A RE-EXAMINATION OF THE MK SPECTRAL CLASSIFICATION

SYSTEM FOR "A" AND "F" MAIN SEQUENCE STARS

by

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I hereby recommend that this dissertation prepared under my

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___FOR "A" AND "F" MAIN SEQUENCE STARS___

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This Work is Dedicated

to

My Father

who, when asked how or why, did not supply
the answer, but rather, pointed the way for
my discovery

and to

My Mother

who dried the tears.

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ABSTRACT

The need for an improvement in the MK classification system for A and F dwarfs is evidenced by the scarcity of standards for types A6 through F4. The difficulty in classifying these stars is principally due to an insufficient number of temperature sensitive criteria. A second difficulty arises from the fact that although the metallic lines show a general increase in strength with decreasing temperature, there are large variations in their strength at a given temperature. These variations in their strength added to the uncertainties in classification due to an insufficient number of available criteria lead to an unduly large dispersion in the spectral type vs. color relation.

The new grating-Schmidt type spectrographs yield classification spectra with useful features extending from Hβ to below 3300A. The numerous metallic lines and blends plus the convergence of the Balmer series present a unique opportunity for improving the MK classification system for these stars.

A temperature sequence of main sequence stars having normal (for the solar neighborhood) metallic line strengths is formed from a study of the uvby photometry of the 1217 A and F stars in the Stromgren-Perry catalogue plus 43 additional stars with photometry obtained at

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Steward Observatory. The c_1 index is used to select only main sequence stars from the above sources. These dwarf A and F stars are plotted on an m_1 vs. b-y diagram from which a mean m_1^o - (b-y) relation is obtained for the most common stars of the solar neighborhood. This relation for the F stars differs significantly from that of the Hyades main sequence.

Using the Steward Observatory Cassegrain spectrograph, over 370 grating spectra (117 A/mm) of A and F dwarfs of widely varying metallic line strength (as indicated by m_1) were obtained. One hundred twenty-four of the spectra are of dwarfs lying on the normal m_1^o - (b-y) relation. The 3300A-3900A region of these spectra is studied in order to determine criteria which indicate accurate spectral types. The resulting spectral type vs. criteria table makes it possible to classify the A and F stars at each 0.1 spectral type interval with an r.m.s. error of about 0.1 type in the mid-A stars and decreasing rapidly towards the late F stars.

The available spectra of MK luminosity standards of types A and F are studied for luminosity criteria. The results are given in the form of tables of luminosity class vs. criteria at each 0.5 spectral type. The increased sensitivity of the new criteria makes it possible to classify A and F stars according to luminosity with significantly improved accuracy.

The increased accuracy in two dimensional classification plus the availability of the m_1 index makes possible a more thorough study of the third dimension (metallic line strength) in spectral classification. Criteria sensitive to metal abundance in the F stars and well correlated with rotation and possibly microturbulence in the A stars are given.

One hundred sixty-two stars of varying m_1 are classified on a three dimensional scheme. The temperature and luminosity classifications are similar to the MK system while the metallic lines strengths are divided into 5 groups. These 162 stars are plotted on a spectral type vs. color diagram and yield a smooth continuous relation with representatives at each 0.1 type.

A statistical study of the available uvby and Hβ data for the late F dwarfs reveals that the m_1 index is principally a measure of the metals to hydrogen ratio in these stars--not a measure of microturbulence. It also shows that the b-y index is sensitive to blanketing effects. Apparently the variations in microturbulence among these stars is so small that variations in metallic abundances contribute to most of the observed variations in line blanketing.

CHAPTER I

INTRODUCTION

In the wonder of a rainbow, in the multicolored arch of light dancing in the midst of a waterfall, man first saw the spectrum of a star. It would still be centuries before his growing curiosity would overwhelm his aesthetic wonder and he would seek an explanation to this mystery.

To be sure, it was Descartes who first correctly explained the rainbow, but it was Sir Isaac Newton who first spread the light of the sun into its many component colors using a glass prism. He called this synthesized rainbow a spectrum (Thackeray 1961).

Nearly two more centuries came and went before Fraunhofer combined a prism with a theodolite telescope and gave alphabetic names to the dark absorption lines previously discovered by Wollaston in the solar spectrum. In 1859, Kirchhoff and Bunsen showed that the bright lines emitted in the laboratory by a sodium flame were located at the same position in the spectrum as the solar "D" lines of Fraunhofer. Other observers had noted that the spectra of the brightest stars contained patterns of dark lines very similar to the Fraunhofer lines in the solar spectrum.

It was concluded that by studying the spectra of various elements in the laboratory, their characteristic line patterns could be sought for in the complicated spectra of the sun and stars, thereby revealing the composition of these inaccessable objects. The science of stellar spectroscopy had been born.

The Italian astronomer Secchi was probably the first to classify spectra in groups according to their appearance, but it wasn't until the invention of the photographic plate that the first widely used system of spectral classification came into being. Using small objective prism telescopes in the northern and southern hemispheres, over a quarter of a million stars were classified by A. J. Cannon and E. C. Pickering (1918-24) on the Henry Draper system. It was on this system that the familiar O-B-A-F-G-K-M sequence originated and it was first realized that this sequence reflected the variation of a single parameter in the classified stars--the surface temperature (Curtiss 1932).

Even before this catalogue had been published, Maury and Pickering (1897) had noticed that the width and sharpness of the lines in the spectra appeared to vary at a given spectral type. They introduced the small prefixes "a," "b" and "c" to designate this. By 1909, Hertzsprung had shown that the "c" stars had much higher luminosities than the broader line stars of the same temperature class.

This pointed the way for two dimensional spectral classification (Keenan 1963).

Adams and Kohlschutter (1914b) at Mt. Wilson used slit spectrograms of higher dispersion to find correlations between line strengths and the independently determined parallaxes of stars of various surface temperatures. After spectral types were determined, curves were drawn for each type relating various line differences in the spectra to absolute magnitude. Thus, it became possible to determine stellar luminosities by visual studies of their spectra.

It was soon noticed however, that there were systematic differences in the spectral types assigned on the Mt. Wilson system and on the H.D. system. A photometric investigation showed that the H.D. types were more consistent with color temperatures than the Mt. Wilson types for A stars. However, the Mt. Wilson types and luminosities were a very useful improvement over the older H.D. system.

In the late 1930's, W. W. Morgan began to develop a more modern system of spectral classification which later became known as the MKK system (Morgan, Keenan and Kellman 1943). Since the system described in this dissertation is a direct descendant of the MKK system, we shall now review the relevant philosophy of the MKK system as outlined in the original atlas.

First of all, Morgan states that the atlas and its outline "have been prepared from the viewpoint of the practical stellar astronomer. Problems connected with the astrophysical interpretation of the spectral sequence are not touched on; as a consequence, emphasis is placed on 'ordinary' stars."

On the other hand, Morgan emphasizes the need for selecting spectral criteria which will reflect variations in a physical parameter. "The system should be as closely correlated with color temperature (or color equivalent) as is possible. The criteria used for classification should be those which change most smoothly with color equivalent."

Again, quoting Morgan, "The present system depends, then, to a considerable extent on the work of these investigators" (earlier investigators in temperature and luminosity classification schemes), "combined with data which were not available until recently. These data are of two kinds: accurate color equivalents for many of the brighter stars and accurate absolute magnitudes for a number of the same stars. These results have been used to define the system of classification more precisely, both in the temperature equivalents and in the luminosity class."

To sum it up, Morgan's idea was to: (1) classify the spectra according to line differences and spectral appearances only; (2) choose these criteria such that the resulting classification sequence is well correlated with

the physical parameters related to each dimension in the scheme; (3) use the latest and most accurate available observational data pertaining to these physical parameters as a guide in choosing the spectral criteria. That this philosophy has been maintained through the years is shown in the following quotation (Keenan 1963). "It is practically necessary for the classifier to take into account all the physical information available for the group of stars with which he is working. He must use all these clues in developing an arrangement that will separate the physical parameters as sharply as possible, . . ."

The revised MKK system (MK system) is briefly described by Johnson and Morgan (1953) and a list of standard stars with types is given. There were no changes from the philosophy of the older MKK system, only some minor changes in the classification scheme. The G0-K2 giants "did not show a satisfactorily smooth relationship with color equivalent" and therefore new criteria were chosen in order to give a classification scheme more compatible with measured color equivalents. The list of standard stars with types defined the MK system and claims of higher accuracy in both luminosity class and spectral type were made.

In 1962, "A Discussion of Spectral Classification" was held at Kitt Peak National Observatory and a report on this discussion is given by Abt (1963). In the two decades

following the MKK Atlas, major changes have been made in the design of the spectrograph. The general trend is to replace the prisms with blazed reflection gratings while replacing the lenses with mirrors. The advantages realized are an increased ultraviolet transmission such that the H and K lines of Ca II are moved toward the center of the spectrum, and a nearly linear dispersion. These two effects produce a radical change in the appearance of the spectrum and thereby create a need for a new spectral atlas.

Even though the dispersion is roughly the same as the MKK system, the higher resolution and the greater linearity of the dispersion called for the redefining of old criteria plus the defining of some new criteria. It was hoped that the newly acquired ultraviolet portion of the spectrum would supply some of these criteria. In fact, some ultraviolet luminosity indicators were found with a resultant improvement over the MK classification (Abt 1963).

The second session of this discussion was devoted to the possibilities of spectral classification by non-photographic techniques such as photoelectric photemetry. In this session the uvby system (used in this dissertation) was discussed along with many of the current theoretical and observational problems involved in photoelectric methods of spectral classification.

Prior to completing this discussion of the evolution of the MKK system, it will be profitable to review some of the highlights of the history of the third parameter in spectral classification and indicate the development of the uvby system.

In the MKK Atlas, similar spectral peculiarities in some G and K type high velocity giants are mentioned-- the most striking being the weak CN absorption. This peculiarity suggested the possibility of classification in a third dimension. It remained for the numerous investigators in more recent years to show that the physical parameter relevant in this case is the chemical composition (Schwarzschild, M. and B. 1950; Schwarzschild, Spitzer, and Wildt 1951; Schwarzschild, M. and B., Searle, and Meltzer 1957; Greenstein and Keenan 1958).

In the early 1950's, Miss Roman (1950) found a correlation between the spectroscopic and the dynamical characteristics of late F and early G stars. She noted that stars of the same spectral type and luminosity class could still be divided into two groups--one group having systematically weaker lines than the other. A study of the motions of these two groups of stars showed that the weak-line group had a greater velocity dispersion than the strong-line group.

In a later paper, Miss Roman (1954) discussed the characteristics of 17 F stars selected for their spectral

similarities from a large number of high velocity objects.
She states that the 17 subdwarfs "certainly form the purest
Population II objects isolated as yet within 100 parsecs of
the sun." She also noted an ultraviolet excess of
approximately 0.2 magnitudes for these stars on the UBV
system.

Stromgren (1958a) gives a review of the work on
composition differences between stellar populations up to
that date. After a discussion of earlier investigations
in the field, he states that "differences in composition
can be detected and investigated through photometry in a
few properly selected wave length bands." Combining the
"m" index with his "l-c" system, he observed a number of F
stars of Populations I and II. He found that "the range of
variation of 'm' for the group of Population I F stars
considered is much larger than it would be if the varia-
tions were due to a variation in B-V and absolute magnitude
alone so that there is evidence for the influence of a
variable 3rd parameter." He identified this third
parameter with the ratio of heavy elements (metals) to
hydrogen. Further evidence for this third parameter is
given in the same volume by Stromgren (1958b) and by
Chalonge (1958).

In the early 1960's, Stromgren (1963a, 1963b)
introduced his uvby intermediate band photometric system.
The color index (b-y) is a temperature indicator relatively

insensitive to blanketing effects. The c_1 color difference measures the Balmer discontinuity, and the m_1 color difference measures the strength of the metallic absorption lines in the band-pass of the v filter. The chief advantage of this color system over others is that it allows a three dimensional classification of unreddened A and F stars giving a good separation between the effects of absolute magnitude and chemical composition. The history and reasoning behind its development may be found in the above references by Stromgren. Johnson (1963) and Becker (1963) also give reviews of some of the earlier photoelectric systems.

Stromgren (1963b) published an m_1-(b-y) diagram using preliminary data from the so called "Stromgren-Perry. Catalogue" (1967). A study of the diagram plus a knowledge of the photoelectric accuracies involved indicates the ability of the uvby system to measure the third parameter. For the F6-G2 stars, there is a large spread in m_1. It has been shown (Stromgren 1963a, 1963b) that there is an excellent correlation between $(\Delta m_1)_{Stromgren}$ and Wallerstein's (1962) [Fe/H] ratios for this range of spectral types.

The F2-F4 stars show a much smaller scatter in m_1-- in fact, only about 30% larger than the errors attributed to the photometry. Stromgren concludes that since the declining sensitivity of the m_1 index to chemical

composition with decreasing b-y is not sufficient to account for the small scatter, the stars in this range must be more homogeneous with regard to chemical composition. The A2-F1 stars would be expected to show even less scatter in m_1 since the index is less sensitive to composition and the stars as a group are younger and probably chemically more homogeneous. However, a very large scatter in m_1 has been observed in this spectral range. Stromgren (1963b) feels that it probably cannot be directly identified with any quantity characterizing the chemical composition. It should be noted however, that the metallic line stars generally have high m_1 values--but not always.

The problem of determining the physical parameter(s) responsible for producing the scatter in m_1 in the A stars is a complicated one and not yet satisfactorily answered. Stromgren (1963b) has found a strong correlation between the m_1 index and projected stellar rotational velocities. Kraft and Wrubel (1965) found a correlation between the mean rotational parameter $\overline{Y}$ and Stromgren's Δc_1 for main sequence Hyades stars brighter than $M_v = 3^m\!.6$. Kraft (1967) further discusses the effects of rotation on colors in a review article to appear in the _Otto Struve Memorial Volume_.

As was indicated earlier, the physical parameter(s) responsible for the dispersion in m_1 observed in the late F and early G stars was originally thought to be the ratio of

the abundances of the metals to that of hydrogen. Conti
and Deutsch (1967), in correcting their (1966) results,
have shown that the m_1 index is twice as sensitive to
differences in [V] (a parameter which incorporates the
velocity of microturbulence in a stellar atmosphere) as it
is to differences in [Fe/H]. Using the numerical results
of Conti and Deutsch (1967), the spectroscopically observed
relation between [Fe/H] and [V] due to Wallerstein (1962),
and the available photoelectric uvby and Hβ data for the
Hyades and the nearby field stars, observational tests are
described in Chapter VII of this dissertation which lead to
the conclusion that the m_1 index is principally a measure
of the metals to hydrogen ratio in these stars. It must be
emphasized that most references to m_1 and its predecessor
"m" in the literature and to some extent in this disserta-
tion refer to m_1 as a metal index or chemical composition
indicator--whereas in reality, it is a measure of these
particular quantities only for unreddened main sequence
stars in the narrow spectral range including late F and
early G.

In August, 1964, I. A. U. Symposium No. 24 (Loden,
K. and L. O., and Sinnerstad 1966) was held for the purpose
of discussing "Spectral Classification and Multicolor
Photometry." This Symposium and the earlier discussion at
Kitt Peak (Abt 1963) demonstrate the increasingly intimate
relationship which is developing between the fields of

spectral classification by visual inspection and photo-
electric photometry.

While it has been argued by some that subjective
systems of spectral classification (e.g., the MK system)
will be replaced by the more accurate photoelectric
systems, the leaders in the development of these photo-
electric systems are quick to disagree. For example,
Stromgren has stated that ". . ., both methods must be
pushed, and I must say that I like to hold the hand of a
person who obtains spectra" (Abt 1963, p. 103). Both
Morgan and Stromgren agree that there are certain advan-
tages to both methods. With the increasing use of image
intensifier tubes, the disadvantages of the low quantum
efficiency and non-linear response of the photographic
plate are being overcome.

Morgan (1966a) discusses the evolving definition
of the term "normal stars" since it was first used in An
Atlas of Stellar Spectra (Morgan, Keenan, and Kellman
1943). In the MKK system, a star was considered "normal"
if it fit into the two dimensional spectral type-
luminosity array. At the present time, a stellar spectrum
is considered normal if it can be classified in a three
dimensional array--where the metallic line intensity is the
third parameter.

Jaschek and Jaschek (1966) report on a statistical
study they made concerning the internal accuracy of the

classification of spectra on the MK system. They obtained

the data from the recent catalogue of spectra classified on

the MK system (Jaschek, Conde, and de Sierra 1964). These

authors conclude that the MK system is internally more

accurate than the Victoria, Harvard, and Mt. Wilson

systems. Also, they point out the areas in the two

dimensional temperature-luminosity array where the largest

discrepancies between various classifiers occur. In the

region of the A and F stars, they find that most dis-

crepancies occur around types A0-A5, F5-F9 and luminosity

classes IV and V.

Aside from the internal accuracy of the MK system

of classification as it applies to the A and F stars, it is

shown in this dissertation that there are systematic errors

involved. A plot of the 1217 A and F stars of the

"Stromgren-Perry Catalogue" (1967) in an m_1-(b-y) diagram

(Stromgren 1963b) may be used to study correlations between

the positions of the MK standards in the diagram and their

MK type (Meinel 1965). This study reveals that variations

in the metallic line strength of both the A and F stars

tend to be confused with variations in effective tempera-

ture.

A spectral type vs. (b-y) color diagram for the MK

standards of types A and F and luminosity class V is given

in Figure 3 of this dissertation. The most striking feature

of this diagram is the large gaps in color index between

types A5 and F5 where few MK standards are given. The departure of these few points (e.g., at F0 and F2) from the otherwise apparently smooth continuous relation between MK standard type and (b-y) is also noticeable. Both of these features are probably due to the lack of accurate criteria available in the spectra of these stars for classification on the MK system.

Morgan (1966a) lists several reasons for improving the accuracy of the MK system. Among these is "the furnishing of a general frame of reference of optimum value for quantitative methods of stellar classification." In order to achieve this goal, the following tasks must be accomplished: (1) the spectral type-color index relation must be improved; (2) the color index range corresponding to each spectral type must be defined as accurately as possible. However, in order to accomplish these tasks, the system of spectral classification itself must be improved by reducing both the internal error of the system and its systematic error. These improvements can only be achieved by revising the MK classification system for the A and F dwarfs through the addition of new spectroscopic criteria and a description of their use for classification purposes.

The new Schmidt camera-blazed grating spectrographs are capable of producing spectra of classification quality from wave lengths shortward of 3300 Angstroms out to beyond $H\beta$ on a single exposure. A brief investigation of the KPNO

Atlas of Grating Spectra (Meinel and Schulte 1967) reveals that the 3300A-3900A region of the spectrum contains numerous features which might be suitable for classification purposes.

With the availability of uvby photometry for a large sample of the A and F dwarfs in the solar neighborhood (Stromgren and Perry 1967), and the new Steward Observatory Cassegrain spectrograph, the problem of revising the MK system of classification of the A and F dwarfs is undertaken in this dissertation.

CHAPTER II

OBSERVATIONS

The choice of which stars to observe spectro-
scopically was made from a study of their positions on the
m_1 - (b-y) diagram. Since <u>uvby</u> photometry was not
available for a number of the MK standards of types A and
F and luminosity classes IV and V, it was decided that
<u>uvby</u> photometry supplementary to the Stromgren-Perry
catalogue would have to be carried out.

In addition to obtaining photoelectric and subse-
quent spectroscopic data for all of the above MK standards,
it seemed desirable to include as many as possible of the
normal A stars included in Abt's (1965) investigation and
the A_m stars included in his (1961) investigation.

In order to carry out this photoelectric
observing program, a set of <u>uvby</u> filters was obtained for
use in the Steward Observatory Photoelectric Photometer at
the Newtonian focus of the 36 inch reflector. The existing
IBM 7072 program written by Dr. Walter S. Fitch for the
reduction of <u>UBV</u> photoelectric data was modified to handle
<u>uvby</u> photometry as well.

A discussion of the photoelectric observations and
reductions is given in Appendix A. From one to six <u>uvby</u>

observations were made for 43 stars. Twenty-two of these had no previously published uvby measures while the remaining 21 lacked a sufficient number of observations for the accuracy desired in placing them in the m_1 - (b-y) diagram.

It is shown in Appendix A that the Steward Observatory uvby data (reduced by a linear transformation to the standard system of Stromgren and Perry) can be used as a supplement to the catalogue observations. The mean internal probable errors of the 21 stars measured on both systems and averaged together are very similar in size to the internal probable errors for two measures on the standard system. The errors introduced in the transformation are largely compensated for by an increased number of observations per star on the Steward Observatory system.

The new photoelectric data combined with the data in the Stromgren-Perry catalogue was used to plot an m_1 - (b-y) diagram similar to that described by Stromgren (1963b). Corrections (for the effect of Hδ on the v filter) were made to the measured m_1 index of stars of (b-y) $<$ 0.225 as described by Stromgren.

In addition to the MK standards of types A and F, and the A and A_m stars observed by Abt (1965 and 1961), stars were selected at intervals of approximately 0.010 magnitudes in (b-y) along five roughly parallel sequences in the m_1 - (b-y) diagram. The "preferred sequence,"

roughly equivalent to the lower curve given in Figure 2 of
Chapter III, was drawn on the m_1 - (b-y) distribution
through the heaviest populated regions along the approxi-
mate center line. It is paralleled on either side by a
"high preferred" and a "low preferred" sequence at
intervals of m_1 approximately 0.015 magnitudes above and
below the preferred m_1 sequence. In addition to these
three sequences, two lists of stars on and outside of the
upper and lower envelopes of the m_1 - (b-y) distribution
were composed and named the "extremely high" and
"extremely low" sequences respectively. It should be
noted here that in contrast with the m_1 - (b-y) diagram
of Stromgren (1963b), all discussions of m_1 in this
dissertation assume that the m_1 ordinate increases upward
such that stars having high m_1 values lie at the top of
the distribution. In this way, the A_m stars are observed
to lie high in the diagram whereas the metal deficient
subdwarfs lie low in the diagram.

A list of approximately 400 stars was chosen in
the fashion described above. Classification spectra for
370 of these stars were obtained using the Steward
Observatory Cassegrain Spectrograph on the 36 inch
reflecting telescope during the 1965-66 observing season.

This spectrograph shown in Figure 1 was designed
by Dr. Aden B. Meinel. It combines a 600 line per mm.
Bausch and Lomb grating blazed at 3500 Angstroms with an
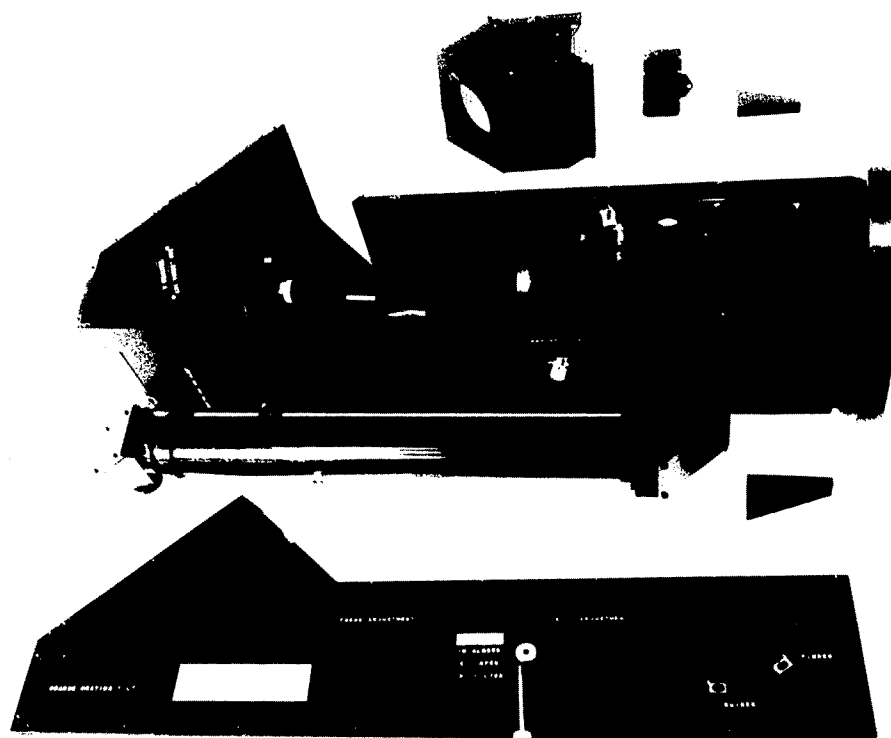
Figure 1. The Steward Observatory Cassegrain Spectrograph

f/2 folded Schmidt camera. The f/15 beam from the tertiary mirror of the folded Cassegrain 36 inch telescope passes through the slit of the spectrograph and illuminates the secondary mirror of the Cassegrain collimator. The collimated beam leaves the Cassegrain primary and falls on the grating where it is dispersed. It then passes through the Schmidt corrector and is reflected to the Schmidt primary by the perforated folding mirror. The Schmidt primary focuses the beam through the perforation in the folding mirror where it passes through the field flattener and on to the photographic plate located immediately beyond.

The slit size used for this program is 110 microns or 1.7 seconds of arc. Using a reduction factor of 7.5, the slit size imaged on the plate is approximately 15 microns. Since the dispersion of the spectrograph in the 3300A-5000A region is approximately 117 A/mm., and the resolution of the Kodak IIa-0 emulsion is approximately 20 microns, the resolution of the system is plate limited at approximately 2.4 Angstroms.

All spectra were taken on Kodak IIa-0 emulsion and were developed $4\frac{1}{2}$ minutes in D-19 at 68° F. The exposures were heavier in the visual region than ordinarily used for classification purposes so as to render the 3200A-3700A region useable. The spectra were widened 0.61 mm. and were placed up to nine on a plate at minimum separations of

0.66 mm. No comparison spectrum was used. For most of the
370 program stars only one spectrum was obtained--although
a number of the brighter stars were observed two or more
times. The spectra are consistent in exposure and of
reasonably good quality.

After the observing program had been completed and
the author had become familiar with the crisp appearance of
a nicely focused spectrum, it was discovered quite
unexpectedly that the plate focus (on plates usually con-
taining nine spectra) was a function of position on the
plate. The top one to three exposures on many of the
plates were often out of focus by amounts decreasing toward
the center of the plate. This problem was not discovered
earlier due to the method used for focusing the spectro-
graph at the start of each night's observing.

To focus the spectrograph, a series of nine
exposures of the hollow cathode iron comparison source were
made at successively incremented settings of the secondary
of the Cassegrain collimator. Since the general region of
best focus (indicated on the focusing micrometer) was
known, the first exposure was usually made well inside the
focused position and moved outward through the best focus
and beyond. The focusing micrometer would be set for the
night at the position corresponding to the iron spectrum
judged to be in best focus. This test was inadequate since
it did not test the focus as a function of plate position.

After the focus problem was discovered, its source was traced to some loose screws associated with the internal structure of the Schmidt camera module.

