# DISCOVERY OF VERY-LOW MASS BINARY STARS AND CIRCUMSTELLAR DISKS IN THE INFRARED 

by

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## Statement By Author

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SIGNED: Nicholas Siegler

## AcKnowledgments

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Rather than having climbed onto the shoulders of giants, it may be more accurate to say I was catapulted. Thank you all.

## DEDICATION

To those who sparked the wonder and passions of a young boy -

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Isaac Asimov, Star Trek, Patrick Moore, H. A. Rey
The Apollo missions, Voyager I and II, Viking I and II,
... and my loving father Marcel, for whom I was the center of the world.

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#### Abstract

We present results from three infrared observational studies investigating different aspects of stellar evolution. The first survey, conducted in the near-infrared with adaptive optics, measures for the first time the stellar multiplicity properties of field M6-M7.5 dwarf stars. We report that their binary fraction, separation distribution, and mass ratio distribution are very similar to those of later spectral type stars and brown dwarfs while distinct from more massive stellar binaries. These differences, when coupled with age, shed light on possibly different formation mechanisms and kinematic evolution between binary systems of different primary masses. I incorporate these results with those from all known very-lowmass binary systems $\left(\mathrm{M}_{t o t} \leq 0.2 \mathrm{M}_{\odot}\right)$ and present their statistical properties. We also present the discovery of a very tight ( 66 mas ) brown dwarf companion to a mid-L dwarf demonstrating the capabilities of laser guide star adaptive optics.

In the second study we present mid-infrared Spitzer observations of members of the $\sim 50$ Myr open stellar cluster IC 2391 where, using photometric techniques, we report that about a third of the solar-like stars (spectral types FGK) likely possess debris disks. With respect to several other stellar groups of known age, we show for the first time the evolution of the debris disk fraction of solar-like stars. We conclude that, along with more massive late-B and A stars, the formation of planetesimals around solar-like stars appears to be a universal process of star formation.

Lastly, we present preliminary near- and mid-infrared Spitzer observations of stars in the direction of the $\sim 6 \mathrm{Myr}$ open cluster IC 2395 . Using photometric techniques, we identify upper main sequence cluster members and lower-mass candidate members with evidence of circumstellar disks at different stages of disk


evolution - primordial, transition, and debris. We present for the first time the evolution of the median IRAC flux ratios emitted from the inner $\sim 0.2$ AU regions of classic T Tauri stars. These results are possibly consistent with the processes of grain growth and dust settling as a mechanism for planetesimal formation.

## CHAPTER 1

## Introduction

Pushing the limits of technology has been key to improving our understanding of the Universe. From the moment Galileo brought a spyglass to his eye, our solar system became a larger and more complex place. This dissertation's science objectives have ridden the coat tails of recent technological advances in infrared detectors, adaptive optics (AO), laser beacons, and the improved sensitivity and resolution of NASA's most recent infrared observatory, the Spitzer Space Telescope. The investigations to follow examine different aspects of the lives of stars, from the youngest epoch when they are still surrounded by primordial disks, to slightly older more evolved dusty disks which possibly reveal the existence of planets in the making, to older stars where we search for faint companions. As well, we span the full range of stellar masses from stars several times the mass of the Sun all the way to brown dwarfs ( $\lesssim 0.08 \mathrm{M}_{\odot}$ ).

Our observations are conducted in the infrared at wavelengths between 1$25 \mu \mathrm{~m}$ because these are wavelengths where relatively cool objects shine brightest. Our study of circumstellar disks is actually a study of circumstellar dust. Micron-sized dust, heated by incident ultraviolet and visible radiation from their host stars, remit thermally at longer infrared wavelengths. Depending on several factors such as their composition, distance from the star, and the star's intrinsic luminosty, dust temperatures can range from $\sim 1500 \mathrm{~K}$ to $\sim 30 \mathrm{~K}$. In sufficient planar densities, their extant radiation can be detected in the mid-infrared. When unresolved, visible wavelengths would only "see" the stellar photosphere and completely miss out on the places where planets form.

To work at these longer wavelengths, however, I have capitalized on the un-
parallel sensitivity of Spitzer, working above the Earth's atmosphere where it observes unimpeded from the effects of water absorption. Spitzer, launched in 2003, is the latest generation of a lineage of infrared space observatories commencing with NASA's Infrared Astronomy Satellite (IRAS; launched in 1983, 10-month mission) and then ESA's Infrared Space Observatory (ISO; 1995-1998). Spitzer has a primary mirror $42 \%$ larger than ISO's and almost 100 times improved point source sensitivity. Much of Spitzer's enhanced sensitivities are due to advanced infrared detector arrays and cryogenic cooling designed to reduce unwanted background signal. The telescope's wider field of view also allows for the study of disks around many stellar cluster members of a wide range of ages from which this dissertation greatly benefits from.

Old ( $\gtrsim 1$ Gyr), very-low-mass stars ( $\lesssim 0.1 \mathrm{M}_{\odot}, \mathrm{VLM}$ ) emit their peak emission in the near-infrared ( $1-5 \mu \mathrm{~m}$ ), as do slightly lower-mass objects such as brown dwarfs. Both types of objects can be detected from their thermal emission, the former from the burning of hydrogen in their core and the latter from gravitational contraction. Any investigation searching for faint companions, stellar or substellar, requires both sensitivity - the capability of clearly detecting photons from an object of interest (signal) from unwanted photons (noise) - and resolution - the smallest angular separation two objects can still be clearly resolved. The Earth's turbulent atmosphere negatively effects both capabilities by introducing turbulent distortions and "blurring" of point sources. Without corrective optics to compensate for the wavefront aberrations introduced by our terrestrial atmosphere, a telescope's resolution is reduced to $\lambda / r_{o}$, the observed wavelength divided by the maximum size of the atmospheric patch that introduces one radian of wavefront aberration (known as the Fried parameter; typically about 10 cm at
visible wavelengths). Despite continuously increasing mirror sizes after Galileo's initial observations with his spyglass, angular resolution did not improve for centures, limited by the natural "seeing" limit of $\lambda / \mathrm{r}_{\circ}$ produced by the Earth's atmosphere (see Figure 1.1). It was not until telescopes began being placed at higher elevations that improvements were obtained. In the near-infrared ( $\sim 2 \mu \mathrm{~m}$ ) on a tall mountain, above much of the Earth's water molecules, the seeing patch ( $\mathrm{r}_{\mathrm{o}}$ ) can be almost 80 cm , allowing approximately $0.6^{\prime \prime}$ resolution. This is typically the best natural $\lambda / \mathrm{r}_{\circ}$ resolution obtainable in the near-infrared (and is independent of telescope aperture size).

Until mirrors with diameters greater than $\sim 10 \mathrm{~m}$ will be utilized in space, the highest resolutions in the near-infrared will be with ground-based telescopes utilizing the corrective abilities of AO (Figure 1.2). Developed in the late 1960s and 1970s for military applications, AO systems were designed to improve angular image resolutions to that limited only by the wave nature of light (diffraction). This is generally quantified as $\lambda / \mathrm{D}$ where $\lambda$ is the wavelength of the observation and D is the aperture size, namely the diameter of the telescope's primary mirror. AO-corrected resolution can be a factor of $\mathrm{D} / \mathrm{r}_{\circ}$ better than that of seeing limit. An 8 m telescope observing in the near-infrared can ideally reach resolutions of 57 milliarcsec (mas) at $K$-band ( $2.2 \mu \mathrm{~m}$ ), an order of magnitude improvement in resolution.

AO corrects the aberrations introduced by the turbulent atmosphere and, ideally, returns planar wavefronts with a resolution limited only by diffraction effects. It attempts to accomplish this by sampling light from a point source near one's science target by a wavefront sensor that, with the aid of high-speed computers, can measure the deviations from planar wavefronts ${ }^{1}$. A corrective algo-

[^0]

Figure 1.1 The evolution of angular resolution. Galileo's one-inch $17^{\text {th }}$ century spyglass resulted in approximately a 16 -fold improvement over the naked eye in angular resolution. However, due to atmospheric limitations, no further improvement in resolution were made until the early 1900s when telescopes were placed at higher elevations. Despite nearly a 400 -fold increase in telescope mirror size by the 1990s, angular resolution only improved by only about 12 -fold since Galileo, still limited by atmospheric effects. Not until adaptive optics were implemented on large telescopes in the late-1990s did ground-based telescopes receive the resolution benefits from larger mirrors. Keck II with its AO system can today obtain 50 mas angular resolution in the near-infrared. Our utilization of AO at the Keck, Gemini North, Subaru, and VLT telescopes represents a similar 16-fold increase in resolution - a jump of that magnitude has not occured since Galileo (Source: ESO).


Figure 1.2 Example of the point source function observed with AO off (seeing limited) versus AO on (near-diffraction limited); source: Lick Observatory.
rithm is calculated and communicated to a deformable mirror in the optical train which corrects the aberrated waves. In practice, the correction to planar waves is never perfect due to several uncertainties in the process which we discuss in more detail in Chapter II. The figure of merit for an AO system is called the Strehl ratio (peak intensity in a corrected point source divided by the peak from an ideal point spread function). How high a Strehl ratio is needed depends on the science requirements. ${ }^{2}$

From the AO and laser beacon systems associated with today's high-resolution imaging techniques to Spitzer's exquisite sensitivity in the near- and mid-infrared, I consider myself very fortunate to have had the opportunities to conduct these experiments at this point in time. Galileo would be envious.

[^1]I now provide some relevant astronomy background for each of this dissertation's subjects in order to motivate their investigation:

### 1.0.1 Multiplicity of Very-Low-Mass Stars

It has been long known that stars are born not as solitary objects but in groups. Most solar-like stars retain stellar companions even after their natal associations have dissipated (eg. Duquennoy \& Mayor, 1991). Binary properties such as frequency of companions, separation distribution, and mass ratio ${ }^{3}$ distribution provide important observational constraints to star formation theories and evolution. Studies of slightly lower mass stars, ( $\sim 0.2-0.6 \mathrm{M}_{\odot}$; Fischer \& Marcy, 1992), show a decrease in the frequency of multiplicity, a tighter binary separation distribution, and a broad mass ratio distribution. Do these trends continue for even lower-mass stars and brown dwarfs? Answering these questions is important because star formation theories must also be able to account for multiplicity at the extreme ends of the mass spectrum. Differences between the binary properties of stars of different masses could tell us about how star formation depends on mass. And it may also suggest something about the dynamical interactions during the lives of stars. Coupled with data comparing young to old binary systems may also shed light into their kinematic evolution.

By 2000, very few surveys had been conducted to measure the multiplicity of low-mass stars (indeed, only a handful of such objects were known). In addition, no data was available regarding the multiplicity of young low-mass stars. Leveraging new advances in both larger infrared arrays and AO wavefront sensors along with the availability of new 8 m class telescopes, our group, led by Dr. Laird Close at the University of Arizona, was the first to conduct a high-

[^2]resolution multiplicity survey of a large sample of VLM stars (spectral type $\geq$ M6, mass $\lesssim 0.1 \mathrm{M}_{\odot}$. . In Chapter II, I present results from the portion of the survey that targeted M6-M7.5 stars and place these results in context of more and less massive stars. I also introduce the unique Very-Low-Mass Binaries Archive that I maintain containing a statistical account of these systems' properties.

### 1.0.2 The Discovery of a Tightly Separated Brown Dwarf Using Laser Guide Star Adaptive Optics

In Chapter II we utilized an observational strategy that optimized the detection of faint companions. By using high-resolution, large-aperture, near-infrared imaging to probe for faint companions near VLM stars rather than solar-like stars, the contrast difference is reduced by almost two orders of magnitude. This is quite important considering that one of the key results shown in Chapter II is the tight separation distribution of field VLM binaries. This means that at a detector's focal plane, a faint companion to a low-mass star is likely located in the halo of the primary star's point spread function. Hence, by targeting less luminous primary targets, the potential of detecting fainter companions also improves.

A problem arises, however, when the science target is too faint to also serve as the natural guide star (NGS) for the AO system. In such a case, the wavefront sensor receives an insufficient number of photons and hence cannot provide an accurate or timely measurement to correct for the atmospheric aberrations. The limiting factor then becomes the probability of finding sufficiently bright stars ( $\mathrm{V} \lesssim 14 \mathrm{mag}$ ) within $\sim 30^{\prime \prime}$ of one's science targets that can serve as the NGS (AO systems with infrared wavefront sensors can do a little better). There is less than a $10 \%$ chance of finding a NGS meeting these requirements at $30^{\circ}$ galactic latitude (Roddier, 1999) (the probabilities increase along the Galactic plane).

The latest technological advancement to high-resolution imaging is the use of


Figure 1.3 The Keck II telescope emitting its laser beacon (picture credit: John McDonald/CFHT).
laser guide stars (LGS) which we discuss in more detail in Chapter III (Figure 1.3). By providing its own light beacon ( $\mathrm{V} \sim 8-10.5 \mathrm{mag}$ ) anywhere the telescope can point, LGS AO can provide access to about $2 / 3$ of the night sky (Liu, 2006). LGS AO therefore allows for near-infrared surveys to target even fainter objects further leveraging the contrast-observing strategy used in Chapter II.

In terms of availability, LGS AO today is perhaps where NGS AO was 7-10 years ago. Only four systems as of the spring of 2007 have become fully tested and operational on large telescopes, the Keck II, Palomar, Gemini North, and VLT telescopes. Every other 8 m class telescope with an existing AO system is scheduled to commission LGS AO systems within the next three years.

In Chapter III, we present the discovery of a brown dwarf companion to a mid-L field dwarf using LGS AO with the Keck II telescope. It is among the first VLM binaries discovered with this technology and the most tightly separated ( 66 mas) to date. It also proves that a LGS can obtain near-diffraction limited
resolution on a large diameter mirror telescope.

### 1.0.3 Open Cluster IC 2391 and the Evolution of Debris Disks

Frank Drake's famous equation, which gallantly attempts to estimate the number of technologically-advanced civilizations in our Galaxy, is made up of a product of 7 probabilities. One of them is the fraction of stars in our Galaxy that have planets, $\mathrm{f}_{P}$. Most astronomers, after considering the observational sensitivities and biases inherent in the lower limit results from radial velocity, transit, and micro-lensing studies, believe that the fraction is quite large. In addition, theoretical studies suggest that terrestrial planetesimal formation within primordial disks occurs rather early and rapidly (eg. Wiedenschilling, 1997). Unabashedly, we'd like the fraction to be high. But scientists should never wish.

An alternative and indirect approach to estimating $f_{P}$ is by measuring the fraction of young stars with evidence of debris disks. Debris disks are dusty, gas-poor disks around main sequence stars (Figure 1.4). For disks detected by their thermal emission, infrared through millimeter wavelengths infer micronsized dust grains (recall ISM grains are believed to be sub-micron). These thermal emissions are best modeled by a cool blackbody with typical temperatures of 110120 K . It is now believed that debris disks, the subject of Chapter IV, are evolved primordial disks, the subject of our work in Chapter V.

Because most young stars are currently too far from us to be spatially resolved, most debris disks are identified indirectly from their SED morphology or, at minimum, mid-infrared flux densities in "excess" of that expected from stellar photospheres. Dust in the plane of the disk is heated by ultraviolet and visible radiation by the central star and reradiates at longer wavelengths. The amount of dust needed to be detected by Spitzer in the mid-infrared depends largely on the star's luminosity and distance. As an example, a sample of solar-like stars observed


Figure 1.4 Top: The 30-250 million year old, G2 star HD 107146 as imaged in scattered light by the Hubble Space Telescope (image credit: NASA, ESA, D.R. Ardila (JHU), D.A. Golimowski (JHU), J.E. Krist ( STScI /JPL), M. Clampin ( NASA /GSFC), J.P. Williams (UH/IfA), J.P. Blakeslee (JHU), H.C. Ford (JHU), G.F. Hartig ( STScI ), G.D. Illingworth (UCO-Lick), and the ACS Science Team.) Bottom: The 220 Myr A3 star Fomalhaut as imaged from scattered light by the Hubble Space Telescope. These disks are brighter than the stars whose light it reflects, inferring that they contain small grains about half a micron in size. Our solar system today has 3-4 orders of magnitude less dust (image credit: NASA, ESA, P. Kalas and J. Graham (University of California, Berkeley), and M. Clampin (NASA/GSFC)).
in the Scorpius-Centaurus OB association (118-145 pc) are estimated to possess between $10^{-3}$ and $10^{-2}$ Moon masses in their disk (eg. Chen et al., 2005). Typical dust mass in debris disks is 1-20 Moon masses, a tiny fraction of the 10-300 Earth masses ${ }^{4}$ measured in pre-main sequence T Tauri and Herbig AeBe stars (Chen et al., 2005).

So what is the connection between debris disks and planets? The dust is believed to be generated from collisions between planetesimals and/or planets and not remnant of the original collapsed molecular cloud. This conclusion stems from estimates of circumstellar dust grain lifetimes typically being significantly smaller than the estimated ages of the stellar systems. The associated removal timescales depend on the central stellar luminosity, strength of its stellar wind, and on the grain distance from the central star. Dust removal mechanisms include radiation effects such as Poynting-Robertson drag and radiation pressure from the central star (eg. Artymowicz, 1988), stellar wind effects analagous to those induced by radiation pressure but through proton rather than photon interactions (eg. Plavchan, Jura, \& Lipscy, 2005), and sublimation. Regardless of the mechanism, submicron, interstellar-medium grains that survived the collapse and formation of the original central star/circumstellar disk system, would have been removed on timescales much less than a million years. This suggests that the dust grains are replenished from a reservoir of colliding objects and, to a lesser degree, sublimation of comets. The reservoir may be analagous to an Asteroid or Kuiper Belt.

The most likely process for dust replenishment is steady state collisions between solid bodies which we call planetesimals. Ejecta from collisions, particularly at earlier times when planetesimal belts were more massive and densely populated, may experience a series of collisions with other planetesimals, each

[^3]collision resulting in the generation of smaller masses. The micron-sized population is then likely removed via radiation pressure and/or stellar winds. This is commonly referred to as a collisional cascade (Stern, 1995; Kenyon \& Bromley, 2001). To initiate a collisional cascade something must sufficiently excite the velocity dispersion of objects in the disk. Possible perturbers are planet-sized objects (eg. Kenyon \& Bromley, 2004b), passing stars Kenyon \& Bromley (2002), and migrating gas giants causing Heavy-Late-Bombardment-like events (Strom et al., 2005; Gomes et al., 2005).

