathbf{f}}$ |  |
| S3537 | ..... | ........... | K1?d | $\mathrm{H}^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S3546 | W168 | - | K4d | 1 | ................ |
| S3552 | ..... | LkHa 54 | K4 | Ca, $\mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\epsilon}$ | h |
| S3556 | ..... | .......... | K1 | Ha |  |
| S3568 | . | ......... | K4d | $\mathrm{Ha}^{\text {f }}$ |  |
| S3579 | ..... | ........... | M3g? | $\mathrm{H} \alpha \boldsymbol{\beta}^{\text {f }}$ | 10-pixel boxcar ${ }^{\text {k }}$ |
| S3580 | ..... | . | K4d | $\mathrm{H} \alpha \boldsymbol{\beta}^{\text {f }}$ |  |
| S3583 | W170 | ........... | M1d | $\mathrm{Ha}^{\text {f }}$ | .................... |
| S3584 | W169 | ........... | G5d | Ha |  |
| S3592 | ... | ........... | M1d | Har ${ }^{\text {r }}$ | j |
| S3602 | W175 | ........ | K4d | $\mathrm{Ha}^{\text {f }}$ |  |
| S3607 | W171 | ........ | G5d |  |  |
| S3611 | ..... | ........... | M3d |  |  |
| S3618 | W173 | ........... | K7d | Ha | ............... |
| S3628 | , | ....... | G5d | ........... | ............... |
| S3636 | W174 | ........ | K4d | $\mathrm{Ha}^{\text {f }}$ | ..... |
| S3646 | ..... | ......... | M3g | Ha | ..... |
| S3650 | ..... | ......... | K4d | ${ }_{H} \boldsymbol{\alpha} \boldsymbol{\beta}^{\boldsymbol{f}}$ |  |
| S3659 | ..... | ......... | M3d | H ${ }^{\circ}$ |  |
| S3666 | ..... | ...... | M3d | H ${ }_{\boldsymbol{\alpha}}$ |  |
| S3679 | $\ldots$ | ........... | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \varepsilon^{\text {f }}$ | j |
| S3683 | W179 | ......... | A0 | ........... | A0 spectroscopic binary ${ }^{\text {i }}$ |
| S3686 | ..... | ... | K4d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \mathrm{c}^{\text {f }}$ | h |

TABLE 5.6-Continued

| Source | Walker \# | LkH $\alpha$ \# | Type ${ }^{\text {a,b }}$ | Lines ${ }^{\text {c }}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S3690 | ..... | ........... | K4d | ${ }^{H} \alpha \beta \gamma^{\text {f }}$ | .................................. |
| S3692 | $\ldots$ | ............ | A4 | , | ................................. |
| S3693 | ..... | ........... | M3g | Ha | 3-pixel boxcar ${ }^{\text {k }}$ |
| S3698 | $\ldots$ | ........... | M5d | Ha ${ }^{\text {f }}$ |  |
| S3702 | ..... | ........... | K4d | H ${ }^{\text {f }}$ |  |
| S3712 | ..... | ........... | M3d | H $\alpha \beta \boldsymbol{\gamma}$ |  |
| S3719 | W181 | ............ | B8 |  | B9-A0; IV-Va B9 |
| S3725 | ..... | ........... | K7? | Ca, $\mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S3761 | ..... | ............ | M3d |  |  |
| S3767 | W184 | LkH $\mathrm{c}^{6}$ | K4d | $\mathrm{Ca}, \mathrm{H} \alpha \boldsymbol{\beta} \boldsymbol{\varepsilon}$ |  |
| S3772 | W185 | ........... | K4d | H ${ }^{\text {f }}$ | .................................. |
| S3776 | ..... | ............ | K4d | H $\alpha$ | ............................... |
| S3790 | W186 | ........... | M1d | H ${ }^{\text {a }}$ | ................................. |
| S3792 | .... | ........... | M1d? | Ho | ................................ |
| S3796 | . | ............ | M1d | H ${ }^{\text {a }}$ | - |
| S3799 | …' | LkH 61 | K4 | Ca, $\mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\varepsilon}$ | $h$ |
| S3802 | W189 | ....... | F5d | ........... | ................................... |
| S3806 | ... | ........... | M1g? | ........... | 3-pixel boxcark |
| S3810 | . | ........... | M3? | …........ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S3811 | ..... | ........... | M7 | Ca, $\mathrm{H} \alpha \beta_{\gamma} \boldsymbol{\delta}^{\text {c }}$ | ${ }_{\mathrm{h}, \mathrm{q}, \mathrm{r}}$ |
| S3812 | $\ldots$ | LkH $\alpha 6$ | K4d | Ca, $\mathrm{H} \alpha \beta \gamma \delta \varepsilon^{\text {f }}$ | h |
| S3813 | W190 | ......... | F9d | ........... | $\ldots$ |
| S3815 | ..... | ........... | K7d |  | j |
| S3834 | ..... | ........... | M1d | ${ }^{H} \alpha \beta^{1}$ | j |
| S3844 | W191 | - | K4d | $\mathrm{H} \alpha$ |  |
| S3861 | ..... | ............ | M5d? |  | 9 |
| S3866 | ..... | ........... | M3d | $\mathrm{H} \alpha \boldsymbol{\beta} \boldsymbol{\gamma} 6 \mathrm{c}^{\text {f }}$ | h |
| S3869 | ..... | ........... | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \boldsymbol{\gamma} \boldsymbol{\delta \varepsilon}$ | h |
| S3871 | ..... | ............ | K1 | $\mathrm{H} \alpha$ |  |
| S3872 | ..... | LkH $6^{6}$ | M1d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \varepsilon^{\text {f }}$ | h |
| S3873 | W193 | ........... | A8 | ........... | A7III ${ }^{\text {e }}$ |
| S3875 | ... | ........... | G1d | ........... | ................................. |
| S3878 | ... | . | M5d | $\mathrm{H}_{\alpha} \beta^{\text {f }}$ | 3 -pixel boxcar ${ }^{\text {k }}$ |
| S3880 | W194 | - | G5d | ...... |  |
| S3884 | ..... | ........... | M1g | $\mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ | h |
| S3889 | ..... | ............ | K4d | $\mathrm{H} \alpha \beta \gamma^{f}$ | $j \quad 1{ }^{j}$ |
| S3895 | ..... | ........ | M1?g | Ca, $\mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta} \boldsymbol{\gamma} \boldsymbol{\delta} \boldsymbol{\varepsilon}$ | 3-pixel boxcar ${ }^{\text {j,k }}$ |
| S3897 | W195 | .... | F9d |  |  |
| S3913 | ..... | ...... | M1d | . |  |
| S3915 | ..... | ........... | K1 | $\mathrm{H} \alpha \beta^{\text {r }}$ | - |
| S3917 | . | - | M3d | $\mathrm{H} \alpha \beta^{\text {f }}$ |  |
| S3920 | W197 | LkHa 66 | K?g? | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{e}$ | j,n |
| S3923 | . | LkH $\alpha 65$ | K4d | $\mathrm{H} \alpha \beta \boldsymbol{\gamma} \boldsymbol{\delta} \boldsymbol{\epsilon}$ | j ${ }^{\text {j }}$ |
| S3947 | ..... | ........... | G7? g ? | $\mathrm{H} \alpha$ | Luminosity class III-V |
| S3956 | .... | ........... | M3d | $\mathrm{Ca}, \mathrm{H} \boldsymbol{\alpha} \boldsymbol{\beta} \boldsymbol{\gamma} \epsilon^{\text {f }}$ | ${ }^{\text {h }}$ |
| S3963 | . | ............ | M3d | Ho | ................................. |
| S3964 | .. | ... | M1d | Ha ${ }^{\text {f }}$ | - |
| S3969 | ... | .......... | M1d | $\mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ |  |
| S3973 | ..... | LkH $\alpha 67$ | M1g? | $H \alpha \beta \gamma \delta^{\text {f }}$ | 3 -pixel boxcar ${ }^{\text {k }}$ |

TABLE 5.6-Continued

| Source | Walker \# | LkH ${ }^{\text {\# }}$ | Type ${ }^{\text {a }}$ b | Lines ${ }^{\text {c }}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S3974 | W199 | LkH ${ }_{\text {c }} 68$ | K4 | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\epsilon}$ | h |
| S3979 | ..... | ............ | M1d? | $\mathrm{H} \alpha \beta \boldsymbol{\gamma} \boldsymbol{\delta} \boldsymbol{\epsilon} \epsilon^{f}$ | . $\cdot$.................................... |
| S3982 | ..... | ............ | M5d | Ha $\beta^{\mathbf{f}}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S3990 | ..... | ......... | K1d | Ha ${ }^{\text {f }}$ |  |
| S3995 | *.... | ............ | M5d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \boldsymbol{\gamma} \delta \epsilon^{\text {f }}$ | h |
| S4003 | ..... | LkH 66 | M3d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \epsilon$ | h |
| S4005 | ..... | ........... | M3d | $\mathrm{H} \alpha \beta \gamma^{\mathrm{f}}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S4011 | ..... | ............ | K1 | $\mathrm{H} \alpha^{\text {f }}$ |  |
| S4015 | W203 | . ........... | G5d | ............ | ................................... |
| S4016 | ..... | ............ | K4d | H ${ }^{\text {f }}$ | ...................................... |
| S4037 | ..... | ............ | M1g | $\mathrm{H} \alpha$ | 5-pixel boxcar ${ }^{\text {k }}$ |
| S4038 | ..... | ........... | K1d | Ha |  |
| S4053 | ..... | ............ | M1d | $\mathrm{H} \alpha \beta \gamma \delta \epsilon^{\text {f }}$ | j |
| S4062 | W204 | LkHa 70 | K4d | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \boldsymbol{\epsilon}$ | h |
| S4073 | ..... | ............ | M3d? | $\mathrm{H}^{\mathbf{i}}{ }^{\mathbf{i}}$ | 10-pixel boxcar ${ }^{\text {k }}$ |
| S4078 | ..... | ............ | K4d | H ${ }^{\text {f }}$ | ....................................... |
| S4082 | ..... | . ......... | K7d | Ha | . |
| S4087 | ....' | ........... | K4d | $H \alpha$ | ....................................... |
| S4090 | W206 | * * * * * . . . * | B6 | ............ | B8 optical binary ${ }^{\text {i }}$ |
| S4112 | ...... | ........... | K4d | ........... | ...................................... |
| S4121 | ..... | LkHa 71 | K4d | $\mathrm{Ha}^{\text {f }}$ |  |
| S4124 | ..... | ........... | M3d | $H \alpha \beta$ | .................................... |
| S4126 | ..... | ............ | M3d | $\mathrm{H} \alpha \beta^{\boldsymbol{f}}$ | .. .................................... |
| S4133 |  | * * * * * * * | M1d | Ha |  |
| S4136 | W208 | ............ | G5d | H $\alpha$ | ....................................... |
| S4146 | ..... | ............ | K7 | Ha | . ....................................... . . |
| S4176 | W209 | ........... | F4d | ............ |  |
| S4194 | ..... | ........... | K4d | $H \alpha$ | ......................................... |
| S4200 | ..... | ........... | M3d | $H \alpha \beta \gamma^{f}$ | ..................................... |
| S4201 | ..... | ............ | M5d | $\mathrm{H} \boldsymbol{\alpha}$ | ....................................... |
| S4210 | ..... | ............ | M1d | $\mathrm{H} \alpha \beta_{\gamma}{ }^{\text {f }}$ | 3-pixel boxcar ${ }^{\mathbf{k}}$ |
| S4212 | W210 | ............. | G7d? | ............ | ..................................... |
| S4214 | ..... | ............ | M1g? | $\mathrm{H} \alpha \beta$ | ..................................... |
| S4220 | ..... | ........... | M3g | $\mathrm{H} \alpha$ | 5-pixel boxcar ${ }^{\text {k }}$ |
| S4229 | ..... | ........... | M5d | $H \alpha \beta \boldsymbol{\gamma} \boldsymbol{\delta}$ | j |
| S4236 | ..... |  | M1d | ............ |  |
| S4238 | W211 | ........... | A6? | ............ | 3-pixel boxcar ${ }^{\mathbf{k}}$ |
| S4281 | ..... | .......... | M1d | $\mathrm{H} \alpha$ | ...................................... |
| S4282 | ..... |  | F5d | ............ | ..................................... |
| S4292 | ..... | ........... | M1d | $\mathrm{H} \alpha \beta \boldsymbol{\gamma} \boldsymbol{\delta} \epsilon^{\text {f }}$ | j |
| S4296 | ..... | ........... | K1 | $\mathrm{H} \alpha$ | ..................................... |
| S4307 | ..... | ............ | M3?g? | Ha ${ }^{\text {f }}$ | 3-pixel boxcar ${ }^{\mathbf{k}}$ |
| S4314 | ..... | ............ | K4d | ............ | .................................... |
| S4363 | ....' | ............. | K7d |  | ................................................ |
| S4365 | W214 | ............ | G5d | Ha ${ }^{\text {f }}$ | ..................................... |
| S4392 | W213 | ............ | A1 | ............ | ...................................... |
| S4433 | W217 | LkHa 72 | K1 | $\mathrm{Ca}, \mathrm{H} \alpha \beta \gamma \delta \epsilon$ | h |
| S4473 | ..... |  | M3g? | H ${ }^{\text {a }}$ | 3-pixel boxcar ${ }^{\text {k }}$ |
| S4494 | W218 | ............ | K4d | H ${ }^{\text {f }}$ | ..................................... |

TABLE 5.6-Continued

| Source | Walker \# | LkH $\alpha$ \# | Type ${ }^{\text {a }}$ b | Lines ${ }^{\text {c }}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S4508 | W219 | ............ | K4d | H ${ }^{\text {f }}$ |  |
| S4675 | W223 | ... | F4d | ...... | ....................... |
| S4737 | W225 | .......... | G3d | ........ | Fe I 6495§ in emission? |
| , | ..... | LkHa 06 | K7d | Ca, $\mathrm{H} \alpha \beta^{\boldsymbol{\gamma}} \boldsymbol{\delta} \boldsymbol{\epsilon}$ | , |
| ..... | W032 | ........... | A3 | ............ | Classification uncertain |
| .... | W034 | ......... | F58? | ............ | ................... |
| ..... | W060 | ....... | FOd | ........... | ....................... |
| ..... | W087 | ... | A3 | ............ | ...................... |
| ..... | W091 | ...... | G3d | ............ | ..................... |
| ..... | W094 | .... | F5d | ............ | ...................... |
| ..... | W098 | $\cdots$ | F8d | ........... | ....................... |
| ..... | W114 | ............ | F6d | ........... | ................. |
| ..... | W128 | ........... | A4 | ........... | .................... |
| $\cdots$ | W172 | . | B8 | . | ......... |
| ..... | W180 | . | F6 | .... | ...... |
| ..... | W182 | ... | A1 | ... | A2V ${ }^{\text {e }}$ |
| ..... | W196 | ... | F9d | . | F6-F8 ${ }^{\text {e }}$ |
| ..... | W221 | ... | F5d | ... |  |