While the focus problem did decrease the number of spectra available for this study, it did not appear necessary to re-observe these stars since most areas of the m_1 - (b-y) plane still had representative spectra in good focus.

The effect of a defocused plate on the appearance of a spectrum is to generally soften the metallic features such that they appear weaker than they normally would. In other words, a weak line star tends to be classified as extremely weak if the spectrum is out of focus. Some of the late F and early G stars of low m_1 (which will be shown to be correlated with weak lines) were also among the faintest stars on the observing program and were usually the first to be observed on a plate. For this reason they are sometimes out of focus making it difficult to judge the weakness of their metallic lines. Spectra with serious focus problems were omitted from the program while some with slight focus problems are indicated in Table 9.

CHAPTER III

CLASSIFICATION ACCORDING TO SPECTRAL TYPE

Derivation of a Temperature Sequence

The spectra and photometry of approximately 370 stars spread over the entire m_1 - (b-y) diagram were obtained as described in Chapter II. The next step was to make the best use of all of the available data to set up a spectral sequence well correlated with the measured color indexes.

The effectiveness of the b-y color index as a temperature indicator is demonstrated by Stromgren (1963a, 1963b). He also shows that the c_1 color difference is very nearly a pure measure of the Balmer discontinuity--i.e., relatively free from composition effects. The m_1 index is a chemical composition indicator relatively free from luminosity effects. The same cannot be said for the wide band U-B index since it includes the effects of variations in both of these parameters.

The relative merits of the uvby system have been demonstrated in actual use in recent papers by Stromgren (1963a, 1963b, 1964), Crawford (1966), Crawford and Stromgren (1966), Crawford and Perry (1966), Cameron (1966), and Perry (1967). Since this discussion is readily

available in the literature, we will not dwell any longer here on why the uvby system was used but rather will go on to discuss how it was used.

A number of investigators have given evidence of a correlation between photometric indicators of abundances and spectral appearances at classification dispersion (Roman 1954, Crawford and Perry 1966, Cameron 1966). Therefore, it is felt that only stars in the solar neighborhood whose m_1 values at any particular color index (b-y), as well as whose c_1 values indicate that they are main sequence stars, should be used to set up the standard spectral sequence.

The first step is to eliminate all of the higher luminosity stars. This is accomplished using Stromgren's (1963a, 1963b) Δc_1 method. The most recently published c_1 - (b-y) relation is that of the Hyades (Crawford and Perry 1966). It differs significantly from the c_1^o - (b-y) relation (identified by Stromgren as the Zero Age Main Sequence) for the local A and F field stars at both the blue and red ends of this spectral range. Using the published values of c_1^o(b-y), a quantity $\Delta c_1 = c_1 - c_1^o$ can be calculated for any unreddened star whose c_1 and (b-y) values have been measured. This quantity is then multiplied by $(\Delta M_V/\Delta c_1)_{b-y}$ for the appropriate (b-y), and added to the published M_V^o for that (b-y) to obtain the visual absolute magnitude M_V of the observed star. The quantity

$(\Delta M_v / \Delta c_1)_{b-y}$ (Stromgren 1963a) was obtained by using stars with known trigonometric parallaxes or cluster parallaxes, and particularly, a number of members of the Hyades cluster. The heavy use of the Hyades cluster in this calibration should not affect the M_v's obtained by this method for the field stars too seriously as long as the c_1^o - (b-y) relation for the field stars (as opposed to the Hyades relation) is used. This is due to the fact that the proportionality factor $(\Delta M_v / \Delta c_1)$ between absolute visual magnitude and Δc_1 is not expected to vary between the two groups of stars nearly as much as the c_1^o zero point.

Since the c_1^o - (b-y) relation for the field stars is essentially the ZAMS c_1 - (b-y) relation, it is expected that the vast majority of Δc_1 values calculated for individual field stars will be positive. If the Hyades main sequence c_1 - (b-y) relation is used however, many of the early A field stars will have relatively large negative values of Δc_1. This is just another way of saying that the c_1 - (b-y) relation for the Hyades lies above the c_1^o - (b-y) relation for the ZAMS field stars.

The actual c_1 - (b-y) relation used in this paper (Stromgren 1963a) was plotted as a smooth curve and extrapolated from (b-y) = $0\overset{m}{.}050$ to $0\overset{m}{.}000$. This extrapolation is in slight disagreement ($0\overset{m}{.}025$ too high) with Stromgren's published value (1963b) of c_1^o at (b-y) = $0\overset{m}{.}000$, but the effects are not important as will be shown below. Also,

there were very few stars of negative Δc_1 in this color range but many with small positive values of Δc_1--which would lend some support to the validity of the extrapolation.

It should be mentioned here that Stromgren (1963b) gives corrections for the effect of the variation of c_1 due to variations in the chemical composition (supposedly measured by the m_1 index) among the stars. However, among the F stars, these corrections improve the accuracy of the photoelectrically obtained absolute visual magnitudes by only a few tenths of a magnitude. This is insignificant for our purposes. In the A stars, the correction is usually very small (on the order of the probable errors in the photometry) and is in a direction towards improving the separation of higher luminosity stars from those of the main sequence. Therefore, these corrections were not applied in this problem.

The Δc_1 values obtained were used to calculate the absolute visual magnitude of each of the stars by the relation: $M_v = (M_v^o)_{b-y} - \Delta c_1 (\Delta M_v / \Delta c_1)_{b-y}$. The absolute magnitudes were then used to assign a luminosity class (purely from the photometry) to each star. The absolute magnitude calibration of the MK luminosity classes given by Keenan (1963, Table 6) was used for this purpose. All stars whose Δc_1 values indicated class IV or higher were thrown out of the discussion for the time being. The

remaining stars were mostly of class IV-V or V with possibly a few class IV stars left. If the extrapolation of the c_1^o - (b-y) relation used in this calculation were a few hundreths of a magnitude high, the effect would be to include a few more A0-A2 class IV stars. However, the spectral differences at classification dispersion between an early A IV star and an early A V star are at best doubtful anyway.

Having eliminated essentially all but main sequence stars from our discussion, the next problem was to define a mean m_1^o - (b-y) relation for the local field main sequence A and F stars. All of the main sequence stars in the Stromgren-Perry catalogue plus the additional stars whose photometry was obtained at Steward Observatory were plotted in a corrected (for the effect of Hδ on the v filter) m_1 - (b-y) diagram. This diagram is <u>not</u> the same as the m_1 - (b-y) diagram of Stromgren (1963b) discussed earlier since all stars not lying on the main sequence have been omitted.

The mean m_1^o - (b-y) relation used throughout the remainder of this dissertation was obtained by drawing in a smooth curve through the apparent center line of the distribution of points in the diagram described above. The quantity $\Delta m_1 = m_1 - m_1^o$ is defined as the difference between a star's observed m_1 index and the mean or most common m_1^o index for a star of the same (b-y) color. The A_m stars

have strong metallic lines, lie high in the m_1 - (b-y)
diagram, and have large positive values of Δm_1. The sub-
dwarfs have weak metallic lines, are situated low in the
m_1 - (b-y) diagram, and have numerically large negative
values of Δm_1.

Comparison with the positions of the MK standards
of types A and F, in the m_1 - (b-y) diagram, showed that
they too are well represented by the mean m_1^o - (b-y) rela-
tion for the field stars. But these stars were defined in
the MKK atlas as being representative of the most typical
or normal stars in the solar neighborhood. In this sense,
the positions of the MK standards in the diagram confirm
the validity of the chosen m_1^o - (b-y) relation for the
local field stars.

Stromgren (1963a, Table 5) has published a standard
m_1 - (b-y) relation for the Zero Age Line of the local
field A and F stars. Crawford and Perry (1966) have pub-
lished the standard m_1 - (b-y) relation for the Hyades
cluster. Except for the early G stars, these two relations
are very nearly the same. However, the mean m_1^o - (b-y)
relation for the local A and F dwarfs is shown in Figure 2
to lie significantly below the Hyades (and ZAMS) relations
at spectral types later than F0. Since a number of Hyades
stars were included among the field stars in this data,
their presence would tend to bias the apparent center line
of the distribution to higher values of m_1. Therefore, the
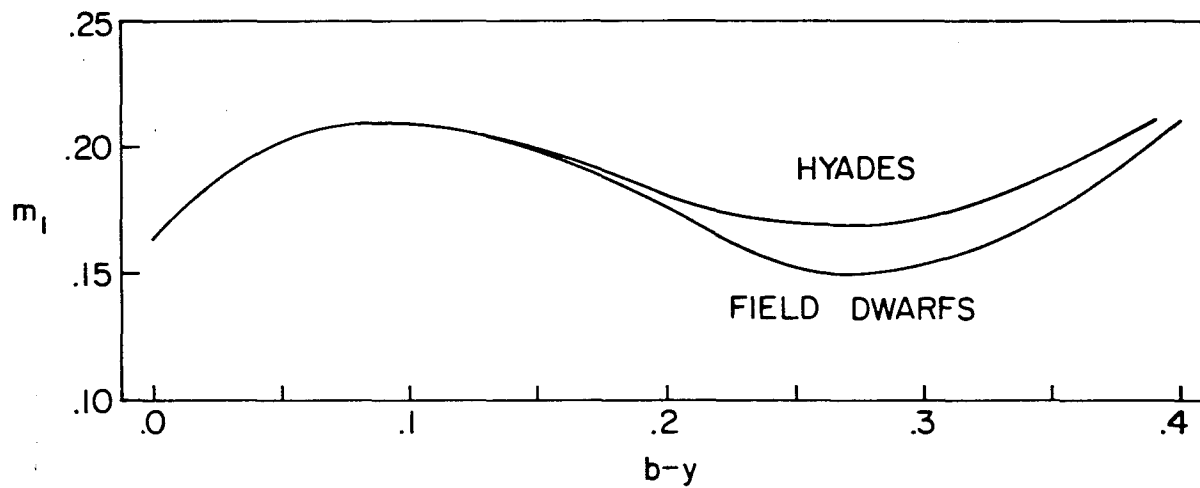
Figure 2. The mean m_1^o - (b-y) relation for the A and F dwarfs lies below the same relation for the Hyades Main Sequence

difference between the two relations shown in Figure 2 may be slightly underestimated.

At (b-y) = 0.225, the difference in m_1 between the two relations is about $0\overset{m}{.}01$ and increases with b-y. Stromgren (1963b) has shown that an increase in the probable errors of the photometry by about 30% would suffice to account for the entire scatter in m_1 for the F stars between 0.22 $\langle$ b-y $\langle$ 0.25. However, the definite difference between the two relations in this interval as well as at greater b-y values indicates that even in the early F stars the scatter must be due at least partially to a real physical difference in the individual stars concerned.

The mean m_1^o - (b-y) relation for the field dwarfs can be used as a standard for determining which stars at a given b-y have high or low m_1 indices (positive or negative Δm_1). For the purpose of setting up as pure a spectral sequence as possible, all stars of $\left| \Delta m_1 \right|$ $\leq$ $0\overset{m}{.}012$ were set aside from the discussion at this point. They will be considered in Chapter V. The choice of the above limit on Δm_1 allowed a sufficient number of sample stars to remain available at each 0.1 spectral type interval and yet hope-fully would not include stars at any given b-y whose spectra would differ solely due to the physical effects causing the variation in m_1.

The 124 star temperature sequence which remained after the above described selection procedures were completed are listed in Table 1. According to the photometry, these are all main sequence A and F field stars in the solar neighborhood whose m_1 indices lie on or near the mean m_1^o - (b-y) relation for the field dwarfs. Thirty-seven of these stars are MK Standards of types A and F and largely of luminosity class V. (Only 5 are class IV Standards.) Of the other 24 MK Standards included in the study, 10 were thrown out due to high c_1 (luminosity) and 14 were thrown out due to m_1 being too high or too low. Four of the 10 MK Standards thrown out for high luminosity reasons were class V stars while the other 6 were of class IV. To sum it up, over 60% of the A and F class IV and V MK Standards made the final list--half of the class IV standards being rejected for high luminosity and one more for extreme m_1.

Philosophy of Spectral Classification

How much use should be made of photometry in the assignment of spectral types? This question strikes deep into the philosophy of spectral classification. While most would agree that the photometry should not be considered when classifying according to the appearance of a spectrum on a photographic plate, almost no one would deny the great accuracy of classification which can be attained using the

Table 1

Photoelectrically Determined Temperature Sequence of
A and F Dwarfs of Normal Metallic Line Strength

HD	Photo-electric types	HD	Photo-electric types	HD	Photo-electric types
48915	B9.5	222603	A7	129502	F4*
71155	B9.5	33641	A7(m)*	130817	F4
95418	A0*	116842	A7	160910	F4*
172167	A0	76644	A7*	151613	F4*
148330	A0	92941	A7*	106022	F5*
130109	A0*	87696	A7*	15524	F5
12471	A0	44769	A7*	134083	F6
103287	A0*	79439	A7*	8634	F6
140775	A1	75698	A8(m)*	99373	F6
21447	A1	121607	A8	17948	F6*
36777	A1	112171	A8*	185912	F6
161868	A1	91312	A8*	210027	F6*
1280	A2*	203280	A8*	30652	F6*
106661	A2*	124675	A8*	86146	F6*
85795	A2	125161	A8*	166285	F6
170073	A3	34499	A9	61859	F7*
216956	A3	28910	A9*	130945	F7*
143894	A3	115514	A9*	173667	F7*
27962	A3	30034	A9*	82328	F7*
32977	A3	118660	A9*	124425	F7*
102647	A3*	104513	F0(m)*	11443	F7*
138338	A3*	211336	F0*	111456	F7*
56537	A3	11973	F0	142860	F7*
70313	A3	27176	F0*	216385	F7*
13041	A4*	143466	F1*	16895	F8*
165777	A4	219080	F1	155646	F8*
97603	A5*	37788	F1	126660	F8
11636	A5	17094	F1*	128332	F8
29388	A5	204485	F2*	127986	F8*
118232	A5*	137391	F2*	9826	F9*
27934	A5	28294	F2	136064	F9*
154494	A5	132052	F2*	102870	F9
89904	A5*	182640	F2	198084	F9
32301	A6	32537	F3*	88737	F9
27819	A6	40136	F3	4614	G0*
6961	A6*	42278	F3	114710	G0*
29488	A6	56986	F3*	14214	G0*
28527	A6*	138290	F4*	43587	G0*
22522	A6*	110379	F4	115043	G1*

Table 1--<u>Continued</u>

205767	A6*	136751	F4	10307	G1*
29140	A6(m)*	208703	F4	72905	G1*
116831	A6*				

*This type is confirmed spectroscopically in Table 9.

photoelectric method. The ideal situation would be to study the spectra of a list of stars whose photometry (or another suitable method) indicates that they form a smooth temperature sequence. Hopefully, a spectral criterion (or criteria) would be found which varied at a reasonably uniform rate with the color index. Then the entire sequence might be divided up into the finest divisions for which one could detect a change in that spectral feature. Again hopefully, these intervals representing equal divisions of the total variation in the spectral criterion would also correspond to roughly equal intervals in the color index. Unfortunately, this ideal situation is not to be found in the spectral region corresponding to the A and F stars.

For low dispersion classification, the K line of Ca II might be used as the spectral criterion for classifying A stars. A plot of spectral type vs. color index would then reveal a dispersion of points which would be indicative of the accuracy of the classification (assuming the

photometry to be a much more accurate temperature indicator than the visual classification according to the K line). Using higher dispersion, numerous other spectral features (e.g., faint metal lines) are found to vary with color index. If use of these new features is made, the dispersion of points on the spectral type-color index diagram is found to decrease. The net result is a more accurate system of spectral classification.

Now it is found that stars classified in one spectral type interval (defined according to the K line strength) can be divided up into sub-types within that interval. Also, stars assigned adjacent types according to K line strengths might be found very similar when only their faint metal line criteria are considered. These stars must be re-classified to the same spectral type. The decision as to which type to assign them is made such that the dispersion in the spectral type-color index relation is a minimum. Since there are a number of faint metal line criteria, the sequence cannot be divided up into intervals representing equal increments of change in all criteria. Instead, all of the criteria must be considered at once and a decision made as to how far one must move along the sequence from a given point to detect real changes in the appearance of the criteria. This distance, in terms of color index, will still vary with the point on the sequence being considered, the number of criteria available, the

mental weight assigned to each criterion, and the various rates of change of these criteria with color index.

The stars classified principally on the strength of the K line were assigned to various groups corresponding to small but equal changes in that feature and each of these groups was given a label (e.g., A0, A2, A5, etc.). However, the smallest detectable changes in the new criteria will not necessarily coincide with those of the K line. The question that arises is: What is the meaning of the old labels on the new system?

A first method of attack might be to give new labels to each of the smallest detectable sub-groups using the new criteria and at equal intervals of change in these criteria. This of course would be ideal in that the original philosophy used in setting up the earlier system would be maintained. But, on the other hand, it would mean that the earlier system itself would be discarded. Only those standard stars whose types on the old system just happen to be the same as those assigned on the new system would remain standards at that type.

A second method of attacking the problem might be to look at the new spectra of the old standards at a given old type-label and try to define the new criteria at this type by the appearance of the spectra of (hopefully) the majority of the old standards. Some of the old standards would have to be rejected completely or shifted to adjacent

types while some new standards might be added to provide a sufficient number of examples at each type. The great advantage of this procedure is that most of the older system would be kept in tact--providing the increase in accuracy of the new system over the old is not too great. On the other hand, the original philosophy of defining types as the smallest detectable changes in the available criteria would have to be abandoned.

In both methods, just as in the old system, the type-labels (e.g., A0, A2) always correspond to some range of color indexes--usually with some overlap of types corresponding to a particular color index. If the first method of attack is followed, the new type-labels will probably correspond to completely new intervals of color index. If the second method is followed, only relatively minor changes in the color index interval corresponding to each type-label would be made--except that as new sub-types were added, the old color index intervals would have to be subdivided also. To sum it up, the first method adheres to the original philosophy but greatly changes the original system of type-labels and their spectral and photoelectric definitions while the second method partially abandons the original philosophy but largely retains the original system.

To this date, the evolution of the MKK system has involved a mixture of both methods. The largest single

revision in this system is discussed by Morgan (Johnson and
Morgan 1953), and the resulting revised MKK system is
called the MK system. Changes in the MKK system were of
several kinds. For example, the groups of stars previously
labeled F2-F8 class III were literally re-labeled as class
IV. Apparently no particular changes in the criteria were
involved other than that the MKK class III criteria and
standards became the MK class IV criteria and standards.
New criteria, however, were defined for the new groups of
standards which were to be labeled class III. This is an
example of the first mentioned type of change. Possibly a
better example of it would be the changes made in the
spectral type sequence of the late G giants. Morgan states
that these stars did not show a satisfactorily smooth
relationship with color equivalent. Therefore, the types
G5, G8 and K0 (class III) were re-defined in terms of new
criteria which were more closely related to the temperature.
Of course, these new criteria gave new meanings to the old
type-labels in that these labels now corresponded to new
groups of stars and new ranges of color index. The extent
of the change in the MKK system is quite large when it is
realized that all of the G5 III standards, 6 out of 9 of
the G8 III standards, and 7 out of 10 of the K0 III
standards were not included in the MK system.

Examples of the second type of change are to be
found in MKK standards of a given type and luminosity class

which were moved to a new MK type and luminosity class
usually immediately adjacent (e.g., χDRA moved from F6 V to
F7 V). Others were simply dropped (e.g., αCMA at MKK type
Al V). Those standards which were dropped were usually
replaced by other more suitable stars.

A Method for Revising the MK System

With the advent of the grating-Schmidt type
spectrographs, a large number of new and useful spectral
criteria have become available in the 3300A-3900A region.
A few of these features were mentioned in "A Discussion of
Spectral Classification" (Abt 1963) but almost no mention
was made of features below the Balmer discontinuity. To
the contrary, it was mentioned at the discussion that
objective prism work reaching out to 3300A had as of that
time revealed no features below the Balmer discontinuity
(Abt 1963, p. 103).

The KPNO Atlas of Grating Spectra (Meinel and
Schulte 1967) however, reveals a great many features in
the ultraviolet spectrum of all stars except for the late
B and early A types. The numerous features and their
rapid increase in strength in the middle A and F stars plus
the precise photometry available in the Stromgren-Perry
Catalogue suggested the merit of re-examining the MK system
of classification for these stars. It was felt that the

new criteria would allow a more precise correlation between the spectral features and the color index.

The 124 stars (Table 1) described earlier in this chapter provided a relatively smooth continuous temperature sequence which could be studied for variations in spectral criteria. It was felt that the MK system of classification should be changed as little as possible due to its widespread and most successful use up to the present time. This thought suggested that the approach be that of the second type--i.e., to examine the standards at each MK type and define the new criteria from the average appearance of their spectra. Those standards whose new criteria fit better at an adjacent type or did not fit at all would either be moved to an adjacent type (e.g., A8 to A9) or discarded. Possible replacement standards would be suggested from the list of 124 stars in Table 1. The word "possible" is used because these suggested stars might be considered as standards only after many more plates of each have been taken and further studies have verified that they are normal single dwarfs of the solar neighborhood.

It became evident however, that an approach of the second type toward modifying the MK system would not be entirely satisfactory. It was found that the ultraviolet criteria take on significant importance for classification purposes around A3 to A5 and allow a greatly improved classification scheme in the late A stars. However, the

MK system supplies standards only at types A5, A7, F0, and F2. Also, for the class V standards, the photometry indicates an interval in color index between A7 and F0 slightly greater than the interval from A0 to A7--even though the slope of the relation is approximately constant (cf., Figure 3). Furthermore, the dispersion in the spectral type - (b-y) diagram in the A5 to F5 range (cf., Figure 4) is quite large relative to the dispersion at other types. Note that the F0 and F2 standards of class IV (Figure 4) follow the apparent spectral type - (b-y) relation more closely than the class V standards.

For these reasons, a modified approach of the second type was carried out, keeping in mind that the changes in the original MK system were to be kept as small as possible without seriously compromising the increased accuracy made available by the new ultraviolet criteria.

A plot of spectral type vs. b-y was made for all of the MK standards of types A and F and luminosity classes IV and V. The approximately 40 A and F Hyades main sequence stars classified by Morgan and Hilther (1965) for which uvby photometry was available (Crawford and Perry 1966) were plotted on the same diagram (Figure 4). These stars are claimed by Morgan to form a frame of reference for spectral classification more accurate than the MK standards.

A smooth curve of spectral type vs. b-y was drawn free hand through the points on the diagram keeping in mind
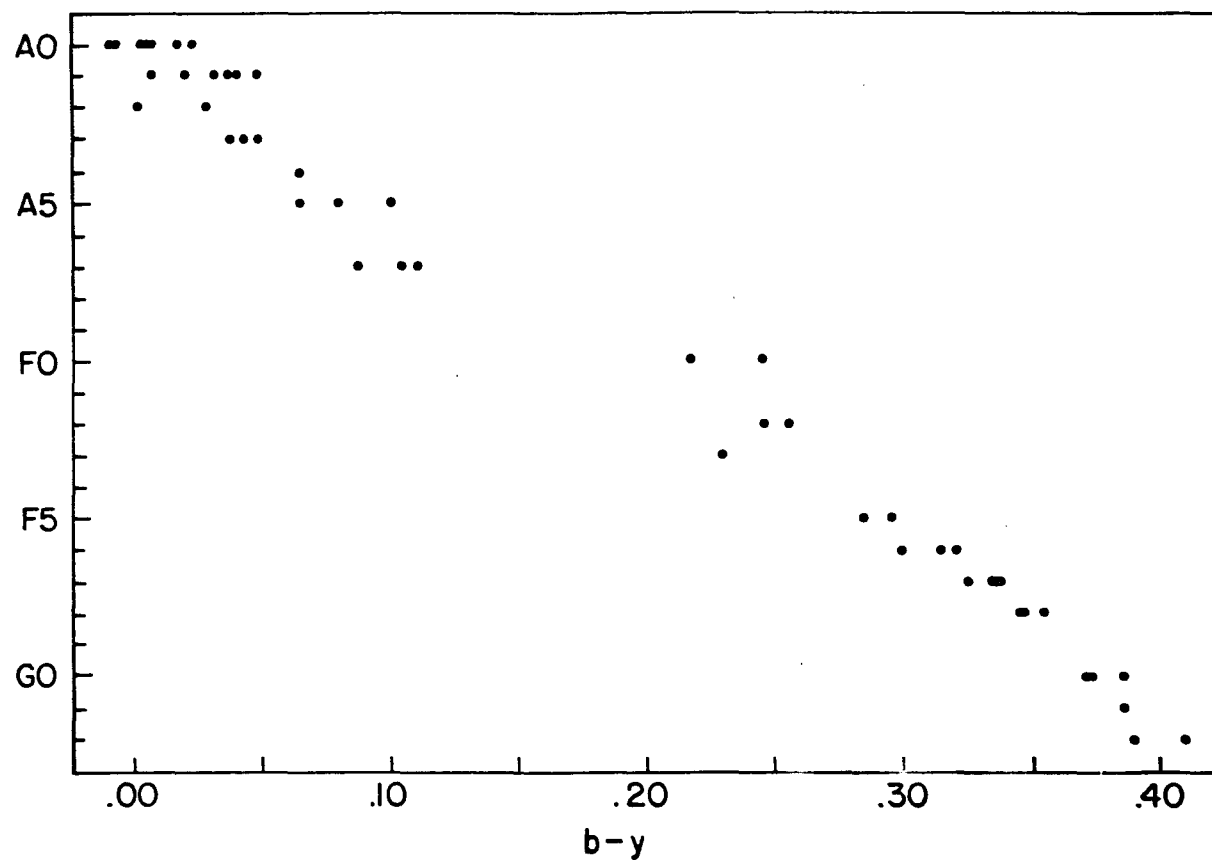
Figure 3.   The MK Standards of spectral types A and F and luminosity class V are plotted against b-y color index
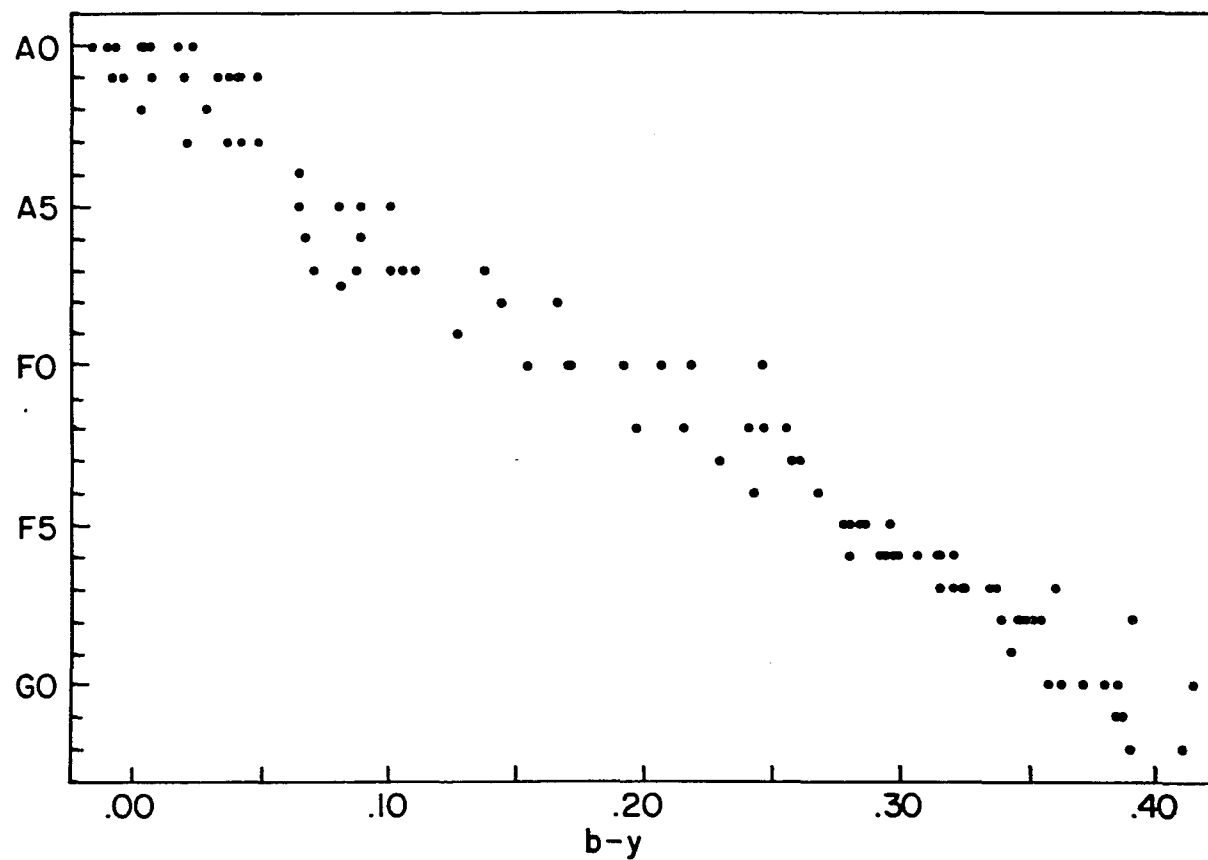
Figure 4. The MK Standards of types A and F and luminosity classes IV and V are combined with the Hyades Main Sequence Stars classified by Morgan and Hiltner (1965) and plotted against b-y color index

that the curve should always pass through the regions of highest areal population density and yet remain a slowly varying function of b-y. This curve was divided up into intervals of color index corresponding to each 0.1 spectral type. Care was taken to keep as many of the stars classified at a given MK type within the b-y interval corresponding to that type on the proposed revised system. In other words, the intervals were arranged so as to make as few changes as possible in the MK system. At the same time, it was sought to keep the color index intervals roughly the same size--or at least, that the size should vary slowly with spectral type. The proposed b-y intervals selected by this process are given in columns 2 and 3 of Table 2. Of the 37 MK standard stars included in the photoelectrically defined temperature sequence, 22 retained the same type, 14 were changed by 0.1 spectral types, and one (γVIR) was changed by 0.4 types. Since the latter is a visual binary, the photometry may be suspect in this case.