A study of 76 A-type stars by Rieke et al. (2005) showed that younger stars have a higher probability of having a $24 \mu \mathrm{~m}$ excess than older ones. Roughly half of the stars less than 25 Myr have evidence of debris disks while only about $12 \%$ of those older than $\sim 190 \mathrm{Myr}$ do. The earlier large fraction implies that most A-type stars have evidence of planetesimal formation at younger ages.

A stars only make up a small fraction of the stars in the Galaxy. Within a volume of 10 pc from the Sun, there are only about $3 \mathrm{~A} / \mathrm{F}$ stars but about 54 $G / K$ stars. What can we expect about the frequency of debris disks from the less massive but more numerous solar-like stars? In Chapter IV, we conduct a mid-infrared investigation of the $\sim 50 \mathrm{Myr}$ old open cluster IC 2391 to measure the fraction of stars with debris disks across a wide range of masses. We then compare the results with several other recent Spitzer investigations and observe for the first time a debris disk evolution for solar-like stars.

### 1.0.4 Open Cluster IC 2395 and Evidence of Disk Evolution

In Chapter IV, we measured the fraction of stars that have evidence of planetesimal collisions in a $\sim 50 \mathrm{Myr}$ old open stellar cluster and measured the evolution of debris disks around solar-like stars. In Chapter V we go even further back in the life of stars to study their primordial disks and garner additional clues to the
formation of planets.
Except possibly for the very most massive stars, the formation of protoplanetary accretion disks is now understood to be a universal process of star formation. As giant molecular clouds collapse inward due to their own gravitational attraction, they fragment into smaller more dense clouds. Within these fragments, embedded dense cores grow larger while rotating more rapidly as angular momentum is conserved. These cores continue to collapse until eventually forming gaseous spheres partially supported by their own thermal radiation pressure and surrounded by hot, optically-thick circumstellar disks. These primordial disks, made up of mostly gas and peppered with dust, are from which planets form.

Over the next 10 Myr, most primordial disks dissipate (Haisch, Lada, \& Lada, 2001; Mamajek et al., 2004). Much of the gas, as it becomes partially ionized through collisions, accretes onto the star's surface via strong magnetic field lines from the inner regions of the disk (also known as viscous accretion; see Figure 1.5). The dissipation timescale is consistent with results from CO surveys Zuckerman, Forveille, \& Kastner (1995); Pascucci et al. (2006). As gas accretes onto the stellar surface, the star-disk system conserves angular momentum through bipolar jet emissions as well as matter in the disk's outer regions expanding outward, decreasing the overall disk surface density. By 10 Myr , most stars have finished accreting gas.

Based on the radial velocity evidence for planets around solar-like stars and our own mid-infrared excess results from Chapter IV, grains must agglomerate into larger masses. The timescales for this agglomeration must be less than about 10 Myr so that gas remains available to accrete onto giant planets. We can speculate that agglomeration from submicron- to micron-size grain must therefore commence earlier than 10 Myr. Furthermore, theoretical expectations predict that


Figure 1.5 The inner disk of a classical T Tauri star is a dynamic and complicated region whose processes are not yet fully understood. In this illustration from Camenzind (1990) we see the magnetic field lines carrying plasma from the inner disk region accreting onto the star. The disk does not extend to the stellar surface but truncates at the dust sublimation distance ( $\sim 1400 \mathrm{~K}$ ). The puffed-up inner region is shown along with a flared disk. The interaction of the magnetic field lines and the gas/dust disk is still an active area of research.
dust grain growth via collisions should occur most quickly in the inner regions of primordial disks because of the higher surface densities and orbital velocities there (eg. Wiedenschilling, 1997; Dominik \& Decin, 2003). This process suggests an inside-out clearing of disk material as the disk evolves and planetesimals grow. This is supported by near-infrared suveys of young stellar clusters and associations that observe the fraction of stars with excess dust emission probed at $2.2 \mu \mathrm{~m}$ (inner dust at radial distances $\lesssim 0.1 \mathrm{AU}$ ) decays to zero quicker than at $10 \mu \mathrm{~m}$ (slightly larger radii). In Chapter V we add an additional line of evidence supporting this model.

In Chapter V we present preliminary results from a Spitzer IRAC and MIPS investigation of the poorly known $\sim 6 \mathrm{Myr}$ old open cluster IC 2395 ( $\sim 800 \mathrm{pc}$ ). One of our objectives is to identify circumstellar disks at different stages of evolution - primordial, transition, and debris - and later compare them to systems both younger and older. It is part of a larger Guaranteed Time Observation investigation designed to measure and understand gross circumstellar disk properties for statistically significant samples for the first time. Our investigation in Chapter V also adds additional evidence for grain settling in the inner-most regions further supporting the model of planetesimal formation occurring early and rapidly in the primordial disk.

## CHAPTER 2

## An Adaptive Optics Survey of Nearby M6.0-M7.5 Stars

The content of this chapter consists of work originally published in the December 1, 2003 edition of The Astrophysical Journal by Siegler, N., Close, L. M., Mamajek, E. E., EE Freed, M., the March 10, 2005 edition of The Astrophysical Journal by Siegler, N., Close, L. M., Cruz, K. L., Martín, E. L. E Reid, I. N, and a chapter in 2007 Planets and Protostars V by Burgasser, A. J., Reid, I. N., Siegler, N., Close, L. M., Allen, P., Lowrance, P. J., $\mathcal{E}$ Gizis, J. E..

We present the results of a high-resolution, magnitude limited ( $\mathrm{K}_{s}<12 \mathrm{mag}$ ) imaging survey of nearby low-mass M6.0-M7.5 field stars. The observations were carried out using adaptive optics at the Gemini North, VLT, Keck II, and Subaru telescopes. Our sample of 36 stars consists predominantly of nearby ( $\lesssim 30 \mathrm{pc}$ ) field stars, 5 of which we have resolved as binaries. Two of the binary systems, 2MASSI J0429184-312356 and 2MASSI J1847034+552243, are presented here for the first time. All 5 discovered binary systems have separations between $0^{\prime} .08-0^{\prime \prime} .53(2-9 \mathrm{AU})$ with similar mass ratios ( $\left.\mathrm{q}>0.8, \Delta \mathrm{~K}_{s}<1 \mathrm{mag}\right)$. This result supports the hypothesis that wide $(\mathrm{a}>20 \mathrm{AU})$ very low-mass $\left(\mathrm{M}_{t o t}<0.20 \mathrm{M}_{\odot}\right)$ binary systems are rare. The projected semimajor axis distribution of these systems peak at $\sim 5 \mathrm{AU}$ and we report a sensitivity-corrected binary fraction of $9_{-3}^{+4} \%$ for stars with primaries of spectral type M6.0-M7.5 with separations greater than 3 AU and mass ratios greater than 0.6 . Within these instrumental sensitivities, these results support the overall trend that both the semimajor axis distribution and binary fraction are a function of the mass of the primary star and decrease with decreasing primary mass. These observations provide important constraints
for low-mass binary star formation theories.

### 2.1 Introduction

One of the main motivations for measuring the binary fraction of stars is to better understand the process of star formation itself. After all, stars like our own Sun are preferentially produced in multiple systems (Duquennoy \& Mayor, 1991). The classic stellar formation mechanism of molecular cloud core collapse and fragmentation, however, has a hard time explaining the tightest systems. While this mechanism can explain wide binary systems (semimajor axis $\gtrsim 10 \mathrm{AU}$ ), it has some difficulties explaining the formation of tight systems (Bate, Bonnell, \& Bromm, 2002). Additionally, the multiplicities of the lowest mass stars and brown dwarfs appear to be statistically different from those of more massive systems (Close et al. (2003) and references within). These differences, if proven to be real, provide important clues and constraints to theoretical stellar formation models.

The continuously improving statistics of binary stars clarifies the paradigm that the binary fraction and semimajor axis distribution are functions of the central star mass. Surveys of G dwarfs estimate a multiplicity fraction of approximately $50 \%$ for separations of 3 AU and greater (Duquennoy \& Mayor, 1991). Other surveys of similar sensitivity to systems wider than 3 AU have found that early M dwarfs (M0-M4) have measured binary fractions of $\sim 32 \%$ (Fischer \& Marcy, 1992) while late M/early L dwarfs (M8.0-L0.5) estimate fractions $\sim 15 \%$ (Close et al., 2003). The trend appears to continue to the coolest objects - L dwarfs reporting $\sim 10-15 \%$ (Bouy et al., 2003; Gizis et al., 2003) and T dwarfs at $\sim 10 \%$ (?). The same surveys infer semimajor-axis separations to also be a function of primary mass. While G and early M dwarfs (M0-M4) show broad separation
peaks of $\sim 30 \mathrm{AU}$, late $\mathrm{M}(\geq \mathrm{M} 8)$, L, and T dwarfs appear to have separations tightly peaked at $\sim 4 \mathrm{AU}$ (Close et al., 2003). A similar result has been shown to apply to the sequence of members in the Pleiades cluster, from solar-type stars to brown dwarfs (Martín et al., 2003). Together, these results are providing both clues and empirical constraints on star formation mechanisms as well as potentially help calibrate the mass-age-luminosity relation for very low-mass (VLM) stars.

In Siegler et al. (2003), hereafter referred to as Paper I, we presented results from the largest flux limited ( $\mathrm{K}_{s}<12 \mathrm{mag}$ ) survey of nearby field M6.0-M7.5 dwarfs. The binary fraction of this narrowly defined spectral type range had not been quantified as those of stars slightly earlier (M0-M4; Fischer \& Marcy, 1992) and later (M8-L0.5; Close et al., 2003). Considering the differences in binary charactersitics as a function of mass as discussed above, would M6.0-M7.5 binaries have intermediary characteristics to their main sequence neighbors or would they resemble the ultracool dwarfs?

Paper I's sample consisted of 30 stars and presented the discovery of three new binary systems using the University of Hawaii visitor AO system Hokupa'a (Graves et al., 1998) at the Gemini North telescope. The discoveries followed characteristics of other VLM binary systems, namely relatively equal mass components ( $q>0.8$ ) with projected separations less than 16 AU . We present our two latest binary discoveries from this spectral range, 2MASSI J0429184-312356 and 2MASSI J1847034+552243, hereafter referred to as 2 M 0429 and 2M1847. These binaries were discovered with the VLT and the Subaru AO facilities, respectively. The total M6.0-M7.5 sample size is increased to 36 and we update the binary fraction results with those presented in Paper I. We present our observations and results in the following section and examine the systems' derived characteris-
tics such as distance, age, temperature, spectral type, and mass in $\S 2.3$. In $\S 2.4$ we conclude by discussing the binary frequency and separation distribution of M6.0-M7.5 dwarfs.

### 2.2 Observations and Results

### 2.2.1 The Sample

We selected a flux-limited sample of 36 objects consisting of M6.0-M7.5 dwarfs with $\mathrm{K}_{s}<12 \mathrm{mag}$ and $\mathrm{J}-\mathrm{K}_{s}>0.95 \mathrm{mag}$ from mainly 2 MASS stars listed in Cruz et al. (2003), Reid et al. (2002), and Gizis et al. (2000). Paper I discusses the first 30 observations and we report here the most recent six. One of the six targets is a recently discovered high proper motion M dwarf - SO 025300.5+165258 ( $\sim 3.6 \mathrm{pc}$ away; Teegarden et al., 2003). We discuss this star further in §2.2.5. We also note that we observed at Subaru on 2003 July 10 (UT) another recently-discovered high proper motion M dwarf 2MASSI J1835379+325954 ( $\sim 5.7$ pc away; Reid et al., 2003). While not part of this sample due to its later spectral type (M8), it was observed at high resolution and found to have no $\mathrm{q}>0.8$ companions at separations $>0^{\prime \prime} 1$.

### 2.2.2 The Telescopes and their AO Systems

The 30 targets from Paper I were all observed at the Gemini North telescope. The 6 targets presented here were observed at the Subaru and VLT Observatories. Due to its recent discovery and proximity, we conducted additional long integrations of SO $025300.5+165258$ with the Keck II telescope. Interestingly, the AO systems at these telescopes represent the three major wavefront sensor (WFS) technologies currently in use today. Gemini North, at the time of our observations, and Subaru, currently, use 36-element curvature WFSs, the VLT has an infra-red Shack-Hartman, and the Keck II utilizes a visible Shack-Hartman. This survey
provided the opportunity to compare and contrast how different AO WFSs differ in their abilities to lock on faint targets.

As discussed in detail in Paper I, one of the challenges in utilizing AO is locating sufficiently bright guide stars near enough one's science objects to minimize uncertainty in the image quality introduced by isoplanicity. This is best achieved when using the target object itself as the AO guide star. This shifts the criterion of target selection from the availability of bright natural guide stars ( $\mathrm{R} \leq 15 \mathrm{mag}$ ) to the sensitivity of the respective telescope's AO system, in particular the WFS. This becomes quite important because the probability of locating a $\mathrm{R}=15 \mathrm{mag}$ star within $30^{\prime \prime}$ of one's science target is only about $\sim 15 \%$ (Fig. 3.10; Roddier, 1999). The ability to guide on fainter stars also allows for both larger sample sizes and improved contrast ratios.

We were able to observe the faintest of our targets (V~19.0-19.5 mag, I~15.516 mag ) only with the former Gemini North AO system Hokupa'a where we conducted the majority of the observations. No other current AO system can lock onto such faint targets. Hokupa'a, decommisioned in 2003, was a curvaturebased AO system which employed in its WFS red-sensitive, photon-counting avalanche photodiodes with effectively zero read-noise. Consequently, this type of sensor is ideally suited for guiding on intrinsically faint objects as long as they are relatively red (V-I $\sim 4 \mathrm{mag}$ ). The Keck II telescope with a more traditional Shack-Hartman WFS allows for improved angular resolution with higher obtainable Strehl ratios but requires brighter targets ( $\mathrm{V} \sim 15 \mathrm{mag}$ ). We compare and contrast the performance of these two types of WFS technologies in Siegler, Close, \& Freed (2002). At both Subaru and the VLT we were able to lock on our faint low mass targets with $\mathrm{I} \lesssim 15.2 \mathrm{mag}\left(\mathrm{K}_{s} \lesssim 11.2 \mathrm{mag}\right)$

### 2.2.3 Observations

The two discovered binary systems, 2M0429 and 2M1847, were detected at the VLT and Subaru observatories on 2003 February 13 (UT) and 2003 July 10 (UT), respectively. A total of six dwarfs from our sample were observed during these two runs. Table 2.1 lists the four low-mass dwarfs observed with no likely physical companion detections between $\sim 0^{\prime \prime} 1-15^{\prime \prime}$. For completeness we also include the 27 single stars observed in Paper I. Table 2.2 lists the observable properties of the two new binary systems along with the three systems presented in Paper I. Target stars were considered "observed" when a minimum corrected FWHM of $\sim 0^{\prime} .15$ in H band was achieved.

Each of the observations were made by dithering over four different quadrant positions on the infrared camera detector. For all targets we obtained both unsaturated H or $\mathrm{K}_{s}$ images ( $\leq 10 \mathrm{~s}$, "short" images), depending on seeing conditions, and saturated H images ( 30 s , "deep" images) to gain sensitivity to potential faint companions.

At Subaru we used the Coronagraphic Imager with AO (CIAO) without using the coronagraphic mask feature. The detector is a $1024 \times 1024$ ALADDIN II InSb infrared hybrid array with a platescale of $0^{\prime \prime} .0217$ pixel $^{-1}$ (Tamura et al., 2000). For 2 M 1847 we took a total of $12 \times 10 \mathrm{~s}$ short exposures at H and $\mathrm{K}_{s}, 12 \times 20 \mathrm{~s}$ at J , and $12 \times 60$ s deep exposures at H . At the VLT we observed with the Nasmyth AO System/NIR Imager and Spectrograph (NACO) system on UT4 (Yepun) which contains a $1024 \times 1024$ ALADDIN II InSb infrared hybrid array detector with a platescale of $0^{\prime} .0271$ pixel $^{-1}$. NACO is unique in that it utilizes an infrared WFS. We found that the infrared WFS was most efficient for objects with $\mathrm{K}_{s} \leq 11.2 \mathrm{mag}$. For 2 M 0429 we took a total of $16 \times 0.5 \mathrm{~s}$ short exposures at $\mathrm{H}, 8 \times 0.5 \mathrm{~s}$ at $\mathrm{K}_{s}, 12 \times 1 \mathrm{~s}$ at J , and $12 \times 30 \mathrm{~s}$ deep H frames.

Table 2.1. M6.0-M7.5 Stars Observed with No Likely Physical Companion Detections Between 0.1"-15"a

| MASS Name | Other Name | $\mathrm{K}_{s}$ | Spectral Type | Reference |
| :---: | :---: | :---: | :---: | :---: |
| 2MASS J0253008+165253 | SO 025300.5+165258 | 7.59 | M6.5 | 5 |
| 2MASSI J0330050+240528 | LP 356-770 | 11.36 | M7.0 | 1 |
| 2MASSI J0435161-160657 | LP775-31 | 9.34 | M7.0 | 2 |
| 2MASSI J0752239+161215 |  | 9.82 | M7.0 | 2 |
| 2MASSI J0818580+233352 |  | 11.13 | M7.0 | 1 |
| 2MASSW J0952219-192431 |  | 10.85 | M7.0 | 1 |
| 2MASSW J1016347+275150 | LHS 2243 | 10.95 | M7.5 | 1 |
| 2MASSI J1024099+181553 |  | 11.21 | M7.0 | 1 |
| 2MASSW J1049414+253852 |  | 11.39 | M6.0 | 1 |
| 2MASSI J1124532+132253 |  | 10.03 | M6.5 | 2 |
| 2MASSW J1200329+204851 |  | 11.82 | M7.0 | 1 |
| 2MASSW J1237270-211748 |  | 11.64 | M6.0 | 1 |
| 2MASSW J1246517+314811 | LHS 2632 | 11.23 | M6. 5 | 1 |
| 2MASSI J1253124+403404 |  | 11.20 | M7.5 | 4 |
| 2MASSW J1336504+475131 |  | 11.63 | M7.0 | 1 |
| 2MASSW J1344582+771551 |  | 11.83 | M7.0 | 1 |
| 2MASSI J1356414+434258 |  | 10.63 | M7.5 | 2 |
| 2MASSI J1431304+171758 |  | 11.16 | M6.5 | 2 |
| 2MASSI J1521010+505323 |  | 10.92 | M7.5 | 2 |
| 2MASSP J1524248+292535 |  | 10.15 | M7.5 | 3 |
| 2MASSW J1527194+413047 |  | 11.47 | M7.5 | 3 |
| 2MASSW J1543581+320642 | LP 328-36 | 11.73 | M7.5 | 1 |
| 2MASSW J1546054+374946 |  | 11.42 | M7.5 | 1 |
| 2MASSW J1550381+304103 |  | 11.92 | M7.5 | 1 |
| 2MASSW J1757154+704201 | LP 44-162 | 10.37 | M7.5 | 1 |
| 2MASSW J2052086-231809 | LP 872-22 | 11.26 | M6.5 | 1 |
| 2MASSW J2221544+272907 |  | 11.52 | M6.0 | 1 |
| 2MASSW J2233478+354747 | LP 288-31 | 11.88 | M6.0 | 1 |
| 2MASSI J2235490+184029 | LP 460-44 | 11.33 | M7.0 | 1 |
| 2MASSW J2306292-050227 |  | 10.29 | M7.5 | 1 |
| 2MASSW J2313472+211729 | LP 461-11 | 10.42 | M6.0 | 1 |

${ }^{a}$ For near-equal mass companions. For smaller companion masses with $\mathrm{q}<0.8$, sensitivity is a function of distance. See Figures 2.2 and 2.6.