[^0]TABLE 5.7
Spectroscopic Data: Equivalent Widths

| Source | $\begin{aligned} & H \alpha^{\mathrm{a}} \\ & (\AA) \end{aligned}$ | $\mathrm{H} \beta$ <br> ( $\AA$ | $\mathrm{H} \boldsymbol{\gamma}^{\mathrm{b}}$ <br> (A) | $\begin{aligned} & \mathrm{H} \delta \\ & (\AA) \end{aligned}$ | $\begin{aligned} & H \epsilon^{c} \\ & (\AA) \end{aligned}$ | $\begin{aligned} & \text { Ca II Kd } \\ & (A) \end{aligned}$ | $[\mathrm{N} I I]^{e}$ $(\AA)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S0131 | 2.1 | 0.6 | . $\cdot$ | 0.8 | . $\cdot$ | . $\cdot$ | . . |
| S0422 | 12.8 | $16.6{ }^{\text {f }}$ | 16.5 | 18.9 | 15.8 | 1.5 | . $\cdot$ |
| S0445 | 12.6 | $15.8{ }^{\text {f }}$ | 16.1 | 17.2 | 15.3 | 0.6 | $\cdots$ |
| S0710 | 4.6 | 6.8 | 7.0 | 7.9 | 8.8 | $7.1{ }^{\text {f }}$ | -•• |
| S0921 | 13.4 | $17.0{ }^{\text {f }}$ | 16.3 | 21.4 | 16.8 | 1.6 | . $\cdot$ |
| S0967 | 6.3 | 4.0 | 1.0 | 0.5 | 16.9 | 15.1 | 2.3 |
| S1066 | 5.9 | $1.8{ }^{\text {f }}$ | 1.3 | 2.8 | 15.2 | 14.7 | 1.5 |
| S1117 | -1.6 | 2.0 | 0.6 | 1.5 | $8.4{ }^{\text {f }}$ | $9.8{ }^{\text {f }}$ | -0.6 |
| S1129 | 9.4 | $14.4{ }^{\text {f }}$ | 13.8 | 16.3 | 14.5 | 3.9 | $\cdots$ |
| S1212 | -27.4 | -8.0 | -7.5 | -11.5 | -17.4 | -11.8 | ... |
| S1270 | 1.8 | 0.6 | 0.6 | 1.2 | 12.2 | 15.6 | . |
| S1276 | 7.98 | $11.9{ }^{\text {f }}$ | $11.9{ }^{\text {f }}$ | $14.1{ }^{\text {f }}$ | 12.5 | 2.9 | . $\cdot$ |
| S1309 | -25.0 | ... | ... | ... | ... | ... | - |
| S1315 | 5.3 | 0.8 | 1.1 | $\cdots$ | $\cdots$ | $\cdots$ | 2.5 |
| S1316 | 5.5 | 6.1 | 3.7 | 4.8 | 16.1 | 13.1 | 1.9 |
| S1364 | 5.7 | ... | ... | ... | ... | ... | 2.5 |
| S1369 | -2.5 | -1.3 | -0.5 | -** | -13.3 | -16.9 | ... |
| S1382 | 30.4 | 26.5 | $\cdots$ | -•• | ... | ... | 38.1 |
| S1389 | 18.0 | 3.3 | 1.4 | 3.7 | 13.9 | 19.3 | 9.3 |
| S1407 | -22.4 | ... | ... | ... | ... | ... | ... |
| S1447 | 14.9 | 10.3 | ... | ... | -•• | $\cdots$ | 9.5 |
| S1478 | 5.2 | 6.4 | 6.4 | 7.6 | 6.3 | ... | ... |
| S1499 | -1.8 | ... | ... | ... | ... | ... | ... |
| S1500 | 5.8 | 1.7 | 0.4 | . | . . . | . $\cdot$ | 3.6 |
| S1513 | -2.3 | -1.9 | ... | $\cdots$ | $\cdots$ | $\cdots$ | ... |
| S1518 | 16.7 | 4.1 | ... | ... | ... | ... | 10.6 |
| S1529 | -24.6 | -10.0 | -12.3 | -12.7 | -10.3 | -17.2 | ... |
| S1562 | -1.9 | 3.0 | 1.8 | 2.0 | $8.8{ }^{\text {f }}$ | $9.2{ }^{\text {f }}$ | -2.1 |
| S1566 | -65.6 | -13.4 | -21.3 | -12.9 | -69.9 | -47.8 | 4.6 |
| S1590 | -106.0 | -29.9 | ... | . $\cdot$ | . $\cdot$ | . $\cdot$ | -37.0 |
| S1598 | -11.4 | ... | -•• | $\cdots$ | $\cdots$ | -•• | -2.0 |
| S1606 | -10.1 | -2.1 | 0.9 | $\cdots$ | . $\cdot$ | $\cdots$ | ... |
| S1621 | -18.0 | -9.5 | ... | . ${ }^{\text {c }}$ | . . | $\cdots$ | ... |
| S1629 | -35.5 | -4.7 | -2.8 | -1.8 | -5.9 | -9.5 | -•* |
| S1637 | 1.8 | ... | -•• | -•• | . $\cdot$ | $\cdots$ | ... |
| S1645 | -2.6 | -1.1 | -0.5 | -0.6 | - | $\cdots$ | $\cdots$ |
| S1648 | -52.2 | -4.5 | ... | $\cdots$ | ... | $\cdots$ | ... |
| S1665 | 14.4 | $17.7{ }^{5}$ | 17.4 | 15.7 | 18.1 | 5.6 | -•• |
| S1675 | -15.2 | -15.0 | -20.2 | -23.3 | -39.3 | -30.0 | -6.2 |
| S1702 | -4.5 | -1.6 | ... | ... | ... | $\cdots$ | $\cdots$ |
| S1734 | 14.2 | 10.7 | ... | $\cdots$ | ... | $\cdots$ | 3.3 |
| S1758 | -9.5 | $\cdots$ | . $\cdot$. | -• | -•• | ... | -3.6 |
| S1760 | -13.8 | -4.7 | -9.8 | -18.6 | -6.9 | -11.1 | -4.5 |
| S1769 | -0.3 | 4.2 | 0.8 | 2.9 | 14.9 | 13.8 | ... |
| S1776 | 4.3 | 6.2 | 3.9 | 5.1 | $8.1{ }^{\text {f }}$ | $7.1{ }^{\text {f }}$ | -•• |
| S1796 | 35.8 | 24.5 | 12.8 | 3.4 | -•• | $\cdots$ | 11.4 |
| S1804 | -1.4 | $0.3{ }^{\text {f }}$ | 0.7 | 0.5 | 11.7 | $10.1{ }^{\text {f }}$ | -1.0 |
| S1806 | -0.3 | 0.9 | 0.4 | 0.6 | 12.8 | 15.6 | ... |
| S1820 | -0.2 | 10.0 | 6.2 | ... | -42.3 | . $\cdot$ | $\cdots$ |

TABLE 5.7-Continued

| Source | $\begin{gathered} H \alpha^{\mathbf{a}} \\ (\AA) \\ \hline \end{gathered}$ | H $\beta$ <br> (A) | $\begin{aligned} & \mathrm{H} \boldsymbol{\gamma}^{\mathrm{b}} \\ & (\mathrm{~A}) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \delta \\ & (\AA) \end{aligned}$ | $\begin{aligned} & H \varepsilon^{e} \\ & (\AA) \end{aligned}$ | Ca II $\mathrm{K}^{\mathrm{d}}$ <br> (A) | $[\mathrm{N} \mathrm{II}]^{e}$ <br> (A) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S1829 | 5.0 | $6.2{ }^{\text {f }}$ | 5.8 | 7.9 | 8.8 | 7.7 | $\cdots$ |
| S1896 | -143.1 | -45.0 | -26.3 | -21.4 | -38.2 | -38.8 | $\cdots$ |
| S1898 | -5.1 | -2.1 |  | . | ... | ... | -1.8 |
| S1901 | 5.3 | 5.1 | 5.5 | 4.9 | ... | $\ldots$ |  |
| S1932 | -13.5 | -14.7 | ... | $\cdots$ | $\cdots$ | $\cdots$ | -3.2 |
| S1937 | -15.4 | $\cdots$ | $\cdots$ | ... | $\cdots$ | ... | -4.9 |
| S1939 | 4.2 | 4.9 | 4.5 | 4.5 | 5.0 | 0.6 | ... |
| S1947 | 3.3 | 6.1 | 5.4 | 5.4 | 7.1 | . $\cdot$ | $\ldots$ |
| S1950 | 2.1 | 1.8 | 0.8 | 1.3 | 15.1 | 17.1 | $\cdots$ |
| S1960 | 3.0 | 5.0 | 3.7 | 2.9 | 10.6 | 11.3 | ... |
| S1973 | -9.6 | -3.4 | -4.7 | -6.0 | ... | $\cdots$ | $\cdots$ |
| S1976 | $5.8{ }^{\text {f }}$ | $11.3{ }^{\text {f }}$ | $9.7{ }^{\text {f }}$ | $\ldots$ | ... | ... | $\ldots$ |
| S1996 | -58.3 | -41.1 | -77.3 | -35.3 | -24.9 | -28.3 | -11.8 |
| S2006 | 2.1 | 5.8 | 1.3 | 2.1 | 11.4 | $9.9{ }^{\text {f }}$ | ... |
| S2007 | 2.4 | 2.1 | 2.4 | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ |
| S2008 | ... | ... | $\cdots$ | ... | ... | $\cdots$ | $\cdots$ |
| S2009 | 6.1 | 7.2 | 7.4 | 8.9 | 8.0 | ... | $\ldots$ |
| 52022 | -12.2 | -12.7 | -22.9 | -28.0 | -19.3 | -39.2 | -4.1 |
| S2038 | -1.9 | -1.5 | ... | $\cdots$ | $\cdots$ | , |  |
| S2055 | -60.1 | -21.9 | -19.9 | ... | ... | ... | -24.6 |
| S2068 | -1.4 |  | . | $\ldots$ | 12.5 | 12.9 | -1.2 |
| S2079 | -103.9 | -27.6 | -19.9 | -16.6 | -32.0 | -22.0 | -11.2 |
| S2104 | -32.8 | -13.6 | -9.1 | ... | ... | ... | -12.3 |
| 52113 | -8.6 | -2.1 | ... | ... | ... | $\ldots$ | -1.8 |
| S2116 | 1.6 | ... | $\cdots$ | $\cdots$ | $\ldots$ | $\ldots$ | $\ldots$ |
| S2117 | -4.9 | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | -3.8 |
| S2146 | -23.3 | $\cdots$ | $\cdots$ | $\cdots$ | ... | ... | -2.4 |
| S2162 | -24.4 | -9.8 | -8.9 | -3.9 | -10.2 | -5.3 | ... |
| S2163 | -9.3 | $1.8{ }^{\text {f }}$ | 2.2 | 2.0 | 9.5 | $10.5{ }^{\text {f }}$ | $\ldots$ |
| S2167 | 2.9 | ... | $\cdots$ | $\cdots$ | 9. | 1. | 2.5 |
| S2171 | -5.0 | -2.5 | -3.0 | $\ldots$ | ... | $\cdots$ | -0.9 |
| S2173 | -381.0 | -81.5 | -31.4 | -25.6 | -56.0 | -71.0 | $\cdots$ |
| S2190 | -11.9 | ... | $\ldots$ | ... | $\cdots$ | ... | -9.0 |
| S2191 | -13.6 | ... | ... | ... | $\ldots$ | $\cdots$ | ... |
| S2228 | -86.9 | -8.9 | -10.3 | -5.3 | -0.1 | -7.0 | ... |
| S2230 | 11.6 | $\ldots$ | $12.2{ }^{\text {f }}$ | $14.4{ }^{\text {f }}$ | 15.1 | 3.2 | ... |
| S2234 | -5.8 | 4.1 | 2.7 | 2.1 | $6.9{ }^{\text {f }}$ | $7.9{ }^{\text {f }}$ | $\cdots$ |
| S2253 | -1.6 | $\ldots$ | $\ldots$ | $\ldots$ | $12.2{ }^{\text {f }}$ | 15.8 | -1.6 |
| S2268 | 3.7 | $\ldots$ | $\ldots$ | $\ldots$ | $\cdots$ | $\cdots$ | 6.4 |
| S2279 | 4.0 | 3.8 | 2.1 | 2.8 | 11.8 | 13.6 | $\cdots$ |
| S2280 | -47.4 | -13.5 | -13.2 | -8.5 | -11.7 | -7.7 | -4.7 |
| S2284 | -2.3 | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | ... | ... |
| S2289 | 4.9 | 6.6 | 6.8 | 7.8 | 7.0 | $\ldots$ | $\ldots$ |
| S2313 | -1.9 | $3.6{ }^{\text {f }}$ | $4.6{ }^{7}$ | $7.8{ }^{\text {f }}$ | $\cdots$ | $\cdots$ | $\cdots$ |
| S2322 | -6.5 | ... | ... | $\cdots$ | $\ldots$ | $\cdots$ | -1.9 |
| S2325 | -295.2 | $\cdots$ | $\cdots$ | $\cdots$ | $\ldots$ | $\cdots$ | -131.2 |
| S2359 | -2.4 |  | ... | ... | $9.6{ }^{\text {f }}$ | 15.9 | $\cdots$ |
| S2364 | -43.2 | $6.6{ }^{\text {f }}$ | $7.3^{\text {f }}$ | $8.3{ }^{\text {f }}$ | $7.9{ }^{\text {f }}$ | 1.0 | $\ldots$ |
| S2374 | 11.6 | 14.0 |  | 12.5 | 14.8 | 6.6 | $\cdots$ |

TABLE 5.7-Continued

| Source | $\begin{aligned} & \mathrm{H} \alpha^{\mathrm{a}} \\ & (\AA) \end{aligned}$ | $\begin{aligned} & H \beta \\ & (\dot{\AA}) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \gamma^{\mathrm{b}} \\ & (\AA) \end{aligned}$ | $\begin{aligned} & H \delta \\ & (\AA) \end{aligned}$ | $\begin{gathered} H \epsilon^{\mathbf{c}} \\ (\AA) \end{gathered}$ | Ca II K ${ }^{\text {d }}$ <br> (A) | $[\mathrm{N} \mathrm{II}]^{e}$ $(\AA)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S2377 | -4.4 | $\cdots$ | -•• | -•• | $11.4{ }^{\text {f }}$ | 14.3 | -2.2 |
| S2387 | 3.3 | ... | ... | . $\cdot$ | . | ... | ... |
| S2390 | -8.2 | -3.4 | -3.9 | ... | ... | ... | -1.3 |
| S2395 | ... | $\cdots$ | -•• | -•• | -• | -•• | . $\cdot$ |
| S2405 | -2.6 | . | ... | ... | 12.0 | 15.0 | -2.5 |
| S2418 | -53.4 | -1.7 | ... | -•• | . | ... | ... |
| S2424 | -9.6 | -8.9 | -3.8 | ... | $\cdots$ | $\cdots$ | -3.5 |
| S2448 | -1.3 | $\cdots$ | ... | . $\cdot$ | $6.1{ }^{1}$ | $7.7{ }^{\text {f }}$ | -0.4 |
| S2449 | -14.7 | -16.8 | ** | -•• | ... | ... | -3.8 |
| S2495 | -0.2 | ... | - $\cdot$ | - | 11.3 | 14.0 | ... |
| S2506 | -23.1 | -7.8 | -5.6 | -16.7 | ... | ... | $\cdots$ |
| S2510 | 9.2 | 9.4 | 8.9 | 10.9 | 20.8 | 7.8 | . . |
| S2514 | -3.1 | -2.4 | ... | . . | ... | . $\cdot$ | -0.7 |
| S2515 | -56.9 | -26.6 | -25.1 | -26.7 | -36.7 | -12.5 | $\cdots$ |
| S2521 | -19.4 | -3.4 | -2.8 | . ${ }^{\text {a }}$ | ... | ... | . $\cdot$ |
| S2525 | 2.7 | $1.4{ }^{\text {f }}$ | ... | 1.5 | 10.1 | 11.9 | -• |
| S2534 | -19.0 | ... | ... | ... | ... | ... | $\cdots$ |
| S2563 | -91.0 | -22.9 | -35.4 | -11.9 | -22.4 | -19.2 | -•• |
| S2565 | -9.3 | -5.9 | -6.2 | -3.1 | -12.3 | -4.8 | -3.6 |
| S2566 | -7.2 | -3.8 | $\cdots$ | $\cdots$ | ... | ... | -2.3 |
| S2569 | 4.2 | 6.1 | 5.8 | 3.5 | 9.3 | 8.9 | ... |
| S2579 | $5.2{ }^{\text {f }}$ | $12.3{ }^{\text {f }}$ | $12.6{ }^{\text {f }}$ | $14.4{ }^{\text {f }}$ | 12.9 | 1.9 | -•• |
| S2586 | -1.6 | ... | ... | $\cdots$ | ... | . $\cdot$ | . |
| S2593 | -2.5 | -1.0 | $\cdots$ | ... | . | . $\cdot$ | . . |
| S2612 | $7.6{ }^{\text {f }}$ | $13.2{ }^{\text {f }}$ | $11.8{ }^{\text {f }}$ | $14.3{ }^{\text {f }}$ | 12.4 | 3.4 | $\cdots$ |
| S2634 | -40.2 | -1.9 | ... | ... | ... | ... | -•• |
| S2636 | -0.2 | -•• | $\cdots$ | ... | ... | $\cdots$ | -•• |
| S2644 | -0.2 | . | . | . $\cdot$ | $\cdots$ | $\cdots$ | . $\cdot$ |
| S2652 | -53.8 | -18.7 | -17.4 | -15.5 | -19.9 | -8.1 | -•• |
| S2659 | -10.2 | . . | ... | ... | ... | ... | -17.4 |
| S2662 | 0.3 | 2.9 | 0.9 | 1.9 | 11.4 | 14.2 | -0.9 |
| S2664 | -2.2 | ... | . ${ }^{\text {- }}$ | ... | 13.3 | 13.3 | -1.5 |
| S2666 | -15.9 | -3.6 | -4.4 | -3.0 | -4.5 | $\cdots$ | -1.6 |
| S2716 | -0.9 | 4.4 | 3.2 | 2.4 | 7.78 | $8.2{ }^{\text {f }}$ | $\cdots$ |
| S2743 | -25.1 | -6.1 | -4.0 | -1.3 | -5.2 | -8.1 | -•• |
| S2753 | -39.8 | -9.8 | -7.8 | -8.2 | -9.6 | -3.9 | $\cdots$ |
| S2756 | -5.1 | -4.0 | . $\cdot$ | . ${ }^{\text {c }}$ | . $\cdot$ | $\cdots$ | -2.2 |
| S2760 | 10.0 | $13.3{ }^{\text {f }}$ | 13.2 | $13.5{ }^{\text {f }}$ | 12.5 | 0.5 | ... |
| S2761 | -15.3 | -6.3 | -3.0 | ... | -10.2 | -8.1 | -3.5 |
| S2763 | -3.3 | $10.0{ }^{\text {f }}$ | $10.0{ }^{\text {f }}$ | $12.3{ }^{\text {f }}$ | $10.7{ }^{\text {f }}$ | 3.3 | -1.7 |
| S2764 | -1.8 | -1.8 | $\cdots$ | $\cdots$ | . $\cdot$ | ... | -•• |
| S2777 | -0.5 | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | 5 |
| S2809 | -164.1 | -46.7 | -38.7 | -38.6 | -57.3 | -132.9 | -105.9 |
| S2827 | -206.7 | -39.1 | -15.2 | -5.2 | -111.1 | -204.9 | . $\cdot$. |
| S2843 | -18.7 | -2.4 | . ${ }^{\text {c }}$ | ... | $10.7{ }^{\text {r }}$ | $12.6{ }^{\text {f }}$ | -•• |
| S2854 | 3.8 | 5.8 | 5.6 | 3.8 | 9.6 | 9.2 | $\cdots$ |
| S2861 | 1.6 | . . | . . | *. | $\cdots$ | . ${ }^{\text {a }}$ | ... |
| S2862 | -1.2 | 4.7 | 2.9 | 2.6 | 10.0 | $10.4{ }^{\text {f }}$ | -1.5 |
| S2892 | 3.4 | 4.6 | 4.2 | 2.8 | 7.9 f | 8.7 | . . |