It was not obvious at this point that one could distinguish stars belonging to one of these newly defined types from another simply by looking at their spectra. This question would have to be explored by carefully studying the spectra of the 124 star temperature sequence. Only by studying this sequence would it be possible to finally define the b-y intervals which correspond to each 0.1 spectral type. If it were found that A8 stars (as

Table 2

The Proposed and Observed Spectral Type vs.
b-y Intervals

Type	Proposed		Observed (Figure 5)	
	$(b-y)_{min.}$	$(b-y)_{max.}$	$(b-y)_{min.}$	$(b-y)_{max.}$
A0 V	-0.004	+0.012	-0.005	+0.012
A1 V	+0.012	+0.025	+0.013	+0.024
A2 V	+0.025	+0.037	+0.025	+0.036
A3 V	+0.037	+0.050	+0.037	+0.048
A4 V	+0.050	+0.065	+0.049	+0.059
A5 V	+0.065	+0.082	+0.060	+0.077
A6 V	+0.082	+0.100	+0.078	+0.097
A7 V	+0.100	+0.116	+0.098	+0.115
A8 V	+0.116	+0.133	+0.116	+0.136
A9 V	+0.133	+0.150	+0.137	+0.159
F0 V	+0.150	+0.175	+0.160	+0.176
F1 V	+0.175	+0.197	+0.177	+0.193
F2 V	+0.197	+0.215	+0.194	+0.212
F3 V	+0.215	+0.235	+0.213	+0.234
F4 V	+0.235	+0.260	+0.235	+0.262
F5 V	+0.260	+0.283	+0.263	+0.282
F6 V	+0.283	+0.308	+0.283	+0.306
F7 V	+0.308	+0.325	+0.307	+0.325
F8 V	+0.325	+0.340	+0.326	+0.344
F9 V	+0.340	+0.357	+0.345	+0.366
G0 V	+0.357	+0.377	+0.367	+0.384
G1 V	+0.377	+0.397	+0.385	+0.403
G2 V	+0.397	+0.415	+0.404	--

defined photoelectrically) could not be distinguished
spectroscopically from A9 stars, then the labels A8 and A9
would simply lose their meaning with respect to each other.
These stars could be labeled spectroscopically as A8-9
until at some later date criteria were found which could
differentiate between the two types. If, on the other

hand, criteria were found that were so sensitive to temperature that stars between types A8 and A9 could be identified, then a new type A8.5 would be defined which would inherit its own color index interval by chopping appropriate sections from the intervals associated with types A8 and A9.

In summary, it was felt that the defining of preliminary types (for the purpose of setting up a classification scheme) by color index intervals would produce a system that would not have to be changed greatly in the future when new spectroscopic temperature criteria are discovered in some new region of the spectrum. The worst that might happen is that these color index intervals would have to be subdivided into smaller regions (barring the possibility that the b-y index is systematically affected by some other physical parameter; cf. Chapter VII). It should be noted that the final assigning of types (after the criteria at each type have been described) will be according to spectral appearances only. Therefore, there will still be an overlapping of color index intervals for adjacent 0.1 spectral types.

Spectroscopic Study of the b-y Sequence

With the ideas described in the previous section in mind, the actual study of each of the spectra in the 124 star b-y (temperature) sequence was undertaken. The plates

were studied using a binocular microscope with a range of magnification from 7 to 30 power. Most of the work was done at 15 power, but occasionally particular criteria in particular ranges of spectral type were also viewed at lower or higher power.

In order to introduce the various features at a gradual rate, the early A stars were studied first. As each plate was examined, a list of all of the features visible in the spectrum was constructed. Approximate wavelengths were used, saving the actual wavelength determination for more precise coude plate measurements described in Appendix B. As the various features became more familiar, they could be picked out and identified (labeled by approximate wave length) at once. The entire sequence of stars was examined including from one to nine plates (most stars had only one plate) per star.

Plates of the MK standards used in the KPNO atlas were also examined. While the number of these plates was not very great, they were usually of high quality but lighter exposure and didn't reach quite as far into the ultraviolet. However, most of them reached beyond the farthest ultraviolet criterion used. Also, the Kitt Peak plates were at a slightly smaller dispersion (128 A/mm), a slightly wider spectrum in proportion to dispersion, and were made with a projected slit width of 20 microns as opposed to 15 microns at Steward Observatory. The Kitt

Peak spectra did seem to reveal slightly more clearly the faintest of the weak metallic features beyond the convergence of the Balmer series. However, the differences in the appearances of the spectra taken on the two systems were small enough that both sets of plates could be used in this and the following stages of this spectral study.

As all of the exposures were examined in each b-y interval corresponding to 0.1 spectral type, the following questions were kept in mind. Are the spectra similar at the same b-y interval? If not, try to list the differences for a subsequent study to see if the variations might correlate with c_1 or m_1. Are the spectra different for different spectral types? If yes, these differences should be listed for later study. If not, the labels for the two adjacent color index intervals would have to be combined (e.g., A8-9) as described earlier.

After all of the exposures of each of the 124 stars in the temperature sequence had been examined, the entire procedure was repeated. This time however, all of the exposures at a given 0.1 spectral type interval were examined and inter-compared at the same time. As was discussed in Chapter II, some of the spectra were out of focus. These were either retained to be considered with low weight or were set aside from the study.

The number of stars and the number of exposures of each available at each 0.1 spectral type interval varied

greatly in this portion of the study. It may be argued that the best method for accurately classifying stars according to spectral type would be to include as many well exposed plates of each star as possible. Intercomparison of stars for which several similar exposures were available certainly verified this. In fact, individual ratios (to be discussed later) were sometimes found to vary by one or even two tenths of a spectral type between individual plates of the same star. But never were there any systematic variations of all the ratios in any given direction along the sequence.

While it is agreed that a number of plates per star to be classified is the most desirable situation to have, the following procedure was actually used in the name of logic as well as practicality. It must be recalled and emphasized here that the purpose of this study is not to classify stars on the existing MK system, but rather to modify that system such that the average or most commonly encountered stars in the solar neighborhood might be classified with a tighter correlation between spectral type and color index.

The terms "average" or "most common" stars imply that the features of the largest number of stars possible at each 0.1 spectral type interval should be studied. Since these stars should ideally have identical spectra it was felt that an average of each of the criteria over all

of the stars available at each 0.1 spectral type interval would be far more valuable than the average of three or four plates for one or at most two stars at that spectral type. Of course, it would be ideal to have three or four plates for three to six stars at each type but the size of such a program would be prohibitive.

As all of the exposures for each star were examined, notes were made of the average strengths of various possible criteria suggested by the previous study of the sequence. Also, large discrepancies (if any) from the average were noted including variations in the average strength of the metallic lines. The stars and plates most representative of each type were also noted. These stars were later used in the third examination of the entire sequence. Also, the stars used for examples at each type were those that were definitely closer to luminosity class V than to class IV according to the photometry. This further increased their probability of becoming class V spectroscopic standards if their spectral features from numerous plates and other physical information were found to support their nomination.

After all of the stars in the sequence had been thoroughly examined in the manner described above, a list was made of all of the criteria which at that point appeared to be reliable temperature indicators. It must be emphasized that some of these criteria are also

luminosity indicators and/or abundance indicators but that they are still useful as temperature indicators. Since the stars had been selected by the photometry so as to form a sequence of temperatures only, little problem was expected with using any relative change in the spectral features from type to type as a temperature indicator.

Each criterion on the list was further studied as a function of spectral type over the entire b-y range for which it was felt that it might be useful. Some of the suspected criteria recorded at each spectral type in the second survey of the temperature sequence were found to be useless but the majority appeared to make definite changes from one type to the other. Also, some new criteria were discovered even at this late stage of the study and were included in Table 3--the final tabulation of spectral type vs. criteria.

Discussion of Table 3

The criteria listed in Table 3 are identified by their approximate wave length and described by numerical ratios. A few of the criteria may be found in practice to be of limited use. Only attempts at using these criteria on numerous plates of numerous stars will ultimately tell which are the most useful, which should be discarded, and what new criteria should be added. Furthermore, the absolute values of the ratios are not intended to convey

Table 3

Spectral Criteria vs. Type

λ_1/λ_2*	A0	A1	A2	A3	A4	A5	A6
3361/3394	.	.	.	1/4	--	1/3	1/2
3381/3394	.	.	.	2/1	--	1/1-3/2	.
3394/3442	.	.	.	1/4-1/5	1/4	1/3	1/2-2.3
3442/3476	.	.	.	3/2-1/1	--	--	2/1
3442/3497	.	trace	1/2-2/3	2/3	1/1	3/2	2/1
3442/3586	.	.	.	1/1	--	--	2/1
3476/3497	.	.	.	trace	weak	1/2	1/2-2/3
3619/3632	.	.	.	.	.	trace	1/3-1/4
3728/3758	.	.	trace	--	1/2	--	1/2

	A7	A8	A9	F0	F1	F2	F3	F4
3361/3394	1/2-2/3	2/3-1/1	1/1	3/2-1/1	3/2	3/2-2/1	2/1	2/1-3/1
3442/3476	2/1	--	2/1-3/1	.	.	.	.	.
3442/3497	2/1-3/1	3/1-4/1	.	.	.	.	.	.
3454/3461	1/4	1/3-1/4	1/3-1/2	1/2	2/3	.	.	.
3461/3476	.	.	1/4-1/3	1/3	1/2-1/3	1/2	2/3	1/1
3476/3497	1/1	.	.	.	.	.	.	.
3484/3491	1/2	2/3	1/1	.	.	.	.	.
3491/3497	.	.	.	1/4-1/3	1/3	1/3-1/2	1/2-1/3	2/3-1/2
3497/3515	.	.	.	trace	weak	3/1	3/1-2/1	2/1-3/1
3497/3526	3/1-4/1	3/1	2/1-3/1	2/1	2/1-3/2	3/2-1/1	1/1	.
3566/3570	.	.	.	.	.	.	.	3/1-2/1
3566/3586	1/4	1/3	1/2	2/3-1/2	2/3	.	.	.
3581/3586	.	.	.	.	1/4-1/5	1/4	1/4-1/3	1/3
3619/3632	1/3	1/3-1/2	1/2-2/3	2/3-1/1	1/1	.	.	.
3728/3758	1/2	1/2-1/3	1/3	1/3-1/4	--	--	1/4	

Table 3--<u>Continued</u>

3758/H11	•	•	•	1/5	1/4	1/4-1/3	1/3	1/3-1/2
H11/H12	•	•	•	1/1	--	2/3-1/1	--	2/3
3815/3820	•	•	•	•	•	•	4/1-5/1	4/1
3859/3871	trace	weak	1/2	2/3	1/1-2/3	•	•	•

	F5	F6	F7	F8	F9	G0	G1
3350/3361	1/1	1/1-2/3	2/3	2/3-1/2	1/2-1/3	1/3-1/4	1/4
3361/3394	•	•	3/2	2/1-3/2	3/1	3/1-4/1	4/1-3/1
3394/3422	•	•	3/1	2/1-3/1	2/1	3/2-2/1	1/1-3/2
3454/3461	1/2	1/2-1/3	1/3-1/4	1/4	1/5	•	•
3454/3467	•	trace	weak	1/2	1/1	•	•
3491/3497	2/3	2/3-1/1	•	•	•	•	•
3497/3515	2/1-3/2	--	--	--	--	3/2-1/1	•
3497/3526	•	•	3/2-2/3	2/3	1/2-2/3	1/2-1/3	•
3507/3515	1/2	1/2-2/3	1/1-2/3	2/3	1/2	1/3	1/3-1/4
3566/3570	2/1-3/2	3/2-2/1	3/2	3/2-1/1	1/1	•	•
3581/3586	1/2	2/3-1/2	•	•	•	•	•
3609/3619	•	•	1/4	1/3-1/4	1/2-1/3	1/2-2/3	2/3-1/1
3758/H11	1/2	1/2-2/3	2/3	1/1	3/2-1/1	2/1-3/2	3/1
H11/H12	2/3	2/3-1/2	1/2	1/2-1/3	1/3-1/4	1/4-1/5	1/6
3815/3820	3/1	2/1	3/2-1/1	•	•	•	•
3815/H10	•	•	1/4	1/3	1/2	2/3-1/2	2/3-1/1

*λ_1 and λ_2 are approximate wave lengths.

much information. Since the criteria were studied individually, the relative magnitude of a ratio at one 0.1 spectral type interval can be compared with the ratio of the same features at the adjacent spectral type. In this way, the relative waxing and waning of the features with temperature is indicated. A ratio of e.g., 2:1 for one pair of features does not necessarily mean that they appear identical or in direct proportion to another pair of features described with the ratio 2:1 on the same plate or at another spectral type. This is a completely sub-jective description of the features and should not be considered as anything more.

In the process of defining criteria, the ideal to be sought after is to find one feature which is rapidly increasing in strength (with temperature) with an adjacent feature rapidly decreasing in strength. The features should have similar appearances--i.e., broad and shallow or narrow and deep or some combination thereof. The differ-ence in strength should not be too great. This of course limits the range of usefulness since the faster the criterion changes with temperature, the faster the differ-ences become too great. Also, the features should be near each other on the spectrogram. One reason for this is that they can be compared more easily and accurately and another is that the density of the continuum on the plate is similar for both features. The apparent densities at the

extremes of the spectrum appear to vary more than the central region from plate to plate. This effect can produce a variation in the apparent ratio of two widely separated features.

When more than one ratio is given for one pair of features at a particular 0.1 type interval, the first one should be given half again as much weight as the second. The reason for the two ratios may either be that some of the candidates for standards at that type showed one value while the others showed another value or that there was that much uncertainty in each of the stars.

In actual experience with the ratios it was fairly consistently found that the same ratios would be assigned repeatedly in each successive investigation even though the numerical value assigned previously was not looked up. Table 3 was developed in two successive investigations of all of the features. The final published table was smoothed only slightly and will probably require future alterations, deletions and additions as more information becomes available.

In conclusion, this table of spectral type vs. criteria is to be used only for suggestions of possibly useful criteria and for indications of how these criteria vary with temperature. Those features which were found to be luminosity sensitive and/or abundance sensitive in the

studies described in the following chapters are indicated therein.

The actual procedure of classifying stars on the MK system is not one of simply looking at individual ratios of features. In fact, the emphasis on ratios at these early stages of the revision was only to serve as a first step in the quest for standards at each 0.1 spectral type interval. The most accurate procedure for classification involves the direct comparison of several plates of several standards at each type with several plates of the star being classified. In this process, not only are the various ratios compared, but also the much more subtle and all important shadings of the various blended features, the wings of the hydrogen lines, and other features defying quantitative description. Even the ratios can be used as more accurate indicators of spectral type on a basis of qualitative comparison than if they were assigned quantitative values in the classifier's mind.

The overall goal of the work described in this chapter was to find prospective candidates for standards at each 0.1 spectral type interval in b-y. Since the variations in the criteria with luminosity and metallic line strength were not yet known, the spectral types assigned individual stars were still very provisional. The following two chapters discuss the study of the luminosity and metallic line strength classification.

CHAPTER IV

LUMINOSITY CRITERIA BETWEEN 3300A AND 3900A

The variations in the appearances of stellar spectra due to differences in the surface gravities of stars of similar effective temperature have been studied and documented throughout the twentieth century (Maury and Pickering 1897; Hertzsprung 1905, 1907; Adams and Kohlschutter 1914b; Adams et al. 1935; Morgan, Keenan and Kellman 1943). The tremendous value of such an easily obtainable indication of absolute magnitude is well known and need not be further emphasized here.

The problem of deducing the absolute magnitude of a star from its spectral appearance may be broken down into two steps. The first includes the study of stars of similar effective temperatures but known (from other sources of parallax information) to lie in a luminosity sequence--the purpose being to discover the luminosity criteria and to divide the sequence into as many spectro- scopically distinguishable luminosity groups as possible. The second is to calibrate the system by assigning absolute magnitudes to each group with some indication of the dis- persion in absolute magnitude to be expected. This chapter deals only with the first step: the selection of criteria.

The luminosity features used in the MK system for the classification of A and F stars are not numerous but have allowed classifiers to assign these stars to five or six basic luminosity groups labeled by Roman numerals I through VI. Classification into even finer sub-groups and their labels have been described by Keenan (1963).

In order to increase the accuracy of the assignment of stars to various luminosity groups and sub-groups it is desirable to have more luminosity indicators of increased sensitivity available. To find such luminosity indicators at classification dispersion, we must look to new spectral regions.

Apparently, one of the finest luminosity indicators for the A and F stars is the blended triplet O I at 7771A-7775A (Merrill 1925, Keenan and Hynek 1950). However, being situated in the photographic infrared, it has been made little use of to this date.

With the extension of the usable spectrum down to 3200A using the grating-Schmidt type spectrographs, numerous luminosity sensitive features have become available. In Chapter V, these features are utilized to improve the accuracy of the assignment of a star to a luminosity class and to make use of an increased number of sub-classes.

With these ideas in mind, it seemed worthwhile to carry out a preliminary exploration of the 3300A-3900A

spectral region to discover potentially useful luminosity indicators. By describing the location and behavior of these indicators at each half of a spectral type, the way is cleared for future investigators to make use of these features in improving the system as well as in using the system. Some of the features will be more useful than others. However, when one considers the numerous dispersions used and the variations in resolution between spectrographs, it appears wise to list all of the obvious potential criteria on the Kitt Peak system and let the individual classifier use this list as a guide to choosing the best criteria for his particular system. The plates obtained by Drs. A. B. Meinel and D. H. Schulte for the Kitt Peak atlas were used for this purpose.

Tables 4 through 8 give a description of the behavior of some potential luminosity criteria at each half spectral type from A0 through G0. The ratios given are to be taken only as a qualitative indication of the development of the features with luminosity. Ratios were chosen for maximum sensitivity while keeping the two features to be compared as near in proximity and appearance as possible. In some cases it seemed more reasonable to merely note that a feature increased in strength with luminosity. Blanks in the table either indicate a lack of significant change in the features or no information was available due to lack of plate material. The latter problem usually

Table 4

Luminosity at A0

λ_1/λ_2*	V	IV	III	II	I_b	I_a
3422/3442	1/3	1/2-1/3	2/3	1/1	3/2	2/1
3758/H11	·	·	·	·	trace	weak
3859	·	·	·	·	trace	weak
Balmer Convergence	H16	--	H18	--	--	H20

*λ_1 and λ_2 are approximate wave lengths.

Table 5

Luminosity at A5

λ_1/λ_2*	V	IV	III	II	I_b	I_a
3422/3442	$\langle 1/4$	--	1/2	2/3	--	1/1
3609/3632	trace	--	1/3-1/4	1/2	1/1	1/1-3/2
3758/H11	·	·	weak	1/6	1/4	1/2-1/3
3815/H10	1/7	--	1/6	1/5	1/4	1/3
Balmer Convergence	H17	--	H18-19	H19	H20	H21

*λ_1 and λ_2 are approximate wave lengths.

Table 6

Luminosity at F0

λ_1/λ_2*	V	IV	III	II	I_b	I_a
3394/3405-10	trace	trace	3/1	--	--	1/1
3422/3442	1/3-1/4	1/2-1/3	2/3	.	.	.
3497/3506	.	trace	4/1	4/1-3/1	3/1	2/1-3/1
3497/3526	3/2-2/1	2/1-3/2	3/1	4/1	--	trace
3554/3566	.	trace	1/2	1/1	--	3/2
3609/3619	trace	2/3	1/1	2/1-3/2	--	3/1
3632/3645	3/2	2/1	2/1-3/1	3/1	--	4/1
H15/H14	1/3-1/4	1/2	2/3-1/1	1/1	1/1-3/2	.
3815/H10	weak	1/6	1/5	1/4	1/3	2/3

*λ_1 and λ_2 are approximate wave lengths.

Table 7

Luminosity at F5

λ_1/λ_2*	V	IV	III	II	I_b	I_{ab}	I_a
3361/3394	2/1-3/1	2/1	3/2	1/1	1/1-2/3	2/3	--
3454/3461	1/2	1/2-2/3	2/3-1/1	3/2-1/1	3/2-2/1	--	--
3497/3526	1/1	3/2	2/1	3/1	4/1	--	--
3506/3515	1/3	2/3	1/1-2/3	3/2	2/1-3/2	--	--
3566-70/3581-86	1/1-2/3	2/3	1/2	1/3-1/2	1/3	1/3-1/4	--
3619/3632	1/1-2/3	2/3	1/2	1/2-1/3	1/4	--	--
3697/3704	1/4	1/3	1/2	2/3	2/3-1/1	·	·
H15/H14	1/4	1/3	1/2	2/3-1/1	1/1-2/3	·	·
3758/H12	·	·	·	·	1/3-1/4	1/3	1/2
3775/H11	·	·	·	trace	1/4	1/3	1/2-1/3
3787/H11	·	·	·	1/4-1/5	1/3	--	1/2
3815/H10	1/5	1/5-1/4	1/4	1/3	1/2	--	2/3
3850/3859	·	·	trace	1/2	2/3	1/1	3/2

*λ_1 and λ_2 are approximate wave lengths.

Table 8

Luminosity at G0

λ_1/λ_2*	V	IV	III	II	I_b	I_a
3381/3389	4/1	3/1	2/1	3/2	2/1-3/1	--
3434/3461	1/2-1/3	1/2	1/2-2/3	2/3	--	--
3454/3461	1/3	1/3-1/2	1/2	2/3-1/2	2/3-1/1	2/1-3/2
3476/3484	3/1	3/1-2/1	2/1	3/2	--	--
3566-70/3581-86	2/3-1/1	2/3	1/2	1/3-1/2	1/3-1/4	2/3
3586/3619	.	.	.	1/3	1/2	1/1-3/2
3687/3704	1/3	1/2	1/2-2/3	1/1	3/2	--
3758/H12	.	.	.	1/3	1/2-2/3	2/3-1/1
3775/H11	.	.	.	trace	1/2-1/3	2/3-1/1
3787/H10	1/3-1/4	1/3	1/2	2/3-1/2	2/3	1/1
3850/3859	trace	--	trace	1/2	1/1	2/1

	V_b	V_{ab}	V_a
3859/3871**	2/1	1/1	2/3-1/1

*λ_1 and λ_2 are approximate wave lengths.

**Sensitive to metals/hydrogen.

arose only in the high luminosity stars where an increased Balmer discontinuity and/or interstellar reddening caused such a steep gradient between 3500A and 4000A that the ultraviolet portion of the spectrum was sacrificed in order to obtain the proper exposure in the visible region.

The tremendous differences in the spectral appearance of the highest luminosity stars indicates the need for more sub-groups in that region as outlined by Keenan (1963). The use of the ultraviolet will also advance the solution of this problem.

At types earlier than A5, the ultraviolet exposures were very light. Since, in addition, most of the features are very weak, the problem of choosing criteria becomes difficult. However, even at A0, the ratio of the wide blends at 3422A:3442A appeared to be a very sensitive indicator of luminosity. Also, the degree of Stark broadening may be judged fairly accurately from the appearance of the convergence of the Balmer series. This appearance is also a strong function of exposure, dispersion, and resolution. Therefore, no description is attempted other than a rough estimate of the number of the highest Balmer line resolved on the Kitt Peak plates. This number should not be used alone in the luminosity classification, but rather the appearance of the area of convergence.

CHAPTER V

THREE DIMENSIONAL CLASSIFICATION OF A AND F STARS

Temperature Classification

This chapter describes the use of the 3300A to
3900A ultraviolet criteria for the three dimensional
spectral classification of the A and F stars. The main
difference between this system and the MK system is the
slight revision of the temperature sequence as required by
the new criteria. The ultraviolet luminosity criteria
(cf. Chapter IV) were used only to improve the accuracy of
classification on the MK system. An actual revision of the
luminosity classification scheme may prove desirable as
more spectral data accumulates and if the quality of the
calibration data (a known luminosity sequence free from
abundance and temperature variations) merits it.