References. - (1) Gizis et al. (2000) (2) Cruz et al. (2003) (3) Reid et al. (2002) (4) Kirkpatrick, Henry, \& McCarthy (1991) (5) Teegarden et al. (2003).

Table 2.2. The New Binary Systems

| System | $\Delta J$ | $\Delta H$ | $\Delta K_{s}$ | Sep. (mas) | P.A. (deg) | Date Observed (UT) | Telescope |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| LP 415-20 ${ }^{\text {a }}$ | $0.84 \pm 0.15$ | $0.77 \pm 0.10$ | $0.66 \pm 0.06$ | $119 \pm 8$ | $91.2 \pm 0.7$ | 2002 Feb. 07 | Gemini North |
| LP 475-855 ${ }^{\text {b }}$ | $0.48 \pm 0.05$ | $0.43 \pm 0.04$ | $0.48 \pm 0.03$ | $294 \pm 5$ | $131.6 \pm 0.5$ | 2001 Sep. 22 | Gemini North |
| 2MASSI J0429184-312356 ${ }^{\text {c }}$ | $1.20 \pm 0.12$ | $1.10 \pm 0.08$ | $0.98 \pm 0.08$ | $531 \pm 2$ | $298.9 \pm 0.2$ | 2003 Feb. 13 | VLT |
| 2MASSW J1750129+442404 | $0.74 \pm 0.15$ | $0.73 \pm 0.15$ | $0.64 \pm 0.10$ | $158 \pm 5$ | $339.6 \pm 0.7$ | 2002 Apr. 25 | Gemini North |
| 2MASSI J1847034+552243 ${ }^{\text {c }}$ | $0.26 \pm 0.18$ | $0.34 \pm 0.15$ | $0.16 \pm 0.10$ | $82 \pm 5$ | $91.1 \pm 1.4$ | 2003 July 10 | Subaru |

${ }^{\text {a }}$ Also known as Bryja 262.
${ }^{\mathrm{b}}$ Also known as [LHD94] 042614.2+13312 and 2MASSW J0429028+133759.
${ }^{c}$ Results from this paper; otherwise, Paper I.

### 2.2.4 Data Reduction

The images were reduced using an AO data reduction pipeline written in the IRAF language as first described in Close et al. (2002a). The pipeline produces final unsaturated exposures in $\mathrm{J}, \mathrm{H}$, and $\mathrm{K}_{s}$ with deep 720 s exposures at H band for each observed binary system. The dithering of the shorter exposures produces a final $30^{\prime \prime} \times 30^{\prime \prime}$ image with a high $\mathrm{S} / \mathrm{N}$ region in a $10^{\prime \prime} \times 10^{\prime \prime}$ box centered on the binary. In order to detect close companions within $1^{\prime \prime}$ of the central star we filter out the low spatial frequency components of the deep images leaving behind high frequency residuals in the PSF (unsharp masking). No faint companions, however, were found within the halo of our central stars using this technique. Both binary systems were detected from reductions of the shorter exposures. Figures 2.1 and 2.2 show $\mathrm{K}_{s}$ images of the two new systems.

Photometry for the more widely separated 2M0429 was performed using the DAOPHOT PSF fitting photometry package in IRAF. The PSFs used were unsaturated single stars observed during the same night with similar IR brightness, spectral type, and air mass. The errors in $\Delta$ mag, listed in Table 2.2, are the differences in the photometry between 2 similar PSF stars.

DAOPHOT could not successfully separate the strongly blended components of 2M1847 due to lower Strehl ratios caused by observing through a 1.4 airmass (the Strehl ratio and hence resolution were better at airmass of 1 when the binary was initially discovered and its components more clearly separated, however, technical difficulties resulted in delayed image acquisition). Consequently, we remove the low spatial frequencies of the binary revealing their high-frequency cores. We then perform aperture photometry using IRAF PHOT. This purely differential technique preserves the relative magnitude difference between each component while removing sufficient primary halo flux to reveal the companion

## 2M0429



Figure 2.1 An $8 \times 0.5$ s image of the newly discovered binary system 2 M 0429 shown in the $\mathrm{K}_{s}$ band; observed on 2003 February 13 (UT) at the VLT. The platescale is $0^{\prime \prime} .0271 \mathrm{pixel}^{-1}$. The contours are linear at the $80,60,40$, and $20 \%$ levels; north is up and east is to the left.


Figure 2.2 (a) A $12 \times 10$ s image of the newly discovered binary system 2 M 1847 shown in the $\mathrm{K}_{s}$ band; observed on 2003 July 10 (UT) at Subaru. The platescale is $0^{\prime \prime} .0217$ pixel $^{-1}$. The contours are linear at the 80, 60, 40, and $20 \%$ levels. (b) For comparison, the PSF star 2 M 0253 observed in the same evening and at the same airmass is displayed. The contours are linear at the $85,75,65,55,45,30$, and $15 \%$ levels. In both images, north is up and east is to the left.
centroids in $\mathrm{K}_{s}$. The technique gave reliable $\Delta$ mags and was verified on binary images with known $\Delta$ mags.

We calculate individual fluxes and their uncertainties from the measured binary flux ratios and the integrated 2MASS apparent magnitudes (2MASS All-Sky Point Source Catalog), along with their respective uncertainties. Table 2.3 lists the photometry and derived characteristics of the new binary systems.

### 2.2.5 An Example of Sensitivity: The Special Case of 2MASS 0253

One of our targets observed to have no stellar companions deserves special mention. $2 \mathrm{M} 02530084+1652532$ (hereafter 2 M 0253 ) is a newly discovered M6.5 dwarf (Teegarden et al., 2003) remarkably only 3.6 pc away. It was discovered from a search of the SkyMorph database of the Near Earth Asteroid Tracking (NEAT) project (Pravdo et al., 1999) as a high proper motion object ( $5^{\prime \prime} \mathrm{yr}^{-1}$ ). The star's proximity presented a rare observational window for the direct imaging of several Jupiter-mass, extrasolar planets. We were able to both probe semimajor

Table 2.3. Summary of the New Binaries' A and B Components

| Name | $J$ | H | $K_{s}$ | $M_{K_{s}}{ }^{\text {a }}$ | SpT ${ }^{\text {b }}$ | $\mathrm{d}_{p h o t}(\mathrm{pc})^{\mathrm{c}}$ | Mass $\left(\mathrm{M}_{\odot}\right)^{\text {d }}$ | Sep. (AU) ${ }^{\text {e }}$ | $\mathrm{P}(\mathrm{yr})^{\mathrm{f}}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| LP 415-20A | $13.09 \pm 0.06$ | $12.47 \pm 0.05$ | $12.12 \pm 0.04$ | $9.72 \pm 0.38$ | M7.0 | $30 \pm 5$ | $0.097_{-0.012}^{+0.011}$ | $3.6 \pm 0.7$ | $23_{-6}^{+7}$ |
| LP 415-20B | $13.93 \pm 0.16$ | $13.24 \pm 0.11$ | $12.78 \pm 0.08$ | $10.37 \pm 0.39$ | M9.5 |  | $0.081_{-0.010}^{+0.009}$ |  |  |
| LP 475-855A | $13.21 \pm 0.04$ | $12.54 \pm 0.04$ | $12.18 \pm 0.04$ | $9.84 \pm 0.36$ | M7.5 | $29 \pm 5$ | $0.093_{-0.009}^{+0.012}$ | $8.6 \pm 1.5$ | $86_{-19}^{+20}$ |
| LP 475-855B | $13.69 \pm 0.07$ | $12.97 \pm 0.06$ | $12.66 \pm 0.05$ | $10.32 \pm 0.36$ | M9.5 |  | $0.082_{-0.009}^{+0.009}$ |  |  |
| $2 \mathrm{M} 0429 \mathrm{~A}^{\mathrm{g}}$ | $11.18 \pm 0.04$ | $10.55 \pm 0.03$ | $10.14 \pm 0.03$ | $9.88 \pm 0.35$ | M7.5 | $11 \pm 2$ | $0.094_{-0.011}^{+0.010}$ | $6.0 \pm 1.0$ | $50_{-11}^{+12}$ |
| 2 M 0429 B g | $12.38 \pm 0.13$ | $11.65 \pm 0.09$ | $11.12 \pm 0.07$ | $10.86 \pm 0.36$ | L1.0 |  | $0.079_{-0.018}^{+0.005}$ |  |  |
| 2M1750A | $13.23 \pm 0.06$ | $12.62 \pm 0.06$ | $12.24 \pm 0.05$ | $9.77 \pm 0.39$ | M7.5 | $31 \pm 6$ | $0.097_{-0.012}^{+0.012}$ | $4.9 \pm 0.9$ | $36_{-9}^{+10}$ |
| 2M1750B | $13.97 \pm 0.16$ | $13.35 \pm 0.16$ | $12.88 \pm 0.11$ | $10.41 \pm 0.41$ | M9.5 |  | $0.085_{-0.016}^{+0.006}$ |  |  |
| $2 \mathrm{M} 1847 \mathrm{~A}^{\mathrm{g}}$ | $12.55 \pm 0.08$ | $11.87 \pm 0.07$ | $11.58 \pm 0.05$ | $9.72 \pm 0.41$ | M7.0 | $23 \pm 4$ | $0.098_{-0.012}^{+0.022}$ | $1.9 \pm 0.4$ | $9_{-2}^{+3}$ |
| 2M1847B ${ }^{\text {g }}$ | $12.81 \pm 0.20$ | $12.21 \pm 0.16$ | $11.74 \pm 0.11$ | $9.88 \pm 0.42$ | M7.5 |  | $0.094_{-0.013}^{+0.014}$ |  |  |

${ }^{\mathrm{a}} \mathrm{M}_{K_{s}}=7.65+2.13\left(\mathrm{~J}-K_{s}\right)$ with a rms $\sigma_{M_{K s}}=0.33$ derived in Paper I (§4.2); relationship is valid for M6.5 $<\mathrm{SpT}<\mathrm{L} 1$.
${ }^{\mathrm{b}}$ Spectral type estimated by $\mathrm{SpT}=3.54 \mathrm{M}_{K_{s}}-27.20$ with $\pm 1.5$ spectral subclasses of error in these estimates as derived in paper I (§4.5). SpT $=10$ is defined as an L 0 ; valid for $\mathrm{M} 6.5<\mathrm{SpT}<\mathrm{L} 1$.
${ }^{\mathrm{c}}$ Distances based on $\mathrm{M}_{K_{s}}$ as described in $\S 4.2$.
${ }^{\mathrm{d}}$ Mass determination uses the models of Chabrier et al. (2000).
${ }^{e}$ Projected separations.
${ }^{\mathrm{f}}$ Periods include a 1.26 multiplication of the projected separations compensating for random inclinations and eccentricities (Fischer \& Marcy, 1992).
${ }^{\mathrm{g}}$ This paper; otherwise, Paper I.
axis separations to within $\sim 3 \mathrm{AU}$ of the star, comparable to the separations of known extrasolar planets detected through radial velocity studies $(\mathrm{a} \lesssim 6 \mathrm{AU}$; http:/ /exoplanets.org) and outside the speckle-dominated region on the detector ( $\gtrsim 1^{\prime \prime}$ ). We were the first to observe this object with high resolution on 2003 July 14 (UT) using the NIRC2 camera and AO (Wizinowich et al., 2000) on the W. M. Keck II telescope. The $0^{\prime} .01$ pixel $^{-1}$ plate scale mode was used on the $1024 \times 1024$ pixel array.

2M0253 was only observable for approximately 1 hour in the early morning. We achieved sensitivity to companions of $\mathrm{H}=19.6$ at $1^{\prime \prime} .5$ in 24 min of total integration time $(49 \times 30$ s frames in a 4 -dither pattern). We fully saturated the central star so as to allow for the detection of any massive faint Jupiter planets orbiting greater than $1^{\prime \prime}$ ( 2.6 AU ) from the central star. No faint companions were detected.

The 24 min of total integration time enables us to establish upper limits on planetary masses orbiting this star. We construct an unsaturated PSF of the star by replacing the saturated core with scaled unsaturated pixels from a short exposure. We determine maximum H band $\Delta$ mag contrasts by combining scaled models of faint companions (with appropriate PSFs) at various radial distances until a $5 \sigma$ detection is obtained. Figure 2.3 shows the resulting $5 \sigma$ limiting magnitudes at several radial distances from the central star. The horizontal dashed lines indicate the H band $\Delta$ mag required for the detection of $5 \mathrm{Gyr}, 10 \mathrm{M}_{J}$ and $25 \mathrm{M}_{J}$ objects using the models of Burgasser et al. (2003a). We use the peak of their H band spectra to estimate the flux emission in this exercise. The star's age is not known but based on its high tangential velocity we can assume it is an older object (Wielen, 1974). The figure demonstrates sensitivity to an 11 Jupitermass extrasolar planet at only $\sim 4 \mathrm{AU}\left(1.5^{\prime \prime}\right)$ away. In Figure 2.4 we show the fully


Figure 2.3 Instrument sensitivity curve showing $5 \sigma \Delta \mathrm{H}$ detection versus distance in arcsec from the very nearby M6.5 star 2M0253. Total integration time is 24 min using Keck II AO. The "crosses" indicate the $5 \sigma$ sensitivity limits of our data to simulated faint companions. The upper horizontal dashed line corresponds to a 5 Gyr old, $25 \mathrm{M}_{J}$ brown dwarf using the models of Burgasser et al. (2003a) while the lower horizontal dashed line corresponds to a 5 Gyr old, $10 \mathrm{M}_{J}$ planet. We were sensitive to the detection of a $10 \mathrm{M}_{J}$ planet at 4 AU and a $25 \mathrm{M}_{J}$ brown dwarf at 1.5 AU (assuming 2 M 0253 is only 3.6 pc away and 5 Gyr old).
reduced Keck image of 2M0253 spatially filtered of its low frequency halo, leaving behind high frequency residuals in the core (superspeckles). This image also illustrates that with conventional AO , speckle noise limits the detection of faint companions within the inner $\sim 1^{\prime \prime}$ of the halo.

### 2.3 Analysis

### 2.3.1 Are the Companions Physically Related to the Primaries?

From the total of 69 objects already observed in both this survey and a companion survey of M8.0-L0.5 stars by the authors (Close et al., 2003), we did not detect any additional unknown red $\left(\mathrm{J}-\mathrm{K}_{s}>0.8 \mathrm{mag}\right)$ background objects in $6.2 \times 10^{4}$ square


Figure 2.4 Reduced 24 min image of 2 M 0253 observed at Keck II on 2003 July 14 (UT) with its low spatial frequencies removed (unsharp masked). The simulated $5 \sigma$ companion is 33,000 times fainter than the central star $(\Delta \mathrm{H}=11.3)$ at only 3.6 AU (1.5"). Teegarden et al. (2003) report $\mathrm{H}=7.9$ for the central star which allows detection to a 5 Gyr old, $11 \mathrm{M}_{J}$ planet according to the models of Burgasser et al. (2003a). Also visible are the residuals from the 6 spider arms and super speckles. To within our sensitivity limits we find no companions to 2 M 0253 .
arcsec. Therefore, we estimate the probability of a chance projection of a comparably red object within $0.5^{\prime \prime}$ of the primary to be $<1.3 \times 10^{-5}$. As we argued in Paper I, with an M6-M8 dwarf density of $0.007 \mathrm{pc}^{-3}$ in the local solar neighborhood (Reid \& Gizis, 1997a), the probability of an apparent companion being just a background star at, for example, twice the distance of the target star (hence fainter by a $\Delta$ magnitude of 1.5 mag ) and appearing within $0.5^{\prime \prime}$ of any of our targets is estimated to only be $\sim 3 \times 10^{-7}$. Additionally, none of the companion images appear spatially extended as might be expected of background galaxies. Therefore, we conclude that both of the very red companions are physically associated with their primaries and hereafter we will refer to them as 2M0429B and 2M1847B.

### 2.3.2 Distances

Neither of the 2 binary systems have published trigonometric parallaxes. We estimate distances to both primaries from a color-magnitude diagram developed in Paper I based on trigonometric parallaxes of other well-studied, late-M, field dwarfs from Dahn et al. (2002). Using corresponding 2MASS photometry for each star with a trigonometric parallax, we estimated a linear least-squares fit of $\mathrm{M}_{K_{s}}=$ $7.65+2.13\left(\mathrm{~J}-\mathrm{K}_{s}\right)$ for the spectral range M6.5-L1. This relationship has a $1 \sigma$ error of 0.33 mag , which has been added in quadrature to the J and $\mathrm{K}_{s}$ photometric errors to yield the primarys' $\mathrm{M}_{K_{s}}$ values reported in Table 2.3. We then use the distance modulus of the primary to estimate the distances to the binaries. The calculated distances are listed in Table 2.3.

### 2.3.3 Spectral Types and Temperatures

We do not have spatially resolved spectra of the individual components in either of the 2 new systems. We estimate the spectral types of each of the binary compo-
nents by using the relation $\mathrm{SpT}=3.54 \mathrm{M}_{K_{s}}-27.20$ derived in Paper I from the data set of Dahn et al. (2002) (eg. SpT $=8$ is an M8, $\mathrm{SpT}=10$ is an L0, etc). This relationship has a $1 \sigma$ error of 0.85 spectral types which when taken in quadrature with the uncertainty in $\mathrm{M}_{K_{s}}$ gives an overall uncertainty of about 1.5 spectral types. Fortunately, none of analysis is dependent on these spectral type estimates. The results are listed in Table 2.3.