TABLE 5.7-Continued

| Source | H $\alpha^{a}$ <br> ( $\AA$ ) | H $\beta$ <br> ( $\AA$ ) | H $\boldsymbol{\gamma}^{\text {b }}$ <br> (A) | $\begin{aligned} & \mathrm{H} \delta \\ & (\AA) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \epsilon^{\mathrm{c}} \\ & (\AA) \end{aligned}$ | Ca II $\mathrm{K}^{\mathrm{d}}$ <br> ( $\AA$ ) | $[\mathrm{N} I]^{\mathrm{e}}$ $(\AA)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S2898 | -5.0 | -2.1 | -1.0 | $\cdots$ | $\cdots$ | $\ldots$ | $\cdots$ |
| S2920 | -3.7 | -1.5 | ... | $\cdots$ | . | . | $\cdots$ |
| S2926 | -0.1 | ... | $\cdots$ | $\ldots$ | $11.1{ }^{\text {f }}$ | 12.3 | $\ldots$ |
| S2943 | -42.9 | -4.5 | $\cdots$ | $\ldots$ |  | . | -8.9 |
| S2944 | 0.9 | $1.7{ }^{\text {f }}$ | 0.8 | 0.9 | $6.2{ }^{\text {f }}$ | $5.6{ }^{\text {f }}$ | $\cdots$ |
| S2945 | -108.5 | -46.0 | -18.5 | -63.0 | $\cdots$ | $\cdots$ | -9.2 |
| S2958 | -82.2 | -28.5 | -17.9 | -12.8 | -24.6 | -15.2 | ... |
| S2969 | -7.6 | -2.4 | ... | ... | $\cdots$ | ... | -2.5 |
| S2971 | 1.4 | ... | ... | $\cdots$ | $\cdots$ | $\cdots$ | ... |
| S2984 | $1.9{ }^{\text {f }}$ | $2.0{ }^{\text {f }}$ | 3.4 | 2.4 | $7.7{ }^{\text {f }}$ | $7.4{ }^{\text {f }}$ | $\cdots$ |
| S2989 | -83.8 | -17.6 | -20.9 | -29.4 | -51.4 | -11.7 | $\cdots$ |
| S2993 | -2.2 | ... | ... | $\cdots$ | ... | ... | $\cdots$ |
| S3031 | -15.9 | -3.0 | -3.5 | -5.3 | -11.5 | -10.7 | $\cdots$ |
| S3044 | -17.9 | -5.6 | -7.1 | -3.8 | -11.9 | -7.4 | -0.9 |
| S3048 | $6.9{ }^{\text {f }}$ | $13.3{ }^{\text {f }}$ | 12.5 | $13.8{ }^{\text {f }}$ | 12.2 | 1.1 | . |
| S3052 | -1.5 | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | ... |
| S3077 | -10.2 | ... | $\ldots$ | ... | ... | $\ldots$ | -4.5 |
| S3102 | -6.0 | -4.6 | -5.9 | ... | ... | $\cdots$ | -1.6 |
| S3108 | 8.5 | $10.6{ }^{\text {f }}$ | 10.5 | 12.0 | 10.8 | 0.2 | . |
| S3110 | -24.7 | ... | ... | ... | ... |  | -8.7 |
| S3122 | -21.8 | -10.8 | -14.3 | -12.4 | -30.6 | -8.0 | $\cdots$ |
| S3135 | -8.4 | 2.0 | 0.8 | $\cdots$ | ... | $\cdots$ | $\cdots$ |
| S3141 | -11.9 | $\cdots$ | ... | ... | ... | $\ldots$ | ... |
| S3160 | -17.1 | -6.4 | -5.9 | -4.7 | ... | ... | ... |
| S3170 | -3.9 | -16.5 | -4.7 | ... | . | $\cdots$ | ... |
| S3171 | -6.6 | -1.7 | 0.5 | ... | ... | $\ldots$ | -2.4 |
| S3174 | -33.8 | -20.6 | -49.6 | -66.4 | -134.6 | -46.3 | ... |
| S3184 | 7.3 | $9.4{ }^{\text {r }}$ | 9.6 | 11.0 | 9.6 | 0.2 | $\cdots$ |
| S3197 | -2.8 | -1.4 | ... | $\ldots$ | $\cdots$ | ... | -0.7 |
| S3205 | -25.6 | -5.6 | -6.7 | -3.0 | -4.6 | $4.3{ }^{\text {f }}$ | -1.2 |
| S3214 | -2.3 | ... | $\cdots$ | 0.7 | $9.3{ }^{\text {f }}$ | $10.5{ }^{\text {f }}$ | -0.8 |
| S3221 | -5.7 | $\cdots$ | $\cdots$ | . $\cdot$ | $\cdots$ | $\cdots$ | ... |
| S3225 | 9.9 | 14.7 | 14.6 | 16.7 | 14.9 | 0.9 | ... |
| S3232 | -14.7 | -1.9 | ... | ... | ... | , | ... |
| S3251 | -6.3 | -2.8 | $\cdots$ | $\cdots$ | $\ldots$ | $\cdots$ | -2.5 |
| S3252 | -3.7 | $\cdots$ | $\cdots$ | $\cdots$ | $\ldots$ | $\ldots$ | -1.3 |
| S3268 | -26.6 | .. | $\cdots$ | $\cdots$ | ... | $\cdots$ | . |
| S3272 | 12.2 | $16.1{ }^{\text {f }}$ | 15.7 | 17.2 | 15.8 | 1.7 | ... |
| S3276 | -1.6 | $\ldots$ | ... | $\ldots$ | 12.6 | $12.4{ }^{\text {f }}$ | -0.7 |
| S3282 | . | 3.8 | $\ldots$ | 2.3 | $5.0{ }^{\text {f }}$ | $6.3{ }^{\text {f }}$ | . |
| S3308 | -2.8 | 4.0 | 4.7 | 6.3 | $8.8{ }^{\text {f }}$ | ... | -2.1 |
| S3312 | 1.6 | $1.2{ }^{\text {f }}$ | 0.5 | 1.0 | $10.2{ }^{\text {f }}$ | $11.5{ }^{\text {f }}$ | $\cdots$ |
| S3317 | -0.9 | 2.6 | 1.2 | 2.3 | 11.0 | 12.9 | -1.5 |
| S3323 | -1.3 | 7.78 | 6.5 | 8.9 | 9.8 | 5.1 | -1.3 |
| S3351 | -21.5 | -7.0 | -11.1 | $\cdots$ | ... | $\ldots$ | ... |
| S3358 | -6.0 | -4.8 | -8.1 | ... | $\cdots$ | -37.3 | -1.6 |
| S3363 | -6.2 | -3.3 | ... | ... | $\cdots$ | $\cdots$ | $\cdots$ |
| S3365 | ... | 3.2 | 2.0 | 1.4 | $5.2{ }^{\text {f }}$ | $6.1{ }^{\text {f }}$ | ... |
| S3376 | -5.8 |  | ... | ... |  | ... | -1.2 |

TABLE 5.7-Continued

| Source | $\begin{gathered} H \alpha^{a} \\ (A) \end{gathered}$ | H $\beta$ <br> ( $\AA$ ) | $\begin{aligned} & \mathrm{Hr}^{\mathrm{b}} \\ & (\mathrm{~A}) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \delta \\ & (\AA) \end{aligned}$ | $\begin{gathered} H \epsilon^{c} \\ (\AA) \end{gathered}$ | Ca II $\mathrm{K}^{\mathrm{d}}$ <br> ( $\AA$ | $[\mathrm{N} \mathrm{II}]^{-}$ <br> ( $\AA$ ) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S3381 | $3.4{ }^{\text {f }}$ | $9.3{ }^{\text {f }}$ | $9.2{ }^{\text {f }}$ | $8 .{ }^{\text {f }}$ | $8.8{ }^{\text {f }}$ | $\ldots$ | $\ldots$ |
| S3392 | -4.2 | ... | $\cdots$ | ... | $\cdots$ | . | -1.8 |
| S3393 |  | 2.4 | 0.7 | 1.3 | $8.8{ }^{1}$ | $9.3{ }^{\text {f }}$ |  |
| S3395 | -39.8 | -65.9 | -111.6 | . | $\cdots$ | $\cdots$ | -18.1 |
| S3396 | 7.8 | $10.0{ }^{\text {f }}$ | $9.7{ }^{\text {f }}$ | $10.6{ }^{\text {f }}$ | 10.0 | 0.3 | $\ldots$ |
| S3398 | -1.9 | $\cdots$ | ... | ... | $7.8{ }^{\text {f }}$ | $6.6{ }^{\text {f }}$ | $\cdots$ |
| S3402 | $3.7{ }^{\text {f }}$ | $9.7{ }^{\text {f }}$ | 8.7 | 10.8 | 11.8 | 5.5 | $\cdots$ |
| S3408 | 3.4 | 3.8 | 1.9 | 2.5 | 12.6 | 13.7 | $\cdots$ |
| S3425 | -102.5 | -37.3 | -27.1 | -22.2 | -36.8 | -21.2 | ... |
| S3435 | -4.1 | ... | ... | ... | $10.3{ }^{\text {f }}$ | $9.4{ }^{\text {f }}$ | 0.0 |
| S3438 | 11.1 | 15.4 | 15.1 | 17.1 | 14.8 | 1.2 | $\cdots$ |
| S3441 | -15.9 | ... | ... | ... | ... | ... | -6.6 |
| S3442 | -7.2 | $\ldots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | -3.8 |
| S3443 | -2.6 | $\cdots$ | $\cdots$ | $\cdots$ | $\ldots$ | $\cdots$ | -0.6 |
| S3448 | -2.8 | -2.4 | -1.7 | $\cdots$ | $\ldots$ | $\ldots$ | -1.0 |
| S3452 | -24.6 | ... | $\cdots$ | $\ldots$ | $\cdots$ | $\cdots$ | -14.1 |
| S3470 | -6.1 | -2.6 | $\ldots$ | $\ldots$ | $\ldots$ | $\ldots$ | -1.4 |
| S3475 | -24.0 | -11.1 | -13.5 | -14.2 | -23.8 | -9.2 | $\cdots$ |
| S3496 | -6.8 | -3.5 | -6.7 | -16.9 | -25.4 | -5.7 | $\ldots$ |
| S3505 | 0.1 | 0.8 | 0.9 | 2.2 | 12.1 | 13.7 | $\ldots$ |
| S3510 | -7.6 | ... | ... | $\ldots$ | ... | $\ldots$ | -4.4 |
| S3511 | -9.1 | $15.8{ }^{\text {f }}$ | 16.3 | 18.8 | 16.3 | 2.6 |  |
| S3514 | -11.6 | ... | ... |  | 16.3 | 15.2 | $\ldots$ |
| S3529 | -28.7 | -23.1 | -29.2 | -13.4 | ... | ... | -4.0 |
| S3535 | -66.2 | -20.7 | -17.0 | -22.1 | -29.7 | -7.0 |  |
| S3536 | -0.6 | $1.6{ }^{\text {f }}$ | 1.5 | 1.6 | 11.4 | $10.4{ }^{\text {f }}$ | -1.0 |
| S3537 | -20.7 | $\ldots$ | . | . | ... | $\cdots$ | -7.9 |
| S3546 | 8.7 | 4.0 | $\cdots$ | $\cdots$ | $\cdots$ |  | 6.6 |
| S3552 | -97.6 | -18.1 | -9.3 | -5.7 | -11.6 | -14.5 | $\ldots$ |
| S3556 | -0.4 | 2.6 | 0.9 | 1.1 | 12.8 | 13.9 | $\cdots$ |
| S3568 | -4.7 | ... | $\ldots$ | $\ldots$ | ... | ... | -1.4 |
| S3579 | -136.9 | -177.3 | $\cdots$ | $\ldots$ | $\ldots$ | $\cdots$ | -56.2 |
| S3580 | -6.6 | -2.6 | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | -1.9 |
| S3583 | -3.6 | -1.8 | -1.2 | . ${ }^{\text {a }}$ | $\ldots$ | $\cdots$ | -0.6 |
| S3584 | -0.2 | $1.9{ }^{\text {f }}$ | 0.9 | 1.7 | $9.1{ }^{\text {f }}$ | 11.4 | $\cdots$ |
| S3592 | -7.2 | -2.0 | -2.0 | $\ldots$ | ... | ... | -3.0 |
| S3602 | -2.1 |  |  | $\ldots$ | $\ldots$ | $\cdots$ | -1.1 |
| S3607 | 0.9 | 3.9 | 1.2 | 2.1 | 10.0 | $11.2^{\text {f }}$ |  |
| S3611 | -4.4 | $\cdots$ | $\ldots$ | $\ldots$ | ... | $\cdots$ | -26.2 |
| S3618 | -15.2 | ... | ... | ... | $\ldots$ | ... | -2.7 |
| S3628 | 1.3 | 3.1 | 1.3 | 2.3 | 9.8 | 12.4 |  |
| S3636 | -3.3 | $\cdots$ | $\ldots$ | $\cdots$ | ... | ... | -1.6 |
| S3646 | -31.6 | .. | ... | $\ldots$ | $\cdots$ | $\cdots$ |  |
| S3650 | -5.7 | -2.9 | $\ldots$ | $\cdots$ | $\cdots$ | $\cdots$ | -1.7 |
| S3659 | -2.1 |  | ... | ... | $\ldots$ | $\cdots$ | ... |
| S3666 | -1.3 | ... | $\ldots$ | ... | $\ldots$ | $\ldots$ |  |
| S3679 | -75.6 | -30.6 | -21.5 | -12.1 | -12.6 | -26.8 | -28.4 |
| S3683 | 10.0 | 12.98 | 12.4 | 14.8 | 12.5 | 0.3 | , |
| S3686 | -5.6 | -2.7 | -1.6 | -1.8 | -5.3 | -7.9 | -0.9 |

TABLE 5.7-Continued

| Source | $\mathrm{H}^{\alpha}{ }^{\text {a }}$ <br> (A) | $\begin{aligned} & \mathrm{H} \beta \\ & (\AA) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \gamma^{\mathrm{b}} \\ & (\AA) \end{aligned}$ | $\begin{gathered} \mathrm{H} \delta \\ (\AA) \end{gathered}$ | $\begin{gathered} \mathrm{H} \varepsilon^{\mathrm{c}} \\ (\AA) \end{gathered}$ | Ca II K ${ }^{\mathrm{d}}$ <br> (A) | [ N II$]^{\circ}$ <br> (A) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S3690 | -16.7 | -8.3 | -3.4 | $\cdots$ | $\cdots$ | ... | -4.7 |
| S3692 | $7.5{ }^{\text {f }}$ | $10.8{ }^{\text {f }}$ | $10.7{ }^{\text {f }}$ | $13.4{ }^{\text {f }}$ | $11.8{ }^{\text {f }}$ | 1.7 | ... |
| S3693 | -6.2 |  |  |  |  |  | -5.3 |
| S3698 | -6.7 | $\cdots$ | $\ldots$ | $\cdots$ | $\cdots$ | $\ldots$ | -5.5 |
| S3702 | -5.1 | 4.8 | 3.0 | 4.0 | $11.0{ }^{\text {f }}$ | 14.4 | -2.7 |
| S3712 | -11.2 | -14.9 | -12.7 | $\cdots$ | $\ldots$ | ... | $\ldots$ |
| S3719 | 7.8 | $9.5{ }^{\text {f }}$ | $9.5{ }^{\text {f }}$ | $10.6{ }^{\text {f }}$ | 10.3 | 0.5 | $\cdots$ |
| S3725 | -72.2 | -39.3 | -229.5 | -53.5 | -56.1 | -30.3 | -6.3 |
| S3761 | ... | .. | ... | . | ... | $\ldots$ | ... |
| S3767 | -24.8 | -3.2 | -1.7 | $\ldots$ | -4.6 | -10.3 | $\cdots$ |
| S3772 | -1.8 | ... | ... | . | $9.6{ }^{\text {r }}$ | 14.4 | -1.6 |
| S3776 | -2.4 | $\ldots$ | $\ldots$ | $\cdots$ | $6.5{ }^{\text {f }}$ | $12.1{ }^{\text {f }}$ | ... |
| S3790 | -3.6 | $\ldots$ | $\ldots$ | ... | $\cdots$ | $\ldots$ | $\cdots$ |
| S3792 | -1.4 | 5.5 | 3.2 | 5.7 | $\cdots$ | $\cdots$ | $\ldots$ |
| S3796 | -1.9 | ... | ... | ... | $\ldots$ | $\ldots$ | $\ldots$ |
| S3799 | -102.7 | -27.1 | -16.6 | -13.0 | -18.3 | -25.2 | $\cdots$ |
| S3802 | 3.3 | $5.5{ }^{\text {f }}$ | 3.9 | $3.5{ }^{5}$ | 9.1 | 8.6 | $\cdots$ |
| S3806 | $\ldots$ | ... | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\ldots$ |
| S3810 | $\cdots$ | $\ldots$ | $\cdots$ | $\ldots$ | $\ldots$ | ... | $\ldots$ |
| S3811 | -150.1 | -28.8 | -28.1 | -21.4 | -45.0 | -26.3 | $\ldots$ |
| S3812 | -58.0 | -11.8 | -8.6 | -3.1 | -6.6 | -7.1 | -9.9 |
| S3813 | 2.6 | 4.1 | 1.9 | 2.2 | 8.5 | 9.5 | ... |
| S3815 | -7.6 | -4.4 | -5.7 | -3.0 | $\cdots$ | ... | -2.9 |
| S3834 | -12.6 | -7.9 | -7.5 | ... | $\cdots$ | $\cdots$ | -3.2 |
| S3844 | -3.3 | ... | ... | $\ldots$ | $\cdots$ | $\cdots$ | ... |
| S3861 | -22.1 | -13.6 | -12.7 | -5.1 | -14.5 | $\cdots$ | -7.3 |
| S3866 | -118.5 | -106.8 | -92.5 | -40.6 | -56.7 | ... | -46.4 |
| S3869 | -28.4 | -21.8 | -25.5 | -26.2 | -76.4 | -55.2 | ... |
| S3871 | -2.0 | ... |  | ... | $6.6{ }^{\text {f }}$ | $8.0{ }^{\text {f }}$ |  |
| S3872 | -36.5 | -15.9 | -12.8 | -9.9 | -25.9 | -41.6 | -6.7 |
| S3873 | 9.6 | $14.1{ }^{\text {f }}$ | 13.3 | 15.2 | 13.8 | 4.6 | ... |
| S3875 | 1.6 | 3.8 | 2.9 | 3.0 | 10.0 | 11.1 | $\cdots$ |
| S3878 | -32.9 | -37.5 | ... | ... | ... | ... | -19.5 |
| S3880 | 2.9 | 3.3 | 1.6 | 2.5 | $9.7{ }^{1}$ | 11.6 | ... |
| S3884 | -9.3 | -10.0 | -11.3 | -5.8 | -11.1 | ... | -2.6 |
| S3889 | -4.2 | -5.7 | -4.0 | -1.4 | ... | $\ldots$ | -1.2 |
| S3895 | -167.5 | -47.6 | -35.0 | -28.3 | -61.4 | -7.0 | ... |
| S3897 | 2.6 | 4.4 | 3.8 | 2.7 | $7.3{ }^{\text {f }}$ | 9.1 | $\ldots$ |
| S3913 | $\ldots$ | . | $\ldots$ | $\cdots$ | $\cdots$ | ... | $\ldots$ |
| S3915 | -34.1 | -7.9 | ... | $\ldots$ | $\cdots$ | $\cdots$ | -5.1 |
| S3917 | -12.2 | -8.9 |  |  |  | $\ldots$ | -4.5 |
| S3920 | -49.9 | -22.3 | -29.9 | -19.3 | -17.0 | -2.7 | ... |
| S3923 | -89.8 | -18.9 | -16.2 | -7.8 | -9.4 |  |  |
| S3947 | -9.1 | . | ... | ... |  | $\cdots$ | $\ldots$ |
| S3956 | -5.1 | -3.6 | -5.0 | -1.7 | -15.7 | -15.8 | -1.3 |
| S3963 | -5.8 | ... | ... | ... | ... | ... |  |
| S3964 | -136.1 | ... |  |  | $\ldots$ | $\cdots$ | -5.3 |
| S3969 | -7.7 | -9.3 | -7.3 | -14.0 | -39.8 | $\cdots$ | -2.6 |
| S3973 | -68.0 | -30.8 | -46.6 | -102.6 | , | ... | -5.2 |