The increased accuracy obtainable using the ultra-
violet criteria for a two dimensional classification of A
and F stars makes possible a more thorough study of the
third dimension (metallic line strength) than was previ-
ously possible. It was felt therefore, that the next step
should be the two dimensional classification of the program
stars according to their spectral appearances. (The
"program" stars include all of the stars of reasonable

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plate quality which were not rejected for high c_1

(luminosity) in Chapter III.) At the same time, their

spectral appearances would be compared with the photometry

in order to discover any systematic variations with m_1.

Each star was listed on a separate fly sheet in a

notebook along with its plate number(s) and photometry.

Each spectrum was investigated in order of decreasing b-y

and compared with other stars of similar b-y. While the

b-y value was known at the time of classification, heavy

emphasis was placed on the spectral appearance in the

assignment of a spectral type.

Figure 5 shows the spectral type-color index rela-

tion for the program stars. Since the photometry was

available at the time of classification, the dispersion in

spectral type at a given color index may be optimistic.

However, the color index was ignored as much as possible in

classifying the F stars.

The A stars were classified with a slightly differ-

ent approach--i.e., a little more consideration was given

to the photometry. This was necessary due to the lack of

sufficient plates of good quality for the accurate classifi-

cation of some of these stars. If the spectral features

were slightly discordant (e.g., 0.1 spectral type) with the

photometry, the star was classified according to its

spectral appearances only. However, if the photometry

disagreed with the spectral criteria by 0.3 or more
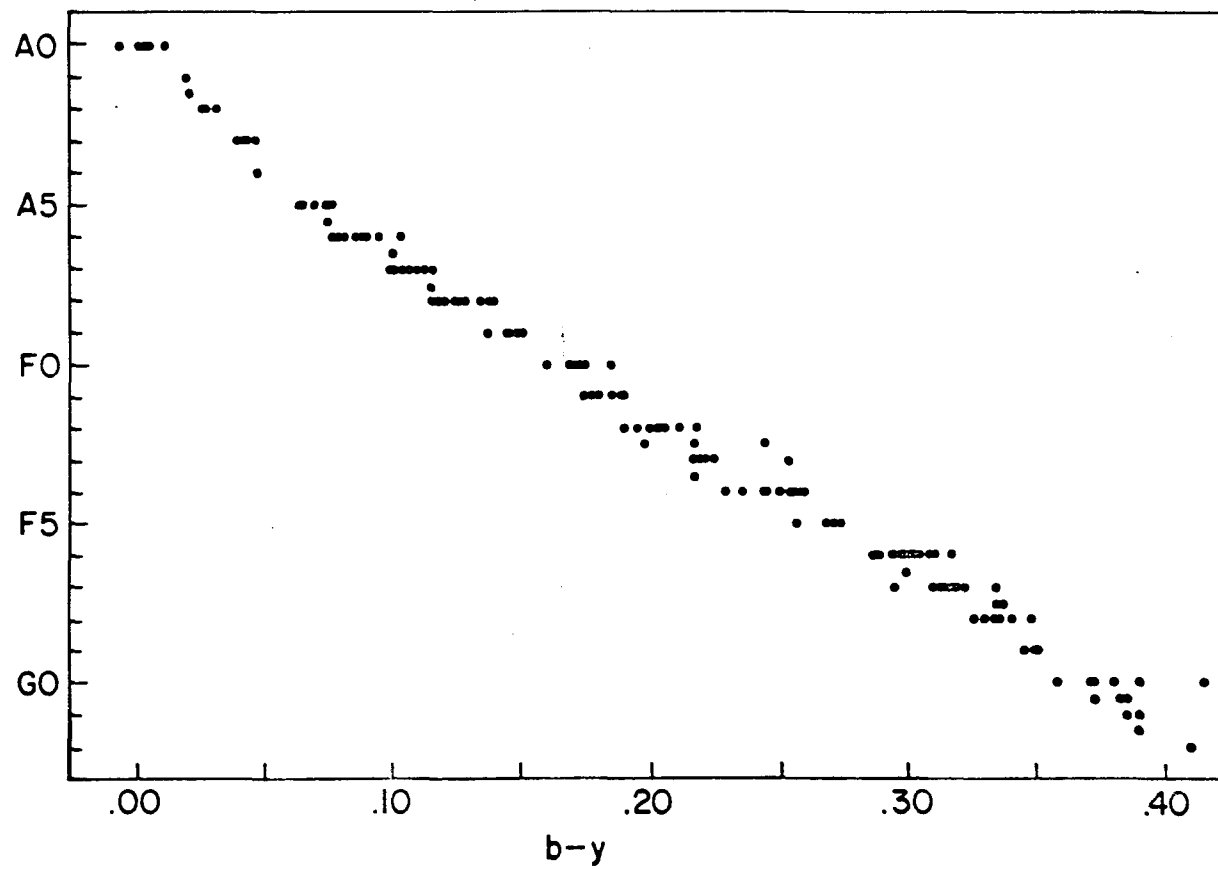
Figure 5.   The spectral type vs. b-y relation for the stars listed in Table 9

spectral types, the star was dropped from the study.   It was felt that in nearly all of the latter cases that the plate quality was insufficient for accurate classification.

Only a few stars earlier than A5 have ultraviolet features which are strong enough to be used for classification.   Only these stars are included in Figure 5.   The small dispersion at these early types is due primarily to the lack of sufficient numbers of stars at each type.   It is my impression from the experience of classifying these stars that the dispersion in spectral type for b-y $>$ 0.200 is only slightly optimistic while the dispersion for b-y $<$ 0.200 should be larger than for the later type stars.

The actual types assigned the stars (Table 9) are probably fairly good.   However, their main value here lies not in the fact that a given star has been assigned a given spectral type, but rather that this group of stars describes a spectral type vs. b-y sequence which is a well defined, continuous, smoothly varying function.   Using Figure 5, we can list reasonable b-y intervals for each 0.1 spectral type which will enable one to more accurately predict revised MK types from photoelectric measures.   This final list of b-y intervals for each 0.1 spectral type is given along with the proposed list in Table 2.

The improvement in the spectral type - (b-y) relation in the late A and early F stars (cf. Figures 3 and 4)

Table 9

Final List of Revised MK Types

H.D.	Type	Bright star type	b-y	Δm_1	Δc_1	Comments
95418	A0 IV	A1 V	-0.004	-0.005	+0.076	
31647	A0 V	A0 V	0.003	+0.015	+0.045	
130109	A0 V	A0 V	0.006	-0.004	+0.021	
103287	A0 IV	A0 V	0.007	+0.001	+0.083	
158460	A0 IV-V	A2	0.012	-0.028	+0.077	
27962	A1 IV h	A2 IV	0.021	+0.012	+0.042	
47575	A1-2 V h	A3 V	0.022	+0.017	+0.042	
1280	A2 IV h	A2 V	0.028	-0.008	+0.053	
106661	A2 V 1	A2 V	0.028	-0.004	+0.063	
6658	A2 III vh	A2m ?*	0.028	+0.041	+0.049	
113865	A2 V h	A3 V	0.032	+0.024	+0.006	
193702	A3 V 1	A1 V	0.040	-0.020	+0.078	
102647	A3 V 1	A3 V	0.042	+0.014	-0.007	
138338	A3 V h	A2	0.043	+0.014	+0.027	
56537	A4 IV	A3 V	0.048	+0.005	+0.083	
18331	A3-4 IVb v1	A1 V	0.048	-0.026	+0.088	
13041	A4 V	A5 V	0.055	0.000	0.100	Focus
11636	A5 IVb	A5 V	0.064	+0.007	+0.025	
97603	A5 V 1	A4 V	0.064	+0.002	+0.086	
154494	A5 IV 1	A3 IV	0.071	+0.003	+0.050	
118232	A5-6 Va	A4 V	0.075	-0.004	+0.111	
15385	A5 IV vh	A5	0.076	+0.028	+0.002	
89904	A5 Va 1	A3	0.076	-0.013	+0.080	
107168	A5 III vh	Am*	0.076	+0.054	-0.005	
141795	Am6 IV	Am	0.077	+0.034	+0.020	
40536	Am6 III vh	Am	0.080	+0.050	+0.060	
39586	A6 V 1	A3	0.082	-0.015	0.110	

Table 9--<u>Continued</u>

6961	A6 IV h	A7 V	0.087	+0.012	+0.084	
28527	A6 IV vh	A7 V	0.088	+0.013	+0.053	
22522	A6 V	A3	0.089	+0.003	0.000	
29488	· A6 V	A5 V	0.088	-0.006	+0.102	Focus
205767	A6 Va	A7 V	0.090	-0.003	+0.105	
29140	Am6-7 III-IV 1	Am	0.095	-0.010	+0.049	Focus
116831	A6 IVb	A3	0.096	+0.012	+0.072	
33641	Am7 IVb h	Am	0.099	+0.004	-0.013	
116842	A6-7 Va vl	A5 V	0.100	-0.002	+0.037	
173648	Am7 IV vh	Am	0.101	+0.031	+0.106	
98673	A5-7 V vl	A2	0.103	-0.031	+0.094	
76644	A7 V	A7 V	0.104	+0.005	-0.024	
92941	A7 V vl	A3	0.107	-0.013	-0.005	
87696	A7 V 1	A7 V	0.110	-0.012	-0.005	
44769	A7 IVb vl	A5 IV	0.111	-0.011	+0.095	
79439	A7 V 1	A5 V	0.113	-0.010	+0.022	
211356	A7 Va vl	A4	0.116	-0.028	+0.087	
140232	Am8 Va h	A2	0.116	+0.020	+0.003	
60652	Am8 IVab vh	A3	0.118	+0.047	+0.044	
75698	Am8 Va h	Am	0.118	+0.005	-0.038	
112171	A8 V 1	A5 V	0.121	-0.011	+0.025	
91312	A8 Va 1	A7 IV	0.121	+0.001	-0.005	
209625	Am8 IV vh	Am	0.124	+0.038	+0.073	
203280	A8 IV	A7 IV-V	0.125	-0.007	+0.090	
124675	A8 IV 1	A7 IV	0.126	-0.005	+0.082	
125161	A8 V 1	A7 V	0.128	-0.008	-0.001	
30121	Am8 IVb vh	Am	0.135	+0.032	+0.057	
187642	A9 V vl	A7 V	0.137	-0.019	+0.065	
33254	Am8 IV h	Am	0.138	+0.045	+0.025	
141675	Am8 IVa vh	Am	0.139	+0.048	+0.063	
28910	A9 V 1	F0 V	0.144	+0.006	+0.023	
155514	A9 IV 1	A3	0.144	+0.007	+0.081	4171 peculiar?

Table 9--<u>Continued</u>

30034	A9 V h	dA5	0.149	-0.002	+0.024	
33204	Am9 V vh	Am	0.149	+0.047	+0.013	
29499	A9 Va h	dA9	0.150	+0.027	+0.037	
118660	A9 V h**	gF0	0.150	+0.015	+0.004	
102910	Fm0 IV h	A3	0.160	+0.014	-0.036	
78209	Fm0 IV vh	Am	0.169	+0.044	+0.030	
104513	Fm0 Va	Am	0.170	0.000	+0.013	
211336	F0 IV	F0 IV	0.171	+0.010	+0.040	
159560	Fm0 IV vh	Am	0.173	+0.030	-0.007	Under exposed
68703	F1 IV vh	F0	0.174	+0.039	+0.083	
27176	F0 V	dA8	0.175	+0.003	+0.057	3526 peculiar
143466	F1 IVab 1	F0 IV	0.178	+0.005	+0.051	
27749	Fm1 III vh	Am	0.180	+0.052	+0.018	
26574	F1 IIIa	F2 III	0.181	+0.026	+0.062	
218396	A7-F0 V 1	A5	0.184	-0.051	-0.017	Weak K line focus
14622	F1 IVb**	dF2	0.186	-0.020	+0.063	Under exposed
155103	Fm1 IVa h	A5	0.189	+0.027	+0.030	
17094	F1 IVb h	F0 IV	0.189	+0.012	+0.072	
110951	Fm2 IIIb vh	Am	0.191	+0.053	+0.087	
69997	F2 III vh**	A5	0.196	+0.063	+0.110	Under exposed
27628	Fm2 IIIb vh	Am	0.196	+0.030	+0.044	
105702	F2-3 III vh	Am*	0.198	+0.080	+0.030	
204485	F2 V h	dF2	0.200	+0.021	-0.012	
11257	F2 V 1	F0 V	0.203	-0.025	-0.008	
137391	F2 IV a	F0 V	0.203	+0.014	+0.090	
132052	F2 IV	F0 IV	0.206	+0.010	+0.063	Under exposed
203843	F2 III vh	gA9	0.206	+0.044	+0.061	Slight focus
225003	F2 Va	dF0	0.212	-0.015	+0.015	
58946	F2-3 Va h	F0 V	0.217	-0.014	-0.003	
78362	Fm3-4 III vh	Am	0.217	+0.084	+0.113	
32537	F3 Va	F0 V	0.217	-0.010	+0.032	

Table 9--<u>Continued</u>

42278	F3 IV l	F0	0.218	+0.007	+0.063	
40136	F2 V vl	F0 V	0.218	0.000	+0.020	Slight focus
147449	F3 Va	F0 V	0.220	+0.017	+0.049	
56986	F3 IVa l	F0 IV	0.221	+0.001	+0.096	
199611	F3 V l	F0	0.224	+0.017	+0.120	
26690	F4 V h	F3 V	0.229	+0.014	+0.002	
138290	F4 V l	F2	0.236	+0.007	-0.050	
136751	F4 IVb h	F0	0.245	+0.012	+0.103	
113139	F4 V h	F2 V	0.246	+0.019	+0.036	
20193	F4 V vl	F0	0.251	-0.030	+0.060	
128167	F3 V vl	F2 V	0.254	-0.017	-0.030	
129502	F4 Va	F3 IV	0.254	+0.015	+0.010	
64235	F5 IVb h	gF5	0.257	+0.026	-0.030	
160910	F4 V l	dF1	0.258	+0.003	+0.026	
151613	F4 IVb l	F2 V	0.259	+0.006	+0.012	
99747	F5 Va vl	dF1	0.268	-0.027	+0.004	
106022	F5 V	F2	0.272	+0.006	+0.103	Under exposed
72291	F5 Vb vl	dF1	0.272	-0.015	-0.022	Focus
17948	F6 Va vl	dF4	0.287	-0.020	-0.014	
218235	F6 V h	dF4	0.287	+0.036	+0.020	
113022	F6 V h	dF4	0.288	+0.025	-0.009	
157373	F6 Va vl	F2	0.294	-0.035	+0.029	
185912	F6 Va vh	dF4	0.294	+0.011	+0.011	
210027	F6 Va l	F5 V	0.296	+0.005	+0.006	
8774	F7 IVb vh	F5	0.296	+0.024	+0.021	
89449	F6 IVb h	F6 IV	0.297	+0.017	+0.024	
2454	F6 Va vl	F2 V	0.298	-0.041	+0.019	
30652	F6 Vb h	F6 V	0.299	+0.007	-0.017	
86146	F6 Va h	F5 V	0.300	+0.010	+0.027	
99373	F6 IV	F5	0.302	-0.005	+0.071	Focus
221950	F6 Vb vl	dF0	0.304	-0.036	-0.030	
207978	F6 IV vl	dF0	0.309	-0.050	+0.029	

Table 9--<u>Continued</u>

219291	F6 IV 1	F5	0.309	-0.024	+0.139	
61859	F7 Va	F0	0.310	-0.005	+0.076	
130945	F7 IVb 1	dF4	0.313	+0.010	+0.081	
173667	F7 IVb 1	F6 V	0.314	-0.010	+0.084	
82328	F7 IVab 1	F6 IV	0.314	-0.007	+0.063	
124425	F7 Vb 1	F6 IV	0.315	+0.004	+0.010	Luminosity uncertain
11443	F7 IVab 1	F6 IV	0.316	-0.004	+0.101	
106516	F6 Vb v1	F6 V	0.317	-0.042	-0.067	Slight focus
111456	F7 V v1	F6 V	0.319	-0.003	-0.028	Focus
59380	F7 Vab 1	dF9	0.320	-0.026	+0.012	Slight focus
142860	F7 Vab 1	F6 IV-V	0.320	-0.009	+0.008	Slight focus
216385	F7 IVb 1	F7 IV	0.321	-0.013	+0.038	
16895	F8 Vb	F7 V	0.326	+0.001	-0.012	
220460	F? v1	F5	0.327	-0.044	+0.020	Focus
155646	F8 IVb 1	F5	0.330	-0.009	+0.104	
126660	F7 V v1	F7 V	0.334	-0.011	+0.048	
89125	F8 Vb 1	dF3	0.336	-0.028	-0.018	
222368	F8 Va 1	F7 V	0.336	-0.016	+0.029	
107213	F8 Va h	dF8	0.336	+0.024	+0.081	
170153	F8 Vb v1	F7 V	0.337	-0.019	-0.060	S. Binary
127986	F8 IVb 1	F5	0.340	+0.000	+0.121	
9826	F9 Va	F8 V	0.346	+0.004	+0.055	
51530	F8 Vab v1	dF4	0.348	-0.039	+0.040	
136064	F9 IVb	F8 V	0.350	-0.002	+0.072	
123999	F9 IVb 1	F8 IV	0.350	+0.000	+0.090	
198084	G0 IVb	F8 V	0.358	+0.006	+0.095	
165908	F7-9 v1	F7 V	0.361	-0.039	-0.015	Focus
114710	G0 Vb	G0 V	0.372	+0.004	+0.006	
4614	G0 Vb	G0 V	0.372	-0.004	-0.055	
14214	G0.5 IVb	F9 V	0.373	+0.002	+0.060	
121370	G0 IV	G0 IV	0.379	+0.010	+0.157	

Table 9--<u>Continued</u>

43587	G0.5 Vab	dG0	0.382	+0.003	+0.011
109358	G0.5 Vb 1	G0 V	0.385	-0.016	-0.024
115043	G1 Vb	--	0.386	-0.001	-0.014
10307	G1 Va	G2 V	0.389	+0.001	+0.023
72905	G1.5 Vb	G0 V	0.390	+0.004	-0.033
220657	G0 IV v1	F8 IV	0.390	-0.018	+0.145
186408	G2 Vab h	G2 V	0.410	+0.000	+0.070
150680	G0 IVb 1	G0 IV	0.415	-0.015	⟩0.100

*K line is not weak for revised spectral type.

**Marginal Am characteristics including a slightly weak K line.

is significant and can be attributed to the numerous ultraviolet criteria used in this study. This fact is verified by the classification of a number of A and F stars with no available photoelectric knowledge and is discussed in Chapter VI.

Luminosity Classification

Since only a few luminosity standards were available (on Kitt Peak plates only), all luminosity classes were assigned on the basis of Tables 4 through 8 and a comparison with other stars of the same spectral type. The c_1 index was available but the spectral appearance was the principal factor considered in the assignment of luminosity classes. If there were discrepancies between the luminosity as indicated by the c_1 index and the spectroscopic luminosity, in all cases the spectroscopically indicated luminosity class was assigned.

The luminosity class labels described by Keenan (1963) were used extensively. However, the value of these labels as used here lies only in the fact that they indicate a sequence of luminosity types at a given color index. In other words, the label IVb is assigned to a star which spectroscopically appears to be less luminous than another star assigned to class IVab. Since no class IVb standards are defined on the MK system, it may be that these classifications will have to be changed systematically at

some later date. When it was felt that the use of the small letters "a" and "b" was not justified, they were omitted from the description and the usual IV or V was used.

Since the photometry had been used to screen out class IVa and the higher luminosity stars, it was surprising to discover numerous stars which showed indications of higher luminosity than others of the same spectral type. This is attributed to the extreme sensitivity of some of the ultraviolet features to a reduction in surface gravity. In the late F and early G stars, the ratio 3859A/3871A was found to be very sensitive to luminosity among the main sequence stars--i.e., it showed a very strong correlation with Δc_1. When Δc_1 is approximately zero, the ratio is nearly unity. When Δc_1 is large and positive (e.g., $0^m.10$ to $0^m.14$), the ratio is slightly less than one. But when Δc_1 is negative, the ratio becomes correspondingly much greater than unity until the 3871A and 3878A features nearly disappear.

This same ratio is also sensitive to metallic abundances but to a much smaller degree. A class IV star may appear to be Va or Vab (on the basis of this criterion alone) due to low metal content. However, a careful study of other features (to be discussed later) which are sensitive to metal content should reveal the error and due compensations can be made in classifying the star.

While there is no need to mention other individual luminosity criteria used for the classification of late F and early G stars, the improvement in the accuracy of assigning classes is worthwhile and should be explored further for the giants and supergiants as well as the dwarfs.

In the late A and early F stars (b-y $\langle$ 0.220), the ultraviolet spectral criteria indicated that some of the program stars were of luminosity class III and occasionally II. It appears as though the luminosity criterion $\Delta c_1 \langle$ 0.110 were not sufficient to exclude some of the stars whose spectral features indicated higher luminosity. The apparent high luminosity of the stars stood out very plainly in the excessive strength of $\lambda 3497$ and $\lambda 3586$ and other sensitive features. While it is somewhat uncertain (for reasons mentioned earlier) if the stars classified as II or III actually belong to these particular luminosity classes, it is relatively certain that they should be assigned to higher luminosity classes than program stars of classes IV and V. Whether the stars are actually more luminous or merely have atmospheric conditions which simulate the effects of low surface gravity at classification dispersion is open to question. This phenomenon will be discussed further in the section dealing with the metallic line stars where it apparently occurs much more frequently.

The use of the ultraviolet luminosity criteria has permitted differentiation between stars of class IV and class V through type A5 and earlier if the overall strength of the ultraviolet features were normal to higher than normal. At this point, the 3300A-3900A region of the spectrum had yielded criteria permitting two dimensional classification of the A and F stars which appears to be of greater accuracy than the MK system.

Metallic Line Strength in the F Stars

The large sample of accurately classified A and F stars of widely varying m_1 presented an excellent opportunity for an investigation of the variations in spectral appearance with m_1 at a given temperature and luminosity. The A and F stars were treated as two separate groups since the m_1 index is apparently a measure of two different physical parameters in the two groups. The late F and early G stars are treated first. It is shown in Chapter VII that the m_1 index is a measure of metallic abundances in these stars.

A literature study was made for the purpose of constructing a list of the spectral features which are known to be abundance indicators in the F stars at classification dispersion. Although this dissertation is concerned only with the most commonly found stars in the solar neighborhood, it was felt that a list of spectral anomalies

associated with the F stars of extremely low metallic
abundances (rarely found within the distances of the pro-
gram stars) would be helpful in picking out slight spectral
anomalies in slightly under-abundant or over-abundant
stars.

Roman (1965), in a review article on high-velocity
stars, gives an historical summary of the subject. The
first F subdwarfs to be discovered were included in an
early list of high-velocity stars by Adams and Kohlschutter
(1914a). These stars were classified as types A and F due
to their extremely weak metallic features. Today, they are
classified at later types and listed as metal deficient.

Keenan and Keller (1953), studied the spectra of
high-velocity stars to determine features which would allow
a two dimensional temperature and luminosity classification
which would be relatively unaffected by low metallic
abundances. For the F stars, they gave the ratios
$H\delta/\lambda 4226$, $H\gamma/\lambda 4325$, and the G band strength as the best
spectral type indicators. They also reported that the more
serious anomalies noticed in the spectra of some of the
high velocity stars of types F5-G5 were the general
weakening of the lines of hydrogen and the metals. Similar
effects were noted by Roman (1950). It was also mentioned
that the effect of line weakening is less striking in the
dwarfs and was actually noticeable in only 4 out of 14 of
the high velocity dwarfs studied.

Roman (1965) states that the weakness of the metallic lines in the high-velocity stars ranges in degree from that in normal stars near the sun to that in globular clusters. Since we are concerned only with dwarf stars of metallic abundances on the same order of magnitude as that of the sun, there appeared to be some doubt as to whether abundance variations would be detectable in the appearance of the ultraviolet portion of the spectrum.

Roman (1965) reviews the F subdwarfs as an individual group apart from the other types of high-velocity stars. On prism spectra of classification dispersion, these stars show sharp hydrogen lines similar to those in normal F stars and a strong Calcium K line similar to type F, but the G band and Calcium 4226 and the strongest metallic features are either absent or very weakly present.

It is interesting to note here that Keenan and Keller (1953) report that the G band was abnormally strong in 4 out of 14 high velocity dwarfs--the same number showing weakened metallic lines. They conclude that an abnormally strong G band or abnormally weak metallic lines are about equally good indicators of high-velocity character among F5-G5 stars. The behavior of the G band is apparently also disputed among theoreticians as a comparison of Pagel (1962) and Schwarzschild, Spitzer, and Wildt (1951) will reveal.

Other spectral differences between the F subdwarfs and normal F dwarfs have been noted by Divan (1956). She showed that the subdwarfs lie below normal stars on a plot of the depth of the Balmer jump vs. its position. These differences however, are not useful for spectral classification by visual inspection methods.

Roman (1950) showed that among the giants and dwarfs of types F5-G5, some stars have systematically weaker lines than others of the same type and luminosity. Distinguishing two groups of stars on this basis, she found that the group of stars with weaker lines had a larger dispersion in its velocity distribution than the other group. She listed the following spectroscopic differences which are correlated with abundance differences. In the F5-F6 stars, the metallic lines are fairly weak. The most obvious difference between the two groups is that Ca I 4226 stands out noticeably in the weak line stars but is one of many lines in the strong line stars. By F8 the weakening of the metallic lines is obvious in the dwarfs. At G0, she states that the ratio of $\lambda 4340/\lambda 4325$ is noticeably smaller in the weak line stars for the same $\lambda 4226$ strength. These differences are reported to be small at best and require comparable plates of high quality to detect them.

As was stated earlier, one purpose of this dissertation is to find correlations between spectroscopic appearances and the Stromgren m_1 index. The question of

whether stars of low m_1 are weak line stars and stars of high m_1 are strong line stars was investigated by Stromgren (1958a). Although he had photoelectric "m" measures (predecessor to m_1) for only nine stars on Roman's (1950) list, he found that in three cases out of nine that the strong line stars have low m values. However, the extreme weak line subdwarfs did have low m values as expected.

The apparent lack of correlation between the m index and the strong line stars could be explained if the two methods were actually measuring two different effects. Another possibility is that the strong line designation is subject to error due to the extremely small differences in the spectra and the difficulty of assigning accurate temperature types independent of abundances.

Morgan (Stromgren 1958a, Discussion, p. 263) makes the comment that "In all F stars one has a background of arc metallic lines gradually becoming more intense as the spectral type becomes later. If one misclassified an F7 star and called it F8 one might later wrongly classify it as a weak line star. Some stars of moderate weak line characteristics there undoubtedly are, but I would not rely absolutely on all of those in Miss Roman's list. The kinematic correlation might be explained partly by the presence of a few extreme examples that will affect the mean."

In order to further check for correlations between the Stromgren indices and the strong line, weak line designations, all stars on Miss Roman's (1950) list having uvby photometry and grating spectra available were listed in Table 10 for further study. The revised types assigned in this dissertation are given along with the earlier MK types.