Effective temperatures of the binary components are estimated from the DUSTY evolutionary tracks (Chabrier et al., 2000) using calculated $\mathrm{M}_{K_{s}}$ values and estimated ages (see Figures 2.5 and 2.6). We estimate 2M0429A and 2M0429B to have effective temperatures of $2690_{-170}^{+160} \mathrm{~K}$ and $2240_{-260}^{+190} \mathrm{~K}$, respectively; 2M 1847A and 2 M 1847 B are estimated at $2760_{-260}^{+280} \mathrm{~K}$ and $2690_{-210}^{+220} \mathrm{~K}$, respectively. These estimated temperatures are in very good agreement with those predicted in Dahn et al. (2002) for the given spectral types.

### 2.3.4 Ages and Masses

Estimating the age of late-type field dwarfs without Li measurements or established cluster membership is difficult. Consequently, we conservatively assume a mean age of $\sim 5 \mathrm{Gyr}$ for our objects with uncertainty spanning the range of common ages in the solar neighborhood (0.6-7.5 Gyr; Caloi et al., 1999).

To estimate masses of these objects we rely on luminosity-mass-age models for VLM stars and brown dwarfs. We utilize the DUSTY models to provide theoretical estimates for both stellar and substellar masses as a function of both absolute $\mathrm{K}_{s}$ magnitude and age. The tracks are calibrated for the $\mathrm{K}_{s}$ bandpass (I. Baraffe, private communication) and we extrapolate the isochrones from 0.10 to $0.11 \mathrm{M}_{\odot}$ so as to enclose the upper mass limits of our central stars. The companion's absolute magnitude is simply determined by adding the measured $\Delta \mathrm{K}_{s}$ to its primary star's $\mathrm{M}_{K_{s}}$. The crosses in Figures 2.5 and 2.6 indicate the best estimates of where


Figure 2.5 Chabrier et al. (2000) DUSTY stellar and substellar evolutionary tracks custom integrated over the $\mathrm{K}_{s}$ bandpass $([\mathrm{m} / \mathrm{H}]=0)$. The best-guess values of the individual binary components of 2M0429 are indicated by the bold "crosses" with the primary at the top right and the companion lower and to the left. The shaded polygons enclose each components' region of uncertainty. The components' derived $\mathrm{M}_{K_{s}}$ is listed in Table 2.3. With no knowledge of the binary's age, we conservatively assign a mean age of 5 Gyr and uncertainties spanning the range of ages in the solar neighborhood (0.6-7.5 Gyr; Caloi et al., 1999). The model suggests a primary mass of $0.094_{-0.011}^{+0.010} \mathrm{M}_{\odot}$ and a temperature of $2690_{-170}^{+160} \mathrm{~K}$. For the companion, the model predicts a mass of $0.079_{-0.018}^{+0.005} \mathrm{M}_{\odot}$ and a temperature of $2240_{-200}^{+190} \mathrm{~K}$. The isochrones plotted are (left to right) $0.6,0.65,0.7$, $0.85,1.2,1.7,3.0,5.0,7.5$, and 10.0 Gyr (the oldest 4 isochrones are indistinguishable at the given scaling).


Figure 2.6 As in Figure 2.5, but for 2M1847. In this case the shaded regions of uncertainty of the 2 components overlap. Hence, we outline the primary star's in solid and the companion in dotted lines (where the two regions overlap solid takes preference). The model suggests a primary mass of $0.098_{-0.012}^{+0.022} \mathrm{M}_{\odot}$ and a temperature of $2760_{-260}^{+280} \mathrm{~K}$. For the secondary the model suggests a mass of $0.094_{-0.013}^{+0.014} \mathrm{M}_{\odot}$ and temperature of $2690_{-210}^{+220} \mathrm{~K}$.
the binary components lie on the 5 Gyr tracks and their uncertainties are represented by the shaded regions. 2M0429A's region of uncertainty is displayed in the upper right while its companion is displayed in the lower left. Because the 2 M 1847 binary system is of near equal magnitudes, their regions of uncertainty largely overlap. In this case the slightly more massive primary's region of uncertainty is indicated in bold outline and the portion of the companion's not overlapping is dashed. The maximum mass is related to the minimum $\mathrm{M}_{K_{s}}$ at the oldest possible age; the minimum mass is related to the maximum $\mathrm{M}_{K_{s}}$ at the youngest possible age. Table 2.3 lists the estimated masses for both binary systems. Both systems' primary masses are consistent with M7-type dwarfs and their secondaries are most likely stellar, however, 2M 0429B's uncertainties extend well into the substellar region according to the model. The uncertainty in the masses, as well as in the effective temperatures, is largely driven by the uncertainty in our determination of $\mathrm{M}_{K_{s}}(\sigma=0.33 \mathrm{mag})$ as obtained from the $\left[\mathrm{M}_{K_{s}}, \mathrm{~J}-\mathrm{K}_{s}\right]$ color magnitude diagram linear fit from Paper I. Future observations of trigonometric parallaxes would significantly reduce the uncertainty in $\mathrm{M}_{K_{s}}$ and hence the masses and temperatures.

### 2.3.5 The Binary Frequency of M6.0-M7.5 Stars

We update the binary fraction statistics of M6.0-M7.5 stars combining the latest results presented here ( 2 binaries resolved out of 6 ) with those from Paper I (3 binaries out of 30). This implies an observed, uncorrected binary fraction of $14_{-4}^{+8} \%$ using a Poisson distribution for the uncertainty (Burgasser et al., 2003a). However, this sample was originally drawn from a magnitude-limited sample and hence the observed binary fraction is biased due to the leakage of equal magnitude binaries into our sample from further distances (Malmquist bias). We therefore need to correct our result due to this bias as well as consider sample
incompleteness due to undetected very tight lower mass companions.
To compensate for the fainter single stars not included in our flux-limited sample we first adjust for a larger observed volume due to the discovered binaries by a volume correction factor. This factor is simply the ratio of the spherical volume containing $95 \%$ of our detected binaries and the spherical volume containing $95 \%$ of our target objects. This results in a volume correction factor of $(30 \mathrm{pc} / 24 \mathrm{pc})^{3}=2$ and a Malmquist-corrected binary fraction of $5 /(36 \times 2)$ or $7_{-2}^{+4} \%$.

The possibility that there were faint companions, both stellar and non-stellar, not detected due to instrument insensitivity is a real one. The curve in Figure 2.7 shows the instrumental sensitivity of our sample in the speckle noise limited region ( $<1^{\prime \prime}, 30 \mathrm{AU}$ for a star assumed 30 pc away) as a function of mass ratio and projected separation in AU. It is based on modelling of a 5 Gyr (typical of the ages expected for field stars Gizis et al. (2000)), M6.5 dwarf placed at 30 pc (typical of the distances of our discovered binaries) observed at the 8-m Gemini North telescope. We use the DUSTY models to convert $\Delta \mathrm{H}$ magnitudes to mass ratios. The reason we convert to mass ratios is because it allows us to use the observed mass ratio distribution for VLM binaries (Close et al., 2003) to predict the number of missed companions with $\mathrm{q} \geq 0.6$. The five large asterisks in Figure 2.7 represent the five discovered binary systems from this survey. Interestingly, they are all found in the upper left corner of the sensitivity curve. The fact that some are so near the curve strongly infers that binaries just below the sensitivity curve were most likely missed.

To apply an instrument-sensitivity correction we need to estimate how many binaries went undetected in our sample. We generate a Monte Carlo simulation of 11670 synthetic companions with the binary properties of VLM systems. For our


Figure 2.7 The results from a Monte Carlo simulation generating 11,670 companions distributed according to a bivariate distribution (mass ratio $q$ and separation a) is plotted over the instrumentation sensitivity curve (connected lines). We assume the two distributions are independent. We assume a power law declining from unity to 0.6 for the mass ratio distribution (Close et al., 2003) and the profile from Figure 2.8 for the separation distribution for a $>3 \mathrm{AU}$. The instrumentation sensitivity curve is based on modeling of a $\sim 5 \mathrm{Gyr}$ M6.5 dwarf placed at 30 pc , typical of the distances of our discovered binaries. The DUSTY models (Chabrier et al., 2000) are used to convert $\Delta \mathrm{H}$ magnitudes to mass ratios. The 5 discovered binary systems are indicated by large asterisks. $21 \%$ of the synthetic companions fall below the instrumentation sensitivity curve but above the instrument sensitivity mass ratio cutoff of $\mathrm{q}=0.6$. This results in a sensitivity correction of 1.3 binaries.
model we use the mass ratio and separation distributions for VLM binaries and assume that the distributions are independent. For the mass ratio distribution we assume a power law decline from unity to 0.6 from Close et al. (2003). We created the separation distribution profile by plotting the 42 most tightly separated and resolved VLM ( $\mathrm{M}_{t o t}<0.20 \mathrm{M}_{\odot}$ ) binaries known in the literature in 2004. Last presented in Siegler et al. (2005), we update the list of all known VLM binaries and present it in Table 2.4 (see $\S 2.3 .6$ ). The peak of this distribution, $\sim 5 \mathrm{AU}$, is much tighter than the $\sim 30 \mathrm{AU}$ distribution peak of slightly more massive M0-M4 dwarfs (Fischer \& Marcy, 1992) and solar-mass stars (Duquennoy \& Mayor, 1991). The separation distribution is bound by the smallest separation the instruments were able to obtain in H band ( $\sim 0^{\prime \prime} .08 \times 30 \mathrm{pc}$ ) on the near side and the empirically sampled wider separation encompassing $95 \%$ of the VLM binaries (Table 2.4) on the far side.


Figure 2.8 Distribution of projected separation for known VLM binary systems (Table 2.4). The number of VLM binary systems in each 0.3 dex bin is labeled and uncertainties (vertical lines) are derived from a binomial distribution. Note that spectroscopic binaries with unknown separations are not plotted but included in the total number of binaries for scaling the distribution. The distribution peaks at separations around 3-10 AU, with steep declines at shorter and longer separations. While there is likely observational incompleteness for separations less than about 3 AU , the sharp drop in binary systems with separations greater than about 25 AU is a real, statistically robust feature. The shaded bins represent the ten systems with ages less than 10 Myr . While the statistics are still small, the separation distribution of these young binaries is flatter and suggests a peak at wider separations than that of the field and older cluster binaries.

Table 2.4. All Known Resolved VLM Binaries ${ }^{\text {a }}$

| Name | Sep. ${ }^{\text {b }}$ <br> (AU) | Sep. (mas) | $\mathrm{SpT}_{A}$ | $\mathrm{SpT}_{B}$ | Mass $_{A}$ $\left(M_{\odot}\right)$ | Mass $_{B}$ $\left(M_{\odot}\right)$ | Period ${ }^{\mathrm{C}}$ <br> (yr) | $\begin{gathered} \text { Age }{ }^{\mathrm{i}} \\ (\mathrm{Myr}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 2MASSJ0253202+271333 | - | - | M8 | M8: | 0.092 | 0.092 ? | - | - |
| 2MASSJ0952219-192431 | - | - | M7 | M7: | 0.098 | 0.098 ? | - | - |
| LHS292 | - | - | M7 | M7: | 0.098 | 0.098 ? | - | - |
| ChaHa8 | - | - | M6.5 | - | 0.08 | - | - | 2 |
| 2MASSJ2113029-100941 | - | - | M6 | M6 | 0.085 | 0.085 | - | - |
| PPl15 | 0.03 | - | M7 | M8 | 0.070 | 0.060 | 0.0159 | 120 |
| 2MASSJ0535218-054608 | 0.04 | - | M6.5 | M6.5 | 0.054 | 0.034 | 0.0268 | 1 |
| 2MASSJ1534498-295227 | 0.9 | 65 | T5.5 | T5.5 | 0.035 | 0.035 | 4 | - |
| GJ569B | 0.90 | 103 | M9.0 | M9.0 | 0.071 | 0.054 | 2.4 | 100? |
| 2MASSJ0004348-404406 | 1.0 | 87 | L4.5 | L4.5 | 0.068 | 0.068 | 4 | - |
| LP349-25 | 1.3 | 125 | M8 | M9 | 0.090 | 0.085 | 4 | - |
| 2MASSJ1112256+354813 | 1.5 | 70 | L4.5 | L6 | 0.073 | 0.070 | 7 | - |
| 2MASSJ0920122+351742 | 1.5 | 70 | L6.5 | T : | 0.068 | 0.068 | 6 | - |
| 2MASSJ2132114+134158 | 1.8 | 66 | L5 | L7.5 | 0.078 | 0.075 | 10 | - |
| 2MASSJ0518599-282837 | 1.8 | 51 | L6: | T4: | 0.07 | 0.05 | 10 | - |
| 2MASSJ1847034+552243 | 1.9 | 82 | M7 | M7.5 | 0.098 | 0.094 | 8 | - |
| 2MASSJ2252107-173013 | 1.9 | 140 | L6: | T2: | 0.075 | 0.065 | 10 | - |
| 2MASSJ0700366+315727 | 2.1 | 170 | L3.5 | L6: | 0.071 | 0.060 | 12 | - |
| DENIS-PJ035726.9-441730 | 2.2 | 98 | M9 | L1.5 | 0.085 | 0.08 | 11 | - |
| HD130948B | 2.4 | 134 | L4 | L4 | 0.070 | 0.060 | 14 | - |
| SDSS-J042348.57-041403.5 | 2.5 | 164 | L6.5 | T2 | 0.06 | 0.05 | 19 | - |
| 2MASSWJ0746425+200032 | 2.5 | 220 | L0 | L1.5 | 0.085 | 0.066 | 11 | $300 ?$ |
| SDSS-J092615.38+584720.9 | 2.6 | 70 | T4: | T4: | 0.07 | 0.06 | 17 | - |
| epsilonIndiB | 2.6 | 732 | T1 | T6 | 0.045 | 0.027 | 22 | 1300 |
| 2MASSWJ1430436+291541 | 2.6 | 88 | L2: | L3: | 0.076 | 0.075 | 15 | - |
| 2MASSJ1728114+394859 | 2.7 | 131 | L7 | T: | 0.069 | 0.066 | 16 | - |
| 2MASSJ1047138+402649 | 2.8 | 122 | M8 | L0 | 0.092 | 0.084 | 15 | - |
| LHS2397a | 3.0 | 207 | M8 | L7.5 | 0.090 | 0.068 | 18 | - |
| LSPM1735+2634 | 3.2 | 290 | M9: | M9: | 0.082 | 0.074 | 20 | - |
| LHS1070B | 3.4 | 446 | M8.5 | M9 | 0.070 | 0.068 | 16 | - |
| 2MASSJ0856479+223518 | 3.4 | 98 | L5: | L8: | 0.071 | 0.064 | 24 | - |
| 2MASSWJ1017075+130839 | 3.4 | 104 | L2 | L2 | 0.076 | 0.076 | 23 | - |
| SDSS2335583-001304 | 3.5 | 57 | L1: | L4: | 0.079 | 0.074 | 24 | - |
| 2MASSJ1600054+170832 | 3.5 | 57 | L1 | L3 | 0.078 | 0.075 | 23 | - |
| LP415-20 | 3.6 | 119 | M7 | M9.5 | 0.095 | 0.079 | 22 | 625 |
| 2MASSJ1225543-273946 | 3.8 | 282 | T6 | T8 | 0.033 | 0.024 | 43 | - |
| SDSS-J153417.05+161546.1 | 4.0 | 110 | T1.5 | T5.5 | 0.05 | 0.04 | 28 | - |
| 2MASSJ1426316+155701 | 4.0 | 152 | M8 | L1.5 | 0.088 | 0.076 | 27 | - |
| 2MASSJ2140293+162518 | 4.0 | 155 | M9 | L2 | 0.092 | 0.078 | 27 | - |
| LHS1901 | 4 | 275 | M6.5 | M7.5 | 0.085 | 0.082 | 20 | - |
| 2MASSJ1553022+153236 | 4.2 | 349 | T6.5 | T7 | 0.040 | 0.035 | 44 | - |
| SCR1845-6357 | 4.5 | 1170 | M8.5 | T5.5 | 0.09 | 0.04 | 37 | - |
| 2MASSJ1239272+551537 | 4.5 | 211 | L5 | L5 | 0.071 | 0.071 | 35 | - |
| 2MASSJ2206228-204705 | 4.5 | 168 | M8 | M8 | 0.092 | 0.091 | 31 | - |

From this sample of nearly 12,000 simulated companions, $21 \%$ were below the instrument sensitivity curve (but above the instrument sensitivity mass ratio cutoff of $\mathrm{q}=0.6$ ) as shown in Figure 2.7. With 5 detected binaries, this predicts 1.3 companions were missed in our survey. Hence we conclude that the binary fraction for M6.0-M7.5 stars is (5+1.3)/36/2 or $9_{-3}^{+4} \%$. It should be pointed out, however, that the true fraction is most certainly larger than this figure since we cannot rule out the possibility of the existence of low $q$ binaries due to the sensitivity of this survey. Therefore, our reported binary fraction, accurate within the uncertainties for M6.0-M7.5 dwarfs for separations greater than 3 AU , represents a low-end estimate to the intrinsic binary fraction.

With slightly improved statistics, this latest result for the binary fraction of M6.0-M7.5 stars is now more comparable with those of later spectral types: $15 \pm 7 \%$ for late M/early L dwarfs (Close et al., 2003), 10-15\% and 15 $\pm 5 \%$ for L dwarfs (Bouy et al., 2003; Gizis et al., 2003, respectively) and $9_{-4}^{+15} \%$ for T dwarfs (Burgasser et al., 2003a). These cooler dwarfs including the ones presented here all have binary fractions significantly lower than the $\sim 32 \%$ observed for earlier M0M4 dwarfs (Fischer \& Marcy, 1992) and the $\sim 50 \%$ for solar-mass stars (Duquennoy \& Mayor, 1991) over the same $\mathrm{a}>3$ AU separation range. Our conclusion from Paper I is strengthened: for spectral type M6.0-M7.5 binary systems with separations 3 AU $<a<300$ AU the binary fraction from our survey is $9_{-3}^{+4} \%$, statistically consistent with cooler $M, L$, and $T$ stars and significantly less common than that of $G$ and early $M$ stars.