TABLE 5.7-Continued

| Source | $\begin{gathered} \mathrm{H} \alpha^{\mathrm{a}} \\ (\AA) \end{gathered}$ | $\begin{aligned} & \mathrm{H} \beta \\ & (\AA) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \gamma^{\mathrm{b}} \\ & (\mathrm{~A}) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \delta \\ & (\AA) \end{aligned}$ | $\begin{aligned} & \mathrm{H} \epsilon^{\varepsilon} \\ & (\AA) \end{aligned}$ | Ca II $\mathrm{K}^{\mathrm{d}}$ <br> (A) | $[\mathrm{N} \mathrm{II}]^{e}$ $(\AA)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S3974 | -48.5 | -3.4 | -3.2 | -4.0 | -6.6 | -1.6 | $\cdots$ |
| S3979 | -12.5 | -11.0 | -17.9 | -20.5 | -29.2 | $\cdots$ | -4.9 |
| S3982 | -32.4 | -35.6 | $\cdots$ | . | $\cdots$ | $\ldots$ | -9.8 |
| S3990 | -5.7 | -0.8 | $\cdots$ | $\cdots$ | 18.3 | 28.5 | -2.5 |
| S3995 | -16.8 | -11.0 | -14.8 | -11.2 | -30.5 | -40.9 | -5.9 |
| S4003 | -172.9 | -40.8 | -28.8 | -32.2 | -23.0 | -8.2 | ... |
| S4005 | -56.7 | -56.0 | -31.0 | $\ldots$ | ... | ... | -32.5 |
| S4011 | -3.2 | ... | ... | ... | $10.7{ }^{\text {f }}$ | $12.6{ }^{\text {f }}$ | -1.7 |
| S4015 | ... | 2.7 | 1.6 | 2.0 | 10.8 | $11.2^{\text {f }}$ | $\ldots$ |
| S4016 | -2.0 | $\cdots$ | $\cdots$ | $\cdots$ | ... | $\cdots$ | -0.5 |
| S4037 | -24.5 | ... | $\cdots$ | $\ldots$ | $\ldots$ | . | $\cdots$ |
| S4038 | -3.0 | $\cdots$ | $\cdots$ | $\cdots$ | ... | $\cdots$ | $\cdots$ |
| S4053 | -10.9 | -8.8 | -8.8 | -4.3 | -8.4 | $\cdots$ | -4.8 |
| S4062 | -17.1 | -8.1 | -8.2 | -4.5 | -11.8 | -6.3 | ... |
| S4073 | -29.0 | $\ldots$ | ... | $\cdots$ | $\cdots$ | ... | -14.1 |
| S4078 | -5.1 | $\ldots$ | . $\cdot$ | $\cdots$ | $\cdots$ | $\cdots$ | -1.2 |
| S4082 | -2.8 | $\ldots$ | $\cdots$ | $\ldots$ | $\cdots$ | $\cdots$ | ... |
| S4087 | -2.0 | $\cdots$ | $\cdots$ | $\ldots$ | $\cdots$ | $\cdots$ | $\cdots$ |
| S4090 | 6.7 | 9.1 | 9.5 | 11.3 | 9.5 | ... | $\cdots$ |
| S4112 | ... | ... | $\ldots$ | $\cdots$ | 13.0 | $12.4{ }^{\text {f }}$ | ... |
| S4121 | -3.4 | $\cdots$ | $\ldots$ | ... | $\cdots$ | . | -1.8 |
| S4124 | -8.1 | -3.2 | $\cdots$ | $\cdots$ | . | ... | $\cdots$ |
| S4126 | -26.9 | -12.1 | ... | $\cdots$ | $\cdots$ | ... | -6.2 |
| S4133 | -9.1 | 6.5 | $\cdots$ | ... | $\ldots$ | \% | , |
| S4136 | -0.3 | 2.1 | 1.8 | 1.7 | $9.2{ }^{\text {f }}$ | $10.8{ }^{\text {f }}$ | $\cdots$ |
| S4146 | -5.8 | $\ldots$ | $\ldots$ | $\cdots$ | $\cdots$ | ... | $\ldots$ |
| S4176 | 5.9 | 7.8 | 7.3 | 8.1 | 9.6 | 6.9 | ... |
| S4194 | -1.7 | ... | ... | ... | $\cdots$ | $\cdots$ | $\cdots$ |
| S4200 | -22.6 | -14.6 | -6.6 | ... | $\ldots$ | ... | -8.9 |
| S4201 | -18.7 | $\cdots$ | ... | $\cdots$ | $\cdots$ | ... | ... |
| S4210 | -47.6 | -40.8 | -54.5 | ... | $\ldots$ | $\cdots$ | -16.2 |
| S4212 | $\cdots$ | 2.3 | 1.2 | 2.0 | 11.3 | 12.5 | ... |
| S4214 | -18.3 | -6.3 | -1.9 | $\cdots$ | $\cdots$ | $\cdots$ | ... |
| S4220 | -17.5 |  | $\cdots$ | $\ldots$ | $\cdots$ | $\ldots$ | $\cdots$ |
| S4229 | -15.5 | -13.7 | -34.3 | -205.6 | $\cdots$ | $\cdots$ | $\cdots$ |
| S4236 | ... | ... | ... | ... | $\ldots$ | ... | $\ldots$ |
| S4238 | 15.4 | $17.3{ }^{\text {f }}$ | 18.0 | 17.5 | 19.8 | 5.6 | $\ldots$ |
| S4281 | -2.3 | $\cdots$ | ... | ... | ... | ... | $\cdots$ |
| S4282 | 4.1 | 7.1 | 5.9 | 6.9 | 9.9 | 10.1 | $\cdots$ |
| S4292 | -25.3 | -16.3 | -35.7 | -27.3 | -85.2 | ... | -9.0 |
| S4296 | -0.8 | ... | ... | ... | $9.4{ }^{\text {f }}$ | $9.1{ }^{\text {f }}$ | $\ldots$ |
| S4307 | -41.0 | ... | $\ldots$ | $\cdots$ | $\cdots$ | $\cdots$ | -9.4 |
| S4314 | $\ldots$ | ... | ... | $\cdots$ | $\ldots$ | $\ldots$ | $\cdots$ |
| S4363 | -4.4 | $\cdots$ | $\cdots$ | $\cdots$ | 17.4 | 16.4 | -3.4 |
| S4365 | -0.4 | 1.98 |  |  | $8.6{ }^{\text {f }}$ | $10.4{ }^{\text {f }}$ | -0.7 |
| S4392 | 11.4 | $9.5{ }^{\text {f }}$ | $9.3{ }^{\text {f }}$ | $12.4{ }^{\text {f }}$ | 12.3 | 1.1 | ... |
| S4433 | -56.9 | -10.5 | -5.6 | -3.2 | -10.5 | -16.8 | $\cdots$ |
| S4473 | -3.7 | $\ldots$ | ... | ... | ... | . | $\ldots$ |
| S4494 | -4.2 | -1.1 | ... | $\cdots$ | 15.1 | 17.7 | -1.3 |

TABLE 5.7-Continued

| Source | $\begin{aligned} & \mathrm{H} \alpha^{\mathrm{a}} \\ & (\AA) \end{aligned}$ | $\begin{aligned} & H \beta \\ & (\AA) \end{aligned}$ | $\mathrm{H} \gamma^{\mathrm{b}}$ <br> ( $\AA$ ) | $\begin{aligned} & \mathrm{H} \delta \\ & (\AA) \end{aligned}$ | $\begin{aligned} & H \epsilon^{e} \\ & (\AA) \end{aligned}$ | Ca II K ${ }^{\mathrm{d}}$ <br> (A) | $[\mathrm{NII}]^{\text {e }}$ <br> ( $\AA$ ) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S4508 | -5.1 | -2.0 | 0.3 | $\cdots$ | 12.8 | 17.9 | -2.0 |
| S4675 | 6.7 | 9.8 | 9.1 | 9.7 | 10.1 | $5.4{ }^{\text {f }}$ | ... |
| S4737 | 2.7 | 3.3 | 2.0 | 2.3 | 9.8 | 11.8 | $\cdots$ |
| LkHo 06 | -38.4 | -15.2 | -16.4 | -15.0 | -21.8 | -5.6 | $\cdots$ |
| W032 | 12.6 | $13.7{ }^{5}$ | $12.5{ }^{5}$ | $12.1{ }^{\text {f }}$ | $10.5{ }^{\text {f }}$ | 2.1 | $\ldots$ |
| W034 | 6.1 | 8.6 | 7.3 | 10.2 | 10.5 | 7.3 | $\cdots$ |
| W060 | 7.8 | $10.0{ }^{\text {f }}$ | 8.6 | $10.5{ }^{\text {f }}$ | $9.0{ }^{\text {f }}$ | $3.7{ }^{\text {f }}$ | $\cdots$ |
| W087 | 10.5 | 13.9 r | $12.9{ }^{\text {f }}$ | $14.6{ }^{\text {f }}$ | 13.2 | 2.3 | $\cdots$ |
| W091 | 2.3 | 3.4 | 2.0 | 1.6 | 9.8 | $9.0{ }^{\text {f }}$ | $\cdots$ |
| W094 | 4.8 | 7.3 | 6.5 | 6.2 | 8.8 | 6.78 | $\cdots$ |
| W098 | 3.8 | 6.2 | 4.8 | 3.6 | 8.9 | 9.0 | $\cdots$ |
| W114 | 4.9 | 7.2 | 5.8 | 5.2 | 9.8 | 9.3 | $\cdots$ |
| W128 | $8.3{ }^{\text {f }}$ | $12.7{ }^{\text {f }}$ | $11.0{ }^{\text {f }}$ | $13.4{ }^{\text {f }}$ | 12.18 | 3.0 | $\cdots$ |
| W172 | $7.3{ }^{\text {f }}$ | $9.1{ }^{\text {f }}$ | $9.2{ }^{\text {f }}$ | $10.1{ }^{\text {f }}$ | 11.4 | 0.2 | $\cdots$ |
| W180 | 4.7 | 6.6 | 3.5 | 2.8 | 14.4 | 13.5 | $\ldots$ |
| W182 | 13.0 | $17.2^{\text {f }}$ | 16.7 | 17.9 | 15.7 | 1.6 | $\cdots$ |
| W196 | 3.1 | 4.7 | 3.5 | 2.9 | $7.8{ }^{\text {f }}$ | 9.6 | $\cdots$ |
| W221 | 5.6 | 6.5 | 5.6 | 4.3 | $7 .{ }^{\text {f }}$ | $5.2{ }^{\text {f }}$ | $\cdots$ |

${ }^{\text {a }}$ Deblended from [ NII ] forbidden lines.
${ }^{\mathrm{b}}$ Deblended from the G band.
${ }^{\text {c }}$ Blended with Ca II H , this line was deblended from Ca II K .
${ }^{\text {d }}$ Deblended from the Ca II $\mathrm{H}+\mathrm{He}$ system.
${ }^{\circ}$ A line at $6583 \AA$ deblended from $\mathrm{H} \alpha$.
${ }^{\text {f }}$ This equivalent width is at least $2 \AA$ smaller than the main sequence values of the fits discussed in the text.
Note.- Negative equivalent widths indicate emission lines. Fields with no entry indicate the source was too faint and the spectrum too noisy to measure at that wavelength.

## Chapter 6

## INTERWEAVING THE DATASETS

### 6.1 Overview

In this chapter the various sets of data from the previous chapters are combined to explore the ecology of the stars and dust in NGC 2264. The nature of the hydrogen and calcium lines are used to separate the stars from Chapter 5 into various classes. These stars do not have main sequence colours, and since the colour excesses are consistent with dust extinctions, their magnitudes were dereddened. Nearly all the stars, even the most spectrally inactive, are pre-main sequence objects. A population of stars with absorption lines that are abnormally weak (or veiled) are identified. These anemic stars are explained as stars with absorption lines partially filled in by emission. The dust extinctions obtained by dereddening indicate that the spectroscopic survey does not completely penetrate the interstellar material associated with NGC 2264. These extinctions are
compared with the IRAS column depths obtained in Chapter 2 but the two sets of measurements exhibit no correlation, indicating that the two probes measure different components of the cluster and background GMC material. Finally, spectral energy distributions are produced for the spectroscopic survey stars, and fourteen reveal long-wavelength excesses which are successfully modelled assuming viscous accretion disks surrounding pre-main sequence objects. To fit the data, the models require inner holes in the disks. All the disk stars exhibite $\mathrm{H} \alpha$ or Ca II emission lines if their usable spectral data ranges span those features.

### 6.2 Extinction and the Art of Dereddening

Since the starlight from the cluster stars suffers extinction from the intracluster material, the photometric data from Chapter 3 are certainly not perfectly representative of the intrinsic colours of the embedded sources. If the stars in the sample were normal main sequence objects, it would be a straightforward matter to deredden their photometry, using the colour excesses as indications of the degrees of extinction. But a pre-main sequence star's colours might also differ from a main sequence star's-primarily because of circumstellar dust emission or peculiar chromospheric activity-so it can be difficult to disentangle the simultaneous effects of dust reddening from the intrinsic stellar colours that may be associated with the pre-main sequence syndrome. An additional danger stems from the fact that the various bands of data were not observed absolutely simultaneously. Rapid variations in flux have long been observed in young stars (see Section 1.3.1) so such variability could produce spurious colours. In this section the methods used to deredden the photometric data are outlined and results are discussed.

### 6.2.1 Indications of Reddening

The stars in the spectroscopic survey were divided into two classes based upon the nature of their hydrogen and calcium lines. The first class-the quiescent group-consists of those stars with absorption lines that have equivalent widths that were normal, or at least no more than $2 \AA$ narrower than the JHC standards. A second class, one of active stars, have either emission lines or lines more than $2 \AA$ weaker than expected. It is likely these two groups represent stars in two different sets of generalized conditions, environments, or evolutionary phases. Colour-magnitude diagrams for the two samples of stars are presented in Figure 6.1. In constructing this diagram the active stars are split into those with nebular emission lines and those without. The reasons for this distinction were discussed in Chapter 5. However, as it will be seen, all the data suggest that the sample of stars with nebular emission lines and the sample of those without are very similar, so the distinction ultimately is only important in determining the strengths of the emission or absorption lines. The stars-both quiescent and active-all lay well above the main sequence as Walker first observed, but where would they appear if dust absorption corrections were made? Furthermore, if the active and quiescent classes represent two intrinsically different kinds of stars, the same dereddening techniques may not be applicable to both types.

In Figure 6.2 the $V-I$ colours of the stars are plotted against spectral type. Nearly all are redder than the colours of main sequence stars of the same type. The dereddening done in this dissertation is based upon the assumption that the spectral types derived from the MX spectra yield representative intrinsic colours. Thus, the $V-R, V-I$, and $R-I$ colour excesses away from main sequence values are due, not to odd intrinsic colours of the sources, but rather to dust reddening


Fig. 6.1.- Colour-magnitude diagrams for the cluster, before correcting for reddening. The active stars-those with emission lines-have been decomposed into nebular-contaminated and noncontaminated stars. The reddening vector indicates the effect of $A_{V}=1$. The solid line indicates main sequence data assuming a distance modulus of 9.7.