Figure 6 shows a plot of Δm_1 vs. b-y for these stars. It is expected that weak line stars would lie at large negative Δm_1 while the strong line stars would be found at large positive m_1. Ignoring photometric error, it is seen that six out of sixteen weak line stars have positive Δm_1 values and four out of eleven strong line stars have negative Δm_1 values. Since Δm_1 includes the error of measurement of m_1 (p.e. $\pm 0^m.005$) as well as the error in choosing the mean m_1^o - (b-y) relation (cf. Chapter III), the above statistics must be considered with caution. It does seem reasonable to state however, that for $0.250 < b-y < 0.300$ there are three stars of high metal content which have weak line designations. These stars are classified by Roman as F3 IV, F5 V, and F6 IV and were apparently designated as weak line stars due to the strong appearance of Ca I 4226. Between $0.300 < b-y < 0.400$ there are three stars of low metal content with strong line designations. One of these (ν PEG) is classified too early

Table 10

Program Stars Common with Roman's (1950) List

| H.D.	Type	Roman type	b-y	Δm_1	Δc_1
Strong Line					
210027	F6 Va 1	F5 V	.296	+.005	+.006
30652	F6 Vb h	F6 V	.299	+.007	-.017
86146	F6 Va h	F5 V	.300	+.010	+.027
216385	F7 IVb 1	F7 IV	.321	-.013	+.038
170153	F8 Vb vl	F7 V	.337	-.019	-.060
136064	F9 IVb	F8 V	.350	-.002	+.072
102870	--	F8 V	.354	+.012	+.067
114710	G0 Vb	G0 V	.372	+.004	+.006
121370	G0 IV	G0 IV	.379	+.010	+.157
10307	G1 Va	G2 V	.389	+.001	+.023
220657	G0 IV vl	F8 IV	.390	-.018	+.145
Weak Line					
129502	F4 Va	F3 IV	.254	+.015	+.010
134083	--	F5 V	.285	+.014	-.011
89449	F6 IVb h	F6 IV	.297	+.017	+.024
173667	F7 IVb 1	F6 V	.314	-.010	+.084
82328	F7 IVab 1	F6 IV	.314	-.007	+.063
11443	F7 IVab 1	F6 IV	.316	-.004	+.101
142860	F7 Vab 1	F6 IV-V	.320	-.009	+.008
16895	F8 Vb	F7 V	.326	+.001	-.012
126660	F7 V vl	F7 V	.334	-.011	+.048
222368	F8 Va 1	F7 V	.336	-.016	+.029
9826	F9 Va	F8 V	.346	+.004	+.055
198084	G0 IVb	F8 V	.358	+.006	+.095
165908	F7-9 vl	F7 V	.361	-.039	-.015
4614	G0 Vb	G0 V	.372	-.004	-.055
109358	G0.5 Vb 1	G0 V	.385	-.016	-.024
150680	G0 IVb 1	G0 IV	.415	-.015	$>$+.100
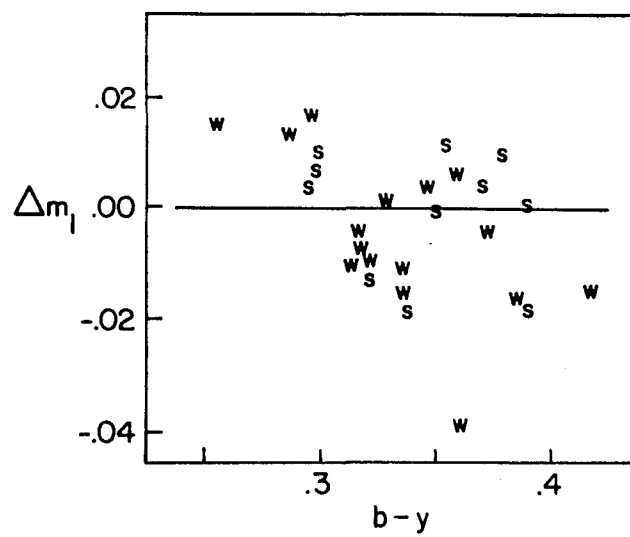
Figure 6. The Δm_1, b-y diagram for all program stars which are also included in Roman's (1950) list

and the other two appear to have weaker than normal
metallic features.

Figure 7 is a plot of Δm_1 vs. Δc_1 for this same
group of stars. A positive $\Delta c_1 = 0^m\!\!.150$ is a photometric
indication that the star's luminosity is about class IV.
It should be noted that these stars were selected (cf.
Chapter III) for study because their individual Δc_1 values
indicated that they were fainter than luminosity class IV.
A negative value of Δc_1 indicates that the star lies below
the envelope of the distribution in the c_1^o - (b-y) diagram
(Strömgren 1963a). There may exist a tendency for stars
of small or negative Δc_1 to be classified as weak line.
More will be said about this later.

Keeping in mind the short list of abundance
sensitive criteria obtained from the literature, the
grating spectrum of each of these stars was carefully
studied in order to become familiar with the anomalies
which led to their particular classification. In the more
extreme cases, the strong or weak line criteria could be
recognized in the spectral features at our dispersion and
resolution. However, a number of the stars did not appear
to be either strong line or weak line according to the
above criteria while a few stars with definitely weak
ultraviolet features were classified as strong line (cf.
Table 10). These stars also have low m_1 values--a fact
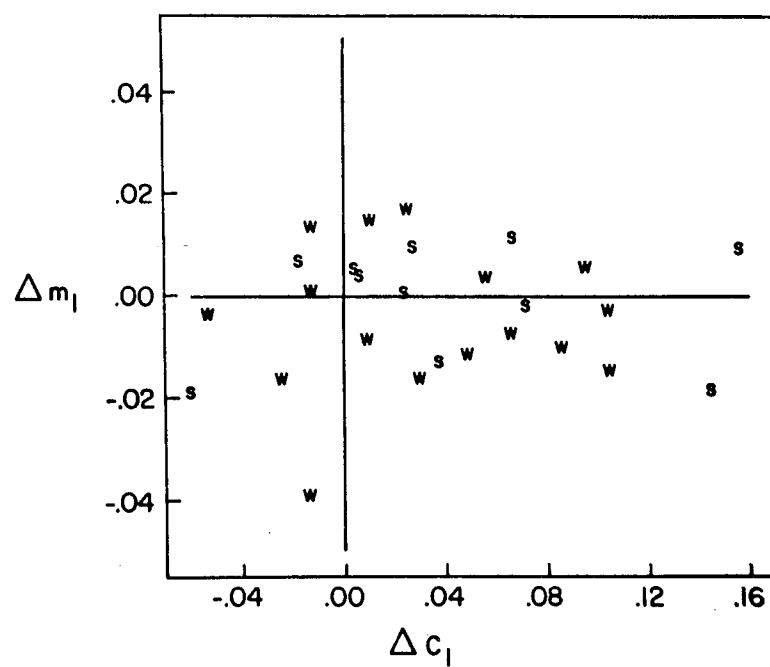which indicated the desirability of searching for new

Figure 7. The Δm_1, Δc_1 diagram for all program stars included in Roman's (1950) list

abundance criteria in the ultraviolet region of the spectrum.

Starting with the early G stars in the group of stars which had previously been classified in two dimensions, a systematic study of each spectrum was made to discover features which varied with m_1 at any given luminosity and spectral type. The most obvious and reliable criterion was again found to be the overall appearance of the strength of the metallic lines--but especially in the 3600A-3900A region of the spectrum. In particular, the relative strength of the 3815A-H_9 group of features, the 3859, 71, and 78A features and the 3615A-3640A region appeared most sensitive to abundance in the late F stars. The overall strength of the 3442A-3497A group and the pair of paired features at 3566-70A and 3581-86A also gave an indication of the abundance. In the visible, the absolute strength of the Mn I 4032 blend above the continuum appeared to be well correlated with m_1. The G band, $\lambda 4325$, and $\lambda 4226$ were not used as indicators of line strength since they appeared to be somewhat inconsistent with the m_1 index. However, it must be admitted that the spectra were often slightly over exposed in this region.

As was mentioned earlier in this chapter, the 3859A/3871A ratio is very sensitive to luminosity among class IVb to Vb stars at late F and early G. If abundances

are low, these features are correspondingly weakened in a nonuniform fashion such that a luminosity assignment on this basis alone might underestimate the luminosity of the star.

Since higher luminosity strengthens a number of the ultraviolet features, it can slightly affect the temperature classification but can strongly affect the abundance classification. Using the photometry as a guideline, it was possible to discover which abundance features are least affected by luminosity and vice versa. As a better understanding of the 3859A/3871A ratio developed, some of the luminosity classifications of these stars were changed slightly while no changes were made in the temperature classification.

When it was felt that the abundance criteria were familiar enough to allow it, the entire group of program stars were classified according to their metallic line strength. Stars of similar temperature type and luminosity class were compared for differences in line strength. The mean appearance of the spectra of a number of stars of $\Delta m_1 \approx 0\overset{m}{.}000$ was compared with the spectral appearance of stars having large positive and negative Δm_1 values. After a feeling was obtained for the overall range of variation in the line strength at a given spectral type, the stars indicating low or high abundances (weak or strong ultraviolet metallic features) were marked "l" or "h" (low or

high abundance) irregardless of their photometry. Stars
with extremely weak or strong features for their type were
marked "vl" or "vh" (very low or very high). Stars which
seemed neither low nor high were not labeled. A few stars
were not classified due to inadequate plate material.

The designation "l" or "h" ranges from stars which
have only slightly weak or strong ultraviolet metallic
features to stars with very weak or strong features. For
this reason, a number of these judgments (made only from
one plate) may be in error. However, the stars marked
"vl" or "vh" have spectra which are obviously metal weak or
metal strong. Misclassifications in the group of "vl"
stars could occur due to spectra which are slightly out of
focus (cf. Chapter II). This effect was avoided as much as
possible.

Figure 8 is a Δm_1 - (b-y) diagram for all of the
program stars. At this point we are discussing only stars
of b-y $>$ $0^m\!\!.250$. (Figure 8 may be compared with Figure 6.)
The dots represent stars not classified in the third
dimension. The large number of these near $\Delta m_1 \approx 0^m\!\!.000$
and b-y $>$ $0^m\!\!.350$ is due to the fact that the spectra of all
the stars at this late type have fairly strong lines.
Therefore a star would have to be extremely over- or under-
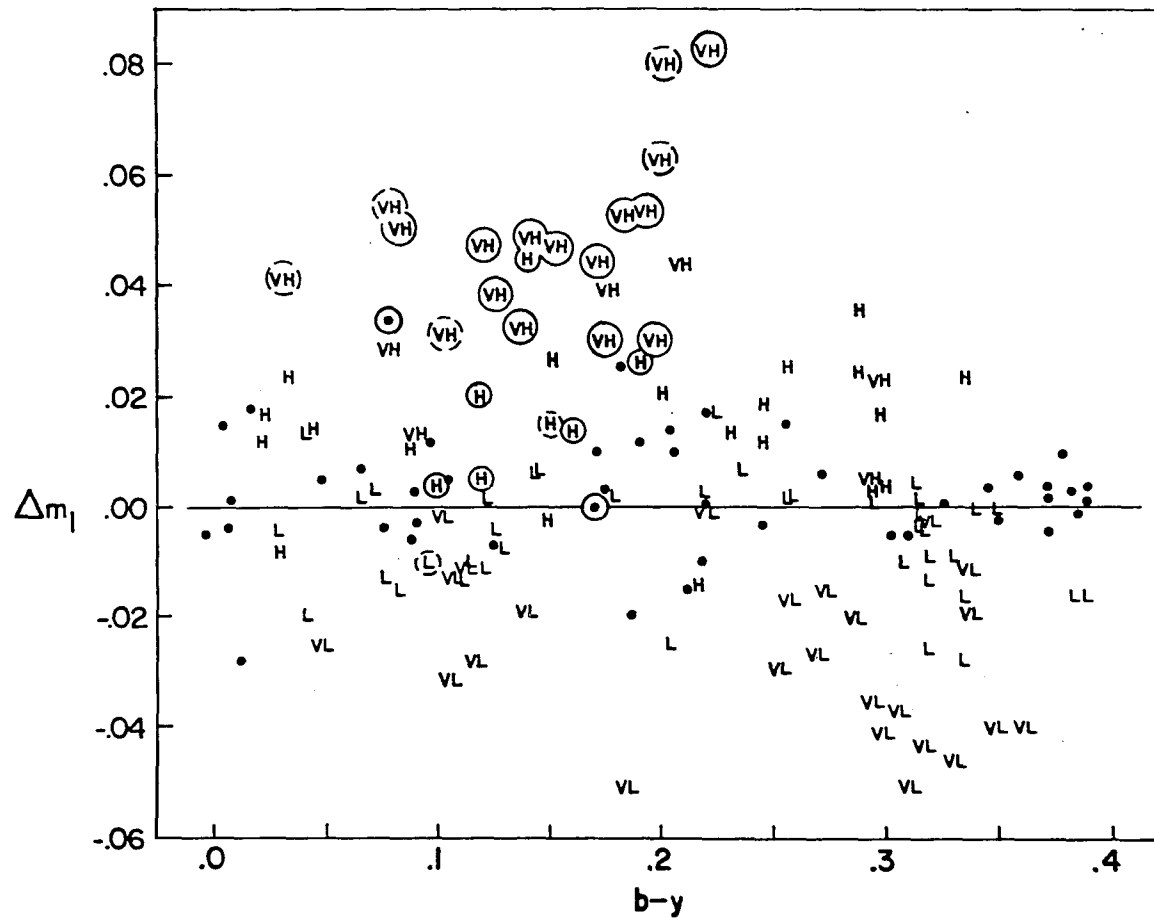abundant for the features to be noticeably enhanced or
weakened.

Figure 8.   The Δm_1, b-y diagram for the program stars

The solid circles represent the Am stars.   The broken circles represent stars whose Am classification may be disputed (cf. Chapter V).

There appears to be a good correlation between the assigned types and the m_1 index. The stars classified "vl" usually have negative Δm_1 indices indicating that their metal abundance is below normal. The relatively few stars at high m_1 is attributable to the way in which the stars are distributed on the m_1 - (b-y) diagram from which they were selected--i.e., there is a relatively tight envelope which includes the Hyades stars at high m_1 while there is a great spread down to low m_1 values. The fact that there are only two stars classified as "vh" and only one of these at high m_1 may be due to the difficulty of differentiating by inspection between normally strong metallic lines and stronger metallic lines. As we proceed to earlier types, the problem disappears and there are great differences between "vh" spectra and normal spectra.

Figure 9 is a plot of Δm_1 vs. Δc_1 for all stars of b-y $>$ $0^m.250$. The same correlation between the metallic line strengths and the quantity Δm_1 is seen here. This diagram reveals in addition however, that the stars classified "vl" have a strong tendency to be low Δc_1 or even negative Δc_1 stars. A slight tendency towards the same phenomenon was noted in the discussion of Figure 7.

One now might wonder whether the spectral criteria used for three dimensional classification is confusing low abundance with low luminosity. That this is probably not the case is evidenced by the fact that every symbol in
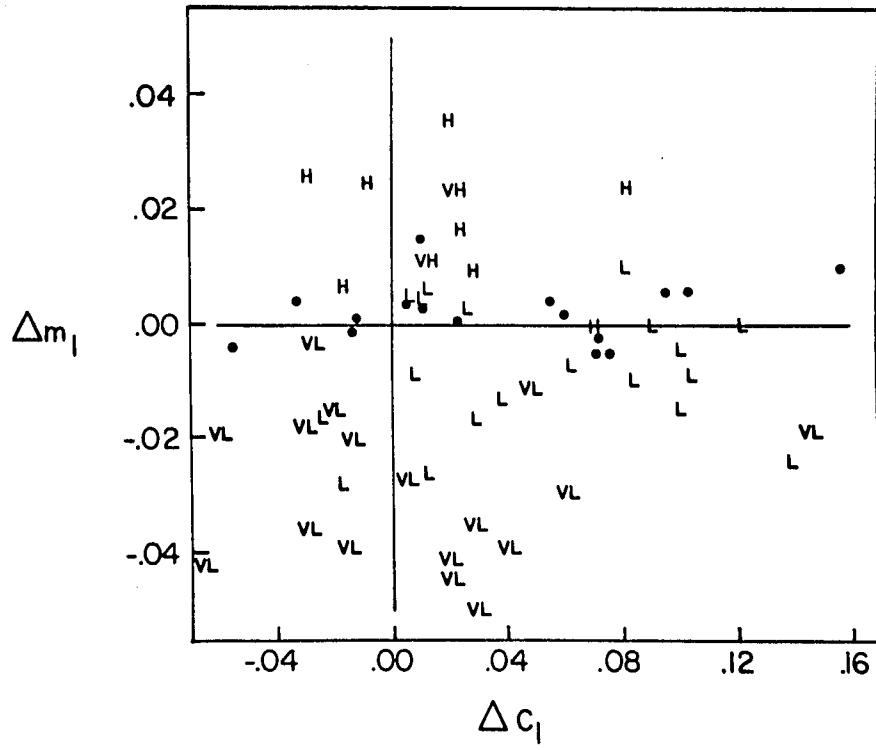
Figure 9. The Δm_1, Δc_1 diagram for the program stars of $b-y > 0^m.250$

Figure 9 is located at a photoelectrically determined point. In other words, it is the photometry itself which indicates that low m_1 stars tend to have low c_1 values for their particular b-y. Or, if we assume that the indices are an accurate measure of the quantities for which they were defined, we can say that stars of low metal abundance tend to be slightly sub-luminous. These two quantities mixed together apparently produce a spectrum with very weak metallic lines.

Aside from the star classified as "h" at $(-0^{m}.029$, $+0^{m}.026)$, the second quadrant of the diagram is very nearly empty. This particular star has only one uvby measure and appeared to have only slightly strong ultraviolet metallic features. For these reasons it is felt that the photometry could be in error. It is suggested that stars having high m_1 indices tend to have higher c_1 indices than normal for their b-y. Again, whether this is a characteristic of the uvby system or whether stars of high metallic abundances are being observed to form a slightly more luminous main sequence is open to question.

In this respect it should be noted that Stromgren (1963b) gives a correction of $0.75 \cdot (\Delta m_1)_{\text{Stromgren}}$ to be added to c_1 for stars of $0^{m}.250 < \text{b-y} < 0^{m}.400$ when his formulae are to be used to calculate absolute magnitudes. Replacing his $(\Delta m_1)_{\text{Stromgren}}$ with the Δm_1 used in this dissertation, the correction term becomes $+0.75 \, (-\Delta m_1$

+ $0^{m}_{.}015$). Application of this correction to Figure 9 will tend to reduce the number of stars having negative Δc_1 but there will still be a strong tendency toward the phenomenon described above. It was a combination of the photometry and the appearances of the spectra of the stars in the third quadrant which led to the observational test for determining the nature of the third parameter (for which m_1 is a measure) which is discussed in Chapter VII.

Pagel (1962) has made a study of the influence of metal abundance on spectra and spectral classification in G and K dwarfs. Using mean atmospheric parameters for stars of varying hydrogen to metal ratios, he applied the curve of growth technique to determine the relative intensities of strong lines commonly used in the Mt. Wilson and MKK classification systems. He compared his computed values with observations to determine the influence of metal deficiency on spectral types assigned to dwarfs at a given effective temperature.

He found that an extreme subdwarf assigned a specific spectral type (near early G) on the Mt. Wilson system might be cooler than a normal dwarf of the same type by as much as 0.5 spectral types. The same effect was found for stars classified on the MKK system but it was not nearly as strong. He feels that this is due to the emphasis placed on line ratios when classifying on the MKK system.

Care had to be taken to untangle the effects of blanketing on the photoelectric B-V index. In fact, it wasn't until R-I colors were used as an indication of effective temperature that the above described errors became apparent in the MKK system. The need for temperature criteria independent of abundances was well demonstrated.

A search for temperature criteria which are relatively free from abundance effects was carried out among the program stars of type F. Among the stars marked "vl" all of the temperature criteria appear to be affected by the low metallic abundances. However, the ratio of H_{11}/H_{12} (H_{12} being blended) appears to be the least affected by the low metallic abundances. The ratio 3497A/3526A was also useful for classifying the "vl" stars. The most sensitive indicator of spectral type in the late F and early G stars (3758A/H_{11}) was seriously affected by very low metallic abundances and by very high luminosity.

Since the metallic lines continue to increase in strength from type A to beyond the low temperature limit of this study, it is easy to confuse stars of low metallic abundance with those of normal abundance at a higher effective temperature. This effect can be demonstrated by looking up the abundance classification of stars located at the red extreme of various b-y intervals corresponding

to successive tenths of a spectral type in Figure 5. Almost without exception, these stars are classified as "l" or "vl"--i.e., these stars would probably have been classified a tenth of a type later if they had stronger metallic features. If the abundance classification for stars on the blue end of any spectral type interval are checked, they will often be "h" ("vh" at F7) or no classification is given. Occasionally a "vl" classification will also show up here but this may be the result of letting the photometry bias the spectral type assignment by 0.1 type too late. The "vl" stars are often classified 0.1 to 0.2 types too early (with respect to their color). The extreme "h" and "vh" stars may sometimes be classified 0.1 type too late. Most of the "l" and "h" stars are not affected by as much as 0.1 type by variations in abundance.

Metallic Line Strength in the A Stars

Melbourne (1960) has shown that the blanketing in stars later than F2 is due primarily to the metallic lines while for stars earlier than A5 it is due primarily to the lines of hydrogen. In the A5-F2 spectral region, the hydrogen lines gradually give way to the metallic lines-- the dominant source of blanketing depending on the metals to hydrogen ratio and the amount of microturbulence in the atmosphere of the star involved.

The late A through F spectral range is also a transition range for many other physical properties of the stars. Somewhere in the spectral region of the F stars, the transition between the convective cores of the higher mass stars and the radiative cores of the lower mass stars takes place. In this same spectral region the transition between stars with convective atmospheres (G type) and radiative atmospheres (A type) also occurs. Furthermore, Abt and Hunter (1962), confirming the earlier results of Struve, show that the average rotational velocity of the field stars decreases rapidly from the A stars to the F stars.

Stromgren (1963b) points out the discontinuity in the m_1 - (b-y) diagram between the distribution of the late A stars and the early F stars. The A_m stars, the A_p stars, and the δ SCT stars (Cameron 1966) appear to have unusually high m_1 values for their b-y color. Stromgren also shows that there is a reasonably good correlation between m_1 and V sin i using the data of Slettebak (1955). In order to verify this correlation and form a better idea of the distribution of V sin i in the m_1 - (b-y) diagram, all of the program stars for which V sin i could be found in the literature were plotted in the m_1 - (b-y) plane. These results confirmed the suspected inverse relation between m_1 and V sin i.

Stromgren (1963b) hypothesized that the stars of normal m_1 on the cool side of the discontinuity in the m_1 - (b-y) distribution may have convective atmospheres which would tend to keep them well mixed. The stars of normal m_1 on the hot side of the discontinuity are observed to be rapid rotators which may imply that they also have well mixed atmospheres (if atmospheric mixing can be rotationally induced). The stars of high m_1 on the hot side of the discontinuity (A_m stars) are known to be slow rotators and therefore could not have rotationally induced mixing taking place in their atmospheres. If contamination of an atmosphere as a consequence of circumstellar nuclear processes is necessary to produce a metallic line star, then Stromgren concludes that the picture described above will explain the fact that these contaminations are observed in a slow rotator (A_m star) whose effective temperature is above some threshold near F1 but not in cooler stars or in fast rotators (normal A stars) of the same effective temperature.

Kopylov, Belyakina and Vitrichenko (1963) found no sharp division between the normal stars of late A and early F and the metallic line stars. It has been known for some time (Roman, Morgan and Eggen 1948) that a reasonable correlation exists between the hydrogen line spectral type and the color index for A_m stars. Baschek and Oke (1965) conclude that most of the deviation in the U-B vs. B-V

diagram of the Am stars from the standard main sequence is a result of abnormal line absorption and not of effects such as low surface gravity.

Sargent (1964) sums up the situation by saying that most authors feel that the A_m stars are definitely dwarfs but have abnormally high microturbulent velocities in their atmospheres and spectroscopic surface gravities which are much too low. Although it has been disputed by some, Sargent, in accordance with most other recent authors, feels that there are abundance anomalies in the A_m stars. For the purpose of this discussion only two elements need be mentioned: iron is found in normal abundance (Sargent 1964) or possibly over-abundant (Conti 1965) while calcium is usually deficient by a factor of 4.

The metallic line stars were first defined as a group by Titus and Morgan (1940). Their spectroscopic peculiarities are further discussed by Roman et al. (1948). These authors list the following criteria for distinguishing A_m stars: (1) the K line is weak for the spectral type indicated by the metallic lines; (2) no possibility of explaining the spectrum in terms of one or two normal stars; (3) the spectrum is not explainable in terms of a shell source. Roman et al. add that their study of thirteen bright metallic line stars which have been defined as standards reveals the following facts which are important for classification purposes: (1) there is a

"spurious" absolute magnitude effect in the spectra such that stars may be classified either at an early type and a high luminosity or at a later type and a low luminosity; (2) the K line strengths ranged from A1 to A6; (3) the hydrogen line types range from A5 to F2; (4) the metallic line types range from A5 to F6.

With this background in mind, the group of A and early F stars which had previously been classified according to temperature and luminosity was studied for the purpose of finding spectral criteria correlated with the m_1 index. Since there is an inverse relation between m_1 and V sin i for these stars, criteria which are sensitive to apparent stellar rotation were sought out. Also, criteria which would give an indication of the size of the "spurious absolute magnitude effect" would be desirable.

In Chapter III, the selection requirements on Δc_1 as a function of b-y which the program stars had to meet were discussed. A number of A_m stars recognized in the literature were found to meet the selection requirements and were treated as any other program star. Since the Ca II K line strength is given very low weight in the temperature classification of the A stars, the fact that the K line is known to be weak for the temperature type was not expected to affect the spectral type assigned to the A_m stars.

As was mentioned earlier with respect to the A stars in Figure 5, those A stars whose spectral type strongly disagreed with their photoelectrically assigned types were removed from the discussion and not included in Figure 5. However, the majority of the A_m stars did show spectral types in reasonable agreement with photo-electrically assigned types and were included in Figure 5.

The greatest difficulty encountered in classifying the A_m stars is their well known spurious luminosity effect--i.e., the spectroscopic luminosity criteria usually indicated class III or IV (and occasionally higher) even though the photoelectric index Δc_1 indicated class IV-V or V. By making use of Tables 4 through 8 giving the luminosity criteria as a function of spectral type, it is possible to make mental compensations for the indicated luminosity in making a spectral type judgment for these stars. Among the typical strongly enhanced features which must be compensated for are $\lambda 3381$, $\lambda 3394$, $\lambda 3497$, and $\lambda 3586$. The convergence of the hydrogen lines of the Balmer series did not appear to indicate luminosities as high as these enhanced metallic features, but rather, indicated luminosities somewhere between those indicated by Δc_1 and the enhanced metallic features. In order to evaluate the effect of knowing the photoelectric indices at the time of classification, and to see if the A_m stars (included in

this program) actually formed a reasonable spectral type vs. b-y relation, the following tests were made.