### 2.3.6 The Very Lowest Mass Binary Systems

In Table 2.4, we list the 87 VLM binary systems published in the literature as of March 2007. The mass criterion used in the Table (total system mass less than $<0.20 \mathrm{M}_{\odot}$ ) corresponds to field dwarf binary compo-

Table 2.4-Continued

| Name | $\begin{aligned} & \text { Sep. }^{\text {b }} \\ & \text { (AU) } \end{aligned}$ | Sep. (mas) | $\mathrm{SpT}_{A}$ | $\mathrm{SpT}_{B}$ | $\begin{aligned} & \operatorname{Mass}_{A} \\ & \left(M_{\odot}\right) \end{aligned}$ | $\begin{gathered} \text { Mass }_{B} \\ \left(M_{\odot}\right) \end{gathered}$ | Period ${ }^{\mathrm{c}}$ <br> (yr) | $\begin{gathered} \text { Age }^{\mathrm{i}} \\ (\mathrm{Myr}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 2MASSsJ0850359+105716 | 4.7 | 160 | L6 | T: | 0.04 | 0.03 | 39 | - |
| 2MASSWJ1750129+442404 | 4.9 | 158 | M7.5 | L0 | 0.095 | 0.084 | 36 | - |
| UScoCTIO-109 | 4.9 | 34 | M6 | M7.5 | 0.070 | 0.040 | 46 | 5 |
| SDSS-J102109.69-030420.1 | 5.0 | 172 | T1 | T5 | 0.06 | 0.05 | 48 | - |
| Kelu-1 | 5.4 | 291 | L2 | L4 | 0.060 | 0.055 | 52 | - |
| 2MASSJ0429184-312356 | 5.8 | 531 | M7.5 | L1 | 0.094 | 0.079 | 48 | - |
| WT460 | 5.9 | 511 | M6 | L1 | 0.12 | 0.075 | 40 | - |
| 2MASSJ2152260+093757 | 6.0 | 250 | L6: | L6: | 0.075 | 0.075 | 56 | - |
| MHO-Tau-8 | 6.2 | 44 | M6 | M6. 5 | 0.100 | 0.070 | 53 | 2 |
| 2MASSJ0147328-495448 | 6.3 | 190 | M8: | L2: | 0.084 | 0.080 | 55 | - |
| DENIS-PJ1228.2-1547 | 6.4 | 251 | L6 | L6 | 0.060 | 0.060 | 44 | - |
| DENIS-PJ100428.3-114648 | 6.8 | 146 | M9.5 | L0. 5 | 0.080 | 0.076 | 63 | - |
| 2MASSJ2147436+143131 | 7.0 | 322 | L0 | L2 | 0.084 | 0.078 | 65 | - |
| DENIS-PJ185950.9-370632 | 7.7 | 60 | L0 | L3 | 0.084 | 0.076 | 76 | 5 |
| 2MASSJ1311391+803222 | 7.7 | 267 | M7.5 | M8 | 0.089 | 0.087 | 72 | - |
| 2MASSWJ2101154+175658 | 7.8 | 234 | L7 | L8 | 0.068 | 0.065 | 84 | - |
| IPMBD29 | 7.8 | 58 | L1 | L4 | 0.045 | 0.038 | 106 | 120 |
| 2MASSJ1146345+223053 | 7.9 | 290 | L2 | L2 | 0.055 | 0.055 | 94 | - |
| CFHT-PI-12 | 8.3 | 62 | M8 | L4 | 0.054 | 0.038 | 111 | 120 |
| 2MASSJ1127534+741107 | 8.4 | 246 | M8 | M9 | 0.092 | 0.087 | 80 | - |
| 2MASSJ1449378+235537 | 8.5 | 134 | L0 | L3 | 0.084 | 0.075 | 88 | - |
| LP475-855 | 8.5 | 294 | M7.5 | M9.5 | 0.091 | 0.080 | 85 | 625 |
| DENIS-PJ020529.0-115925 | 9.2 | 510 | L5 | L6 | 0.07 | 0.07 | 105 | - |
| 2MASSJ0025036+475919 | 10.2 | 330 | L4 | L4 | 0.048 | 0.047 | 149 | - |
| UScoCTIO-66 | 10.2 | 70 | M6 | M6 | 0.070 | 0.070 | 122 | 5 |
| G1337C | 10.9 | 530 | L8 | T: | 0.055 | 0.055 | 152 | - |
| 2MASSJ0915341+042204 | 10.8 | 730 | L7 | L7 | 0.072 | 0.072 | 132 | - |
| IPMBD25 | 12.6 | 94 | M7 | L4 | 0.063 | 0.039 | 197 | 120 |
| DENIS-PJ144137.3-094559 | 14.3 | 420 | L1 | L1 | 0.072 | 0.072 | 201 | - |
| 2MASSJ2331016-040618 | 15.0 | 573 | M8.5 | L7 | 0.093 | 0.067 | 205 | - |
| 2MASSJ1707234-055824 | 15.2 | 1010 | M9 | L3 | 0.083 | 0.077 | 210 | - |
| UScoCTIO-55 | 17.7 | 122 | M5.5 | M6 | 0.100 | 0.070 | 255 | 5 |
| 2MASSJ1520022-442242 | 22 | 1174 | L1.5 | L4. 5 | 0.082 | 0.077 | 400 | - |
| CFHT-PI-18 | 34.6 | 330 | M8 | M8 | 0.090 | 0.090 | 679 | - |
| DENIS-J220002.0-303832.9 | 38.2 | 1090 | M8 | L0 | 0.085 | 0.083 | 813 | - |
| 2MASSJ1207334-393254 | 41.1 | 776 | M8.5 | L: | 0.024 | 0.004 | 2250 | 8 |
| 2MASSJ1623361-240221 | 212 | 1696 | M5 | M5.5 | 0.096 | 0.070 | 8000 | 5 |
| DENIS-J055146.0-443412.2 | 220.0 | 2200 | M8.5 | L0 | 0.085 | 0.079 | 11500 | - |
| 2MASSJ1101192-773238 | 241.9 | 1440 | M7 | M8 | 0.050 | 0.025 | 19500 | 2 |
| 2MASSJ1622252-240514 | 243 | 1943 | M9 | M9.5 | 0.017 | 0.015 | 20000 | 5 |
| Koenigstuhl-1 | 1800 | 77760 | M6: | M9.5 | 0.103 | 0.079 | 170000 | - |
| 2MASSJ0126555-502239 | 5100 | 81860 | M6.5 | M8 | 0.095 | 0.092 | 1E6 | - |

${ }^{\mathrm{a}} \mathrm{VLM}$ binaries are defined as systems whose total mass is $\leq 0.20 \mathrm{M}_{\odot}$.
${ }^{\mathrm{b}}$ Projected separation except for the systems where semimajor axes have been measured.
${ }^{\text {c }}$ An estimate assuming a face-on circular orbit except for the systems where the period has been measured.
Note. - (i) Additional data including uncertainties and references for each binary system can be found at the Very-Low-Mass Binaries Archive (see http://paperclip.as.arizona.edu/~nsiegler/VLM_binaries), (ii) Systems without listed separations are spectroscopic binaries.
nents later than about spectral types M5; younger systems may include younger spectral types. Table 2.4 provides a subset of the compiled data for these sources, given in more complete detail through an online database maintained by the author entitled The Very-Low-Mass Binaries Archive (see http:/ / paperclip.as.arizona.edu/~nsiegler/VLM_binaries).

The motivation for the Archive is to provide a common location where the empirical data of low-mass multiplicity can be readily accessed. It targets both observers and theorists who are interested in understanding the range of observations and the constraints they present in theoretical formation models. A list of the lowest mass binaries was last published in Burgasser et al. (2007) where a statistical analysis of the trends and properties was conducted. The list has since been kept updated at the on-line website. For recent reviews of the models attempting to explain the formation mechanisms and characteristics of VLM binaries, see Duchêne et al. (2007); Luhman et al. (2007); Whitworth et al. (2007).

### 2.3.7 The Separation Distribution Function

The 2 M 0429 and 2 M 1847 binary systems have best-estimate projected separations of 6 AU and 2 AU , respectively. In our total M6.0-M7.5 sample, we detected no systems with estimated semimajor axes greater than 15 AU . With our survey sensitive out to about $15^{\prime \prime}$ from the central star, this result suggests a real behavior of VLM binaries and not a result of a sensitivity selection effect. When examining the entire VLM sample of known binary systems in Table 2.4, only $10 \%(11 / 87)$ have a projected separation $>25 \mathrm{AU}$. This suggests that while wide VLM binaries of $q>0.6$ exist, they are infrequent.

The median projected separation of our entire M6.0-M7.5 binary sample is about 5 AU , consistent with the $\sim 4 \mathrm{AU}$ peak distribution of late M/early L binaries (Close et al., 2003), L dwarfs (Gizis et al., 2003; Bouy et al., 2003), and T dwarfs
(Burgasser et al., 2003a). In Figure 2.8, we show the separation distribution for 87 VLM binary systems and observe an overall peak in the distribution near 310 AU. The distribution declines steeply at both shorter and longer separations. While there is likely observational incompleteness for binaries with separations less than about 3 AU , the sharp drop in systems with separations greater than about 25 AU appears to be real. This remains true despite the additional incompleteness for binaries with separations larger than about 100 AU. This distributin contrasts significantly with the $\sim 30 \mathrm{AU}$ broad separation peak of early M and G dwarfs (Fischer \& Marcy, 1992; Duquennoy \& Mayor, 1991). We conclude that the projected semimajor axes of M6.0-M7.5 binaries appear consistent with those of late $M, L$, and $T$ dwarf systems but are significantly smaller on average than early $M$ and $G$ stars.

Figure 2.8 also suggests a potential evolution in the separation of VLM binaries. The shaded bins represent the systems with estimated ages less than 10 Myr . While the statistics are still small, the separation distribution of these young binaries is flatter and suggests a peak at wider separations than that of the field and older cluster binaries. The evolution from wider to tighter separations between binaries may be as a result of wider binaries being more readily disrupted through kinematic interactions in their natal cloud, when stellar densities were highest. The hardening of binaries within young dense clusters in three body interactions may lead to the lowest mass or widest member being ejected (Bate, Bonnell, \& Bromm, 2002; Close et al., 2002b). The former may explain the decrease in binary fraction with spectral type and the latter may speak to the separation distribution differences observed between VLM and intermediate-mass binaries.

Close et al. (2007) conclude that the wide systems found today within open
stellar clusters are likely unstable and will not remain bound as they join the field population. They suggest that only the VLM binary systems formed in very low density groups ( $\lesssim 100 / \mathrm{pc}^{3}$ ) could age and remain bound as wide ( $\gtrsim 100 \mathrm{AU}$ ) systems.

### 2.3.8 The Mass Ratio Distribution Function

The 2M 0429 and 2M 1847 binary systems have best-estimate mass ratios of 0.84 and 0.96 , respectively. In our total M6.0-M7.5 sample, we detected no systems with estimated mass ratios less than 0.84 . Despite sensitivity to mass ratios of $\sim 0.7$ at separations as near as $\sim 6 \mathrm{AU}$ (Figure 2.7), this result suggests another real behavior of VLM binaries and not a result of a sensitivity selection effect. When examining the entire VLM sample of known binary systems in Table 2.4, Figure 2.9 shows a sharp decline in the mass ratio distribution where the surveys are complete $(0.6 \leq q \leq 1)$. This suggests that even among VLM binary systems, there is a mass-dependent process that preferentially drives the mass ratios of the components to unity.

The median mass ratio of our entire M6.0-M7.5 binary sample is 0.9 , consistent with the results from the later spectral types discussed in the previous section. The peak of the mass ratio distribution of all VLM binaries is between 0.9 and 1 (Figure 2.9); almost half of the known VLM binaries have $\mathrm{q}>0.9$. The distribution declines sharply towards smaller mass ratios. While there is likely observational incompleteness for binaries with mass ratios less than 0.6 , the sharp drop from unity appears to be real. As with the separation distribution, the mass ratio distribution contrasts significantly with the broader distribution for F-K stellar systems (Burgasser et al., 2007). We conclude that the mass ratio distribution of M6.0M7.5 binaries appear consistent with those of late $M, L$, and $T$ dwarf systems but is more significantly peaked towards unity than more massive stars.


Figure 2.9 The mass ratio $(\mathrm{q})$ distribution of known VLM binary systems from Table 2.4. The number of VLM binary systems in each 0.1 fractional bin is labelled and uncertainties are derived from a binomial distribution. Note that the spectroscopic binaries with unknown mass ratios are not plotted and not included in the total number of binaries when scaling the distribution. The distribution shown peaks near unity for binary systems with separations greater than about 3 AU and matches a power law. Incompleteness is likely for mass ratios less than about 0.6 . The shaded bins represent the ten systems with ages less than 10 Myr . While the statistics are still small, the mass ratio distribution of these young systems suggest a flatter distribution than that of field and older cluster binaries.

As with the separation distribution, Figure 2.9 also suggests a potential evolution in the mass ratio of VLM binaries. The shaded bins represent the systems with estimated ages less than 10 Myr. While the statistics are still small, the mass ratio distribution of these young binaries is flatter and suggests a peak at smaller mass ratios than that of the field and older cluster binaries. The evolution from smaller to unity mass ratios may be a result of lower mass companions being more readily disrupted through kinematic interactions in their natal cloud, when stellar densities were highest. The lower mass companions are consequently ejected or replaced by more massive interlopers resulting in preferential nearunity mass ratios (Bate, Bonnell, \& Bromm, 2002; Close et al., 2002b).

Both the separation (Figure 2.8) and mass ratio (Figure 2.9) distributions imply possible evolutionary processes. The subsample of binaries less than 10 Myr (shaded regions), while now only twelve in number, appear to have distinctly broader distributions. While only $11 \%$ of the field VLM binaries have separations greater than $15 \mathrm{AU}, 50 \%$ of the young subsample have wider separations.

A likely hypothesis explaining the differences between VLM binaries and more massive binaries as well as the age distribution differences invokes dynamical interactions. In a sample of embedded clusters within 1 kpc , Porras et al. (2003) found $80 \%$ of the stars to lie within clusters containing 100 or more stars. At the youngest ages, stellar densities are highest in their natal clusters such that interactions are more frequent (eg. Bate, Bonnell, \& Bromm, 2002). Furthermore, kinematic interactions between three or more objects often result in the ejection of the lowest-mass component leaving behind more tightly-bound "harder" binaries with near-unity mass ratios. In other cases, gravitational impulse forces
from nearby stars as well as molecular clouds may disrupt wide VLM binaries.
In Figure 2.10, we show the binding energy of a wide range of known binaries from the literature along with the 83 VLM systems from the Archive that have measured projected separations and masses. We observe that the mimimum empirical binding energy for field VLM binaries is 10-20 greater than that of more massive systems. Interestingly, six of the eight VLM binary outliers have reported ages less than 10 Myr . This is consistent with the separation and mass-ratio distribution differences observed in Figure 2.8 and Figure 2.9, suggestive of different binary properties distribution at younger ages due to more frequent kinematical interactions.

### 2.3.9 Are Kinematic Interactions Still Important at 1-10 Myr?

While stellar interactions are possible explanations for the differences in binary property distributions presented, the bulk of the interactions may have occured very early within clusters' lifetime ( $\ll 1 \mathrm{Myr}$ ). Consequently, there should be little difference in the binary distributions between young (1-10 Myr) and old and perhaps what is observed may be rather due to selection effects. However, if kinematic interactions are shown to still be important at $1-10 \mathrm{Myr}$, then the differences may be real.

Weinberg, Shapiro, \& Wasserman (1987) investigate the stability of wide binaries deriving analytical solutions for the Fokker-Planck coefficients which describe advective diffusion of binaries due to stellar interactions. Using their derived coefficients, Close et al. (2007) compute the timescale a young, wideseparated, VLM binary would become unbound assuming typical young cluster stellar densities. Timescales greater than $\sim 1 \mathrm{Myr}$ for a range of stellar densities would imply that interactions may still be important. From Weinberg, Shapiro, \& Wasserman (1987):


Figure 2.10 Binding energy (in $10^{41} \mathrm{erg}$ ) vs. total binary mass (in $\mathrm{M}_{\odot}$ ) for known binary systems. The 71 VLM field binaries from the Archive that have measured projected separations and masses are plotted as open stars; open circles represent VLM binaries with estimated ages less than 10 Myr . The dashed line indicates the mimimum empirical binding energy for massive binaries and the horizontal solid line indicates the same for VLM stellar and substellar binaries. These limits indicate that lower mass systems are 10-20 times more tightly bound than their more massive stellar counterparts (see also Close et al., 2003). Of the eight VLM binary outliers, six have reported ages less than 10 Myr suggesting a different binary properties distribution at younger ages.

$$
\begin{equation*}
t_{*}\left(a_{o}\right) \sim 3.6 \times 10^{5}\left(\frac{0.05 p c^{-3}}{n_{*}}\right)\left(\frac{M_{t o t}}{M_{\odot}}\right)\left(\frac{M_{\odot}}{M_{*}}\right)^{2}\left(\frac{V_{\text {rel }}}{20 k m s^{-1}}\right)\left(\frac{A U}{a_{o}}\right) G y r \tag{2.1}
\end{equation*}
$$

where $t_{*}\left(a_{o}\right)$ is the time required to evaporate a binary of an initial separation of $\mathrm{a}_{o}$. The variables $\mathrm{n}_{*}, \mathrm{M}_{\odot}$, and $\mathrm{V}_{\text {rel }}$ are the perturber stellar density, average perturber mass, and relative velocity (between perturber and binary), respectively (I assume the $\ln \Lambda$ term not shown in Equation 2.1 is $\sim 1$, as they do). Intuitively, the scalings appear to be in the right directions. As the density of perturbers and their masses increase, binary disassociation timescales decrease; more massive binaries require more interactions, and hence, longer timescales, as do fast passbys due to the emittance of weaker impact forces.