Fig. 6.2.- The $V-I$ colours are shown vs. their spectral types. The reddened colours of the stars are assumed to result from extinctions. Quiescent stars are in the same approximate area as active stars, although are slightly closer to the main sequence which is indicated with a solid line.
(either circumstellar or intracluster). If this assumption is wrong, the house of cards falls apart. This assumption is not followed blindly-various arguments will be presented to defend the validity and efficacy of the method. Magnitudes of T Tauri stars and other young objects have been dereddened using this and other techniques (Cohen \& Kuhi 1979; Rydgren et al. 1976; Mendoza 1968), however the entire issue of dereddening is contentious and has resulted in vindictive pages in the astronomical literature. The colours from the $J, H$, and $K$ photometry were not used in dereddening because the fluxes from the stars are more likely to be augmented by dust emission at these wavelengths.

In Figure 6.2 the regions containing the uncontaminated and contaminated populations of active stars are essentially overlapping. Meanwhile, the quiescent stars tend to be slightly less reddened than active stars (or at least have colours more akin to those of main sequence stars). Very few stars appear below the main sequence, and the few quiescent $A$ and $F$ stars are likely to be background intruders. If the errant colours were due purely to stellar flux variability, it would be expected that many stars would appear below the main sequence. Since this is not the case, the red colours are not due solely to flux variability.

A stronger argument that the colours are not due to variability lies in the colour-colour diagrams shown in Figure 6.3, where the stars in both quiescent and active groups lie in bands along the main sequence line. In ( $V-R, R-I$ )-space the reddening vector is almost parallel to the main sequence, so even reddened stars have main sequence colours (although the colours correspond to the wrong spectral type). Since the stars lie on such well defined and narrow bands in these diagrams, variability was clearly not too important of an effect. There is slightly more fuzz in the active group, indicating a greater incidence of flux variables in this sample, but the effect did not infect the majority of stars. It was unsettling that in both


Fig. 6.3. $-V-I$ vs. $R-I$ colour diagrams for quiescent and active stars are shown. These stars are not dereddened. Main sequence colours and a reddening vector for $A_{V}=2$ have been included.
the quiescent and active groups a systematic effect was present that made both groups of stars lie below the main sequence line by about 0.05 magnitudes. This may indicate a genuine residual colour to the stars or some magnitude zero-point error in the data.

### 6.2.2 Dereddening

The dereddening proceeded assuming the intrinsic colours resulting from the $V, R$, and $I$ magnitudes (before any dust reddening occurred) were all identical to main sequence colours-for at these wavelengths emission from nonstellar components (such as dust in a disk or shell) should be relatively small. Nonphotospheric stellar emission is a real danger but still this method seems to be effective (Mendoza 1968). Standard extinctions for $A_{V}=1$ for the three Johnson bands are $1.0(V), 0.748(R)$, and $0.482(I)$ magnitudes (Rieke and Lebofsky 1985). But the Steward filters, with transmission-weighted bandpass centers at $0.55,0.66$, and $0.82 \mu \mathrm{~m}$, are not standard Johnson filters (Figure 3.3.1). So the extinction coefficents had to be generated from basic principles. This was done for each band by multiplying the spectrum of a blackbody at a temperature $T$ with the wavelength dependent filter efficiency. Integrating under the product of these two functions produced a measure of the total energy flux that passed through the filter. Then the product was dimmed by one magnitude of Johnson- $V$ extinction, using the parameterization of the interstellar extinction curve given by Cardelli et al. (1989). The new flux was integrated, and when taken in ratio with the original flux provided an estimate of the effect to be expected in each band when the starlight suffered the equivalent of $A_{V}=1$ extinction. This calculation was performed over the range of photospheric temperatures observed in the


Fig. 6.4.- Reddening terms calculated for the Steward $V, R$, and $I$ filters are shown as a function of blackbody photospheric temperature. The dashed lines indicate the values adopted for this study.
spectroscopic survey, and the results are plotted in Figure 6.4. The reddening from dust in each colour, for example $V-I$, is usually expressed as $A_{V}-A_{I} \equiv E(V-I)$. The colour terms shown in Figure 6.4 have been normalized by $A_{V}$, and the values used in this study were: $E(V-R) / A_{V}=0.197, E(R-I) / A_{V}=0.239$, and $E(V-I) / A_{V}=0.436$. It is comforting that one Johnson $V$ magnitude of extinction results in 1.01 magnitude of extinction for the $V$ filter used in this survey, so at least the $V$ filter is Johnsonian.

As mentioned before, the stellar colours were assumed to be intrinsically identical to the photospheric values listed in Johnson (1966). The Steward system of filters is compatible with the Cousins system, so the $V-I, R-I$, and $V-R$ colours in Johnson (1966) were transformed into Cousins colours using the transformation equations listed in Taylor (1986). Since the band-centers of the $V$ and $R$ filters were very close, $V-R$ colours of stars are be small and easily overwhelmed by photometric errors. So whenever possible, only non-saturated $V-I$ colours ( $m_{V, I}>12.5$ ) were used to calculate the dereddening. If this colour were not available then the $R-I$ or $V-R$ colour was used. The colours of some stars were bluer than expected, resulting in unphysical computed extinctions $A_{V}<0$. For these stars the extinctions were set to zero. With only a few exceptions these odd colours fell within photometric uncertainties-the others were due to partially saturated magnitudes, or in some cases possibly stellar variability.

The results of stellar dereddening on the colour-colour diagram are shown in Figure 6.5, where the binning due to the spectral assignments is especially obvious for stars in the K1, K4, K7, M1, M3, and M5 slots. The largest quantization effect occurred between K7 and M1, where the difference in $V-I$ colours is 0.47 . This binning could result in a $V$ extinction miscalculation as large as 1.1 magnitude, which is a significant potential source of error. To minimize effects from this


Fig. 6.5.- The same stars from Figure 6.3 are shown dereddened to main sequence colours. The active stars display more scatter. A reddening vector for $A_{V}=2$ has been included.
problem, all the analyses in this work uses samples containing as many sources as possible. The few late-type stars in Figure 6.5 that could not be dereddened are those not sitting in a bin with the other stars. The extinctions obtained are discussed more in Section 6.2.3.

Although the active stars tend to occur at slightly later spectral types as already shown in Figures 5.5.2-5.5.2, this effect is barely visible in the colour-colour diagrams. Of the active stars, the nebular contaminated and uncontaminated stars show no difference in their dereddened colours. But an obvious difference between the active and quiescent stars is in the scatter around the main sequence colours. For example, in the M1 bin the scatter in $R-I$ is $\pm 0.08$ magnitude for the quiescent stars but $\pm 0.14$ for the active stars. If the scatter were due to some intrinsic colour difference between the quiescent and active populations, the scatter would not necessarily be centered upon the same colours. Perhaps the increased scatter result from greater photometric errors for the active populations? This is not likely because as a group the active stars were not fainter than the quiescent stars; for example at M1 the average $V$ magnitude of the quiescent stars is 15.90 and the average $V$ magnitude of the active stars is 15.50 . The photometric errors were comparable, so the increased scatter in the colour-colour diagrams must be due to greater variability in the active stars. The enhanced scatter suggests an active star $R-I$ variability of about 0.11 magnitudes larger than the quiescent star variability. How much of this is because the magnitudes were not obtained simultaneously, and how much was due to genuine colour variability cannot be determined from these data.

Dereddened colour-magnitude diagrams are shown in Figure 6.6. Because of reddening, early-type main sequence stars would mimic the colours and magnitudes of pre-main sequence stars in Figure 6.1. So it is pleasing to see some A stars


Fig. 6.6. - Dereddened colour-magnitude diagrams are shown for quiet and active stars. Very early stars have reached the main sequence, but even quiescent stars are pre-main sequence.
dereddened to their rightful place on the main sequence in Figure 6.6, especially since saturation does not allow this to be observed in the original stars. The two active A stars that lie well below the main sequence are almost certainly background stars. It is interesting that even when dereddened, both the active and quiescent stars float above the main sequence. Clearly the quiescent stars, presumed the most mundane group in the spectral survey, are also pre-main sequence objects. Even though a foreground star could infiltrate the sample and appear to be a quiescent star above the main sequence, this contamination was apparently minor since the quiescent and active stars occupy the same region of the colour-magnitude diagram-for example there are no M stars with suspiciously bright $V$ magnitudes.

It is interesting that in the dereddened colour-magnitude diagrams both the quiescent and active star populations dwell in the same region, and also that emission lines are not found at some characteristic luminosity or colour regime. If the mechanisms that determine a star's spectral activity were strictly governed by the star's mass-or some other intrinsic stellar characteristic-then it might be expected that stars of differing spectral activity would reside in different regions of colour-colour or colour-magnitude diagrams. Since this is not convincingly indicated, then perhaps the factors that determine if a star has emission lines are more related to the stellar environment. This is explored more in Section 6.3.

### 6.2.3 Dust Distribution

In this chapter, the $A_{V}$ extinction estimates obtained from $V-I$ colours (as described in Section 6.2.2) shall be denoted as $A_{V}(V-I)$. When saturation or other reasons prevented the calculation of this extinction, The $R-I$ or $V-R$


Fig. 6.7.- Extinctions calculated for quiescent stars for the $V-I$ and $R-I$ methods are shown and are in good agreement.
colours were used to obtain $A_{V}(R-I)$ or $A_{V}(V-R)$. The extinctions $A_{V}(V-I)$ and $A_{V}(R-I)$ calculated for the quiescent stars are shown in Figure 6.7. It was gratifying that the extinctions calculated using the two colours gave similar results, for if the stellar colours were due to the intrinsic nature of the stars and not dust there would be no reason to expect the colour excesses would be consistent with dust extinction. In Figure 6.8 it is demonstrated that both the $R-I$ and the $V-I$ methods of dereddening produce similar results when applied to the contaminated and uncontaminated populations of active stars. There is more scatter in these extinctions, but as discussed in Section 6.2.2 this could be due to the enhanced variability of these populations. As mentioned previously, when neither the $V-I$ or $R-I$ colours were available the $V-R$ colour was reluctantly used to deredden the data. The results for $V-R$ dereddening are not shown but they tracked the results for dereddening using other colours, but with more scatter.

A plot of the $A_{V}$ extinctions are shown as a function of spectral type in Figure 6.9. The inferred extinctions range from 0.0 to 5.85 magnitudes for the


Fig. 6.8.- Extinctions calculated for active star populations are shown. The extinctions from both the $V-I$ and $R-I$ data are in good agreement for this sample, although they show more scatter than in the quiescent star results.
quiescent stars, and 0.0 to 5.77 magnitudes for the active stars. The median extinctions for these populations are 1.26 and 1.6 magnitudes, respectively. Stars in the range G5-K7 have anywhere from 0-3 magnitudes of extinction; while earlier stars tended to be more extincted while stars later than M1 tended to be less extincted. This is a selection effect that indicates that the survey did not completely penetrate the murky cluster dust. Presumably M3 stars saddled with four magnitudes of extinction exist, but they were too dim to be represented in the spectroscopic sample. Even within each spectral subtype bin the extinctions were correlated with the dereddened $V$ magnitudes; more luminous stars tended to have more extinction. Assuming the highest luminosity stars were correctly dereddened, they set the total extinction lower limits for the cloud as 4-6 magnitudes. Some extinctions calculated for later stars are negative. This nonphysical result was discussed earlier and was probably due to photometric errors and variable sources.

It is entertaining to speculate upon the distribution of the dust extincting


Fig. 6.9. - This shows extinction as a function of spectral type. There is a general trend for earlier type stars to have more extinction. This selection effect is discussed in the text.
these stars: does it lie in close proximity to them as a dusty disk, shell, or nebula, or is it spread uniformly throughout the intracluster volume? In a cartoon model of star formation, one might expect a deeply embedded star to discard its enveloping material, eventually liberating itself of local extinction. Also, in an ensemble of simultaneously created stars, it would be anticipated that the more massive (i.e. earlier type) stars would be more evolved, so they would have less extinction than later type stars. No such trends are seen in the mid-G to early-M stars, nor are there any extinction values which were characteristic to each spectral type. But it is extremely dangerous to draw many conclusions from this since the calculated extinctions were so strongly twisted by selection effects. Furthermore, as mentioned in Chapter 1 there is evidence that star formation in NGC 2264 has been a protracted process, with the more massive stars forming first. Another spectral survey of stars that concentrated on fainter stars may be helpful in obtaining information about the deeper, more embedded cluster members and might clarify if the extinction is local to each star or distributed throughout the cluster.

If the dust in the cloud were distributed smoothly throughout the cluster, each extinction estimate would provide the equivalent of a needle-like core sample into the cloud. Foolishly disregarding the evidence that the cloud was not penetrated by the spectroscopic survey, it might be expected that lower extinctions would be observed near the cloud edges and larger extinctions would be seen near the cloud center. But various surface fits made to the spatial distribution of extinctions were completely uninteresting. In order to make a reddening map that probes the entire cloud, only background stars must be used, and not enough of these are in the sample.

In Chapter 2, $100 \mu \mathrm{~m}$ optical depths were calculated. These were converted into optical extinctions as described in Section 2.4.1, assuming an emissivity
exponent $n=1$. The optical depth map is shown in Figure 6.10, peppered with black and white pixels at the locations where photometric extinctions were calculated. At each location indicated in that figure, the photometric and IRAS optical extinctions were paired and plotted in Figure 6.11. If the dust cloud were optically thin at $100 \mu \mathrm{~ms}$ (which it is) and the spectroscopic survey completely penetrated the cloud (it does not) some correlation might be expected between the two sets of extinction measurements. Since they are apparently unrelated then the situation is clearly more complicated. This can be understood when it is realized that the two measurements probe different components of the cloud. The photometric extinctions measure all the dust along a line of sight to a star, regardless of the dust's temperature. Meanwhile the IRAS column depths sample all the way through the cloud, but only include dust sufficiently warmed by luminous sources, especially the embedded infrared sources. These two samples of dust are not constrained to be related in any way, which explains why no correlation between them is seen.

In Chapter 3 it was noted that while the embedded IRAS point sources are responsible for the brightest emission features in the $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ maps, they could not explain the full spatial extent of emission from the cloud. In Figure 6.12 the locations of the MX quiescent, active, and contaminated sources are shown superimposed upon maps of the IRAS thermal dust luminosity $L_{\mathrm{TH}}$ for $n=2$, as described in Section 2.4.2. All three populations of stars have members spread throughout the region, and could explain the extensive low-level emission that suffuses the region. There is a mild tendency for the active stars to occur in regions of higher dust luminosity, but this is more marked for the contaminated stars. Since the contaminated stars are probably those that are situated in regions of complicated emission nebulae, it is not surprising they often appear in regions


Fig. 6.10. - This image is of the IRAS optical depth map for $n=1$. Black and white pixels indicate locations where extinctions were determined by dereddening stars.


Fig. 6.11. - The extinctions determined by dereddening are plotted against the IRAS dust optical depths, which were converted into $V$ extinctions. As discussed in the text, these quantities are uncorrelated.


Fig. 6.12.- Star locations are indicated in an $n=2 L_{\mathrm{TH}}$ dust map. The sources in the top-left are quiescent stars, top-right are active stars, and bottom-center are contaminated stars.
of complicated IRAS emission. Stars are lacking on the boundaries of the dust emission, but this is due to the spatial coverage of the spectroscopic survey.

### 6.3 Equivalent Widths and Anemic Stars

In the discussion of Figure 6.6 it was noted that the locations of a star in dereddened colour-magnitude and colour-colour diagrams did not identify if the star was spectrally quiescent or active. It was hypothesized that the degree of a star's spectral activity is not governed exclusively by the star itself, but also by how it interacts with its habitat. In this section the spectroscopic and photometric data are exploited to further explore this spectral activity.

### 6.3.1 The Anemic Class

The spectral survey contains data for 361 stars, of which 346 have various amounts of photometric data tabulated in the survey of Chapter 3. Excluding the stars with nebular emission lines in their spectra leaves 201 stars which are probably nicely corrected for telluric and nebular emission. In Section 6.2.1, stars were grouped into quiescent and active stars, categories depending upon how their equivalent widths compared to the values for the JHC standards. Here the quiescent stars are retained as a class, while the active stars are further divided into two classes: the emission class contains those stars with hydrogen or calcium emission lines, while the anemic class contains those stars with hydrogen or calcium absorption lines with equivalent widths at least $2 \AA$ narrower than expected from the JHC atlas. Figure 6.13 is an H-R diagram in which the $\mathrm{H} \alpha$ line is used to categorize the stars into the quiescent, anemic, and emission stars.


Fig. 6.13. - The stars in both the spectral survey and the photometric survey that did not exhibit nebular forbidden lines are plotted in an H-R diagram. The dashed horizontal line at $m_{V}=12.5$ indicates the limit above which the stars are saturated. Data from Walker (1956) are used for stars brighter than this for stars earlier than F0. A main sequence line has been drawn for comparison. Quiescent stars-those with normal equivalent widths-are limited to stars earlier than K0 while emission line stars are exclusively found in later types. Anemic stars have abnormally narrow absorption lines. The anemic A0 star with $m_{V}=16.71$ is S3381, a background star with a noisy spectrum and dubious anemic nature.

Since the quantity plotted on the $x$-axis in that figure is spectral type, it was not necessary to correct for dereddening. The pre-main sequence population, the effects of saturation for $m_{V}<12.5$, and a few A-F background stars are immediately apparent. The transition in stellar type from quiescent to emission occurs very abruptly near spectral subtype G9. It might be expected that anemic stars would be seen there, but none are apparent. This is because the $\mathrm{H} \alpha$ equivalent width at G9 is only approximately $2 \AA$-if a star's $\mathrm{H} \alpha$ line were more than $2 \AA$ narrower than this (the classification requirement for anemia) it would be in emission! The only $\mathrm{H} \alpha$ anemia occurred for a few early A stars, which might be due to the large scatter seen in these equivalent widths (Figure 5.5.1), although others such as S2579 are genuinely active Ae stars. In future work it might be more natural to define anemia by a fractional deviation from normal equivalent linewidths, instead of a uniform difference such as used here.