A list of plate numbers of the metallic line stars included in Figure 5 was formed. Using Table 3 of spectral type vs. criteria and Tables 4 through 8 of luminosity class vs. criteria, each A_m spectrum was studied approximately five to ten minutes and a type was assigned. These types are plotted vs. b-y in Figure 10. No knowledge of the photometry or even the name of the star was involved and no comparisons with other spectra were made.

These crude types were improved by comparing other stars from Figure 5 (whose types were known) with the unknown A_m spectra. These comparisons usually encouraged small shifts in the spectral types assigned in the first step and yielded a final spectral type vs. b-y diagram shown in Figure 11. A few stars were omitted in this second step due to the low quality of the particular plates involved. One star was classified twice from two different plates without knowledge of the fact that it was the same star. The resulting classifications disagreed by 0.1 type and are both shown in Figure 11 at b-y = $0^{m}.217$.

These tests illustrate the value of the spectral type vs. criteria tables for assigning crude spectral types to a group of unclassified stars. The improvement in the accuracy of classification obtainable by using standards as comparisons is illustrated by a comparison of Figures 10
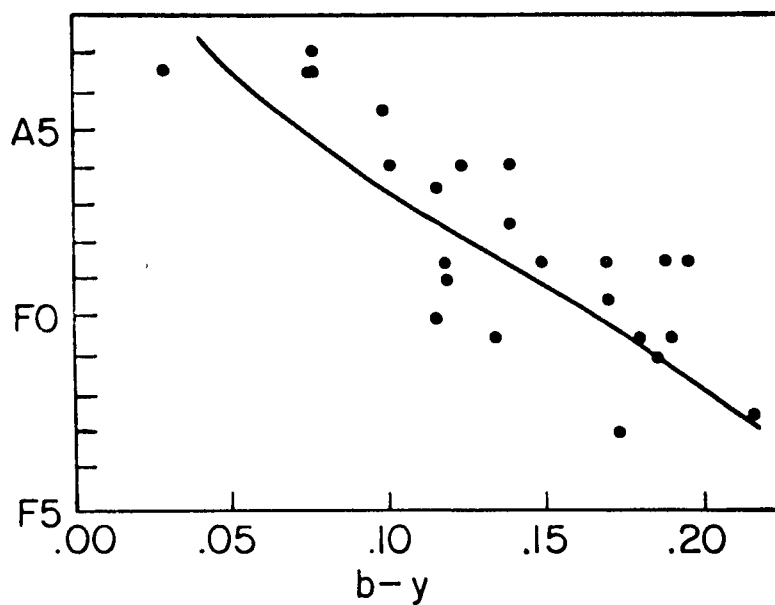
Figure 10.   Preliminary spectral types of A_m stars are plotted vs. b-y

     No comparisons with other spectra were made in these classifications.   The solid line is the spectral type vs. b-y relation for all of the program stars (Figure 5).   The classifications are systematically about 0.1 type early.
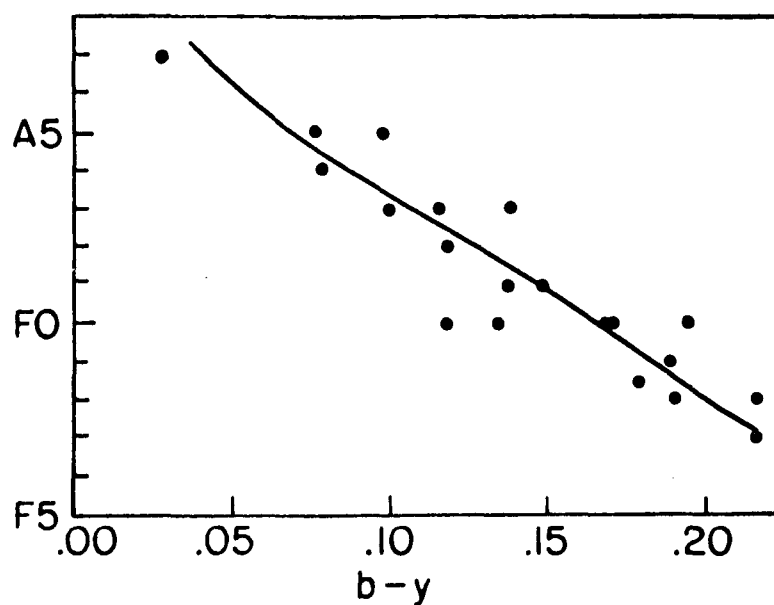
Figure 11.   Final spectral types of A_m stars are plotted
          vs. b-y

        The A_m spectra were compared with program stars
whose spectral types were known and were subsequently
assigned new types.   The solid line is the spectral type
vs. b-y relation for all of the program stars (cf. Figure
5).

and 11. Finally, it appears that this selected group of A_m stars does follow a spectral type vs. b-y relation very similar to that of the normal field stars if the ultraviolet criteria are utilized for classification.

Figure 12 shows the spectral type vs. b-y relation for the thirteen standard A_m stars classified by Roman et al. (1948). The spectral types were obtained from the metallic lines as outlined in the MKK atlas. Eight of the b-y values are observed while three others are converted B-V measures (Johnson et al. 1966) and two more are converted from the C_1 index given in the same paper (Roman et al. 1948). The probable errors in the converted B-V measures and the converted C_1 measures are estimated to be $0^m.02$ and $0^m.04$ respectively.

Three stars in the diagram were classified by these authors at F5 IV or F0 II-III. Both classifications are shown in Figure 12. The class IV classification places the stars on a spectral type vs. b-y relation approximately 0.3 spectral types later than the relation derived in this dissertation (Figure 5). However, if the high luminosity classification is used (as was done in this dissertation), the same three stars are observed to lie on the same spectral type vs. b-y relation as shown in Figures 5 and 11.

In conclusion, there appears to be a good possibility that the majority of the A_m stars will be
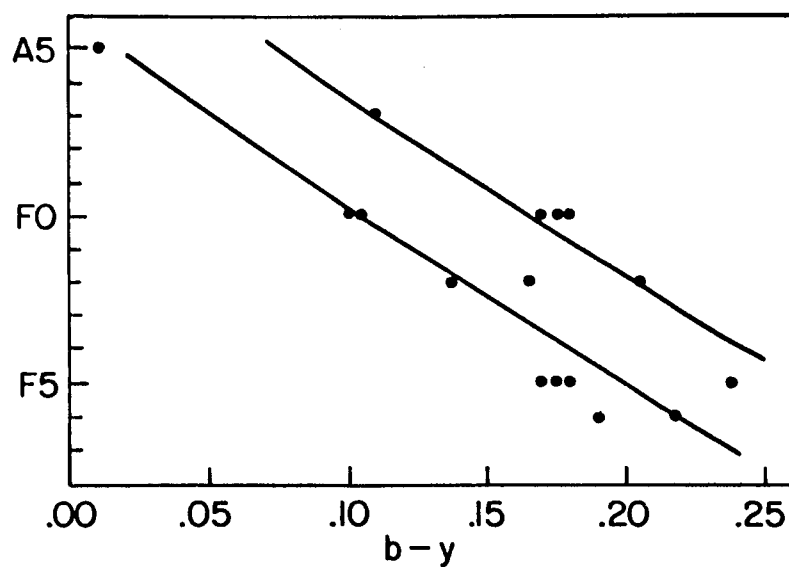
Figure 12.   Thirteen standard A_m stars classified on the
MKK system according to their metallic lines

        The upper curve is the spectral type vs. b-y
relation for the program stars (Figure 5).   The lower
curve is systematically 0.3 types later.   The three stars
nearest b-y = $0^m_.175$ are those given two possible classifi-
cations as discussed in the text.

classifiable on a three dimensional classification scheme as described herein. The significance of the luminosity classification remains open to question. These ideas may be checked and developed further when a complete set of grating spectra of the MK luminosity standards of types A and F become available.

Figure 8 gives the distribution of all program stars (with assigned spectral types) in the Δm_1 - (b-y) diagram. In this section, we are considering the stars of b-y $\langle$ $0^{m}.250$. An obvious feature in the diagram is the gap created by the lack of stars of large positive or negative Δm_1 between $0^{m}.225$ $\langle$ b-y $\langle$ $0^{m}.250$. This gap is not completely an observational selection effect. It is probably related to the small dispersion in the m_1 - (b-y) distribution first noted by Stromgren (1963b).

The sudden increase in the number of stars of high Δm_1 to the blue of b-y = $0^{m}.210$ is obvious. Most of these stars are A_m stars--but not all. Also, the general correlation between the apparent spectroscopic ultraviolet metallic line strength and the m_1 index is demonstrated. For program stars of b-y $\langle$ $0^{m}.020$, the lines were so weak that the third parameter could not be classified.

Abt (1966) noted that the difference in spectral types assigned from the appearance of the metallic features and the appearance of the Balmer lines is well correlated with m_1. Since one of the principal MK temperature

indicators in the late A and early F stars is the strength of the 4032A blend (Keenan 1963), and since the strength of this blend is well correlated with the strength of the ultraviolet metallic features, we would expect the above result--i.e., the strengthened metallic features lead to an MK metallic line type which is too late.

Abt further reports that the difference between the spectral types derived from the Balmer lines and the calcium lines is not correlated with m_1. He found that some of the A_m stars (classified in the literature) had nearly normal calcium line strengths and normal or strong metallic lines while others had weak calcium lines and normal or strong metallic lines. The remaining discussion of the A_m stars is concerned with these and related findings.

The Δm_1, Δc_1 diagram for b-y $< 0\overset{m}{.}250$ (Figure 13) reveals an interesting feature concerning the A_m stars. It has been noted by several authors (including Abt 1966) that the metallic line stars are not completely separated from the normal A stars in the m_1 - (b-y) diagram in the sense that some A_m stars have normal m_1 indices. This fact is also demonstrated in Figure 8. In the Δm_1, Δc_1 diagram however, it is apparent that nearly all of the metallic line stars (included in this program) of normal m_1 have low or negative Δc_1. Furthermore, it appears that with few exceptions among these selected program stars, all of the
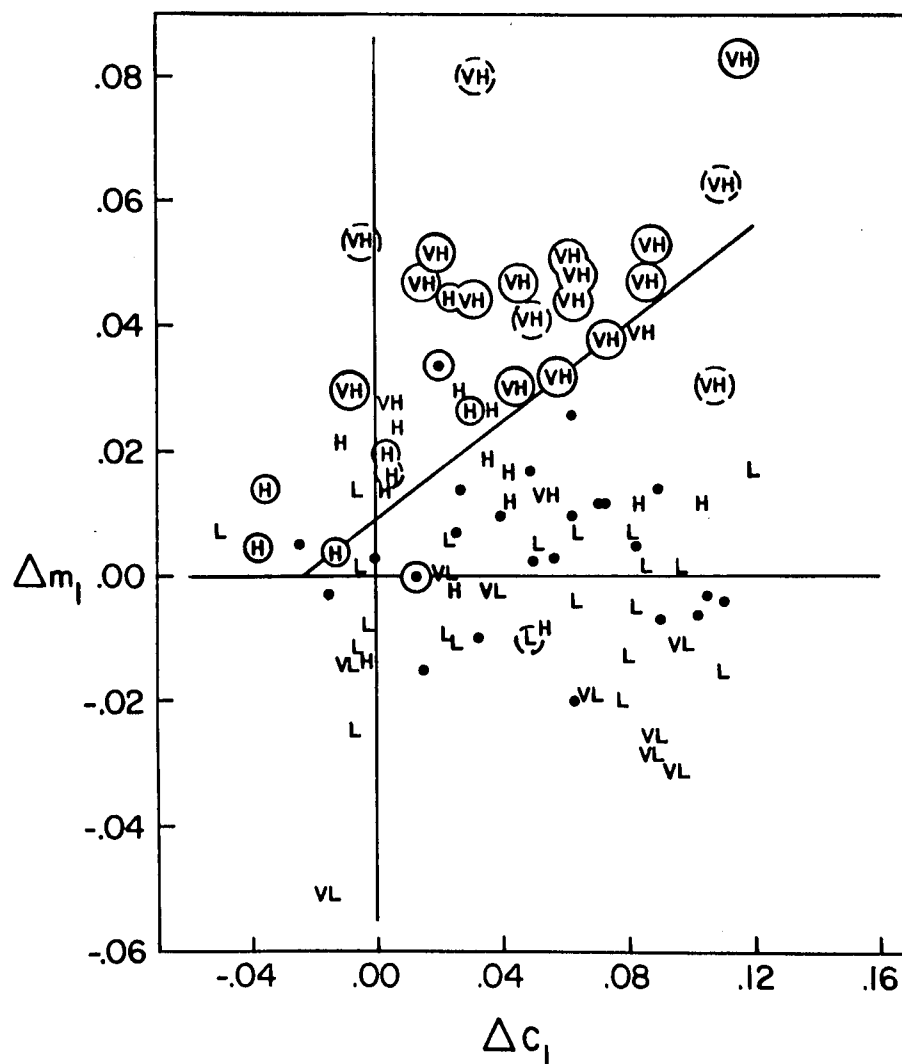
Figure 13. The Δm_1, Δc_1 diagram for all program stars of
b-y $<$ $0^m.250$

The solid circles are A_m stars either recognized as
such in the literature and this dissertation or identified
as A_m in this dissertation. The broken circles are stars
whose A_m classification in the literature might be dis-
puted.

A_m stars lie to the left and above the envelope shown in the diagram. The reality of this envelope is certainly open to question but the general increase of Δc_1 with Δm_1 for the A_m stars appears to be very real.

One obvious exception to the hypothetical envelope described above is the star ζ^1LYR at ($0^m.106$, $0^m.031$)--a Roman et al. (1948) standard star. It is classified at A6 and A7 in Figures 10 and 11 and as A7 IV vh in the classification for all program stars (Table 9 and Figure 5). Roman et al. give its K line spectral type as A4 which would indicate that it would be about 0.3 type weak for the star's spectral type as indicated by the ultraviolet criteria. Although this star's metallic lines are strong and the K line is sharp, the degree of the spurious luminosity effect in the ultraviolet is small and leads to a luminosity class IV classification which is in good agreement with $\Delta c_1 = 0^m.106$. In this author's opinion, the K line is not exceptionally weak for an A7 star. Therefore, ζ^1LYR represents a transition case between an A7 IV vh star and an extreme metallic line star.

Before discussing other transition type or marginal A_m stars of small Δm_1 and small or negative Δc_1 with their counterparts at large Δm_1 and $\Delta c_1 > 0^m.07$. The A_m stars of small Δm_1 and Δc_1 are characterized mainly by K lines which are too weak for their spectral type. The extremely weak K line stars appear to have greatly enhanced

features at 3381A and 3394A. Otherwise they have very
little spurious luminosity effect or enhancement of other
ultraviolet metallic features. The typical luminosity
class assigned is Va or IVb which is only slightly dis-
crepant with the typical Δc_1 values. The typical third
parameter classification is "h" rather than "vh" since the
general appearance of the ultraviolet metallic features is
only slightly stronger than the more normal stars of the
given spectral type.

The stars of high Δm_1 and $\Delta c_1 > 0^m\!.07$ are also
characterized by K lines which are too weak for their type.
These stars have very strong metallic features throughout
their spectrum and suffer much stronger enhancement of their
ultraviolet features leading to typical spectroscopic
(spurious ?) luminosity classifications of class III and
third parameter classifications of "vh." Although the
sample of stars is very small, the latter group of stars
appear to be mostly of types F2 or F3 while the former
group are mostly A7 or A8. There are also A_m stars at both
spectral types which fall in neither group.

There are several stars classified as "vh" which
lie in the section of the Δm_1, Δc_1 diagram filled mainly
with recognized A_m stars. These stars have spectroscopic
appearances which are very similar to the A_m stars but
their K line is not exceptionally weak for the spectral
type indicated by the ultraviolet criteria. Some of these

stars are identified in the literature as A_m stars due to their strong metallic lines and the fact that the spectral types assigned to them are too late.

An example of the latter case is 11 VIR. It was first classified as a metallic line star by Bidelman (1951) who placed its K line type at F0 and its metallic line type at F5 III. The classification given in this dissertation (Table 9) is F2-3 III vh. Since its K line is slightly stronger than H + H_ϵ, it is felt that this star should not be listed as A_m. Abt (1961) lists 11 VIR as one of the very rare A_m stars observed to have a constant radial velocity.

Stars having A_m classifications which are disputed and stars of marginal or transitional A_m characteristics are indicated in Figures 8 and 13. The disputed classifications may be gleaned from Table 9 by comparing the HR types with the revised MK types given in this dissertation.

A few of the program A_m stars have peculiar spectral features or photometry which merit individual discussion. ϵ SER is a well known A_m star with a K line too weak for its spectral type. However, its ultraviolet metallic features were not judged strong enough to merit an "h" classification. This star lies well inside the A_m envelope in the Δm_1, Δc_1 diagram (Figure 13). It is also one of the very few A_m stars found by Abt (1961) to have constant radial velocity.

Another well known A_m star is 88 TAU. It has three
measures on the <u>uvby</u> system which yield $\Delta m_1 = -0.010$. It
is the only A_m star included in the program with a negative
Δm_1. The single plate for this star is slightly out of
focus but the third parameter classification appears more
likely to be "l" than normal.

The A_m stars as a group are still a very compli-
cated problem. The use of <u>uvby</u> photometry along with a
three dimensional classification scheme utilizing the
ultraviolet criteria and including the MK luminosity
standards for types A and F promises to reveal a great
deal more information about these stars. Particular
emphasis should be placed on the problem of the spurious
luminosity effect and its relation to the distribution of
the A_m stars in the Δm_1, Δc_1 diagram. Also, the definition
of a metallic line star should be re-examined. Is a weak
K line for the spectral type a necessary condition for the
A_m designation or is it merely a sufficient condition. If
it is a necessary condition, then there appears to be a
number of late A and early F stars with very strong metallic
features and (apparently) spurious luminosity effects which
cannot be designated as A_m stars since their K line
strengths appear to be normal for their spectral types.

In marked contrast to Figure 9, the Δm_1, Δc_1
diagram for b-y $\langle$ $0^m.250$ (Figure 13) has very few stars in
the third quadrant. Whereas there exists a strong tendency

for the late F and early G stars to have low luminosities accompanying low abundances, the opposite is true for the late A and early F stars.

In the latter spectral range, the low m_1 index usually indicates a high rotational velocity. Due to the relatively low dispersion used for classification purposes, only stars of high projected rotational velocity would be expected to show rotational broadening effects in their lines. In practice, the most obvious indication of rapid rotation is the appearance of the two pairs of features at 3566-70A and 3581-86A. These features take on a distinctive "smeared out" appearance on plates of good quality and can be used to distinguish between very fast rotators (low m_1) and slow (apparent) rotators. Other indications of very high rotational velocities ($>$ 250 km/sec) can be seen in the appearance of the K line and the wings of the blended Balmer lines near the Balmer convergence.

As was the case with the late F stars, there appears to be a good correlation between the strength of the ultraviolet metallic lines and the m_1 index in the late A and early F stars. Since the suspected inverse m_1-V sin i relation appears to be valid for these stars, we would also expect an inverse relation between the apparent strength of the ultraviolet metallic lines and the star's projected rotational velocity.

Although the available rotational velocity data for these stars are limited, nearly all stars of V sin i $\langle$ 75 km/sec are listed as "vh" or "h." The converse is also true. However, the effect of observational selection on the stars chosen for rotational velocity measures strongly affects this conclusion since most of these slow rotators (but by no means all) are listed in the literature as A_m stars. At the other extreme, nearly all stars of V sin i $\rangle$ 175 km/sec are listed as "vl" or "l" and conversely. We conclude that with rare exceptions, there does appear to be an inverse correlation between the ultraviolet metallic line strength and a star's apparent rotational velocity. This does not require the conclusion that the weak lines are caused by high rotation but there probably exists some indirect physical link between the two phenomena.

One exception to the above rule may be ηLEP. It has a $\Delta m_1 = 0.000$ but its ultraviolet metallic lines appeared weak for the type assigned (F2 V vl). The Δm_1 value would lead one to expect a rotational velocity of 75-150 km/sec while the weak lines would lead one to expect the rotational velocity to be $\rangle$ 150 km/sec. Boyarchuk and Kopylov (1958) list V sin i = 0 km/sec for this star. Aside from possible problems with the plate material, it may be that this star is too cool (b-y = 0.218) and lies outside the region of the inverse m_1 - V sin i relation.

Another slight exception to the inverse relation is α CEP. Boyarchuk and Kopylov give its V sin i as 260 km/sec which would lead one to expect a "vl" classification and a large negative Δm_1. The measured Δm_1 for this star is $-0\overset{m}{.}007$ but the high rotational velocity figure is supported by the spectral appearance. However, the surprisingly strong ultraviolet features lead the classifier to place this star at A8 IV with a metallic line strength classification of "normal" for A8 stars. This star may possibly be over-abundant in the metals. HR 687 classified as F1 IVb is another example of this type.

The marked tendency for the "vl" stars of b-y $\langle$ $0\overset{m}{.}250$ to have large Δc_1 values (the original selection of all program A stars included the requirement that $\Delta c_1 \langle$ $0\overset{m}{.}110$) has been mentioned earlier (cf. Figure 13). Kraft and Wrubel (1965), in a study of the effect of rotation on the colors and magnitudes of A and F stars in the Hyades, showed that a star's Δc_1 index would vary with its V sin i. It is expected that a star's Δc_1 would increase by approximately $0\overset{m}{.}05$ to $0\overset{m}{.}10$ as V sin i is increased--the size of the effect being a function of the star's effective temperature and the mass-luminosity relation it follows, as well as its projected rotational velocity. Since m_1 is inversely correlated with V sin i, an application of Kraft's results to the Δm_1, Δc_1 diagram predicts an absence of points in the third quadrant with numerous points at low

Δm_1 and high Δc_1 in the fourth quadrant. Since weak ultraviolet lines are common in rapid rotators, we would expect the last mentioned points to be labeled "vl."

Sweet and Roy (1953) have shown that the apparent effective temperature and absolute magnitude of a rapidly rotating star will be a function of the aspect from which it is observed. More recent work in this area by Roxburgh and Strittmatter (1965) has demonstrated the theoretical affect of projected rotation on the colors of A stars.

A cursory study of the spectra of the "vl" stars of $c_1 \approx 0^{m}.09$ and the two "vl" stars with slightly negative Δc_1 values was made in order to see if any luminosity differences were apparent. The only obvious occupant of the third quadrant in Figure 13 is HR 8799. Although its color indicates type Fl, HR 8799 has been crudely classified as A7-9 V vl. The plate is of poor quality but the appearance of the convergence of the Balmer lines strongly suggests the luminosity class V or Vb designation for this star. The weak K line suggests $\approx$ A7 but the ratios of the ultraviolet features suggest a temperature either 0.3 types earlier or later. The quality of the plate, the peculiarity of the star, or some combination of the two might explain the latter difficulty. The only other occupant of the third quadrant classified as "vl" appeared to be a class V star but with weak lines. The "vl" stars of high

Δc_1 did show enhanced ultraviolet features indicative of higher luminosity and were classified accordingly.

We conclude that if we are actually observing the effects of projected rotation on the colors of these stars, then the slightly higher luminosity we observe in the spectra at classification dispersion is possibly due in part to the rotationally reduced surface gravity of the star in its equatorial regions.

One final point with regard to the Δm_1, Δc_1 diagram should be made. Sargent (1965), in a discussion of a possible relationship between the peculiar A stars and the λBOO stars, lists the following properties of the latter group. They have early A spectral types as judged from the hydrogen lines; they have either weak metallic lines for their spectral types or fall below the main sequence (according to trigonometric parallaxes) or both; they have low radial velocities. Sargent mentions later in the paper that his "four 'genuine' λBOO stars" have a mean V sin i of 131 km/sec. On the basis of these figures and the dis-cussion above, one would expect the λBOO stars to populate the third quadrant of Figure 13 or at least the lower Δc_1 portion of the fourth quadrant since their mean V sin i is probably much lower than for the "vl" stars discussed above. Since this study did not include any recognized λBOO stars, it is not possible to identify any of the stars marked "vl" as certain λBOO types. Further study of this problem is

especially desirable since the probable position of the λB00 stars in the Δm_1, Δc_1 diagram is apparently unique and would thus provide an excellent means for identifying these stars photoelectrically.

CHAPTER VI

EVALUATION OF THE REVISED MK TYPES

In the discussion of the spectral types listed in
Table 9 and the spectral type vs. b-y relation shown in
Figure 5, it was mentioned that the classifications were
made according to the spectral criteria but that the
photoelectric indices were known at the time of the classi-
fication. While it is admitted that photoelectric data
should not be allowed to influence the spectral classifica-
tion of a star, it must be emphasized that the purpose of
assigning the classifications given in Table 9 was to
define an improved spectral type vs. b-y relation which
could then be broken up into b-y intervals which would
correspond well with the assigned spectral types. Aside
from the improvement in the spectral type vs. b-y relation
itself, the new relation permits a more accurate prediction
of the revised MK spectral types through the use of uvby
photometry. The particular spectral types assigned to
individual stars (Table 9) are merely a by-product of the
project. These individual types may be biased slightly by
the photometry--but not intentionally. Most of them are
assigned on the basis of only one plate of reasonable
quality and are not compared with standards, but rather,

with other stars of similar photometry and similar spectral
type.

Even with these limitations, the increased accuracy
in the spectral classification of these stars obtained by
utilizing the ultraviolet criteria is very evident to the
classifier. To demonstrate this increased accuracy in the
temperature classification of the late F and early G stars,
17 MK standards of types F5 through G2 and luminosity
classes IV and V were selected from the plate material to
be used in the KPNO atlas. With only 17 plates, a list of
positions of the relevant spectra on these plates, and the
binocular microscope, these 17 stars were arranged in order
of increasing spectral type. The spectral type vs.
criteria Table 3 was used as a guide but the actual
sequence was arranged solely on the basis of comparisons
between the 17 stars.

Only five stars were found to be out of sequence
spectroscopically with their sequence in b-y. Three of
these five had negative $\Delta m_1 \langle -0^m\!\!.015$ and were classified in
the main program (Table 9) as "vl," "vl" and "l." The
other two stars had negative Δc_1 values of $-0^m\!\!.055$ and
$-0^m\!\!.017$. Even though eleven of these seventeen stars were
MK standards representing only three spectral types, the
power of the revised system is demonstrated in the fact
that the stars within a given MK type could be arranged in
order of b-y with quite high accuracy.

It will be shown in Chapter VII that the b-y index is affected by blanketing in the late F and early G stars. It is found that the Hβ index (Crawford et al. 1966) is a more accurate indicator of effective temperature for these stars. Crawford et al. give the β indices for fifteen of these seventeen stars from which it is possible to predict a b-y value corrected for blanketing according to the method described in Chapter VII.