Assuming a scenario where $0.7 \mathrm{M}_{\odot}$ stellar perturbers pass a wide-separated ( 200 AU ) brown dwarf binary (each $0.05 \mathrm{M}_{\odot}$ ) at relative velocities of $\sim 1 \mathrm{~km} \mathrm{~s}^{-1}$ (typical of young systems), Equation 2.1 reduces to:

$$
\begin{equation*}
t_{*}(200 A U) \sim\left(\frac{900}{n_{*}}\right) M y r \tag{2.2}
\end{equation*}
$$

Assuming stellar densities of young clusters with ages 1-10 Myr to be typically Ophiuchus-like, $10^{2}-10^{3} \mathrm{pc}^{-3}$ (rather than Trapezium-like, $10^{4} \mathrm{pc}^{-3}$ ), estimated timescales from Equation 2.2 are $0.9-9 \mathrm{Myr}$. Slightly higher relative velocities, such as $3 \mathrm{~km} \mathrm{~s}^{-1}$, would lengthen the timescales of interactions to 3-30 Myr. These are within the timescales of the young, wide VLM binaries found in the literature. This may suggest that the clusters where these stars formed may indeed continue to play a role in evaporating them at ages roughly 1-10 Myr, before the binaries enter the field. Note that for $10^{4} \mathrm{pc}^{-3}$ stellar densities, the timescales reduce linearly to $\ll 1$ Myr. Hence, while stellar interactions may still be important in disrupting wide, young VLM binaries at ages 1-10 Myr, this may only be the case of those formed in poor groups and associations since the probability of
surviving till this age in more dense clusters $\left(~ Z 10^{4} \mathrm{pc}^{-3}\right)$ is $\sim 10-100$ less.
This analysis is, of course, approximative. However, as pointed out in Close et al. (2007), an independent analytical solution by Brandeker et al. (2006) predicts that a VLM binary with a total mass of about $0.03 \mathrm{M}_{\odot}$ and separation 240 AU would become unbound in approximately 11 Myr in a cluster of $\sim 10^{3} \mathrm{pc}^{-3}$, longer than predicted by Equation 2.2 but consistent with our conclusion. In addition, wide binaries in older clusters are indeed rare (according to the Archive). Several HST and AO surveys did not detect wide binaries in the $\sim 125 \mathrm{Myr}$ old Pleiades (Martín et al., 2003). Also, neither of the two VLM Hyades binaries discovered in our survey were wide (Siegler et al., 2003). The observation of larger samples of young stars will help confirm if this hypothesis is correct.

For completeness, we note that removing primordial gas from within a spherical region between the components of a wide VLM binary has a neglible effect on the dynamics of the system. The same holds for the effect of molecular clouds since their impact parameters are on order $10^{5} \mathrm{AU}$ (Close et al., 2007).

### 2.4 Summary

We have conducted the largest flux limited ( $\mathrm{K}_{s}<12 \mathrm{mag}$ ) survey of nearby M6.0M7.5 dwarfs using the Keck II, Gemini North, Subaru, and VLT AO systems. We present our two latest binary discoveries, 2 M 0479 and 2 M 1847 , observed at the VLT and Subaru facilities, respectively. When added to our initial results from Paper I, the overall survey consists of 36 stars with 5 discovered binary systems. The two new components are of relatively equal mass ( $q>0.8$ ) with average projected separations of 2 and 6 AU . While none of the binaries have yet been confirmed by common proper motions, they are almost certainly bound based on space density arguments of very red companions. We have used observational
and statistical arguments to characterize the VLM binary fraction and separations that contribute additional empirical constraints to binary formation mechanisms:

- We estimate the binary frequency of spectral type M6.0-M7.5 main sequence stars for separations a $>3$ AU from this survey to be $9_{-3}^{+4} \%$. The figure is statistically consistent with later type ultracool M, L, and T dwarfs. The frequency is significantly less than that measured in studies of earlier M and G dwarfs, inferring that the binary fraction of stars is a function of the spectral type of the central star.
- The separations of the five binary systems from our sample are all less than 10 AU. Projected separations of known VLM binaries > 15 AU are rare. This survey's median separation of 5 AU is consistent with the separations of later type M, L, and T dwarfs (separation peak $\sim 4 \mathrm{AU}$ ). This is in stark contrast with the broad peak separations of $\sim 30 \mathrm{AU}$ for the more massive $M$ and $G$ binaries.
- The mass ratio of the five binary systems from our sample are all greater than 0.8. This result is consistent with the mass ratio of all known VLM binaries whose distribution peaks near unity. This is in stark contrast with the broader distribution for more massive stars.
- There is preliminary evidence from a small sample of young ( $\lesssim 10 \mathrm{Myr}$ ) VLM binaries that young binary distributions may be different from that of older field systems. A possible explanation may be due to more frequent kinematic interactions occuring within young, intermediate-size clusters and associations.


## CHAPTER 3

## Discovery of a 66 mas Ultracool Binary with Laser Guide Star Adaptive Optics

The content of this chapter consists of work originally presented by Siegler et al. (2007b) and will be published in the May 2007 edition of The Astronomical Journal.

We present the discovery of 2MASS J21321145+1341584AB as a closely separated $\left(0.066^{\prime \prime}\right)$ very low-mass field dwarf binary resolved in the near-infrared by the Keck II Telescope using laser guide star adaptive optics. Physical association is deduced from the angular proximity of the components and constraints on their common proper motion. We have obtained a near-infrared spectrum of the binary and find that it is best described by an L5 $\pm 0.5$ primary and an $\mathrm{L} 7.5 \pm 0.5$ secondary. Model-dependent masses predict that the two components straddle the hydrogen burning limit threshold with the primary likely stellar and the secondary likely substellar. The properties of this sytem - close projected separation (1.8 $\pm 0.3 \mathrm{AU})$ and near unity mass ratio - are consistent with previous results for very low-mass field binaries. The relatively short estimated orbital period of this system ( $\sim 7-12 \mathrm{yr}$ ) makes it a good target for dynamical mass measurements. Interestingly, the system's angular separation is the tightest yet for any very lowmass binary published from a ground-based telescope and is the tightest binary discovered with laser guide star adaptive optics to date.

### 3.1 Introduction

The coolest and lowest mass objects have historically been discovered as companions to low-luminosity stars. These objects include the two lowest luminos-
ity spectral classes of low mass stars and brown dwarfs - the L and T dwarfs (Kirkpatrick, 2005, and references within). The first L dwarf, GD 165B, was discovered as the companion to a white dwarf (Becklin \& Zuckerman, 1988) while the first widely accepted brown dwarf, Gliese 229B, was the companion to an M dwarf (Nakajima et al., 1995; Oppenheimer et al., 1995). Hence it is quite possible that the first of the ultracool brown dwarfs with effective temperatures less than $\sim 700 \mathrm{~K}$ will also be discovered as a companion. These objects would likely populate a new spectral type beyond T with masses overlapping the planetary regime.

The hunt today for even cooler objects benefits from advances in high resolution imaging with the Hubble Space Telescope (HST) and large ground-based telescopes fitted with adaptive optics (AO). With the spectral energy distributions of these cool objects peaking in the near-infrared ( $1-6 \mu \mathrm{~m}$ ), observing at these wavelengths are advantageous for their detection and characterization. Thus observational strategies have relied on targetting continuously lower luminosity objects to further improve the contrast differential obtained in the near-infrared.

An advantage in using AO over the HST is that they can be attached to larger ground-based telescopes attaining higher angular resolution and increased sensitivity to fainter sources. The challenge, however, exists in locating natural guide stars sufficiently bright ( $R \lesssim 13.5 \mathrm{mag}, K_{s} \lesssim 12 \mathrm{mag}$ ) and near one's science target (isoplanatic angular distance $\lesssim 30^{\prime \prime}$ ) to provide sufficient wavefront correction. There is less than $10 \%$ chance of finding a natural guide star (NGS) meeting these requirements at $30^{\circ}$ Galactic latitude (Roddier, 1999). The probability improves little even with the use of infrared wavefront sensors when targeting ultracool objects such as mid-L dwarfs (limiting magnitude of the NGS infrared wavefront
sensor on NAOS at the Very Large Telescope is $K_{s} \sim 12 \mathrm{mag}^{1}$ ). Slightly better NGS sensitivity performance has been achieved using curvature wavefront sensors with avalanche photodiodes where $K_{s} \lesssim 12.3 \mathrm{mag}$ (Siegler, Close, \& Freed, 2002).

The search for substellar and planetary-mass objects through direct detection from ground-based telescopes now has a new technique - laser guide stars (LGSs). LGSs serve as artificial beacons for AO systems by exciting sodium atoms in the Earth's mesosphere at their resonant D-line frequency. These beacons serve as artificial (and steerable) guide stars which provide sufficient flux density for wavefront sensing and correcting. While LGS AO still requires a NGS to help correct both the lowest wavefront orders ("tip/tilt", $\sim 2 \mathrm{kHz}$ ) and the higher orders ("low-band wavefront sensor", $\sim 0.01 \mathrm{~Hz}$ ), its flux density requirement is comparatively small ( $R \lesssim 18 \mathrm{mag}$ ). This results in $\sim 2 / 3$ of the night sky accessible to high spatial resolution imaging (Liu, 2006) and opens the door to probing the regions around ultracool L and T dwarfs never previously observed by groundbased telescopes.

While the Keck II is the first of the $8-10 \mathrm{~m}$ class telescopes to have an operational LGS AO system (Wizinowich et al., 2006), several more are expected to be commissioned within just the next 2 years (see Liu, 2006). Several recent investigations using Keck II LGS AO have discovered companions to previously unresolved faint sources ushering in this new era of high-resolution imaging (eg. Liu \& Leggett, 2006; Gelino, Kulkarni, \& Stephens, 2006; Liu et al., 2006; Close et al., 2007).

In this investigation we observe six nearby ultracool ${ }^{2}$ field dwarfs which we

[^4]target for very faint companions. The objects were selected from the literature satisfying the following criteria: spectral type later than M6, never observed at high spatial resolution, too faint for current ground-based NGS AO systems, and spectrophotometric distances less than 30 pc . We present here the discovery of one of the targets, 2MASSJ21321145+1341584 (Cruz et al., 2007) as a closelyseparated $\left(0.066^{\prime \prime}\right)$ L dwarf binary resolved by the Keck II telescope NIRC2 infrared camera in combination with LGS AO. The binary is hereafter referred to as $2 \mathrm{M} 2132+1341 \mathrm{AB}$. The five other targets not found with near-equal mass companions are listed in Table 4.1. This discovery demonstrates the power of LGS AO - the ability to resolve a faint ( $R \gtrsim 20 \mathrm{mag} ; J \sim 16 \mathrm{mag}$ ) binary very near the diffraction limit ( 50 mas ) of a 10 m telescope using an artificial beacon for wavefront correction.

### 3.2 Observations and Data Reduction

### 3.2.1 Imaging

The discovered binary system 2M 2132+1341AB was observed on UT 2006 June 17 with the 10 m Keck II telescope on Mauna Kea, Hawaii. It was the lone binary discovered from our sample of six ultracool dwarf targets. To optimize the resolution capabilities of our observations, we used the facility IR camera NIRC2 in the narrow $\left(0.01^{\prime \prime} /\right.$ pixel $)$ camera mode with a $10^{\prime \prime} \times 10^{\prime \prime}$ field of view, in combination with the sodium LGS AO system (Bouchez et al., 2004; Wizinowich et al., 2004). All targets were observed through the broadband $K_{s}$ filter ( $2.15 \mu \mathrm{~m}$ ) where Strehl ratios are improved over $J(1.25 \mu \mathrm{~m})$ and $H(1.63 \mu \mathrm{~m})$. In the case of $2 \mathrm{M} 2132+1341 \mathrm{AB}$, observations were also made in both $J$ and $H$. All filters are of the Mauna Kea Observatories (MKO) filter consortium (Simons \& Tokunaga, 2002; Tokunaga, Simons, \& Vacca, 2002). Conditions were photometric for the

Table 3.1. Ultracool Field Dwarfs Observed with No Physical Companion Detections ${ }^{\text {a }}$

| 2MASS Name | $K_{s}$ | Spectral Type | References |
| :--- | :---: | :---: | :---: |
| LSR J1610-0040 | 12.02 | sdM:sdL: | 1,2 |
| 2MASS J17210390+3344160 | 12.47 | L3 | 3 |
| SDSS J202820.32+005226.5 | 12.79 | L3 | 4 |
| 2MASS J20343769+0827009 | 13.08 | M:L | 5 |
| 2MASS J22490917+3205489 | 13.59 | L5 | 6 |

${ }^{\text {a }}$ For near-equal mass binaries (mass ratio $\gtrsim 0.7$ ), the angular separation sensitivity is $\sim 50$ mas. For less massive companions ( $q \lesssim 0.7$ ), sensitivity improves with increasing angular separation up to our observation's $10^{\prime \prime}$ radial field of view.
${ }^{\mathrm{b}}$ Object was originally classified as a mid-L dwarf but due to insufficient signal-to-noise ratio is now only roughly estimated as a late-M/early-L dwarf.
${ }^{\text {c }}$ A faint point source at $\mathrm{PA}=194$ 。, separation $\sim 90$ mas was observed in $J, H$, and $K_{s}$ but determined to be a "super-speckle" due to its wavelength-dependent angular separation.

References. - (1) Lépine, Rich, \& Shara (2003), (2) Cushing \& Vacca (2006), (3) Cruz et al. (2003), (4) Hawley et al. (2002), (5) Kelle Cruz, priv. comm., (6) Cruz et al. (2007)

Note. - Each target has at least one bright NGS $\lesssim 30^{\prime \prime}$ serving as the tip/tilt and low-band source.
majority of the night with better than $0.6^{\prime \prime}$ seeing in the optical but with occasional windy periods.

Higher-order AO corrections were produced using the laser's on-axis light in the direction of the science target. This produced an emission similar to a $V \approx 10$ point source. Lower order tip/tilt corrections were obtained using natural guide stars within $60^{\prime \prime}$ of the targets. In the case of $2 \mathrm{M} 2132+1341 \mathrm{AB}$, the natural guide star used was 1036-0598908 ( $R=14.2 \mathrm{mag}$ ) from the USNO-B1.0 catalog (Monet et al., 2003), located $13.6^{\prime \prime}$ away.

Table 4.1 lists the five ultracool dwarf targets observed with no near-unity mass ratio companions detected at separations $\gtrsim 0.05^{\prime \prime}$. Figure 3.1 shows the resolved discovered binary $2 \mathrm{M} 2132+1341 \mathrm{AB}$. Both components are elongated along the telescope elevation axis projected to $\approx 45^{\circ}$, attributed to windshake during the observations (a common problem with LGS AO on windy nights; see also Liu et al., 2006). The LGS AO-corrected images have full width at half-maximum of $0.06^{\prime \prime}, 0.07^{\prime \prime}, 0.07^{\prime \prime}$ at $J, H, K_{s}$, respectively.

Each of the images shown in Figure 3.1 was made by dithering a few arcsecs over three different quadrant positions on the NIRC2 narrow camera detector. Three images were taken per filter per dither position resulting in 2.5 min for total on-source integration time per filter. The object was easily resolved into two components in all our data.

The images were reduced in a consistent manner using an AO data reduction pipeline written in the IRAF language as first described in Close et al. (2002a). Modified for the NIRC2 narrow camera, the pipeline produces final unsaturated $15^{\prime \prime} \times 15^{\prime \prime}$ exposures in $J, H$, and $K_{s}$ with the highest signal-to-noise in the inner $5^{\prime \prime} \times 5^{\prime \prime}$ region. The photometric reduction pipeline uses the IRAF task ALLSTAR


Figure 3.1 $\mathrm{JHK}_{s}$-band images of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ observed with Keck LGS AO; north is up and east to the left. We refer to the brighter component as the "primary" and designate it as $2 \mathrm{M} 2132+1341 \mathrm{~A}$; the fainter component is referred to as the "secondary" or the "companion" and we designate it as 2M $2132+1341 \mathrm{~B}$. The angular separation is only $66 \pm 4$ mas, among the tightest ultracool binaries ever resolved and the tightest yet resolved using a ground-based telescope. The LGS AO-corrected images have full width at half-maximum of $0.06^{\prime \prime}, 0.07^{\prime \prime}, 0.07^{\prime \prime}$ at $J, H$, and $K_{s}$, respectively. Each image is $0.3^{\prime \prime}$ on a side. The binary components are all slightly elongated along the telescope elevation axis (position angle $\sim 45^{\circ}$ ) believed to be due to telescope windshake. Also shown is one of the two PSFs used in the data reduction, 2MASS J16233609-2402209A (Close et al., 2007), a young, stellar-mass M5 observed with similar elongation and air mass.
in the DAOPHOT point spread function (PSF) fitting photometry package ${ }^{3}$. The central regions of the pipeline's output is shown in Figure 3.1.

Two different unsaturated single objects observed during the same night, but from a different program, were selected as PSF stars. These objects were observed with the same instrumental setup and showed similar Strehl ratios, FWHM, elongation due to windshake, and air mass. Both PSF sources, incidentally, are resolved primary objects of newly discovered wide ( $1.7^{\prime \prime}-1.9^{\prime \prime}$ ) binaries. In both cases, the A and B components are sufficiently separated such that there is no flux contamination between them. The two PSFs used are 2MASSJ162336092402209A, also shown in Figure 3.1, and 2MASSJ16223020-2322240A (Close et al., 2007). $2 \mathrm{M} 2132+1341 \mathrm{AB}$ was fit independently with both PSF objects leaving behind clean residuals. The differential photometry in magnitudes is reported in Table 3.2 and the photometric uncertainties are produced from the differences in the photometry between the two PSFs. These dominate the overall uncertainty.

### 3.2.2 Spectroscopy

Unresolved, low-resolution near-infrared spectroscopy of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ was obtained on 2005 October 17 (UT) using the SpeX spectrograph mounted on the 3 m NASA Infrared Telescope facility (Rayner et al., 2003). Conditions during the night were clear with moderate seeing ( $0^{\prime \prime} .7-1^{\prime \prime} .0$ at $J$-band). Data were obtained utilizing the SpeX prism mode, providing a single-order spectrum spanning 0.8-2.5 $\mu \mathrm{m}$ spectrum with a dispersion of 20-30 $\AA /$ pixel. Use of the $0^{\prime} .5 \mathrm{slit}$, aligned with the parallactic angle, provided resolution $\lambda / \Delta \lambda \approx 120$ across the near-infrared band. Six exposures of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ were obtained in an ABBA dither pattern along the slit, with individual exposure times of 150 s . The system

[^5]Table 3.2. 2M 2132+1341AB Observed Properties

| Property | Measurement |
| :--- | ---: |
|  |  |
| $\Delta J$ | $0.84 \pm 0.09 \mathrm{mag}$ |
| $\Delta H$ | $0.88 \pm 0.04 \mathrm{mag}$ |
| $\Delta K_{s}$ | $0.90 \pm 0.04 \mathrm{mag}$ |
| $J_{A}$ | $16.07 \pm 0.07 \mathrm{mag}$ |
| $J_{B}$ | $16.91 \pm 0.12 \mathrm{mag}$ |
| $\left(J-K_{S}\right)_{A}$ | $1.84 \pm 0.09 \mathrm{mag}$ |
| $\left(J-K_{S}\right)_{B}$ | $1.78 \pm 0.14 \mathrm{mag}$ |
| $(J-H)_{A}$ | $1.04 \pm 0.09 \mathrm{mag}$ |
| $(J-H)_{B}$ | $1.00 \pm 0.13 \mathrm{mag}$ |
| Separation | $66 \pm 4 \mathrm{mas}$ |
| Position angle | $121.94 \pm 1.30^{\circ}$ |
| Date observed | UT 2006 Jun 17 |

Note. - Photometry on the MKO system.
was observed at an airmass of 1.02 . The A0 star HD 210501 was observed immediately after the target exposures at a similar air mass, followed by internal flat-field and Ar arc lamps for pixel response and wavelength calibration.