In the same spirit, an H-R diagram was produced in which the classification into quiescent, anemic, and emission stars was performed using the size of the Ca II K line (Figure 6.14). Since this line is approximately $16 \AA$ at G9 it is more useful than $\mathrm{H} \alpha$ for looking for anemia in these stars. Since Ca II K is unaffected by nebular forbidden line emission, spectra with forbidden lines were included when producing the H-R diagram. The transition between quiescent and emission stars still occurs near K 0 , and anemic stars were scattered exactly where they were expected, near G5-K4.

The Ca II K anemia probably results from emission line flux being diluted by the stellar flux. The K4 stars with Ca II K emission and unsaturated photometry and the unsaturated G3 photometry were used to test this idea. The median equivalent width of the Ca II K emission line in this group is $-8.12 \AA$. In order to have such a large emission line, each K 4 star must first fill its Ca II K absorption


Fig. 6.14.- This plot displays all the stars in the spectroscopic and photometric surveys, with the same class definitions as described in Figure 6.13 but this time based upon the Ca II K line. The horizontal dashed line at $m_{V}=12.5$ marks the $V$ magnitude saturation limit. Data from Walker (1956) were used for stars brighter than this for stars earlier than F0. The anemic stars are clearly representative of a population intermediate between emission line stars such as CTTSs and less visibly active young stars. Many stars had spectra so noisy they precluded Ca II K measurements (for example S3381) and so their data are not plotted in this figure.
line, which has a width of approximately $15 \AA$ (Figure 5.5.1), so the total extent of emission is comparable to a line $8.12+15 \approx 23 \AA$ wide. The median dereddened $V$ magnitude of the K 4 sample is 13.50 , while the median dereddened $V$ magnitude of the G3 stars is 12.0 . If the flux from the $23 \AA$ line were dropped onto the G3 spectrum it would be diluted by a factor of approximately $1 / 4$, and the resulting $6 \AA$ emission line-when added to the $12 \AA$ G3 Ca II K absorption feature-would result in an absorption line only $6 \AA$ wide. This star would be classified as an anemic star. The equivalent widths of the spectral lines are quite sensitive to the luminosity of the central source; if a K4 star with emission producing an emission line $6 \AA$ wide increased in luminosity by only 0.5 magnitudes, its line would vanish altogether. The phenomenon of anemia is obviously identical with the incipient emission or spectral veiling effects discussed in Chapter 1.

### 6.3.2 An Evolutionary Sequence

Since dereddening young stars is a controversial topic, the data used in Figures 6.13-6.14 were not corrected for extinction because dereddened data were not needed to illustrate the points they highlighted. But what do dereddened $\mathrm{H}-\mathrm{R}$ diagrams look like? Avoiding the controversy associated with various techniques of dereddening, a noninvasive way to minimize the influences of dust is to shift from the $V$ band to the $H$ band, where the dust absorption is less than $20 \%$ as severe. An $H$ band H-R diagram in which the stellar spectral activity was classified using the Ca II K line is shown in Figure 6.15. The stars float higher above the main sequence in this figure than in the previous two because of the decreased effects from dust absorption. Not only did the segregation of stars into quiescent, anemic, and emission classes survive the transformation to the $H$ band


Fig. 6.15.- An $H$-band version of Figure 6.14 is shown. The horizontal dashed line at $m_{H}=8.5$ marks the $H$ magnitude saturation limit. The anemic and emission line stars are generally farther from the main sequence than the quiescent stars, which are probably slightly more evolved, even within each spectral subtype.
intact, but both the anemic and emission stars became more removed from the main sequence than the quiescent stars. Apparently the active sources, including the anemic stars, tend to be brighter in $H$ than the quiescent stars, a fact mostly masked in the $V$ H-R diagrams because emission and anemic stars suffer more extinction than the quiescent stars (Figures 6.7-6.8). So anemic stars, which were originally distinguished from quiescent stars on the basis of spectroscopy, also exhibit photometric differences from them. Perhaps the explanation that these stars are simply flux-diluted emission stars is simplistic. Rather, anemic stars may be at an evolutionary phase in which the emission activity in active stars is sputtering into docility as the star approaches the main sequence. In any event, it is interesting that emission line stars are seen for G-M stars and also A stars, but the only activity seen in F stars is the occasional anemic source.

### 6.3.3 Generating Emission Lines

It is astounding that even though $T$ Tauri stars have been studied for 50 years since first being identified as a group, the origin of their strong emission lines is still not well understood. In order to produce these spectral features a suitable source of energy is required, and not many are available. For example, consider the prospect of using the energy available in a star's photospheric emission. Models have been able to describe mechanisms that could transform photospheric radiation into emission lines in the Brackett series (Kwan \& Alonso-Costa 1988), but what about the Balmer series? Suppose an optically thick nebular envelope were employed to transform all the energy in a star's ultraviolet continuum into Balmer lines. What is the $\mathrm{H} \alpha$ flux expected from such a situation? Consider a star producing $N$ ionizing photons (i.e. $\lambda<912 \AA$ ) per second. In the Case B scenario
(Osterbrock 1974), the ionizations resulting in recombinations to the ground state level $n=1$ are neglected since they produce new ionizing photons which are subsequently reabsorbed by the nebula. Since recombinations from the continuum directly to $n=2$ do not result in an $\mathrm{H} \alpha$ line, the total number of photons which can be transformed into $\mathrm{H} \alpha$ photons each second is

$$
\begin{equation*}
N_{H_{\alpha}}=f_{\alpha} N \frac{\alpha_{B}-\alpha_{2}}{\alpha_{B}} \tag{6.1}
\end{equation*}
$$

where $\alpha_{B}$ and $\alpha_{2}$ are the recombination coefficients for Case B and for $n=2$. The term $f_{\alpha}$ represents the fact that not all recombinations to $n>3$ result in $\mathrm{H} \alpha$ lines-if they did then $\mathrm{H} \beta$ and higher energy Balmer lines would not exist. Using the relative Balmer intensities listed in Osterbrock (1974), $f_{\alpha}$ was be computed, and fraction of ionizing photons that are converted into $\mathrm{H} \alpha$ photons was found to be approximately 0.50 at $5000-10000 \mathrm{~K}$. Using Equation 6.1 and photospheres modelled as blackbodies, $\mathrm{H} \alpha$ fluxes were calculated as a function of temperature, converted into equivalent widths, and plotted in Figure 6.16. Also shown are the fits to the $\mathrm{H} \alpha$ equivalent widths measured for JHC stars. Notice that emission lines (where $\mathrm{H} \alpha$ emission exceeded $\mathrm{H} \alpha$ absorption) could occur for only extremely hot stars earlier than B6. So this mechanism is useless for T Tauri or even Ae stars. The effects of helium (which would compete for photons with $\lambda<504 \AA$ ) and especially dust grain absorption were not considered in this calculation-they would decrease the amount of flux that could be converted into Balmer emission lines-so the calculations presented in Figure 6.16 are actually only upper limits as to how effective photospheric mechanisms could be.

Emission lines can be produced in stars by nonphotospheric mechanisms; for example, K and M dwarfs can exhibit $\mathrm{H} \alpha$ emission due to collisional excitation in the chromosphere, the energy source ultimately due to rotational energy being


Fig. 6.16.- The dashed line follows the equivalent width of the $\mathrm{H} \alpha$ absorption line measured from the JHC data. The solid line indicates the absolute value of the equivalent width that would be produced if a star used a hydrogen nebula to convert its ionizing radiation into $\mathrm{H} \alpha$ photons. Only stars earlier than B 6 can do this to the extent that they fill their Balmer lines.
transferred by magnetic dynamo effects. But as discussed in Chapter 1, the rotation rates of T Tauri stars are too slow to be able to account for all but the spectrally least active stars. However, accretion and stellar winds can be invoked to produce emission lines, especially from some accretion boundary layer (Cabrit et al. 1990; Kenyon \& Hartmann 1987). Examining the emission lines one last time, the $\mathrm{H} \alpha$ and Ca II K equivalent widths for those stars with emission lines in both-essentially a pure set of T Tauri stars-and unsaturated $V$ and $R$ photometry were transformed into line-fluxes using

$$
\begin{align*}
F_{H \alpha} & =F_{R} W_{H \alpha} 10^{-0.4 m_{R}} \\
F_{C a} & =F_{V} W_{C a} 10^{-0.4 m_{V}} \tag{6.2}
\end{align*}
$$

where $m_{R}$ is the dereddened $R$ magnitude, $F_{R}$ is the flux zero-point for the $m_{R}$ magnitude scale, and $m_{V}$ and $F_{V}$ are defined analogously. The two fluxes are shown to be reasonably well correlated in Figure 6.17, indicating they must be measuring the same physics of disk accretion. The fluxes plotted in this figure did not include the emission required to pull both lines out of absorption, but this would only introduce a systematic increase in the Ca II K fluxes of approximately $3 \times 10^{-13} \mathrm{ergs} \mathrm{sec}^{-1} \mathrm{~cm}^{-2}$.


Fig. 6.17.- The $\mathrm{H} \alpha$ and Ca II K fluxes were plotted for those stars in which both lines were in emission. The Ca II K fluxes do not include the emission necessary to fill the absorption lines, which would add approximately $3 \times 10^{-13} \mathrm{erg} \mathrm{sec}^{-1} \mathrm{~cm}^{-2}$ for $m_{V}=13$.

### 6.4 Ground Truths for the $J-H-K$ Survey

In Lada et al. (1993), the authors speculated at length upon the identity of the sources in their $J-H$ vs. $H-K$ diagrams. The spectral survey in this dissertation provides a ground-truth check. In Figure 6.18 a colour-colour diagram is shown for all the quiescent K and M stars in the sample, and as expected they closely adhered to the main sequence colours indicating fairly mundane astrophysical lifestyles. There is nothing to indicate their enhanced luminosities or pre-main sequence nature. Since Lada et al. (1993) do not have the luxury of spectra for all their infrared sources, they cannot deredden their data. So for the purposes of this section the data in Figure 6.18 are not corrected for dust reddening. Extinction-corrected data will be presented in Section 6.5 in the form of spectral energy distributions.

There is a peculiar tendency for all the stars, even these quiescent sources, to fall lower than expected on the colour-colour diagrams. This problem was exacerbated by reddening corrections, and may indicate some as-yet unrepaired problem with their infrared photometry or dereddening manipulations.

In Figure 6.19 the T Tauri stars, defined by the presence of hydrogen and calcium emission lines, are shown. The dispersion of these stars around the main sequence is much larger. Although many of the sources appear to trail in the direction expected from reddening, after extinction corrections many still retained residual infrared excesses (this will be discussed in Section 6.5). Furthermore, many sources fall in a forbidden region to the left of the main sequence. No combination of photospheric colour and dust reddening could conspire to produce these forbidden colours. There is nothing in the photometry to suggest the data for these sources are corrupt (the infrared magnitudes are all 11.7-14.2, well within


Fig. 6.18.- A $J-H$ vs. $H-K$ colour-colour diagram plotting reddened quiescent K and M star data. Both groups of stars closely hug the main sequence.


Fig. 6.19.- A $J-H$ vs. $H-K$ colour-colour diagram plotting reddened data for K and M stars with hydrogen and calcium emission lines.
saturation limits), so barring some hitherto unexplained T Tauri phenomenon, the colours can only be explained by the stars being variable. As it was shown in Figure 6.5, the active stars tended to be variable in the $V-I$ and $R-I$ colours and this clearly carried over into the infrared regime. The red colours of a comparable number of infrared excess sources must be enhanced by this effect. Finally, in Figure 6.20 the entire set of stars that are spectrally active in either $\mathrm{H} \alpha$, Ca II K, or both, are plotted. This includes both emission-line or anemic-line late-type stars, as well as a few early-type sources. These objects exhibit a broad spread of colours due to extinction, infrared excess, and flux variability similar to the K and M type T Tauri stars. Once again, when studying these tumultuous stars the need for simultaneous photometry is illustrated.


Fig. 6.20.- A $J-H$ vs. $H-K$ colour-colour diagram plotting reddened data for all the sources with emission or anemic lines.

### 6.5 Disk Models

With reliable photometry in six wavelength bands spanning $0.55-2.2 \mu \mathrm{~ms}$, it is possible to produce dereddened spectral energy distributions (SEDs). These are displayed in Figures 6.21-6.29, in order of earliest to latest spectral type. A source's SED is displayed if at least two photometric measurements were made. If the data were so saturated that no reliable work could proceed from the photometry, the data are shown with squares and are connected with dashed lines. If the data were not saturated and could be dereddened, then they are shown with filled circles and are overplotted with a main sequence fit. The sizes of the circles and squares used to plot the data were chosen to approximate the photometric uncertainties. Distributions consisting of somewhat saturated data but that were easily fit with main sequence colours are overplotted with main sequence data. A few sources were not saturated but showed extremely anomalous colours. While plotted with circles, they deviated wildly from their main sequence fits, some to the extent that such fits were useless so the data were simply connected with dashed lines for clarity. A few sources consisted of slightly saturated or unsaturated data that exhibited sufficiently peculiar behavior to suggest flux variability. Such stars were labelled with the letter "V". The source numbers are listed in each figure's caption for each below, categorized by panel letter and ordered within each panel from top to bottom.

Most of the SEDs fit the main sequence colour curves reasonably well, while others have infrared excesses. These sources are of great interest since they may represent disk systems, and a model description of them is described in the remainder of this section.


Fig. 6.21.- See page 295 for complete details. Panel A: 1901, 1939, 1478, 2289, 1947, 2009, 4090, 3184; Panel B: 3108, 3396, 3438, 3719, 3225, 2760, 3048; Panel C: 3381, 3683, 422, 445, 3272, 4392, 921, 2230; Panel D: 2364, 2579, 3511, 3692, 1276, 1129, 1665; Panel E: 2612, 4238, 1976, 2763, 3873, 2313, 2374.


Fig. 6.22.- See page 295 for complete details. Panel A: 3323, 3402, 1829, 2510, 4176; Panel B: 4675, 3802, 4282, 1776, 2569; Panel C: 2854, 2984, 1960, 2234, 2716; Panel D: 2892, 1769, 3813, 3897, 3875, 2163; Panel E: 2279, 2862, 3514, 4737, 1066.


Fig. 6.23.- See page 295 for complete details. Panel A: 2525, 3282, 3317, 3584, 3607; Panel B: 3628, 3880, 4015, 4136, 4365; Panel C: 1316, 1562, 2944, 3312, 3365; Panel D: 3408, 3536, 3947, 4212, 1804; Panel E: 2405, 2418, 2495, 2662, 3251.


Fig. 6.24.- See page 295 for complete details. Panel A: 3920, 967, 1117, 1270, 1629, 1806, 2068, 2079; Panel B: 2377, 2448, 2521, 2843, 2943, 3052, 3135; Panel C: 3214, 3232, 3268, 3276, 3308, 3392, 3393; Panel D: 3435, 3505, 3537, 3556, 3871, 3915, 3990, 4011, 4038; Panel E: 4296, 4433, 131, 1315, 1389, 1606, 1648, 1896.


Fig. 6.25.- See page 295 for complete details. Panel A: 1898, 1950, 2055, 2104, 2113, 2146, 2171, 2190, 2228; Panel B: 2253, 2280, 2284, 2359, 2652, 2664, 2666, 2743, 2753; Panel C: 2809, 2898, 2920, 2958, 2969, 3160, 3171, 3205, 3221; Panel D: 3252, 3376, 3398, 3443, 3470, 3475, 3546, 3552, 3568; Panel E: 3580, 3602, 3636, 3650, 3686, 3690, 3702, 3767, 3772.


Fig. 6.26.- See page 295 for complete details. Panel A: 3776, 3799, 3812, 3844, 3889, 3923, 3974, 4016, 4062; Panel B: 4078, 4087, 4112, 4121, 4194, 4314, 4494, 4508, 1499; Panel C: 1513, 1566, 1637, 1645, 1702, 1973, 2116, 2117, 2268; Panel D: 2390, 2395, 2586, 2634, 2777, 2861, 3197, 3351, 3618; Panel E: 3725, 3815, 4082, 4146, 4363, 2173, 1212, 1369, 1382.


Fig. 6.27.- See page 295 for complete details. Panel A: 1500, 1590, 1796, 1820, 1932, 2008, 2022, 2162, 2191; Panel B: 2322, 2424, 2514, 2515, 2563, 2593, 2756, 2761, 2926; Panel C: 2945, 2989, 3044, 3102, 3122, 3170, 3425, 3448, 3496; Panel D: 3583, 3592, 3679, 3790, 3792, 3796, 3806, 3834, 3869; Panel E: 3872, 3884, 3895, 3913, 3964, 3969, 3973, 3979, 4037.


Fig. 6.28. - See page 295 for complete details. Panel A: 4053, 4133, 4210, 4214, 4236, 4281, 4292, 1407, 1447; Panel B: 1529, 1598, 1621, 1675, 1758, 1760, 1937, 1996, 2038; Panel C: 2325, 2387, 2449, 2506, 2534, 2565, 2644, 2659, 2764; Panel D: 2993, 3031, 3077, 3110, 3141, 3174, 3358, 3441, 3579; Panel E: 3611, 3646, 3659, 3666, 3693, 3712, 3761, 3810, 3866.


Fig. 6.29.- See page 295 for complete details. Panel A: 3917, 3956, 3963, 4003, 4005, 4073, 4124, 4126, 4200; Panel B: 4220, 4307, 4473, 1309, 1364, 1518, 1734, 2007, 2167; Panel C: 2566, 2636, 2827, 2971, 3363, 3395, 3442, 3452, 3510, 3529; Panel D: 3535, 3698, 3861, 3878, 3982, 3995, 4201, 4229, 3811.