A comparison of the blanketing corrected b-y sequence with the spectroscopic sequence reveals that only two of the original five out of sequence stars remain out of sequence while two others become out of sequence by $0^{m}_{.}007$ and $0^{m}_{.}012$ in corrected b-y. It would appear from these results that the accuracy obtainable from the spectral criteria approaches that of the b-y index in the late F and early G main sequence stars.

By using the program classifications (Table 9), five of these stars were selected as standards which the others were subsequently compared against. The sequence of seventeen stars was broken up into seven groups of one to four members representing types F6-G2 in the revised system. The spectral type of the stars assigned to each group was then compared with the spectral types assigned in the main program. Only one discrepancy of 0.1 spectral type occurred among all seventeen stars. Figure 14 gives the MK standard types vs. b-y relation for these seventeen
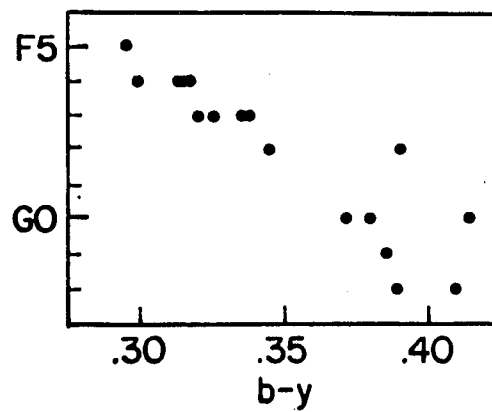
Figure 14. The MK standard type vs. b-y relation for 17 late F and early G stars
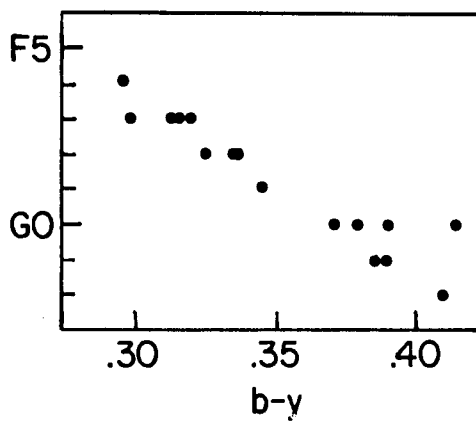

Figure 15. The same stars shown in Figure 14 are re-classified on the revised MK system with no photometric knowledge available at the time of classification

stars while Figure 15 gives the same relation using the revised types assigned in the above test.

The accuracy obtainable using the ultraviolet criteria will decrease as stars of greater effective temperature are considered due to the general weakening and decrease in number of criteria available. In order to demonstrate that the revised MK system removes the kink and fills the gap in the spectral type vs. b-y relation for the MK standards (Figure 3), the following test was carried out.

Twenty-seven program stars with spectra of reasonable plate quality and ranging in program types (Table 9) from A5 to F5 were selected for a test similar to the one described above. A list of plate numbers, the plates, Tables 3 and 4 through 8, and the binocular microscope were the only equipment used in the test. No A_m stars were included.

The twenty-seven stars were sorted out into "early," "middle," and "late" groups depending on the general appearance of the spectra. About one minute per plate was required for this judgment. Next, the above mentioned tables of spectral type and luminosity class vs. criteria were used to assign preliminary spectroscopic types to the twenty-seven stars in the same fashion as for the A_m stars in Figure 10. Before proceeding to the final classifications which would be made by comparing these stars with

standards (or other stars of similar b-y and spectral appearance and with known types), the b-y values for each star were looked up and a preliminary spectral type vs. b-y diagram was constructed (Figure 16).

The root mean square error between the preliminary types assigned in this test and the revised MK types given in Table 9 was calculated to be 0.12 spectral types. A systematic error (Figure 16) appears throughout the entire b-y range in that these preliminary classifications tended to be about 0.1 type earlier than the photoelectric types. The accuracy obtained in this test compares very favorably with the accuracy claimed for the MK system. Morgan (1966b) states that the "boxes" into which the MK system is divided are chosen such that classifiers using spectrograms of the quality and dispersion used at Yerkes Observatory would repeatedly classify different spectra of the same star to the same "box" with a mean error of about one "box" in both temperature and luminosity coordinates. Since the temperature scale of the MK standards is divided up into boxes centered on A5, A7, F0, F2, F3, and F5, a root mean square error of 0.12 spectral types in these preliminary classifications (no standards used for comparison) demonstrates already a significant improvement over the MK system.

Furthermore, it is clear from Figure 16 that the gap in the spectral type vs. b-y relation for the MK
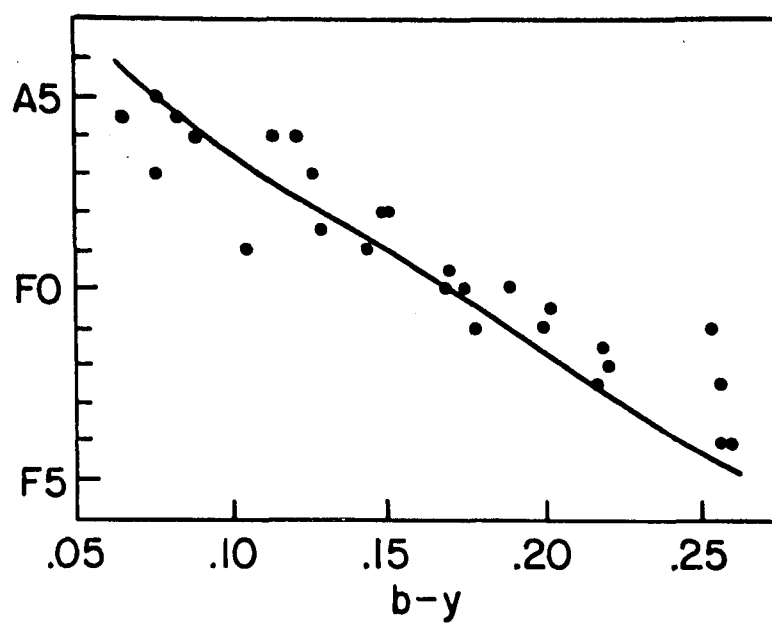
Figure 16.   The preliminary spectral type vs. b-y relation
             for 27 late A and early F dwarfs

standards (Figure 3) has been filled and the kink at F0 has been greatly reduced. The systematic error in the types would be reduced if standards were used in the classification of these stars. This in turn would reduce the root mean square error in the temperature classification below its already quite acceptable value. Since the preliminary spectral types assigned in this test proved the points which the test was designed to check, it was felt that the final classification with standards was not necessary.

It has been demonstrated in this chapter that the revised spectral type vs. b-y relation (Figure 5), the intervals of b-y associated with each spectral type (Table 2), and the revised MK classifications for A and F main sequence stars constitute a substantial gain in the accuracy of spectral classification by means of photoelectric b-y indices or by visual appearances of stellar spectra.

CHAPTER VII

MICROTURBULENCE VS. METAL ABUNDANCE:
AN OBSERVATIONAL TEST

In Chapter V, the discussion of the Δm_1, Δc_1 diagram for b-y $>$ $0^m_.250$ (Figure 9) emphasized the observation that most of the stars classified "vl" (very weak ultraviolet metallic features) also had large negative Δm_1 values and small or negative Δc_1 values. If the b-y index is sensitive to blanketing in this spectral range, then it would be expected that the observed colors of the "vl" stars would be too blue for their effective temperature. This in turn would cause them to appear below the Zero Age Main Sequence in the c_1^o - (b-y) diagram (Stromgren 1963a), whereas in reality they are only moved to the blue in the same diagram by the effect of decreased line blanketing (neglecting the effects of blanketing on c_1).

Conti and Deutsch (1967) have given the sensitivity of the Stromgren indices to microturbulent blanketing in the form $\delta m_1/\delta[V]$ and $\delta(b-y)/\delta[V]$--where $[V]$ is a parameter incorporating the velocity of microturbulence and the partial derivatives are from their (1966) formalism. A ratio of the sensitivities of the two indices to changes in microturbulence of 6.4 is obtained by dividing their tabulated numerical value of the first quantity by that of

the latter. Similarly, $\delta m_1/\delta[\text{Fe/H}]$ divided by $\delta(b-y)/\delta[\text{Fe/H}]$ is the ratio of the sensitivities of the Stromgren indices to a change in metallic abundance. Its value is 1.6.

Since blanketing did appear to be affecting the b-y colors of these stars, it seemed reasonable to make a statistical analysis of the uvby photoelectric data in order to determine quantities directly comparable with these numerical values for the sensitivities of the Stromgren indices m_1 and b-y to changes in abundance and microturbulence.

For the purpose of making an observational test, the partial derivatives may be replaced by small differential changes in the indices due to small differential changes in either microturbulence or abundance while holding the effective temperature constant. Specifically, if the observed ratio of the deviation in m_1 to the deviation in b-y $(\Delta m_1/\Delta(b-y))$ from the values of these indices in a normal solar type dwarf of the same effective temperature were found to be 1.6 rather than 6.4, we would conclude that the cause of the deviations is an abundance difference rather than a difference in microturbulent velocities.

The β index described by Crawford and Mander (1966) has been found in a preliminary investigation by the author to be a relatively accurate indicator of effective

temperature for the late F dwarfs. A rough estimate of the per cent contribution made to the equivalent width of $H\beta$ by the core of the line was made by planimetering the $H\beta$ profiles of αCMI at MK type F5 IV (Hiltner and Williams 1946) and the Sun (Minnaert, Mulders, and Houtgast 1940). In both cases, the core of $H\beta$ appeared to account for 20 to 25 per cent of the equivalent width of the line.

Conti and Deutsch (1966) found that all variations in the m_1 index at b-y = $0^m.400$ could be explained by variations in [V] between -0.1 $\langle$ [V] $\langle$ +0.2. Conti and Deutsch (1967) show that the m_1 index is twice as sensitive to changes in [V] as they originally reported. Since the above range in [V] corresponds to microturbulent velocities from 0.8 to 1.6 times that of the center of the solar disk, we conclude that changes in microturbulent velocity from 0.9 to 1.3 times the solar value would account for the dispersion in m_1. If it is assumed that the equivalent width of the core of $H\beta$ varies directly with the micro-turbulent velocity, then the total range of variation in the equivalent width of $H\beta$ due to variations in micro-turbulence cannot be more than ten per cent.

On the other hand, the continuum measured by the wide band filter of the β index will in effect be depressed by increased microturbulence. This is due to the large number of metallic lines near $H\beta$ in the late F stars and their great sensitivity to changes in microturbulence.

This effect will tend to cancel the effect of increased microturbulence on the core and may in fact be the dominating influence on the index.

If the metals are the principal contributors of free electrons at the atmospheric depths where the metallic lines are formed, then their strength will be independent of the metallic abundances (assuming H^- to be the principal source of opacity). If the metals are also the chief source of electrons at the depths where H_β is formed, then the strength of H_β would be expected to decrease slightly with increasing metallic abundances. In this case, the β index would decrease with increased metallic abundances. Wallerstein (1967) has suggested that the H_β line is probably formed at depths sufficiently deep in the atmosphere for hydrogen to be the principal source of electrons. If this is the case, then the β index would be completely independent of the metallic abundances.

Crawford et al. (1966) have published β indices for the 1217 A and F type stars measured on the uvby system by Stromgren and Perry (1967). Using a mean representation of their β - (b-y) relation (Crawford et al. 1966), it is possible to determine the color a dwarf of a given effective temperature and abnormal abundance would have had if it were of normal metallic abundance. The difference between this color and the observed color is a measure of the

change in color index due to a change in metallic abundances at a fixed effective temperature.

The change in the m_1 index due to a change in abundance for a star of fixed effective temperature is found by subtracting the m_1 value for a normal star of that effective temperature from the observed m_1 value. A mean relation between m_1 and b-y is required for this calculation. This mean relation is shown in Figure 2 as described in Chapter III. The same relation for the Hyades (Crawford and Perry 1966) is shown approximately $0\overset{m}{.}015$ above the mean relation for normal dwarfs.

A sample of 72 late F dwarfs of abnormally high m_1 was selected for a statistical analysis of the ratio of the change in m_1 to the change in b-y. A positive value of Δ(b-y) was found for most of these unreddened stars by using the β - (b-y) relation in the usual fashion for determining color excesses. Values of Δm_1 (positive) for each star were obtained by subtracting the m_1 value given by the mean relation in Figure 2 (normal star) at the normal color index (as indicated by the β index) from the measured m_1 for each star.

The absolute frequency function of the ratio

$$R = \Delta m_1 / \Delta(b-y) \tag{1}$$

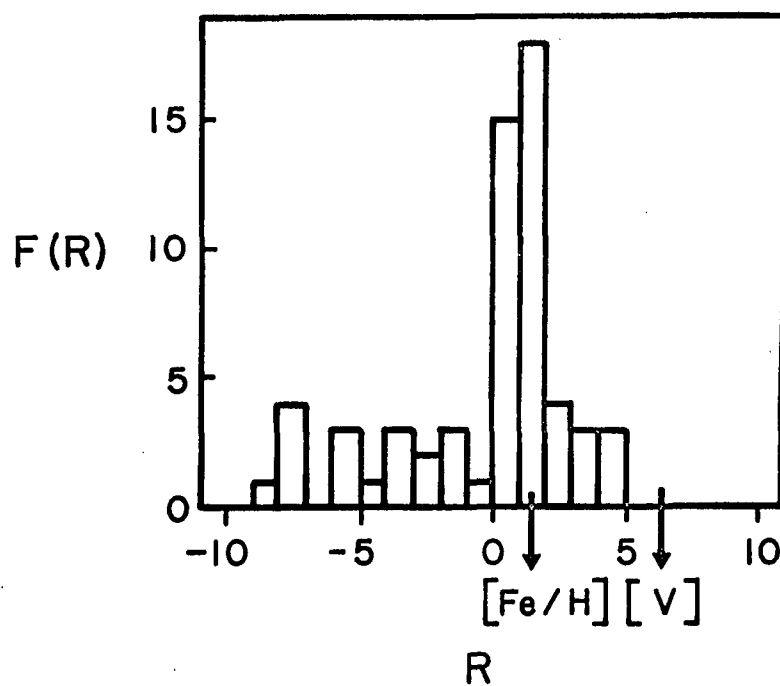is given in Figure 17. The high frequency of occurrence of values of $1 < R < 2$ as compared with $6 < R < 7$ strongly

Figure 17.   The absolute frequency function of R (cf.
eq. 1) for 72 late F dwarfs of abnormally high
m_1

Five of these stars gave R $\langle$ -10 while six others
gave R $\rangle$ +10.

indicates that the effect on the m_1 index of differences in microturbulence among these stars is completely dominated by the effect of variations in the metallic abundances.

A second test was carried out using a sample of 61 late F dwarfs of abnormally low m_1. Most of these were found to have negative color excesses--i.e., their measured colors are too blue for their respective effective temperatures. The absolute frequency function of R for this group is given in Figure 18. The high frequency of occurrence of $1 < R < 2$ gives further evidence of the dominance of abundance variations over variations in microturbulent velocities as the chief source of variations in m_1 at a fixed effective temperature.

The effect of interstellar reddening on these results would be to destroy the peak at $1 < R < 2$ in Figure 18 while shifting the peak in Figure 17 to lower values of R. The effect of abundance blanketing on the β index would be to destroy the peaks in both distributions. Hence, neither effect can alter the frequency distribution of R toward the [V] value.

The numerous but statistically insignificant negative values of R in Figures 17 and 18 are probably caused by scatter in the photometry. The distribution of negative values of R is found to be very sensitive to the mean β - (b-y) relation used. For example, if the mean relation were drawn redward by $0^{m}.008$, a large number of the
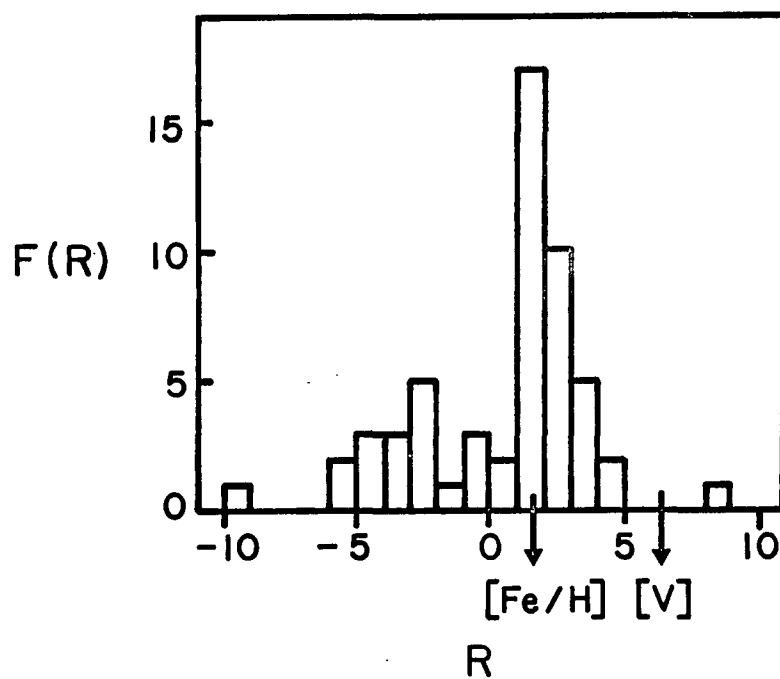
Figure 18.   The absolute frequency function of R (cf.
             eq. 1) for 61 late F dwarfs of abnormally low
             m_1

      Four of these stars gave R $\langle$ -10 while two others
gave R $\rangle$ +10.

negative ratios (R) in the low m_1 sample would become positive and make the distribution even more convincing. However, this same shift would make a number of positive values of R in the high m_1 diagram become negative such that the peak at $1 < R < 2$ would disappear. Since the distributions of the negative values of R in Figures 17 and 18 are similar we feel that the β - (b-y) relation used in this dissertation adequately represents the mean of the distribution given in Figure 2 of Crawford et al. (1966).

Further support for this conclusion and for the assumption that the β index is a blanketing free indicator of effective temperature, and further evidence that the m_1 index actually is a measure of differences in abundance is given by the Hyades photometry of Crawford and Perry (1966). Since the Hyades have abnormally high metallic abundances by $0^{m}.015$ (Figure 2), the above interpretation leads one to expect that the Hyades β - (b-y) relation for late F dwarfs will lie approximately $0^{m}.009$ to the red (Δ(b-y) = $0^{m}.015$/R = $0^{m}.009$ for R = 1.6) of the same relation for normal dwarfs. A comparison of the mean relation used in this dissertation with that of the Hyades does reveal a shift of $0.008 \pm .002$ magnitudes.

Wallerstein (1962) has obtained spectroscopically the variation of [V] with [Fe/H] for G dwarfs. A linear least squares fit through the points in his Figure 8 yields the relation: [Fe/H] = 7.6 [V]. Table 1 of Conti and

Deutsch (1967) indicates that the m_1 index is 1.7 times as sensitive to changes in $[V]$ as to changes in $[Fe/H]$. Using Wallerstein's spectroscopically determined relation between $[Fe/H]$ and $[V]$, we conclude that the contribution to the total observed change in m_1 due to a change in $[Fe/H]$ is 4.5 times the contribution due to a change in $[V]$.

From the above consideration of the photoelectric uvby and Hβ data, the high dispersion spectroscopic data of Wallerstein, and the theoretical line blocking calculations of Conti and Deutsch, it is concluded that the b-y index is affected by abundance blanketing in the late F dwarfs; that the β index is a more accurate indicator of effective temperature than b-y; and that the m_1 index primarily is a measure of the changes in the metallic abundances of these stars.

CHAPTER VIII

CONCLUSION

The two dimensional system of spectral classification introduced by Morgan, Keenan, and Kellman (1943) has since proved to be one of the most accurate and widely used methods of classification by visual inspection. In subsequent years the system has been improved in accuracy with some attempt toward including a third dimension.

Improvements in the MKK system and the later MK system are generally of two types: (1) new criteria are defined or old criteria are re-defined at various spectral types such that an improved spectral type vs. color relation or luminosity class vs. absolute magnitude relation will result; (2) new standards representing these improved criteria are named while old standards which do not fit the criteria are discarded.

The A and F stars have always been difficult to classify due to: (1) the shortage of strong metallic features suitable for classification purposes; (2) the fact that the strength of the metallic features generally increases with temperature and yet may vary considerably at a given temperature; (3) the numerous groups of stars

classified as A_m, A_p, and subdwarf which apparently do not fit into the classification scheme for normal stars.

Due to the shortage of criteria available, there are very few main sequence MK standards defined in the A5 to F5 spectral region. The few standards available at F0 and F2 appear to deviate from a smooth relation with b-y color. The shortage of criteria also makes it difficult to classify the same star to the same type consistently when successive plates are examined.

The new Steward Observatory grating-Schmidt type spectrograph yields classification spectra with usable features extending from $H\beta$ to below 3300A. The numerous features in the 3300A-3900A region have proven very suitable for the three dimensional classification of stars of type A5 and later. These features have been carefully examined and new criteria for each 0.1 spectral type interval have been defined. The new temperature criteria are given in Table 3. The new luminosity criteria are given in Tables 4 through 8 for each 0.5 spectral type. The criteria describing the strength of the metallic lines are discussed in Chapter V.

The method of using the Stromgren uvby indices to define a sequence of stars varying only in effective temperature (Chapter III) proved a very successful source of material for the study of spectroscopic temperature criteria. The spectral sequence was defined along an

m_1^o - (b-y) relation felt to best represent the most
commonly encountered field dwarfs in the solar neighbor-
hood. This relation differs significantly from that of the
Hyades main sequence and the Stromgren equivalent of the
Zero Age Main Sequence. However, it represents the dis-
tribution of the MK standards on the m_1 - (b-y) diagram
very well.

The luminosity criteria obtained by studying a
number of the MK luminosity standards appeared to be very
sensitive to changes in surface gravity. This increased
sensitivity affords an improved accuracy in the assignment
of a luminosity class to an A or F star and should be used
to further improve the luminosity class vs. absolute
magnitude relation when more accurate absolute magnitudes
become available. The tremendous differences in the
spectral appearances of the highest luminosity stars at a
given effective temperature indicates the need for
defining more luminosity sub-groups.

The increased accuracy obtainable using the ultra-
violet criteria for a two dimensional classification of A
and F stars permitted a more thorough study of the third
dimension than was previously possible. Criteria which
appear to be sensitive to metallic abundances in the F
stars and well correlated with apparent rotational
velocities and possibly microturbulence in the A stars are
described in Chapter V. When it was felt that the three

dimensional classification scheme was sufficiently well defined, 162 local field dwarf A and F stars were classified (Table 9) using the ultraviolet criteria. The new spectral type vs. b-y relation for these stars (Figure 5) is a smooth and continuous curve. For the late A through early G stars, this diagram is used to define b-y intervals corresponding to each 0.1 spectral type. These intervals permit the accurate assignment of spectral types for normal stars from a knowledge of the b-y index.

The given temperature, luminosity, and metallic line strength criteria are not completely independent of each other. However, they represent an attempt to minimize the dependences such that stars of a certain effective temperature and stronger than normal metallic lines will not be classified more than 0.1 type too late while stars with weak metallic lines will not be classified more than 0.1 to 0.3 types too early.

In an attempt to classify F5-G2 stars from their spectral appearances only, it is shown that accuracies of better than 0.1 type are attainable and in fact that the accuracy obtained in the test appears to be comparable to that of the b-y index. The A5-F5 spectral type vs. b-y relation is confirmed by classifying 27 stars in this range using only the spectral appearances and the spectral type vs. criteria tables.

The combined photometric-spectroscopic study of the F stars reveals that the majority of the dwarfs with very weak metallic line strengths also have c_1 values which indicate that they lie on or below the ZAMS relation of Stromgren (1963a). The value of the Δm_1, Δc_1 diagram as a method of studying dwarfs of abnormal luminosity and metallic line strength for a narrow temperature range is well demonstrated here.

The A and early F stars of very weak metallic line strength were found to have luminosities well above the ZAMS relation and tending toward the high luminosity selection limit for the program stars. These stars are mostly (if not all) rapid rotators and the effect could be that of a rotationally reduced effective surface gravity near their equatorial regions. It appears likely however, that the λB00 type stars will be found to have lower luminosities and will therefore occupy a unique portion of the Δm_1, Δc_1 diagram. More grating spectra of suggested (Sargent 1965) λB00 type stars and stars whose photometry suggests this type should be obtained in order to verify this hypothesis.

The highly selected (cf. Chapter III) group of metallic line stars included in the program were found to fall on a b-y vs. spectral type relation very similar to that of the normal A and early F stars. The greatest problem encountered in their classification is the so called

"spurious luminosity effect." The grating spectra of more MK luminosity standards and more A_m stars of higher c_1 are needed to further study this effect. Since the convergence of the Balmer series doesn't appear to indicate the high luminosities predicted by the enhanced metallic features, it may be possible to estimate the size of the spurious luminosity effect from the appearance of the Balmer convergence.

It is well known that the Stromgren m_1 index does not separate out all known metallic line stars from the normal A stars. The Δm_1, Δc_1 diagram for the A stars reveals that the A_m stars having normal m_1 values tend to have lower than normal c_1 values. There is a strong suggestion of an envelope in the diagram which separates the majority of the A_m stars from the normal A stars. The question of whether the weakness of the Ca II K line is necessary for assigning a classification of A_m is brought up since a number of the stars within the A_m envelope have all of the A_m features except that the K line does not appear to be weak for the ultraviolet type.

The apparent concentration of the F stars having very weak metallic lines into the low m_1, low c_1 region of the Δm_1, Δc_1 diagram suggests that the b-y index might be affected by blanketing in these stars. A statistical analysis of the <u>uvby</u> and $H\beta$ data available in the literature was made in order to determine the relative change in

the m_1 index for a given change in the blanketing. The most common value of the ratio of the changes in the two indices when compared with the numerical results of Conti and Deutsch (1967) shows that the b-y index is affected by blanketing and that the m_1 index is principally a measure of the metals to hydrogen ratio in these stars.

The principal contribution of this dissertation is the exploration of the 3300A-3900A region of the spectrum as a source of features which hold great promise for the spectroscopic classification of stars of nearly all effective temperatures. The spectral type and luminosity class vs. criteria tables may be used by future investigators who desire to set up their own classification schemes. Since a final list of standards is not given, future investigations might be concentrated toward the stars listed in Table 9 at various representative types for the purpose of eventually defining such a list. The perfection of a revised MK system for the A and F stars is a difficult task which will require years of development. However, the desirability of using the ultraviolet criteria for this task has been amply demonstrated and the first steps of the revision have been completed.

APPENDIX A

PHOTOELECTRIC OBSERVATIONS AND REDUCTION

The majority of the uvby photoelectric data utilized in this dissertation were obtained from a preprint of the Stromgren-Perry catalogue. Supplementary photometric measures were required in order to obtain accurate uvby measures for all of the MK standards and other program stars mentioned in Chapter II.