Data were reduced using the Spextool package, version 3.2 (Cushing, Vacca, \& Rayner, 2004). The raw science data were processed by performing linearity corrections, pairwise subtraction, and division by a normalized flat field. The spectra were then extracted using the Spextool default settings for point sources, and wavelength solutions were calculated using the Ar arc calibration frames. Extracted spectra from the same source were scaled to match the highest singal-to-noise spectrum of the set, and the scaled spectra were median-combined. Telluric and instrumental response features were removed following the procedure of (Vacca, Cushing, \& Rayner, 2003).

The reduced spectrum of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ is shown in Figure 3.2 (black line). Strong absorption features of $\mathrm{H}_{2} \mathrm{O}$ are present at 1.4 and $1.9 \mu \mathrm{~m}, \mathrm{CO}$ is prominent at $2.3 \mu \mathrm{~m}$, and FeH is present at $0.99,1.2$, and $1.6 \mu \mathrm{~m}$. The $J$-band spectral region exhibits a number of features that can be attributed to KI and Na I lines in addition to FeH . There is no indication of $\mathrm{CH}_{4}$ in the spectrum of this source. These features are all indicative of a late-type L dwarf, as also indicated by the optical spectrum of Cruz et al. (2007).

### 3.3 Analysis

The key binary properties of $2 \mathrm{M} 2132+1341 \mathrm{~A}$ and B are derived here and summarized in Table 3.3. Individual apparent magnitudes are calculated from the observed $\Delta$ magnitudes (Table 3.2) and the integrated apparent magnitudes (unresolved) measured by the Two Micron All Sky Survey (2MASS) (Cutri et al., 2003). Since the differential photometry observed with NIRC2 was measured


Figure 3.2 Comparisons between the observed spectrum of 2M $2132+1341 \mathrm{AB}$ and the composite spectra made by combining IRTF Spex spectra of spectral templates. In each panel, the observed near-infrared spectrum is represented by the black line. The upper (red dashed line) and lower spectra (blue dashed) in each panel are template guesses of the primary and secondary, respectively. The combined spectrum is represented by the green dot-dashed line. The $K$ flux ratios between the secondary and primary are set to 2.29 ( $\Delta K=0.9 \mathrm{mag}$ ) in each composite spectrum. The corresponding magnitude differences of the fits at $\Delta J$ and $\Delta H$ are shown in each panel. The two top panels and the bottom left suggest that an L5/L7.5 composite gives the closest match morphologically to the integrated $2 \mathrm{M} 2132+1341 \mathrm{AB}$ spectrum at $J$ and $H$. We include the bottom-right panel to demonstrate that this kind of analysis is sufficiently robust to remove atypical component spectra (an atypically red L5 and an atypically blue L7) even when there is good morphological matching; see §3.3.1.
with the MKO filter system, we converted the integrated $J$ and $H$ photometry from the 2MASS filter system to MKO using the color transformations of Leggett et al. (2006). While they provide no transformation between $K_{s} \mathrm{MKO}$ and $K_{s}$ 2MASS, the transmission curves are very similar (1-2\% difference, S. Leggett private communication) and therefore we apply no correction. Uncertainties in the transformations and photometry are propagated in quadrature and reported in Table 3.3.

With measured differential photometry, derived apparent magnitudes, and a measured combined L6 $\pm 0.5$ optical spectrum from Cruz et al. (2007), what physical properties of the individual components can we infer? Since there is no known trigonometric parallax for the object, we rely on first estimating the component spectral types to derive absolute magnitudes using an empirical relation. This then enables estimates of the distance modulus, bolometric luminosities, and ultimately, with the aid of theoretical evolutionary tracks, masses and a period. The better constrained the component spectral types are, the more constrained (and meaningful) will the derived physical properties be.

### 3.3.1 Spectral Types

The component near-infrared colors listed in Table 3.2 by themselves provide only rough constraint on the individual spectral types (eg. Chiu et al., 2006). While the primary is certainly a mid-L dwarf, L3-L8, the possible spectral types for the secondary extend into the T-range, L3-T1. While the combined light spectrum is similar to that of an L6, the components may have very discrepant spectral types. The secondary could even be a T dwarf without the characteristic $\mathrm{CH}_{4}$ bands appearing in the combined light spectrum.

To derive more precise estimates of the individual component spectral types, we used a spectral synthesis technique based on that used by Burgasser et al.

Table 3.3. $2 \mathrm{M} 2132+1341 \mathrm{AB}$ Derived Properties

| Property | Value |
| :---: | :---: |
| Spectral Types |  |
| A + B (optical) | $\mathrm{L} 6 \pm 1$ |
| A | $\mathrm{L} 5 \pm 0.5$ |
| B | $\mathrm{L} 7.5 \pm 0.5$ |
| $M_{K_{A}}$ | $11.92 \pm 0.33 \mathrm{mag}$ |
| $M_{K_{B}}$ | $12.82 \pm 0.30 \mathrm{mag}$ |
| Distance | $28 \pm 4 \mathrm{pc}$ |
| Luminosities: |  |
| $\mathrm{L}_{A}$ | $6.3 \times 10^{-5} \pm 1.9 \times 10^{-5} \mathrm{~L}_{\odot}$ |
| $\mathrm{L}_{B}$ | $3.0 \times 10^{-5} \pm 1.0 \times 10^{-5} \mathrm{~L}_{\odot}$ |
| Masses (A/B): |  |
| 0.8 Gyr | 0.065/0.048 M $\odot$ |
| 5 Gyr | $0.077 / 0.075 \mathrm{M}_{\odot}$ |
| 10 Gyr | $0.078 / 0.076 \mathrm{M}_{\odot}$ |
| Proper motion (NOMAD): |  |
| $\mu_{\alpha} \cos \delta$ | $-55.3 \pm 9.0 \mathrm{mas} \mathrm{yr}^{-1}$ |
| $\mu_{\delta}$ | $-394.7 \pm 9.0$ mas yr $^{-1}$ |
| Separation (projected) | $1.8 \pm 0.3 \mathrm{AU}$ |
| Orbital period | 7-12 yr |

Note. - (1) All photometry on the MKO filter system, (2) See $\S 3$ for details and references.
(2006a) to study L dwarf plus T dwarf binaries ${ }^{4}$. A large sample of composite spectra were generated by combining various pairings of L5-T6 SpeX prism spectra obtained by A. Burgasser \& K. Cruz (72 individual spectra in all). The spectral types of the template spectra are based on optical classifications for $L$ dwarfs (e.g. Kirkpatrick et al., 1999) and near-infrared classifications for the T dwarfs (e.g. Burgasser et al., 2006a). The components of these spectra were constrained to have the same relative $K_{s}$-band magnitudes as measured for $2 \mathrm{M} 2132+1341 \mathrm{AB}$, and to simultaneously be within $3 \sigma$ of the measured $\Delta J(0.27 \mathrm{mag})$ and $\Delta H$ ( 0.12 mag ). The best matches between the composite spectra and the observed (unresolved) spectrum of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ were quantitatively determined by comparing both relative $J$ and $H$ magnitudes and $\mathrm{H}_{2} \mathrm{O}$ and $\mathrm{CH}_{4}$ spectral ratios (defined in Burgasser et al., 2006b). No assumption was made on the absolute magnitudes of the individual components in this analysis so that the absolute magnitude/spectral type scale was left as a free parameter.

Figure 3.2 illustrates the three best-fit composite spectra based on both the relative magnitudes and spectral ratio comparisons. In all three cases, an L5 spectral classification is selected for the primary along with an L7 or L8 for the secondary. In fact, this was the case for the best twenty fits. While the uncertainty is dominated by one subclass of uncertainties in the individual library spectral classifications, the consistency in the matches likely average out the overall uncertainty. Hence we conclude that the primary is a likely $\mathrm{L} 5 \pm 0.5$ and its companion a likely $\mathrm{L} 7.5 \pm 0.5$.

The fourth fit shown in Figure 3.2 (bottom right) shows one of the combinations that was disqualified due to the disparity between the predicted and measured $\Delta$ magnitudes. The components of this system are the unusually red

[^6]L5 2MASS J062445.95-452154.8 (Reid et al., in prep.) and the unusually blue L7 2MASS J09083803+5032088 (Cruz et al., 2003, 2007). Despite a good morphological fit, this kind of analysis that includes $\Delta$ magnitudes as constraints to the properties of individual components is sufficiently robust to remove atypical component spectra. Of course, resolved near-infrared spectroscopy is required to verify the accuracy of these classifications.

### 3.3.2 Physical Companions?

Are the components of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ physical companions? Calculating spectrophotometric distances of the two sources separately results in equal values, $28 \pm 4 \mathrm{pc}$. We used the fitted spectral types to independently obtain intrinsic flux densities $\left(\mathrm{M}_{K}\right)$ from the polynomial fit of Burgasser (2007). The distance's uncertainty includes those in the spectral types and in a spectral type/absolute magnitude relation (see next section) taken in quadrature. In addition, assuming a surface density of order $10^{-3} \mathrm{deg}^{-2}$ (Cruz et al., 2007) for all nearby L dwarfs, the probability of two lying within $0.1^{\prime \prime}$ is $\approx 10^{-7}$. Hence random alignment is very unlikely. Lastly, the 2M 2132+1341 pair, or at least the primary, shows a large proper motion of 0.4" $/ \mathrm{yr}$ (NOMAD; Zacharias et al., 2004b). A 2MASS $K_{s}$ image of 2M2132+1341 observed in UT 1998 appears single. With sensitivity to point source brightness of $K_{s} \approx 15.3 \mathrm{mag}, 2 \mathrm{M} 2132+1341 \mathrm{~B}$ would have been detectable and resolved at separations $\gtrsim 1.5^{\prime \prime}$ (Burgasser, Kirkpatrick, \& Lowrance, 2005). Therefore we rule out 2M2132+1341B as an unrelated background object since its projected position nearly 8 yrs ago would have been resolved in the 2MASS image. These factors provide strong evidence that the two sources are physical companions.

### 3.3.3 Masses, Age, and Period

With well-constrained spectral types in hand, we can now derive many of the binary's physical properties summarized in Table 3.3. An absolute $K$ magnitude for the primary is obtained using an $\mathrm{M}_{K}$-spectral type relation from Figure 3 of Burgasser (2007), where binaries have been excluded. The companion absolute magnitude is then obtained by applying our measured $\Delta K_{s}(\approx \Delta K$; S. Leggett, priv. comm.). Using our constrained component spectral types, we acquire the K-band bolometric corrections from Golimowski et al. (2004), apply them to our $\Delta K$ photometry, and calculate the bolometric luminosity ratio between the components to be $0.32 \pm 0.08$ dex. Individual bolometric luminosities in units of solar luminosity, estimated from the component $\mathrm{M}_{K}$ and $\mathrm{BC}_{K}$ values, are $6.3 \times 10^{-5} \pm 1.9 \times 10^{-5} \mathrm{~L} \odot$ for the primary and $3.0 \times 10^{-5} \pm 1.0 \times 10^{-5} \mathrm{~L} \odot$ for the companion.

Individual masses of 2M $2132+1341 \mathrm{~A}$ and B can be estimated from theoretical evolutionary models using our derived bolometric luminosities and estimated ages of the system. The system's age, however, is less constrained. The binary does not appear affiliated with any moving-group or open cluster. Its optical spectrum shows no lithium or $\mathrm{H}_{\alpha}$ spectral features (Cruz et al., 2007) suggesting that the source is more consistent with old field L dwarfs (Kirkpatrick et al., 2000; West et al., 2004). Neither is there near-infrared color or optical spectrum evidence of sub-solar metallicity (eg. Burgasser et al., 2003b; Burgasser, 2004) indicating the system is probably not a member of the Galaxy's thick disk or halo populations ( $\gtrsim 10 \mathrm{Gyr}$; Reid \& Hawley, 2005). In addition, the system's tangential motion of $53 \pm 2 \mathrm{~km} \mathrm{~s}^{-1}$ (NOMAD; Zacharias et al., 2004b) is inconsistent with a young object ( $\lesssim 1 \mathrm{Gyr}$ ).

The lack of lithium absorption in the optical spectrum can help place a lower
mass limit to $2 \mathrm{M} 2132+1341 \mathrm{~A}$ of approximately $0.065 \mathrm{M}_{\odot}$ depending on the system's age (Rebolo, Martín, \& Magazzu, 1992; Chabrier, Baraffe, \& Plez, 1996; Basri, Marcy, \& Graham, 1996; Burrows et al., 1997). Objects less than this limiting mass will always have central temperatures below the lithium-burning temperature. Slightly more massive objects will undergo lithium burning such that the element is observable at only younger ages. For example, using the models of Burrows et al. (1997), a $0.075 \mathrm{M}_{\odot}$ object will undergo complete lithium burning in about 140 Myr. In Figure 3.3 we show their theoretical evolutionary tracks where we place the lower mass limit of $2 \mathrm{M} 2132+1341 \mathrm{~A}$ along a constant lithium abundance line of $1 \%$ of the original abundance (similar to Liu \& Leggett (2006), we assume that a decrease in the initial lithium abundance by a factor of 100 marks the lithium absorption detection limit). This provides a lower age limit of $0.8-1.3 \mathrm{Gyr}$, consistent with a weak or absent lithium absorption feature. Assuming the companion is coeval with the primary, this lower age along with the uncertainties in the secondary's luminosity predicts masses of $0.040-0.054 \mathrm{M}_{\odot}$. A 10 Gyr upper limit results in a primary mass of $0.077-0.079 \mathrm{M}_{\odot}$ and a secondary of $0.076-0.077 \mathrm{M}_{\odot}$. According to a theoretical analysis conducted by Allen et al. (2005) of the age distribution of nearby field L dwarfs, there is a $\sim 30 \%$ probability that $2 \mathrm{M} 2132+1341 \mathrm{~A}$ and B are less than $\sim 1 \mathrm{Gyr}$ and $\mathrm{a} \sim 75 \%$ chance that they are younger than $\sim 5$ Gyr. We list the median mass estimates for three ages in Table 3.3 including a 5 Gyr best guess for stars in the solar neighborhood. Both objects likely straddle the hydrogen burning mass threshold $\left(\approx 0.072-0.075 \mathrm{M}_{\odot}\right.$; Burrows et al., 1997; Baraffe et al., 1998) with the secondary most likely substellar.

The projected separation between the two components is only $1.8 \pm 0.3 \mathrm{AU}$ (at a distance of $28 \pm 4 \mathrm{pc}$ ). We estimate the semimajor axis of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ by assuming that on average the true semimajor axis is 1.26 times larger than the


Figure 3.3 Theoretical evolutionary tracks from Burrows et al. (1997) for $2 \mathrm{M} 2132+1341 \mathrm{~A}$ (upper hatched region) and B (lower hatched region). Diagonal solid lines show constant mass tracks; labelled numbers are in $\mathrm{M}_{\odot}$ units. The stellar/substellar boundary for the model is $\approx 0.075 \mathrm{M}_{\odot}$; the bold solid line represents the $1 \%$ lithium depletion boundary drawn between the ages of $0.55-4.5 \mathrm{Gyr}$. The lack of a lithium absorption feature in the combined optical spectrum (Cruz et al., 2007) suggests ages to the right of this line ( $\gtrsim 0.8-1.3 \mathrm{Gyr}$ ). Based on derived luminosity ranges and estimated upper-age limits discussed in §3.3.3, the two hatched regions predict possible primary masses of $0.065-0.078 \mathrm{M}_{\odot}$ and companion masses of $0.040-0.077 \mathrm{M}_{\odot}$.
projected separation (Fischer \& Marcy, 1992) or $<a>=2.3$ AU. Using Kepler's third law and the range of possible masses, we estimate an orbital period of 712 yr. Hence, this system is a good candidate target for astrometric monitoring to derive orbital mass measurements (?Bouy et al., 2004; Zapatario-Osario et al., 2004).

### 3.4 Discussion

### 3.4.1 How Typical are the Binary Properties of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ ?

VLM binaries are characterized by near-unity mass ratios (q~0.8-1.0) and tight separation distributions peaking between 3-10 AU (Burgasser et al., 2007, and references within). According to the Very Low-Mass Binaries Archive ${ }^{5}$, about a third of these systems are L/L binaries. The binary properties of $2 \mathrm{M} 2132+1341 \mathrm{AB}$, $\mathrm{q} \gtrsim 0.9$ and projected separation of $1.8 \pm 0.3 \mathrm{AU}$, are consistent with these distributions.

Currently there are 16 known VLM binaries with angular separations less than the mean 66 mas separation of $2 \mathrm{M} 2132+1341 \mathrm{AB}$. The tightest nine are spectroscopic binaries and are as yet unresolved. The subsequent seven were all discovered with the HST. Despite large aperture ground-based telescopes achieving AO corrected resolutions at $K$ typically twice that of the HST, the space telescope's more stable point spread function allows for the identification of undersampled binaries. Interestingly, 2M 2132+1341AB is the tightest resolved very low-mass binary discovered by a ground-based telescope and the tightest using LGS AO. The clear separation of this system into two well-resolved components indicates that with good AO correction, ground-based facilities can indeed achieve a superior resolution

[^7]in the near-infrared compared to HST.

### 3.4.2 Future Dynamical Mass for 2M 2132+1341AB

Theoretical evolutionary models relating mass-luminosity-age relations are still largely uncalibrated for the lowest mass objects. In fact, only three VLM systems with constrained ages (all young) have had reliable orbits and resolved fluxes leading to derived individual kinematic masses - AB Dor C ( $\sim 50-100 \mathrm{Myr}$; Close et al., 2005; ?), the eclipsing brown dwarf binary in Orion 2MASSJ053521840546085AB ( $\sim 1-2$ Myr; Stassun, Mathieu, \& Valenti, 2006), and finally GJ 569Bab ( $\sim 500 \mathrm{Myr}$; Zapatario-Osario et al., 2004). Unfortunately, neither the age nor the distance of $2 \mathrm{M} 2132+1341 \mathrm{AB}$ is sufficiently well constrained to be used as a high accuracy luminosity-mass calibrator. However, if future high resolution optical spectroscopy (eg. repaired Space Telescope Imaging Spectrograph on HST) shows the presence of lithium in the companion, the system's age could be further constrained to $\sim 0.8-2.5 \mathrm{Gyr}$ making it a useful system for dynamical mass measurements. This would likely require, however, a widening in the components' projected separation. The HST and/or ground-base LGS AO observations should be able to measure significant orbital motion over the next $\sim 6 \mathrm{yrs}$, similar to the study of 2MASSW J0746425+2000321 (Bouy et al., 2004), the only dynamical mass measurement of an L dwarf binary.