### 6.5.1 Model Description

Most of the interesting photometric characteristics of star and disk models occur at long wavelengths (e.g. Adams \& Shu 1986). Although the photometry discussed in Chapter 3 extends only to $K$ at the long wavelength end, this is still long enough to touch upon some of the interesting features of the infrared excess sources. In an attempt to reproduce some of these photometric characteristics, a simple model was adopted from the literature, consisting of a blackbody star surrounded by an optically thick, spatially thin disk (Kenyon \& Hartmann 1987; Friedjung 1985; Shakura \& Sunyaev 1973, Lynden-Bell \& Pringle 1974). It is well known that if the only function of the disk is to reprocess the radiation from the central star, the radial temperature distribution $T_{\text {rep }}(R)$ is given by

$$
\begin{equation*}
T_{\mathrm{rep}}^{4}=\frac{T_{*}^{4}}{4}\left(\frac{R_{*}}{R}\right)^{3} \tag{6.3}
\end{equation*}
$$

where $T_{*}$ and $R_{*}$ are the photospheric temperature and size of the star. If no accretion were occurring, this would be the only source of nonstellar long wavelength emission from the system, and the total luminosity of the disk would be a quarter of the stellar luminosity. But accretion seems to play an important role, so following the derivations of previous authors the temperature distribution in a viscous accretion disk can be written as

$$
\begin{equation*}
T_{\mathrm{acc}}^{4}=T_{1}^{4}\left(\frac{M_{*}}{M_{\odot}}\right)\left(\frac{\dot{M}}{\dot{M}_{\mathrm{o}}}\right)\left(\frac{R_{*}}{R}\right)^{3}\left[1-\left(\frac{R_{*}}{R}\right)^{\frac{1}{2}}\right] \tag{6.4}
\end{equation*}
$$

where

$$
\begin{equation*}
T_{1} \equiv\left[\frac{3 G M_{\odot} \dot{M}_{0}}{8 \pi \sigma R_{\odot}^{3}}\right]^{\frac{1}{4}}=15100 \mathrm{~K} \tag{6.5}
\end{equation*}
$$

The variables $M_{*}$ and $\dot{M}$ are the mass and accretion rate of the star, and $\dot{M}_{\circ}=10^{6} \mathrm{M}_{\odot} \mathrm{yr}^{-1}$. This equation contains the unfortunate artifact that the
temperature decreases for $R / R_{*}<49 / 36$. To remove this the temperature was maintained at its maximum value in these inner regions, specifically

$$
\begin{equation*}
T_{\mathrm{acc}}^{4}=T_{2}^{4}\left(\frac{M_{*}}{M_{\odot}}\right)\left(\frac{\dot{M}}{\dot{M}_{\mathrm{o}}}\right)\left(\frac{R_{\odot}}{R_{*}}\right)^{3} \tag{6.6}
\end{equation*}
$$

where

$$
\begin{equation*}
T_{2}=\left[\frac{1}{7}\left(\frac{36}{49}\right)^{3}\right]^{\frac{1}{4}} T_{1}=7390 \mathrm{~K} \tag{6.7}
\end{equation*}
$$

In practice this formality was unnecessary since dust evaporation occurs at $T \approx 1500-2000 \mathrm{~K}$, which truncates the inner edge of the opaque disk (Lada \& Adams 1992). The temperature distributions from accretion and reprocessing were combined to produce a composite dust temperature to complete the description of the model:

$$
\begin{equation*}
T_{\mathrm{dust}}^{4}=T_{\mathrm{rep}}^{4}+T_{\mathrm{acc}}^{4} . \tag{6.8}
\end{equation*}
$$

The radiation from this disk was integrated from an inner disk radius-a free model parameter-to an outer disk radius set large enough so the dust temperature dropped to only a few Kelvins. The inner radius was usually larger than 49/36R* so Equations 6.6-6.7 were rarely invoked. The model contains five free parameters: $R_{\text {inner }}, M_{*}, \dot{M}, R_{*}$, and $T_{*}$. In the next section three of these will be estimated from the data so the models were more reasonably constrained.

### 6.5.2 Stellar Parameters

In this section the methods used in determining the stellar parameters $M_{*}$, $R_{*}$, and $T_{*}$ for each infrared excess source are described. The temperatures were immediately obtained from the spectral classifications using the values listed in Hayes (1978). This is not the first time in this dissertation that main sequence
values were used in calculating aspects of the stellar population in NGC 2264. While this is potentially dangerous, it is probably as accurate as any other method.

Stellar radii were calculated combining these temperatures and the dereddened $V$ data which were converted into absolute $V$ magnitudes $\left(M_{V, *}\right)$. The flux measured for a star is proportional to its surface area multiplied by its emergent flux, integrated over the bandpass of the filter being used, i.e.

$$
\begin{equation*}
F_{*} \propto R_{*}^{2} \int B_{\lambda}\left(T_{*}\right) K_{\lambda} d \lambda \tag{6.9}
\end{equation*}
$$

where the star's radiation was modelled as a blackbody, and $K_{\lambda}$ is the transmission efficiency of the filter. Using absolute magnitudes allowed the flux from this star to be normalized by solar values:

$$
\begin{equation*}
\frac{F_{*}}{F_{\odot}}=10^{\frac{2}{5}\left(M_{V, \odot}-M_{V, *}\right)}=\frac{R_{*}^{2} \int B_{\lambda}\left(T_{*}\right) K_{\lambda} d \lambda}{R_{\odot}^{2} \int B_{\lambda}\left(T_{\odot}\right) K_{\lambda} d \lambda} \tag{6.10}
\end{equation*}
$$

which can be written more usefully as

$$
\begin{equation*}
\left(\frac{R_{*}}{R_{\odot}}\right)^{2}=\frac{\int B_{\lambda}\left(T_{\odot}\right) K_{\lambda} d \lambda}{\int B_{\lambda}\left(T_{*}\right) K_{\lambda} d \lambda} 10^{\frac{2}{5}\left(M_{V, \odot}-M_{V, \odot}\right)} \tag{6.11}
\end{equation*}
$$

Equation 6.11 was used to calculate the stellar radii and, since the temperature was already known, a blackbody luminosity using $L_{*}=4 \pi R_{*}^{2} \sigma T_{*}^{4}$. Plotting the location of each star on the evolutionary tracks of Cohen \& Kuhi (1979) produced estimates of stellar ages and masses. More recent evolutionary tracks have been published by D'Antona \& Mazzitelli (1994), and comparing the ages and masses from their tracks with those of Cohen \& Kuhi (1979) showed the two methods to be in general agreement. This is partly because D'Antona \& Mazzitelli (1994) present tracks for various computational models, and the disagreements among them are large for the low mass stars in this study; for example the mass of S1212 was variously estimated as $0.25-0.5 \mathrm{M}_{\odot}$, while the result from Cohen \& Kuhi (1979) was $0.45 \mathrm{M}_{\odot}$. The stellar parameters for all the stars modelled are listed in Table 6.1. The accretion
rates in T Tauri stars can be large-Bertout (1988) showed that half the T Tauri sources in the Tauri-Auriga group have accretion rates with $\dot{M}>10^{-8} \mathrm{M}_{\odot} \mathrm{yr}^{-1}$. In their work on Ae stars, Hillenbrand et al. (1992) found a loose correlation between the mass accretion rates for T Tauri stars and the masses of the central stars. This correlation can be approximately fit with

$$
\begin{equation*}
\log \dot{M}=2.45 \log \left[\frac{M_{*}}{M_{\odot}}\right]-6.95 \tag{6.12}
\end{equation*}
$$

where the units of $\dot{M}$ are $\mathrm{M}_{\odot} \mathrm{yr}^{-1}$. This empirical relation was used to make a first guess at the accretion rate of each source.

### 6.5.3 Model Results

The contortions described in the last section reduced the number of free parameters in the disk models to only two-the inner radii of the annular disks and the mass accretion rates. The SEDs were fit using zero accretion (as a baseline), the accretion rate given in Equation 6.12, and various combinations of $R_{\text {inner }}$ and $\dot{M}$, listed in Table 6.2. The results are shown in Figures 6.30-6.31. Nearly all the sources could be successfully fit with at least one combination of model parameters. Unfortunately as mentioned earlier, most could be fit with several sets of model parameters. To uniquely identify which model is most accurate would require longer wavelength observations which, with a few exceptions to be noted, are not yet in hand. This uncertainty is compounded by the effects of geometry; all the models have been assumed to be arranged face-on to the earth, and any other orientation would modify the disk emission by a cosine factor. The face-on assumption may not be too bad because all the sources modelled were bright, and if the system were highly inclined to the earth extinction from the disk might

Table 6.1. Star and Disk Models

| Source | $\mathrm{M}_{V^{\mathrm{a}}}$ <br> $(\mathrm{mag})$ | $\mathrm{T}_{*}$ <br> $(\mathrm{~K})$ | $\mathrm{R}_{*}$ <br> $\left(\mathrm{R}_{\odot}\right)$ | $\mathrm{L}_{*}$ <br> $\left(\mathrm{~L}_{\odot}\right)$ | $\mathrm{M}_{*}$ <br> $\left(\mathrm{M}_{\odot}\right)$ | Age <br> $(\mathrm{yr})$ | Lines |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| S1212 | 6.68 | 3720 | 1.57 | 0.40 | 0.45 | $1.4 \times 10^{6}$ | $\mathrm{H} \alpha, \mathrm{Ca}$ |
| S1566 | 6.59 | 4030 | 1.25 | 0.35 | 0.7 | $3 \times 10^{6}$ | $\mathrm{H} \alpha, \mathrm{Ca}$ |
| S2079 | 5.10 | 5055 | 1.27 | 0.89 | 1.4 | $1.5 \times 10^{7}$ | $\mathrm{H} \alpha, \mathrm{Ca}$ |
| S2173 | 6.49 | 3880 | 1.48 | 0.42 | 0.45 | $1 \times 10^{6}$ | $\mathrm{H} \alpha, \mathrm{Ca}$ |
| S2268 | 7.06 | 4030 | 1.00 | 0.23 | 0.7 | $6 \times 10^{6}$ | -b |
| S2364 | 1.66 | 8900 | 1.94 | 20.00 | 2.0 | $3 \times 10^{6}$ | $\mathrm{H} \alpha$ |
| S2563 | 6.93 | 3720 | 1.40 | 0.32 | 0.45 | $1.7 \times 10^{6}$ | $\mathrm{H} \alpha, \mathrm{Ca}$ |
| S2666 | 5.47 | 4463 | 1.52 | 0.78 | 1.1 | $6 \times 10^{6}$ | $\mathrm{H} \alpha^{\mathrm{b}}$ |
| S2943 | 3.66 | 5055 | 2.47 | 3.37 | 1.5 | $3 \times 10^{6}$ | $\mathrm{H} \alpha^{\mathrm{b}}$ |
| S3044 | 6.54 | 3720 | 1.68 | 0.46 | 0.45 | $1.4 \times 10^{6}$ | $\mathrm{H} \alpha, \mathrm{Ca}$ |
| S3160 | 5.38 | 4463 | 1.58 | 0.84 | 1.1 | $6 \times 10^{6}$ | $\mathrm{H} \alpha^{\mathrm{b}}$ |
| S3552 $^{\text {d }}$ | 2.31 | 4463 | 6.51 | 14.25 | 2.0 | $3 \times 10^{5}$ | $\mathrm{H}, \mathrm{Ca}$ |
| S3725 $^{\text {S3799 }}$ | 5.15 | 4030 | 2.42 | 1.31 | 0.8 | $6 \times 10^{6}$ | $\mathrm{H} \alpha, \mathrm{Ca}$ |
|  | $3.35^{\text {e }}$ | 4463 | 4.03 | 5.47 | 1.5 | $6 \times 10^{6}$ | $\mathrm{H} \alpha, \mathrm{Ca}$ |
|  |  |  |  |  |  |  |  |

${ }^{\text {a }}$ Corrected for reddening, assuming a distance modulus of 9.5
${ }^{\mathrm{b}}$ The absence of Ca or $\mathrm{H} \alpha$ entries is a result of bad signal to noise. Additional observations may reveal the missing emission lines.
${ }^{\text {c }}$ The photometry of this source is marginally saturated.
${ }^{\mathrm{d}}$ The extreme size and youth of this star may result from disk flux masquerading as stellar flux. See the comments in Section 6.5.3.
${ }^{\text {e }}$ Determined from $I$ photometry, assuming normal $V-I$ colours.

Table 6.2. Model Parameters

| Model | $\begin{aligned} & R_{\text {inner }} \\ & \left(R_{\odot}\right) \end{aligned}$ | $\begin{gathered} \dot{M} \\ \left(10^{-6} \mathrm{M}_{\odot} \mathrm{yr}^{-1}\right) \end{gathered}$ | Model | $\begin{aligned} & R_{\text {inner }} \\ & \left(R_{\odot}\right) \end{aligned}$ | $\begin{gathered} \dot{M} \\ \left(10^{-6} \mathrm{M}_{\odot} \mathrm{yr}^{-1}\right) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| S1212 A | 8.6 | 0.3 | S2666 A | 14. | 0.6 |
|  | 3.9 | 0.1 | B | 9.1 | 0.3 |
|  | 0.0 | $0.016^{\text {a }}$ | C | 3.0 | $0.1{ }^{\text {a }}$ |
| $\begin{array}{r} \text { S1566 A } \\ \text { B } \end{array}$ | 3.1 | $0.47^{\text {a }}$ | S2943 A | 16. | 1.0 |
|  | 4.4 | $0.47{ }^{\text {a }}$ | B | 11. | 0.6 |
|  |  |  | C | 7.4 | $0.3{ }^{\text {a }}$ |
| S2079 A | 38. | 5.0 | D | 4.9 | $0.1{ }^{\text {b }}$ |
|  | 22. | $2.0{ }^{\text {b }}$ |  |  |  |
|  | 14. | 1.0 | S3044 A | 3.4 | 0.2 |
|  | 8.9 | 0.5 | B | 0.0 | 0.12 |
|  | 5.1 | $0.25{ }^{\text {a }}$ | C | 0.0 | $0.016^{\text {a }}$ |
| S2173 $\begin{array}{r}\text { A } \\ \text { B } \\ \text { C } \\ \text { D }\end{array}$ | 15. | 0.6 | S3160 A | 13. | 0.3 |
|  | 9.6 | 0.3 | B | 7.1 | 0.14 |
|  | 4.4 | $0.1{ }^{\text {b }}$ | C | 4.7 | $0.07^{\text {a }}$ |
|  | 0.0 | $0.016^{\text {a }}$ |  |  |  |
|  |  |  | S3552 A | 23. | 1.5 |
| S2268 A | 3.5 | 0.047 | B | 16. | $0.61{ }^{\text {a b }}$ |
|  | 0.0 | 0.02 | C | 9.8 | 0.0 |
|  | 0.0 | 0.01 |  |  |  |
|  |  |  | S3725 A | 23. | 1.0 |
| S2364 A | 110 | $20.0{ }^{\text {b }}$ | B | 17. | 0.6 |
|  | 49. | 5.0 | C | 12. | 0.3 |
|  | 29. | 2.0 | D | 0.0 | $0.065^{\text {a }}$ |
|  | 14. | $0.61{ }^{\text {a }}$ | E | 4.8 | $0.065^{\text {a }}$ |
|  | 9.7 | 0.0 |  |  |  |
|  |  |  | S3799 A | 22. | 1.0 |
| S2563 ${ }^{\text {A }}$ ( | 7.7 | 0.3 | B | 10. | $0.3{ }^{\text {a }}$ |
|  | 3.5 | 0.1 | C | 10. | 0.1 |
|  | 0.0 | $0.016^{\text {a }}$ |  |  |  |

${ }^{\text {a }}$ The accretion rate was obtained using Equation 6.12
${ }^{\mathrm{b}}$ The accretion rate is consistent with $10 \mu \mathrm{~m}$ fluxes measured by Young et al. (1995)


Fig. 6.30.- Disk models as described in the text are shown for the dereddened sources which have IR excesses. The dotted curves are for diskless blackbodies at temperatures matching the photospheres of the central stars. The dashed lines are for nonaccreting, passive disks. The key in each figure lists the two model parameters-the accretion rate in units of $10^{-6} \mathrm{M}_{\odot} \mathrm{yr}^{-1}$, and the inner accretion radius in units of $R_{*}$ ( $\mathrm{R}_{\mathrm{inner}}=1$ at the stellar surface). Models using accretion rates estimated using Equation 6.12 are indicated with an asterisk. When available, $10.3 \mu \mathrm{~m}$ data are shown-unless plotted explicitly, errorbars are smaller than the points plotted.


Fig. 6.31.- Disk models as described in the caption for Figure 6.30 are shown.
attenuate the starlight so much that the sources would not be included in the survey.

It is interesting that both inner holes and accretion are essential to fit the data-without an accretion disk the large infrared excesses cannot be produced, and without inner holes the emission at $V, R$, and $I$ would be far too large. It is also satisfying that all the disk systems exhibited emission lines in both hydrogen and calcium-the only disk systems in which these lines were not observed were those in which the signal to noise in the spectroscopic data did not allow those spectral regions to be analyzed. What are the chances of that occurring? Of all the sources which had reliable photometry in at least two of the $V, R$, and $I$ bands (which allowed dereddening be completed) and at least one datum in the $J, H$, and $K$ bands (which allowed infrared excesses to be sought), 311 had enough spectral coverage to look for calcium or hydrogen emission lines. Of these, 241 had emission lines and 70 did not. The probability that 13 disk stars randomly selected from the 311 sources would include only emission-line stars is

$$
\begin{equation*}
100 \% \times \frac{241!}{(241-13)!} \frac{(311-13)!}{311!}=3.4 \% . \tag{6.13}
\end{equation*}
$$

This is strong circumstantial evidence linking the disk phenomenon with the production of emission lines. But since not all emission line stars showed infrared excesses this connection is not exclusive. Some of the models display $10.3 \mu \mathrm{~m}$ data recently taken by Young et al. (1995)-these are consistent with the results from the simple disk models, but little more can be done without incorporating longer wavelength data.