The Steward Observatory Photoelectric Photometer is of the type described by Johnson (1962). It is mounted on an offset guider (also described by Johnson) which is attached to the f/5 Newtonian focus of the 36 inch S. O. reflector. The photometer, offset guider, electronics and read-out systems were all integrated into a working unit by Dr. Walter S. Fitch.

The "v," "b," and "y" interference filters were obtained from Spectrolab, Los Angeles, California. The "u" filter is a compound Schott glass filter consisting of 8 mm. of UG 11 and 1 mm. of WG 3 cemented together with Canada balsam. These were obtained from the U. S. distributors of the Fish-Schurman Corporation, New Rochelle, New York. The filter specifications approximate those of the original Stromgren (1963a) system (cf. Crawford 1966).

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All of the photoelectric observations were made in the first half of 1966. All measures were made with 15 second integrations usually in the order: y, b, v, u. Sky measures were made in the opposite order, either immediately after the star measures or before and after depending on the brightness of the star relative to the moon-lit sky. It was found that sky measures were not necessary for every star measure due to a combination of reasons. First, the reduction program is designed such that a sky measure is interpolated in time for each color at the time of the stellar observation if a sky measure has been made after the star measure. If not, then the latest available sky measure in that color will be subtracted from the star measure. In this fashion all star measures are reduced with at least a first approximation to the sky brightness. Since all of the stars are brighter than seventh magnitude, the sky measure is usually small compared to the star measure. Finally, all of the computed results are given as color indexes or color differences. Therefore, if the sky measures used in the reduction are too faint--i.e., the sky was exceptionally bright at the time of a given stellar measurement due to a nearby moon or perhaps twilight--both measures necessary to form the color index will be a bit too bright but the error will tend to disappear when the difference is taken. Of course, the ultimate justification for the observational technique

described above is the final internal accuracy obtained from the data.

After each 15 second integration, the Mountain Standard Time of the observation, the type and color of the observation, the star number, the gain, and the size of the measure are punched onto cards for later reduction on the University of Arizona's IBM 7072 computer.

In order to transform the Steward Observatory (S.O.) observations for a given night to the system of the Stromgren-Perry catalogue and to obtain the extinction coefficients for that night, a system of standard stars was set up. All stars in the catalogue having six or more observations by Stromgren and Perry were defined as standards. These standards were observed throughout the night at both high and low air mass. Some care was taken to observe both extremes of color index and metal index.

The mean extinction coefficients used at Kitt Peak National Observatory are given by Crawford (1966) as $0^m.068$, $0^m.053$, and $0^m.187$ for b-y, m_1 and c_1. These values may be compared with the mean values for five nights at Steward Observatory of $0^m.055$, $0^m.057$, and $0^m.193$ for the same indices.

Table 11 gives the number of standards used in the final reduction, the zero point, the slope, and the extinction terms along with the probable errors for each night's observations. All of the transformation and extinction

Table 11

Transformation and Extinction Coefficients

Date	#OBS	Zero-point	Slope	Extinction
b-y				
3-31-66	15	$0.778 \pm .006$	$1.034 \pm .013$	$0.053 \pm .002$
4-1-66	15	$0.781 \mp .009$	$1.030 \mp .030$	$0.061 \mp .003$
5-11-66	19	$0.756 \mp .009$	$0.981 \mp .024$	$0.050 \mp .003$
5-12-66	20	$0.791 \mp .009$	$1.044 \mp .025$	$0.051 \mp .004$
5-24-66	28	$0.779 \mp .005$	$1.008 \mp .012$	$0.060 \mp .002$
m_1				
3-31-66	15	$-0.162 \pm .025$	$1.152 \pm .149$	$0.064 \pm .006$
4-1-66	14	$-0.084 \mp .024$	$0.883 \mp .134$	$0.056 \mp .003$
5-11-66	19	$-0.097 \mp .030$	$0.961 \mp .148$	$0.054 \mp .005$
5-12-66	20	$-0.062 \mp .016$	$0.837 \mp .086$	$0.043 \mp .004$
5-24-66	28	$-0.226 \mp .025$	$1.411 \mp .117$	$0.066 \mp .005$
c_1				
3-31-66	15	$-0.563 \pm .012$	$1.058 \pm .015$	$0.220 \pm .006$
4-1-66	14	$-0.537 \mp .023$	$1.007 \mp .029$	$0.171 \mp .006$
5-11-66	17	$-0.526 \mp .025$	$0.996 \mp .036$	$0.187 \mp .009$
5-12-66	20	$-0.592 \mp .012$	$1.032 \mp .013$	$0.191 \mp .004$
5-24-66	28	$-0.626 \mp .011$	$1.065 \mp .014$	$0.198 \mp .006$

coefficients for each night are derived by a least squares fitting procedure. If, in the fitting, a residual greater than $0\overset{m}{.}05$ arises, the measure is disregarded and a new least squares fit is made. "# OBS" is the actual number of observations retained in the final fit for a given index.

It should also be noted in Table 11 that the values of the slope found for all three indices are approximately unity. This indicates that the S.O. filter system is a good approximation to the Stromgren system. Also, it leads one to expect that the linear equations used for the transformation to the Stromgren system are probably adequate.

The average transformed values of the S.O. measures of the standard stars for each of the five nights were listed in three tables for b-y, m_1, and c_1. A study of these (unpublished) tables reveals no significant systematic error in the measured indices with time of observation or the magnitude of the particular index (e.g., color, degree of metallicity, etc.). The residuals for the average measured indices for each of the standard stars over all five nights are plotted vs. the catalogue values in Figures 19, 20, and 21. If the linear transformation equations were insufficient, one would expect to find a systematic dependence of the residuals on the standard values. It is found that the size of the residuals increases from b-y to m_1 to c_1. This is probably due to
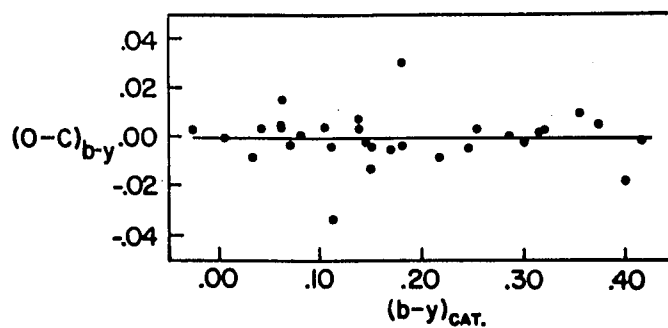
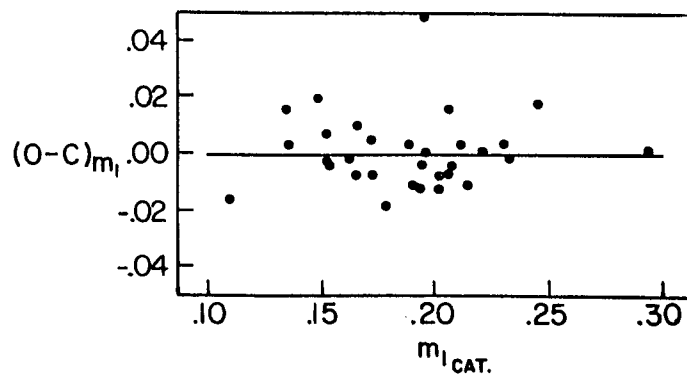Figure 19. The b-y residuals are plotted vs. the catalogue
b-y values

Figure 20. The m_1 residuals are plotted vs. the catalogue
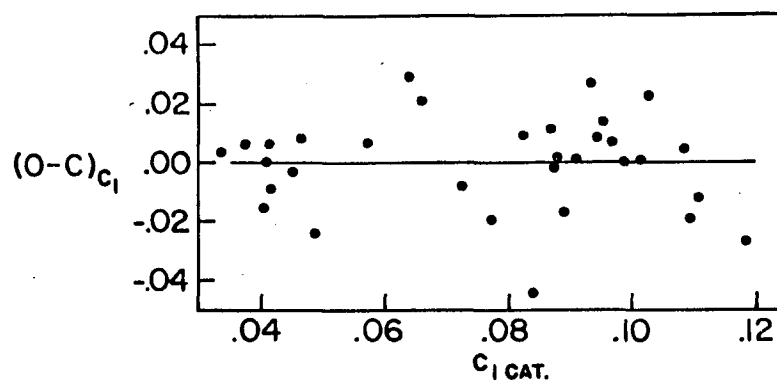m_1 values

Figure 21. The c_1 residuals are plotted vs. the catalogue — c_1 values
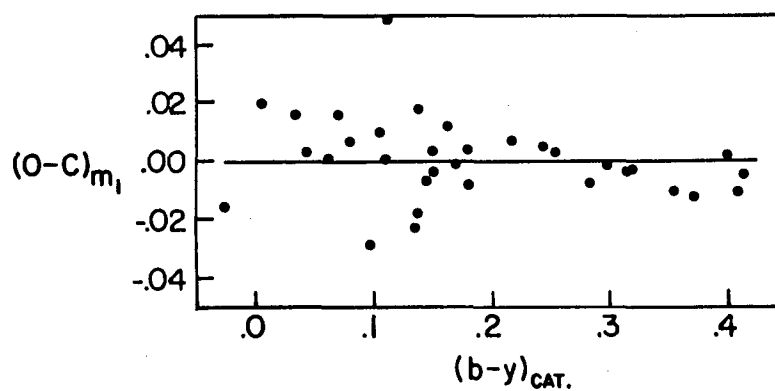

Figure 22. The m_1 residuals for all five nights are plotted vs. b-y

There may be a slight dependence on color.

the increased use of the "v" and especially the "u" filter in the latter indices. Since the mean extinction coefficient for the c_1 index is approximately three times that of the m_1 and b-y indices, one would expect higher residuals.

Figures 22 and 23 are plots of the residuals in m_1 and c_1 vs. b-y. A systematic trend in the residuals with color would indicate a need for a color dependent term in the transformation equations. (Crawford (1966) reports that a color dependent extinction term was found unnecessary in the original system.) Figure 22 does reveal a slight dependence of the m_1 residuals on b-y. Although the scatter in the residuals appears to be larger than the extremes of the systematic variation with color, the m_1 residuals between $0^m.00 < $ b-y $ < 0^m.20$ are usually positive while those between $0^m.20 < $ b-y $ < 0^m.40$ are usually negative.

A glance at Table 11 reveals that the slope and zero point for the m_1 index on May 24, 1966 are substantially larger in an absolute sense than on the other four nights. Figure 24 is the same as Figure 22 except that the May 24 observations are not included. It is doubtful whether any dependence of the m_1 residuals on color remains in this diagram but further observations on the S.O. uvby system should be made before this question can be settled.

Both Figures 22 and 23 show a decreasing dispersion in the m_1 and c_1 residuals with increasing b-y. This is
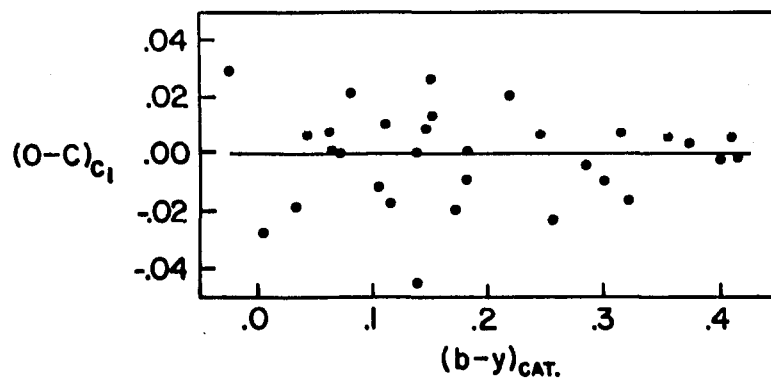
Figure 23.   The c_1 residuals for all five nights are plotted vs. b-y
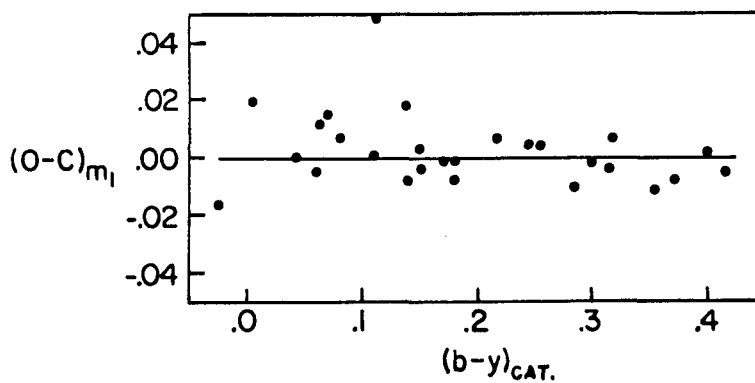

Figure 24.   The m_1 residuals for the first four nights are plotted vs. b-y

There is no obvious systematic dependence on color.

very likely due to the fact that the S.O. "v" filter has a narrower band pass and a higher peak transmission than the original Stromgren "v" filter. Since the Hδ feature is located nearly at the center of the band pass, any variations in this feature from star to star would be expected to have a different effect on the S.O. indices involving this filter than on the same indices measured with the Stromgren filter and hence give rise to large residuals. Furthermore, since the Hδ feature decreases steadily in strength with increasing b-y, the effect of the Hδ variations on the "v" filter would also be expected to decrease. This phenomenon would show up in Figures 22 and 23 as the observed decrease in the residuals towards the redder colors.

Twenty-one program stars measured on the S.O. system also had at least one b-y, m_1, and c_1 measure listed in the Stromgren-Perry catalogue. It was felt that the published photometry was inadequate for the desired accuracies and supplementary measures were made. It is shown in the following paragraphs that the errors introduced into the combined (S.O. plus Stromgren) measures by the transformation and measuring errors of the S.O. system are of the same order as the published errors of two measures on the catalogue system.

An idea of the differences between the transformed S.O. system and the Stromgren system may be obtained by

forming the difference between the average measured value
of one index for a particular star on the S.O. system and
the same index for the same star on the Stromgren system.
The average of these differences for the 21 stars common
to both systems is $+0^{m}_{.}006$, $-0^{m}_{.}000$, and $-0^{m}_{.}008$ for b-y, m_1,
and c_1.

The average probable error for the 35 stars
measured from two to eight times on the S.O. system was
calculated to be $0^{m}_{.}002$, $0^{m}_{.}004$ and $0^{m}_{.}007$ for the three
indices. Stromgren (1967) gives probable errors for two
measures on the catalogue system of $0^{m}_{.}004$, $0^{m}_{.}005$, and $0^{m}_{.}006$
in b-y, m_1, and c_1. The internal errors of the transformed
S.O. system are therefore found to be quite comparable with
the catalogue system--the increase in errors due to the
transformation process being partially compensated
(statistically) by the larger number of observations per
star on the S.O. system.

Table 12 lists the combined results of the two
systems and represents the final data for all of the
photoelectrically measured program stars. The mean value
given for each index is an average of all of the S.O.
observations (each with unit weight) plus the catalogue
value weighted by its stated number of observations.
Therefore, the probable errors for stars having two or
more catalogue observations are somewhat optimistic since
the mean errors in these observations are not included.

Table 12

Photoelectric uvby Data

H.D.	b-y	m_1	c_1	n
196867	-0.018	+0.136	+0.867	3
139006	-0.009	+0.177	+1.025	5
148367	-0.002	+0.121	+0.534	3
97633	+0.002	+0.166	+1.138	5
172167	+0.003	+0.167	+1.080	6
31647	+0.003	+0.189	+0.965	3
146624	+0.004	+0.186	+0.976	6
130109	+0.006	+0.164	+1.039	4
103287	+0.007	+0.164	+1.100	7
198001	+0.007	+0.163	+1.171	6
162579	+0.016	+0.194	+0.962	4
140775	+0.017	+0.171	+1.081	5
161868	+0.023	+0.179	+1.053	8
32977	+0.026	+0.253	+1.003	2
140159	+0.032	+0.177	+1.040	3
170073	+0.037	+0.202	+1.002	5
193702	+0.040	+0.169	+1.058	4
116657	+0.058	+0.250	+0.890	3
97603	+0.064	+0.201	+1.034	6
125337	+0.067	+0.231	+0.994	3
141795	+0.077	+0.240	+0.953	2
8538	+0.080	+0.192	+1.111	6
175638	+0.090	+0.208	+0.963	2
33641	+0.099	+0.214	+0.877	2
116842	+0.100	+0.203	+0.927	7
124675	+0.126	+0.193	+0.927	3
34499	+0.144	+0.188	+0.831	3
155514	+0.144	+0.200	+0.881	4
211336	+0.171	+0.197	+0.785	12
159541	+0.173	+0.220	+0.729	4
106112	+0.190	+0.217	+0.732	3
33276	+0.208	+0.166	+0.943	2
26690	+0.229	+0.173	+0.582	2
110379-80	+0.245	+0.151	+0.524	4
20193	+0.251	+0.122	+0.589	2
151613	+0.259	+0.157	+0.524	3
106022	+0.272	+0.157	+0.586	3
134083	+0.285	+0.165	+0.449	10
2454	+0.298	+0.113	+0.454	3
170153	+0.337	+0.149	+0.308	6
198084	+0.358	+0.186	+0.435	2

Table 12--<u>Continued</u>

121370	+0.379	+0.203	+0.477	4
115043	+0.386	+0.197	+0.306	6
$\overline{p.e.}$	±0.003	±0.005	±0.007	

However, only seven stars fall into this category and only two of these have more than two measures on the catalogue system. The average values of the probable errors for each of the indices on the combined system are $0\overset{m}{.}003$, $0\overset{m}{.}005$, and $0\overset{m}{.}007$ for b-y, m_1, and c_1. These values compare very favorably with the internal errors stated in the catalogue. For these reasons and the evidence given in Figures 19 through 24, we conclude that the stars measured photo-electrically at Steward Observatory may be averaged in with the stars listed in the Stromgren-Perry catalogue with the end result being a fairly homogeneous system.

APPENDIX B

APPROXIMATE WAVE LENGTHS OF SPECTRAL FEATURES

The most efficient method for naming spectral
features is to label them by their approximate wave length.
This method allows other investigators working at a similar
dispersion to quickly identify them for use in their own
classification scheme.

Since an iron comparison spectrum was not used on
any of the program plates (except for focus tests--which
did not include a stellar spectrum), it was necessary to
identify several stellar features in the 3300A-3800A region
and use them as a basis for measuring the wave lengths of
the remaining unidentified features.

A coude (13 A/mm.) plate of 9 AUR covering the
ultraviolet region was obtained for this purpose by Dr.
Helmut Abt using the Kitt Peak National Observatory's 84
inch reflector. A hollow cathode comparison spectrum made
it possible to calculate accurate wave lengths for the
features present in this early F star.

A total of 57 iron comparison lines were measured
along with their suspected counterparts in the stellar
spectrum using the Grant measuring engine of the K.P.N.O.
The mean shift in the scale readings due to the star's

apparent radial velocity at the time and place of observation was measured to be 17.0 ± .4 microns p.e. The root mean square deviation from the mean value was 4.68 microns. This large dispersion is probably due to a large number of blended stellar features which were measured as suspected stellar iron lines. Only those stellar lines whose measured displacement from a comparison line was within one r.m.s. deviation from the mean were assumed to be identified. Laboratory wave lengths were assigned to these features making it possible to calculate lab wave lengths for features located between two identified lines merely by linear interpolation.

The use of linear interpolation is justified by the following argument. First, the desired accuracy for identifying features (on the coude plate) which are also seen at classification dispersion need not be greater than 0.2 A (1/10 the resolution of a classification program plate). Second, the average distance between the identified iron lines was about 20 A--a very short base line for linear interpolation since the dispersion of the grating spectrograph is even more nearly linear in the ultraviolet than in the visible. Third, the variable compression of the stellar spectrum along its length due to the apparent radial velocity of the star is negligible over these small spectral intervals.

Since rough estimates ($\pm$3 A) of the wave lengths of the features used for classification had already been made using a millimeter scale and enlarged prints, it was fairly easy to identify the features due to Fe I on the classification spectra and to assign the appropriate laboratory wave lengths.

For this purpose the spectrum of HR 672 (G0.5 IVb) was measured on the Grant measuring engine of K.P.N.O. Making use of the identified Fe I features, wave lengths were calculated for most of the classification features. These wave lengths (rounded to the nearest Angstrom) are the names by which the features are referred to in the dissertation (cf. Figure 25). It is not expected that many of these features will later be found to have central wave lengths differing from their names by more than one Angstrom. Since the resolution of the program spectra is approximately two Angstroms, an error of one Angstrom in naming the features should not lead to any mis-identification problems. A few of the features not measured on this plate (e.g., λ3422) may still be in error by several Angstroms.

Two spectra of the ultraviolet region of HD 222368 are shown in Figure 26. The top print is taken from a K.P.N.O. plate of good quality. The bottom print is from an S.O. plate of unusable quality. Since the prints were
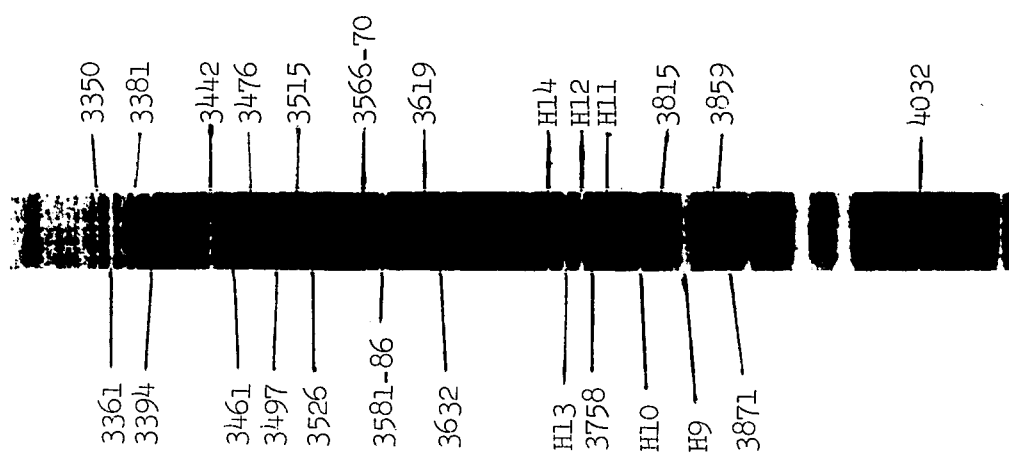
Figure 25.   Names and identifications of some of the most
             commonly used ultraviolet classification
             features

        H12 through H15 refer principally to the strong
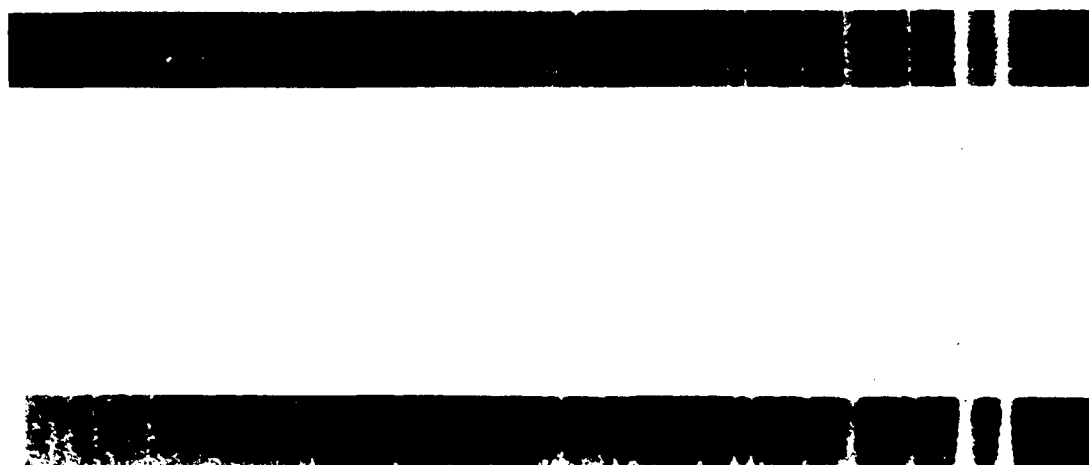FeI features which dominate each blended Balmer line.

Figure 26. The ultraviolet spectrum of HD 222368 (F8 Va 1) is shown in focus on a plate taken with the KPNO 36 inch telescope (top), and out of focus on a S.O. plate (bottom)

The weak metallic lines appear even weaker on the poorly focused plate.

made from film copies of the original plates, considerable degradation in quality has occurred.

Having reasonably good wave lengths for the classification features, the coude measures were carefully investigated for a possible identification of the remaining unidentified classification features. As might be expected, most of the features are blends of several lines due to several different atoms or ions.

Since only selected features on the coude plate were measured (i.e., lines forming the blends which make up the classification features at the lower dispersion), the method of using multiplets to identify the atom or ion responsible for a measured line was not feasible. However, the principal contributors to the Fraunhofer features and some of the Fe I lines were identified with fair certainty and are listed in Table 13. The Fraunhofer lines "L" through "P" were all identified. More complete identification lists are available in the literature (Merrill 1956).

In summary, the classification features were named using the measured central wave lengths of the blends in the spectrum of a very early G star. Stars of late A and early F will show some of the features at slightly different wave lengths due to the reduction in blending at the earlier types.

Table 13

Features with Tentative Identifications of Sources

Name	Fraunhofer	Source*
3337		TiII, CrII, MgI
3350		TiII
3361	P	TiII, ScII
3371 (Wide Blend)		TiII, FeI, FeII, CrII
3380		CrII, TiII, SrII, ScII
3384		CrII, TiII, FeI
3389		TiII, FeII
3394		FeI, TiII
3405		TiII, CrII
3422		CrII
3433		CrII
3442	O	FeI, FeII, MnII
3461		TiII, MnII
3476		FeI, TiII, VII, CrII
3491		TiII, FeI, MnII
3497		MnII, FeI, FeII, VII, ZrII
3506		TiII, VII
3515		FeI, FeII, NiI, NiII, VII
3526		VII, FeI, NiI
3566		FeI, FeII, TiII, NiI, VII
3570		FeI
3581	N	FeI, ScII
3586		FeI, CrII
3609		FeI
3614		ScII
3619		FeI, NiI, VII
3632		FeII, ScII, CrII, FeI
3648		FeI, CrII, ScII, VII
3695		H17, FeI, CrII
H15 (3707)		CaII, FeI, TiII, VII, YII, ZrII, H15
H14 (3721)		TiII, FeI, H14
3728	M	VII, FeI
H13 (3735)		FeI, CaII, H13
H12 (3749)		FeI, VII, H12, FeII, TiII
3758		TiII, FeI
H11 (3770)		H11, TiII, VII, NiII, FeI
H10 (3798)		H10, FeI
3815		FeI, TiII
3820	L	FeI
3826		FeI
3828		FeI
H9 (3833)		MgI, YI, FeI, H9

Table 13--Continued

3838	MgI
3850	FeI
3859	FeI, SiII
3871	FeI
3878	FeI, VII

*Cf. Merrill (1956) and especially Swings and Struve (1941) for more detailed information.

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