### 6.5.4 Disk, Emission, Quiescent, and Anemic Stars

Although the age of NGC 2264 is often given as almost $10^{7} \mathrm{yr}$ old (the first estimate of the cluster age was $5 \times 10^{6} \mathrm{yr}$ and was obtained by Walker (1956) by fitting the main sequence turn-on point at A0), this is misleading. In Figure 6.6 the populations of young stars can be seen evolving towards the main sequence. The stars in this figure are not distributed in a narrow band, but are scattered in a region with substantial breadth in the $m_{V}$ direction, indicating a wide range of ages-for typical cluster stars, a difference of three magnitudes translates to a spread of ages comparable to the age of the cluster itself! It was shown by Cohen \& Kuhi (1979) that while the peak era of star formation in the cluster occurred approximately $1.6-3.2 \times 10^{6} \mathrm{yr}$ ago, timescales for star formation are $4-6 \times 10^{6} \mathrm{yr}$ (in their sample they had stars as young as a few $\times 10^{5} \mathrm{yr}$, and others older than $10^{7} \mathrm{yr}$ ). This was verified by Lada et al. (1993), who estimated a timescale for formation of $4-5 \times 10^{6} \mathrm{yr}$. Indeed, the small sample of stars in this dissertation for which ages were calculated also demonstrate a large range of ages.

Because of the noncoeval nature of star formation in the cluster, it is difficult to clearly separate samples into distinct evolutionary groups. But as discussed in Section 6.3.2, the emission, anemic, and quiescent stars are populations which were defined spectroscopically, yet separate from each other nicely on H-R diagrams. This triumvirate was interpreted as an evolutionary sequence from youngest to oldest type. But where do the disk stars-objects presumably some of the most active in the sample-occur in the H-R diagrams? The data from Figure 6.15 are reproduced in Figure 6.32, but the disk sources are now indicated. Notice that with the exception of S2364, all the disk stars are found in the region occupied by the emission stars. The mixing of the disk stars with the anemic stars is minimal-at


Fig. 6.32.- The data from Figure 6.15 are replotted, but in addition the stars with infrared excesses are shown. They are clearly closely allied with emission stars.
most there is some overlapping at the boundaries of the respective regions for each. This emphasises the distinction between the emission and anemic stars.

Unlike their photometric characteristics, the locations of the disk stars on the sky are not compelling. They are simply scattered throughout the cluster, although are never found too far from the regions of bright IRAS emission.

### 6.5.5 Comments on Individual Sources

S1566: The $K$ magnitude is consistent with a passive, reprocessing disk, while the $J$ and $H$ magnitudes mandate accretion. The irregular $V, R$, and $I$ magnitudes are slightly pathological suggesting this may be a variable star.

S2079: The extremely large infrared excess implies large accretion rates. The magnitudes suggest this may be a variable.

S2173: Large accretion rates are required to fit the $K$ datum well, but these are not corroborated by the $10 \mu \mathrm{~m}$ datum.

S2268: Inner holes are not required to fit this source well.
S2364: To fit the sharp turn in the SED at $J$, both extreme accretion rates and large inner hole radii are required to fit this Ae star. These values are verified by the $10 \mu \mathrm{~m}$ datum.

S2666: The $I$ datum is anomalous and may be corrupted.
S3044: No hole is required to fit this SED.
S3552: This star's radius ( $R_{*}=6.51 R_{\odot}$ ) may seem too large, but it is a cool K4 star with $m_{V}=12.0$ and so must be large. It is not a foreground star because it has hydrogen and calcium emission lines. It is possible that this is a smaller
star but with large amounts of accretion and little or no inner hole in its disk; such an arrangement would increase the flux at all wavelengths and explain the observations. But which of these two hypotheses is correct cannot be determined with the data in hand.

### 6.6 Binaries

Although they no doubt have some effect on the ecology of the cluster, very little has been said about binaries in this work. This is partly because they would be very difficult to detect in the data presented in these pages. As noted in Chapter 3, unless some of the bad-clump warning flags were activated, the processing involved in creating the photometric survey would have merged the data of binaries separated by less than $3.6^{\prime \prime}$ (3000 a.u.), and even careful inspection of the images would not resolve binaries separated by less than several hundred a.u. It might be thought that the spectroscopic data of Chapter 5 could reveal multiplicity in many stars, but sadly this is not the case. Two stars of similar spectral type would have a merged composite spectrum indistinguishable from a single star, and its reddening estimate, although less accurate, would not reveal the duplicitous nature of the stellar system. Such a source would appear approximately 0.75 magnitudes abnormally bright and this could be hidden in the spread of magnitudes observed in the pre-main sequence scatter. If one of the disk-model stars were such a multiple, its greater flux would be misinterpreted as being due to as star approximately $\sqrt{2}$ larger than it really was, resulting in an underestimated stellar age and mass. Systems including two stars of different significantly different mass types would result in the light from the earlier star dominating, producing a nearly normal spectrum. Such a star would be thought
to have a colour excess which would be partly removed by a misguided attempt at dereddening. The overly-dereddened data would be too bright, and again the source would be misinterpreted as younger than it actually is. The magnitude spreads on the various colour-magnitude and H-R diagrams are comparable or larger than 0.75 magnitudes, and perhaps if the effects of binaries could be detected and removed the various populations of quiescent, anemic, and active stars would be more spatially segregated on such plots. Unfortunately, to identify the binaries would require data with qualities that exceed what is presented here. The most effective method would be to look for velocity splittings in spectral features, using high resolution spectroscopy. Even this approach might be complicated by the possible occurences of P Cygni line profiles. As a final comment on the importance of multiples, it is ironic that the extremely interesting source S3321 discussed in Chapter 4 is in fact a double source.

### 6.7 Highlights From This Study

This work studied NGC 2264 using a variety of astronomical methods, and each avenue of exploration illuminated different aspects of the young, dust-enshrouded stellar population. In particular, the results of this study are several...

- Data from IRAS reveals the extent to which the dust in the region is being heated by energizing sources. The $60 \mu \mathrm{~m}$ and $100 \mu \mathrm{~m}$ fluxes are consistent with values expected for dust emission, while the $12 \mu \mathrm{~m}$ and $25 \mu \mathrm{~m}$ radiation is produced mostly by nonthermal means. The morphology of the emission indicates that the energizing sources are embedded young infrared objects and pre-main sequence stars scattered throughout the region.
- The cluster region was surveyed in the bands $V, R$, and $I$, and the results were then merged with an already existing survey in the $J, H$, and $K$ bands. This yielded a six-band inventory of nearly 5000 point sources in the cluster region, which is an invaluable tool both for this project and for future research.
- A polarimetric study of a reflection nebula in NGC 2264 revealed its illuminating source. This source was found by other authors to be an extremely reddened binary object which is associated with a high velocity bipolar molecular outflow. Photometry of this object-in comparison with photometry of portions of the nebula-and the general morphology of the intensity and polarization structure of the reflection nebula, suggest the presence of an obscuring, collimating disk.
- The MK spectral classification system was expanded from the blue part of the spectrum to the red end. Using this extension, 361 stars from the cluster were classified to an accuracy of a few spectral subtypes.
- Based upon characteristics of the Balmer and especially Ca II lines, the spectroscopic sample of stars is found to consist of three important groups: quiescent, anemic, and active stars. Spectral anemia is mostly confined to later spectral types, and its paucity in earlier stars may be due to the effect being masked by the greater photospheric flux from those hot objects.
- The quiescent, anemic, and emission stars are shown to occupy different zones in H-R diagrams. An evolutionary sequence is proposed in which as stars age (i.e. approach the main sequence) and shed their circumstellar material, they evolve from being emission-line stars to anemic stars, and finally become quiescent stars-all before the main sequence.
- Examining the photometry of the spectroscopic groups, it is found that the quiescent stars are less variable than the other types, especially in their $J-H$ and $H-K$ colours.
- Using the MK spectral classifications, the multiband data were dereddened using $V-I$ colours. The resulting spectral energy distributions and colours are surprisingly similar to main sequence values, although the luminosities are enhanced. A small sample shows strong infrared excesses even after dereddening.
- The dereddened spectral energy distributions of sources with infrared excesses were modelled as star and disk systems. These models successfully reproduce the spectral energy distributions as long as the disks are truncated at inner radii. The infrared excess is found to depend almost exclusively upon the mass accretion rate, but estimates of the accretion rate require new data at wavelengths longer than the $K$ band. The disk stars are strongly associated with the emission line sample of stars, but not with anemic stars.
- The broad vertical spread of stars on colour-magnitude diagrams indicates that star formation in NGC 2264 has proceeded over a long time. Although ages for NGC 2264 are commonly given as several million years, it is clear that star formation was not a short duration event in the cluster, and is still continuing as in the disk stars or the young polarimetry source S3321.


### 6.8 The Contents of Chapter 7

Merle Walker's original study of NGC 2264 was extensive yet did not completely describe the nature and interactions of the stars and dust in the cluster.

Similarly, this study has just laid the foundation for a modern reassessment of the region. The giant photometric survey contains a treasure trove of data to be processed, while the spectroscopic data similarly has many secrets still hidden. Hybridizing the two has already been very rewarding, and these mountains of data cry out for further development as well as additional data for additional cross-analysis. But this dissertation has to be ended somewhere, so it will be on a note of things abandoned, still to be accomplished.

A short exposure survey of the region as mentioned in Section 3.8 would be useful to incorporate the bright and presently saturated stars into the survey-after all, these are the stars which are most important in illuminating much of the IRAS dust! The raw source lists used in constructing the photometric survey could be used as a blink survey, as described at the end of Section 3.6.4. This is important because several times in this study it was apparent that many of the stars in this study were surely variable. Indeed, it should be emphasised that multiband surveys of young stellar clusters must obtain the data as simultaneously as possible.

As noted in Section 6.2.3, the dust cloud containing the stars was not fully penetrated by this survey, and the truly interesting young stars were only partly sampled. Another set of spectroscopic observations concentrating on as-yet unobserved stars would be rich ore. If data were obtained with an instrument that retained continuum information with higher fidelity than did the MX instrument, an independent check on the extinction estimates could be made. Higher resolution spectra ( $\sim 1.5 \AA$ ) could look for key features such as [O I] $6300 \AA$ emission since it is becoming apparent they are correlated to both infrared excesses and mass loss or accretion (Cabrit et al. 1990). High resolution data could be used to look for binary systems as well.

It will eventually be discovered that E-band emission is associated with collapsing protostars and small wormholes are often found near CTTSs (Data \& Riker 2367). A search for these in NGC 2264 should provide many insights into the dymanics of star formation in the GMC region.

As noted in Section 6.5.3, more photometric coverage is achingly needed for the small set of stars with infrared excesses. Longer wavelength observations could both fix the accretion rates in the disk, as well as provide disk masses resulting in a dynamical timescale estimate. The ages of stars in the quiescent, anemic, and emission populations could be estimated from evolutionary tracks to test the hypothesis that the spectrally less active stars are older, and the results could be used to look for stellar birthlines. Age estimates could shed light on the matter of whether the star formation is a short-lived, continuous, or episodic process. Assuming extinction scaled with depth into the cloud, three dimensional maps of the cluster could be constructed. It would be very interesting to look at extinction estimates from close star pairs to look for two-point correlations between the extinction estimates. If background stars were used for this it might reveal information about the clumpiness of the cluster dust. The data are in hand to complete all these investigations, only time would be needed to plow through it!

Finally, as discussed in Chapter 4, polarimetry of the S3321 nebula could be further refined. It would be fascinating to see what the polarimetric structure of the nebula looks like at $K$. And of course, there are several other infrared nebulae in the cluster ready to be mapped-S3321 was just the first.

NGC 2264 is continually transforming itself as some of its youthful stars mature, while others are still emerging from the murk. No doubt even younger and more exotic objects lurk within the shadowy mists of cloudbanks.

## Appendix

## A SPECTRAL ATLAS

The 361 spectra described in Chapter 5 are presented in this Appendix. The stars are shown in order of increasing spectral subtype. When more than one star of the same spectral subtype is present, the stars are ordered by survey number, and stars with no survey number were shown last (i.e. Walker or L H $\alpha$ stars). Each spectrum is shown over the wavelength range in which the $S / N$ was good. For clarity of presentation, some of the spectra are clipped in the vertical direction. Usually these features are noise spikes (e.g. the B0 star S1901) but real emission features are occasionally truncated-in those cases the clipping is demarked with a horizontal solid line (e.g. the A2e star S2364). An "e" after spectral type indicates the presence of emission features in the spectrum.

## Comments

B stars: Fourteen stars were catalogued and shown on pages 325-326. The features near $4050 \AA, 4260 \AA$, and $5265 \AA$ are not astronomical in origin.

A stars: Twenty-four stars were catalogued and are shown on pages 327-330. Two more are presented on page 394.

F stars: Thirty stars were catalogued-see pages 331-335. The last spectrum (S2313) appears to be a composite of an $F$ spectrum and an $M$ spectrum.

G stars: Thirty-four stars were catalogued and are shown on pages 336-341
K stars: One hundred-eighteen stars were catalogued and are plotted on pages 342-367. Eight more are presented on pages 394-396.

M stars: Ninety-nine stars were catalogued and are shown on pages 368-393. The last in the listing are those with indications of being M7. Thirty-two more are presented on pages 396-406.

Odds and Ends: Forty-two peculiar or very noisy spectra are presented on pages 394-406. These were smoothed by boxcars, the widths of which are listed in the comment field of Table 5.7. The stars S2173 and S3920 were not smoothed, but they are shown here since it was difficult or impossible to assign these continuum stars a photospheric spectral type. M5 stars which showed indications of being M7 candidates are shown last.


Fig. A.1.- B star spectra



Fig. A.2.- A star spectra
Fig. A. 2 (Continued).-A star spectra

$87 \varepsilon$
Fig. A. 2 (Continued). A star spectra


Fig. A.3.-F star spectra

Fig. A. 3 (Continued).-F star spectra

Fig. A. 3 (Continued).- F star spectra

Fig. A. 3 (Continued).-F star spectra



Fig. A. 3 (Continued).-F star spectra

Fig. A.4.- G star spectra

$98 \varepsilon$

## Fig. A. 4 (Continued).- G star spectra


Fig. A. 4 (Continued).- G star spectra

$\underset{\infty}{\infty}$
Fig. A. 4 (Continued).- G star spectra






Fig. A.5.- K star spectra


Fig. A. 5 (Continued).-K star spectra




Fig. A. 5 (Continued). - K star spectra



Fig. A. 5 (Continued).- K star spectra


Fig. A. 5 (Continued).- K star spectra


Fig. A. 5 (Continued).-K star spectra


Fig. A. 5 (Continued).-K star spectra

Fig. A. 5 (Continued).-K star spectra


398


Fig. A. 5 (Continued).-K star spectra




Fig. A. 5 (Continued).-K star spectra


Fig. A. 5 (Continued).-K star spectra


Fig. A. 5 (Continued).- K star spectra


Fig. A. 5 (Continued).-K star spectra

Fig. A. 5 (Continued). - K star spectra


198
Fig. A. 5 (Continued).-K star spectra

Fig. A. 5 (Continued). - K star spectra

$\stackrel{( }{\Phi}$



Fig. A. 5 (Continued).-K star spectra


Fig. A. 5 (Continued).- K star spectra


Fig. A. 5 (Continued).-K star spectra


Fig. A.6.- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra



Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).-M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra
Fig. A. 6 (Continued). - M star spectra

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Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A. 6 (Continued).- M star spectra


Fig. A.7.- Contentious spectra
Fig. A. 7 (Continued).- Contentious spectra

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Fig. A. 7 (Continued). - Contentious spectra


Fig. A. 7 (Continued).- Contentious spectra


Fig. A. 7 (Continued).- Contentious spectra


Fig. A. 7 (Continued). - Contentious spectra


Fig. A. 7 (Continued).- Contentious spectra


Fig. A. 7 (Continued).- Contentious spectra


Fig. A. 7 (Continued).- Contentious spectra


Fig. A. 7 (Continued).- Contentious spectra


Fig. A. 7 (Continued).- Contentious spectra


Fig. A. 7 (Continued).- Contentious spectra


Fig. A. 7 (Continued). - Contentious spectra

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[^0]:    a Stars with question marks, i.e. "G7?", have questionable subtype classification. Stars with a question mark and no subtype entry, i.e "M?", have very uncertain spectral classifications.
    ${ }^{b}$ Luminosity classifications " d " and " g " indicate secure typification as dwarf or giant stars. A question mark indicates the classification is not secure.
    ${ }^{c}$ The Ca II K and Balmer lines from Ho-He are listed if they occurred in emission. A star with several emission lines, but not a complete list, may be suffering from a noisy spectrum. With sufficiently sensitive spectra more emission lines could be measured.
    ${ }^{\text {e }}$ Walker 1956.
    ${ }^{\mathbf{f}}$ Forbidden lines in Spectrum.
    ${ }^{h}$ T Tauri Star.
    ${ }^{i}$ Trumpler via Walker 1956.
    ${ }^{\mathrm{j}}$ Possible T Tauri Star.
    ${ }^{k}$ Spectrum smoothed by a boxcar of the dimension given in the comments column. The spectrum is displayed with the other smoothed spectra.
    ${ }^{m}$ The large disparity between the classification of this star and Walker's classification is discussed in the text.
    ${ }^{n}$ This confusing spectrum is displayed with the smoothed spectra, although it was not smoothed.
    PMgH 5211 $\AA$ and TiO bands suggest an M1V companion to this star.
    9 Vo 5737 $\AA$ suggests an M5-M7 classification.
    ${ }^{r}$ Probably the latest star in the MX survey.