### 3.5 Summary

Keck II LGS AO observations of 2MASS J21321145+1341584 show that this very low-mass dwarf is a binary system. Observed differential near-infrared photometry and integrated spectra (optical and near-infrared) indicate that both components are consistent with mid-L dwarfs. Based on modeling the integrated optical spectra with spectra from 72 known $L$ and $T$ dwarfs, we identify $2 \mathrm{M} 2132+1341 \mathrm{~A}$
as an an $\mathrm{L} 5 \pm 0.5$ and $2 \mathrm{M} 2132+1341 \mathrm{~B}$ as an L7.5 $\pm 0.5$. The lack of lithium in the optical spectra suggests the primary's age is older than 800 Myr . The system's very close separation $\left(0.066^{\prime \prime}\right)$ and common proper motion from 2MASS infers a physical association. With conservative age estimate of 5 Gyr , model-dependent masses suggest a system whose components straddle the hydrogen burning limit threshold with the primary likely stellar and the secondary likely substellar. The close projected separation $(1.8 \pm 0.3 \mathrm{AU})$ and near unity mass ratio of the system are consistent with previous results for field VLM binaries. The relatively short estimated orbital period of this system ( $\sim 7-12 \mathrm{yr}$ ) make it an ideal target for dynamical mass measurements. At the time of this writing, $2 \mathrm{M} 2132+1341 \mathrm{AB}^{\prime}$ s angular separation is the tightest for any VLM binary discovered from a groundbased telescope and is the tightest using LGS AO.

## CHAPTER 4

## Spitzer 24 Micron Observations of Open Stellar Cluster IC 2391 and Debris Disk Evolution of FGK Stars

The content of this chapter consists of work originally published in the January 1, 2007 edition of The Astrophysical Journal by Siegler, N., Muzerolle, J., Young, E. T., Rieke, G. H., Mamajek, E. E., Trilling, D. E., Gorlova, N., and Su, K. Y. L.

We present $24 \mu \mathrm{~m}$ Spitzer/MIPS photometric observations of the $\sim 50 \mathrm{Myr}$ open cluster IC 2391. Thirty-four cluster members ranging in spectral type from B3-M5 were observed in the central square degree of the cluster. Excesses indicative of debris disks were discovered around 1 A star, 6 FGK stars, and possibly 1 M dwarf. For the cluster members observed to their photospheric limit, we find a debris disk frequency of $10_{-3}^{+17} \%$ for B-A stars and $31_{-9}^{+13} \%$ for FGK stars using a $15 \%$ relative excess threshold. Relative to a model of decaying excess frequency, the frequency of debris disks around A-type stars appears marginally low for the cluster's age while that of FGK stars appears consistent. Scenarios that may qualitatively explain this result are examined. We conclude that planetesimal activity in the terrestrial region of FGK stars is common in the first $\sim 50 \mathrm{Myr}$ and decays on timescales of $\sim 100$ Myr. Despite luminosity differences, debris disk evolution does not appear to depend strongly on stellar mass.

### 4.1 Introduction

Nearly all stars are believed to form with primordial accretion disks, but it is not clear whether the formation of planets is also a nearly-universal process of stellar evolution. Answering this question would help us understand the inci-
dence of planetary systems in the Galaxy. Current planet detection techniques, while continuously improving, all suffer from some instrument sensitivity limitation. Many of the planets may very well be insufficiently massive to be detected through gravitational recoil, too faint against the glare of the central star to be imaged directly, too small to significantly reduce the star's measured brightness, or positioned unfavorably along the line of sight to produce a lensing event.

Planetary debris disks, however, provide an additional approach. Debris disks contain micron-sized dust grains predominantly produced in collisions between larger-sized bodies (such as rocks). These dust grains are heated by the parent star and re-radiate at longer wavelengths. A key facet of debris disks is that the dust grains must be short-lived compared to the age of the system given the efficiency of typical loss mechanisms like Poynting-Robertson drag and radiation pressure (with timescales of $10^{6}$ to $10^{7}$ years). The dust must therefore be regenerated either through a continuous collisional cascade or through stochastic collisions. Therefore, the presence of dust implies the existence of larger bodies that can collide and produce dusty debris (Backman \& Paresce, 1993; Lagrange, Backman, \& Artymowicz, 2000; Zuckerman, 2001). The largest of these bodies could be meter-sized up to planet-sized, and we may well refer to them generally as planetesimals. Therefore, any system with excess thermal emission implies planet formation at least to the extent of forming planetesimals. The ability to measure thermal emission in the mid-infrared is therefore a powerful technique in identifying systems in which planetary system formation has occurred or is occurring. However, since debris disks are cool, optically and geometrically thin, and gas-poor, they are generally harder to detect than the primordial, optically-thick accretion disks found around very young stars ( $\lesssim 10 \mathrm{Myr}$ ).

The Spitzer Space Telescope's unprecedented sensitivity in the mid-infrared
allows for the first time a statistical study of debris disks and their evolution across a wide spectral range. Excesses detected at $24 \mu \mathrm{~m}$ generally imply temperatures on the order of 100 K . This equilibrium temperature is achieved in the vicinity of 1-5 AU for spectral types FGK and 5-30 AU for the more luminous B and A stars. By probing these distances in the mid-infrared, we are therefore studying potential planet-forming and planet-bearing regions around other stars. Building on earlier work from the Infrared Astronomy Satellite (IRAS) and Infrared Space Observatory (ISO) which showed that the amount of dust in debris disks steadily declines over time (e.g. Spangler et al., 2001; Habing et al., 2001), Rieke et al. (2005) showed that more than half of A-type stars younger than $\sim 30 \mathrm{Myr}$ have mid-infrared excess. This result implies that planetary system formation occurs frequently around stars a few times more massive than the Sun. However, the same result also shows that up to $\sim 50 \%$ of the youngest stars have small or nonexistent excesses in the mid-infrared, pointing to a possible range of planetesimal formation and clearing timescales.

Can we expect similar behavior for lower-mass, longer-living, solar-like stars? Both IRAS and ISO were in general not sufficiently sensitive to detect the photospheric emission from lower-mass stars. Only with Spitzer have mid-infrared surveys of lower-mass stars begun (Gorlova et al., 2004; Young et al., 2004; Meyer et al., 2004; Stauffer et al., 2005; Kim et al., 2005; Beichman et al., 2005b; Chen et al., 2005; Bryden et al., 2006; Silverstone et al., 2006; Beichman et al., 2006; Gorlova et al., 2006; Chen et al., 2006). These studies conducted at 24 and/or $70 \mu \mathrm{~m}$ have shown that debris disks exist around solar-like stars at a wide range of possible distances ( $\sim 1-50 \mathrm{AU}$ ) and temperatures ( $\sim 10-650 \mathrm{~K}$ ) with an agedependent frequency. It is one of the goals of this investigation to constrain this age-dependence. Continued surveys of stars with known ages at mid-infrared
wavelengths will bring us nearer to understanding how debris disks evolve and ultimately will provide constraints on planet formation time scales.

In this investigation we use the $24 \mu \mathrm{~m}$ channel on Spitzer to study the incidence of debris disks in the open cluster IC 2391. IC 2391 is estimated to be $50 \pm 5$ Myr old (Barrado y Navascués, Stauffer, \& Jayawardhana, 2004), an age consistent with both theoretical (Chambers, 2001) and observational (Kleine et al., 2002) timescales of terrestrial planet formation. It is believed to be of intermediate size with $\sim 100-200$ members. At a distance of 154 pc (Forbes, Dodd, \& Sullivan, 2001), the cluster is amongst the closest and best studied. Furthermore, its proximity allows for the detection of photospheric emission at mid-infrared wavelengths from low-mass stars. With little observed $24 \mu \mathrm{~m}$ cirrus structure and visible extinction $(E(B-V)=0.006 \pm 0.005$; Patten \& Simon, 1996), IC 2391 offers an attractive combination of age, distance, and background in which to study debris disks.

The aim of this investigation is to measure the incidence of debris disks found around $\sim 50 \mathrm{Myr}$ stars across a broad range of spectral types. We discuss the ensemble properties of excesses in IC 2391 by placing our data in context with other relevant samples. In the process we begin characterizing the evolution of debris disks around FGK stars, and compare this result to that previously established for more massive A stars.

### 4.2 Observations and Data Reduction

The Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al., 2004) was used to image a 0.97 square degree area $\left(0.66^{\circ} \times 1.47^{\circ}\right)$ centered on IC 2391 (RA 08:40:16.8, Dec -53:06:18.9; J2000) on 9 April 2004. The $24 \mu \mathrm{~m}$ observations used the medium scan mode with half-array cross-scan offsets resulting in a total expo-
sure time per pixel of 80 s . The images were processed using the MIPS instrument team Data Analysis Tool (Gordon et al., 2005), which calibrates the data, corrects distortions, and rejects cosmic rays during the coadding and mosaicking of individual frames. A column-dependent median subtraction routine was applied to remove any residual patterns from the individual images before combining them into the final $24 \mu \mathrm{~m}$ mosaic.

While MIPS in scan-mode provides simultaneous data from detectors at $24 \mu \mathrm{~m}, 70 \mu \mathrm{~m}$, and $160 \mu \mathrm{~m}$, this study is based on only the $24 \mu \mathrm{~m}$ channel. The longer wavelength channels are insensitive to stellar photospheric emissions at the distance of IC 2391 and in addition no cluster stars were detected at $70 \mu \mathrm{~m}$ nor $160 \mu \mathrm{~m}$.

We measured the $24 \mu \mathrm{~m}$ flux density of individual sources in a $15^{\prime \prime}$ aperture using the standard PSF-fitting photometry routine allstar in the IRAF data reduction package daophot. We then applied an aperture correction of 1.73 to account for the flux density outside the aperture, as determined from the STinyTim $24 \mu \mathrm{~m}$ PSF model (Engelbracht et al., in prep). Finally, fluxes were converted into magnitudes referenced to the Vega spectrum using a zero-point for the [24] magnitude of 7.3 Jy (from the MIPS Data Handbook, v2.3). Typical $1 \sigma$ measurement uncertainties for the MIPS $24 \mu \mathrm{~m}$ fluxes are $50 \mu \mathrm{Jy}$ plus $\sim 5 \%$ uncertainty in the absolute calibration (Engelbracht et al., in prep). The two are independent of each other and dominated by the latter.

The $24 \mu \mathrm{~m}$ mosaic of the central region of IC 2391 is displayed in Figure 4.1. It likely covers a bit less than half of the spatial extent of the entire cluster (Barrado y Navascués et al., 2001). There is relatively little background cirrus or extended emission in the field of view. As explained in §5.3.3, MIPS is sensitive to detecting the photospheres of mid-K dwarfs at the distance of IC 2391.


Figure 4.1 A 0.97 square degree mosaic of the central region of IC 2391 taken with the MIPS $24 \mu \mathrm{~m}$ channel. Open circles: debris disk candidates; open squares: cluster members with no apparent $24 \mu$ m excess. The point-source FWHM is $5.7^{\prime \prime}$ and the platescale is $1.25^{\prime \prime}$ / pixel. The image is displayed with a linear stretch and epoch J2000 celestial coordinates.

### 4.3 Results and Analysis

### 4.3.1 IC 2391 Cluster Members Detected at $24 \mu \mathrm{~m}$

To determine the fraction of $\sim 50 \mathrm{Myr}$ stars possessing $24 \mu \mathrm{~m}$ emission excess, we must match the detected sources in our mosaic to bona fide IC 2391 cluster members. There are 1393 sources detected at $24 \mu \mathrm{~m}$ in the Spitzer/MIPS mosaic (Figure 4.1) with a limiting magnitude of $11.7 \mathrm{mag}(0.15 \mathrm{mJy})$. Using a two arcsec search radius, 505 of these sources matched objects in the 2MASS All-Sky Point Source Catalog (Cutri et al., 2003) providing both corresponding near-infrared photometry and standardized 2MASS celestial coordinates. It is expected that all IC 2391 cluster members detected at $24 \mu \mathrm{~m}$ in the MIPS mosaic will have corresponding 2MASS detections since the faintest known cluster members in the literature have $K_{s} \approx 14.5$ mag (M5-M7; Barrado y Navascués, Stauffer, \& Jayawardhana, 2004), (2MASS $K_{s}$ sensitivity limit is $\simeq 15.3 \mathrm{mag}$ ).

To obtain $V$ band magnitudes and proper motions for cluster member selection, we ran the list of 505 sources through the United States Naval Observatory Flagstaff Station (USNOFS) image and catalog archive database NOMAD (Naval Observatory Merged Astrometric Dataset ${ }^{1}$; Zacharias et al., 2004a). This database selects for each source the "best" astrometric and photometric data chosen from its catalogs ${ }^{2}$ and merges the results into a single dataset. Due to the cluster's distance, most of the sources had measured USNO-B1.0 (Monet et al., 2003) or UCAC2 (Zacharias et al., 2004b) proper motions. In the cases where $V$ magnitudes were not available through the database, we used alternate catalogs through the VizieR Search Service or photometry directly from literature sources listed hereafter.

[^8]To our list of 505 stars with $V, J, H, K_{s}$, and [24] photometry, we applied the following membership criteria in sequential order (numbers in parenthesis indicate the number of sources that still remained after the criterion was applied):

- object positions located on the stellar main sequence locus of a dereddened J - H vs $\mathrm{H}-\mathrm{K}_{s}$ color-color diagram that indicate membership. (228)
- object positions located on dereddened $V$ vs $V-K_{s}$ (Figure 4.2) and $K_{s}$ vs $J-K_{s}$ color-magnitude diagrams (CMDs) that indicate membership. (111)
- proper motions within two sigma of the cluster mean $(\approx 95 \%$ of true members; estimated through a $\chi^{2}$ comparison to the mean Hipparcos cluster motion ${ }^{3}$ which includes the object's proper motion uncertainty and an assumed intrinsic velocity dispersion of $1 \mathrm{mas} / \mathrm{yr}$, where $1 \mathrm{mas} / \mathrm{yr}$ $\approx 0.7 \mathrm{~km} / \mathrm{s}$; p. 71 in Bevington \& Robinson, 1992). Using this criterion is expected to result in only $\approx 5 \%$ of bona fide cluster members being rejected.

The evolutionary models of Baraffe et al. (1998) and Siess, Dufour, \& Forestini (2000) were used to determine the mean cluster CMD isochrones and color-color positions for 50 Myr old stars placed at the distance of IC 2391 (154 pc). We selected candidate members using a band 1 mag in apparent magnitude on either side of the mean theoretical isochrones and 0.1 mag in color-color positions. The selection bands are sufficiently broad to take into account photometric, distance, age, binarity, and model uncertainties; reddening is not a factor here. However, with the cluster being close to the Galactic plane ( $\mathrm{b}=-6.90$ ), there is no clear separation between the field stars and the location of the cluster isochrones. We reduce the interloper contamination of our sample by using the combination of

[^9]

Figure 4.2 Dereddened $V$ vs $V-K_{s}$ color-magnitude diagram (CMD) of 33 IC 2391 cluster members (filled circles) observed in our $24 \mu \mathrm{~m}$ mosaic (Figure 4.1); stars have been uniformly dereddened using $E(B-V)=0.006$ (Patten \& Simon, 1996) and the near-infrared reddening laws of Cambrésy et al. (2002). Not included is the brightest star of the cluster $o$ Velorum (ID 20) which is saturated at $K_{s}$. Overplotted are 50 Myr theoretical isochrones from Siess, Dufour, \& Forestini (2000) (dotted line) and Baraffe et al. (1998) (solid line) placed at the distance of IC 2391. Since the models begin diverging at $V-K_{s} \gtrsim 4.4$, we also plot $22 \mathrm{M} 4-\mathrm{M} 7$ dwarfs (small open circles) that are spectroscopically-confirmed cluster members from Barrado y Navascués, Stauffer, \& Jayawardhana (2004) to illustrate the empirical sequence for the coolest known members. The M5 dwarf ID10, the faintest member in our sample detected at $24 \mu \mathrm{~m}$, appears consistent with membership but as a likely binary.
photometric and kinematic measurements as listed above. For later-type stars, however, the evolutionary models appear to diverge at $V-K_{s} \gtrsim 4.4$ and hence we used the spectroscopically-confirmed mid-M dwarfs from Barrado y Navascués, Stauffer, \& Jayawardhana (2004) to define an empirical cluster sequence for latertype members.

Only those sources that satisfied all of the criteria were classified as members and are included in the statistics. From the original 505 sources, 26 met all three criteria for membership. As a consistency and completeness check, we compared our list to probable cluster members from the literature lying in the MIPS field of view in Figure 4.1. While there have been many cluster membership investigations of IC 2391 measuring proper motions, optical and near-infrared photometry, radial velocities, rotational velocities, X-ray emission, spectral classification, and spectral youth diagnostics, there is no single complete listing. The Open Cluster Database ${ }^{4}$ as provided by Prosser \& Stauffer is composed of both members and candidate members extracted from the literature up until 1997. Later cluster membership references come from Simon \& Patten (1998), Patten \& Pavlovsky (1999), Barrado y Navascués et al. (2001), Forbes, Dodd, \& Sullivan (2001), Randich et al. (2001), and Barrado y Navascués, Stauffer, \& Jayawardhana (2004). All 26 sources from our analysis were also classified in the literature as probable or possible cluster members with all but two (ID 7 and 11) having spectral confirmation. Having satisfied our membership criteria, we are confident that these 26 sources are bona fide IC 2391 cluster members and we list them in Tables 4.1 and 4.2.

In addition, there were seven sources which were originally deselected due to proper motions slightly exceeding our $\chi^{2}$ criterion or not measured but are cited

[^10]Table 4.1. General Characteristics of IC 2391 Cluster Members with $24 \mu \mathrm{~m}$
Detections

| ID | RA (2000) | Dec (2000) | SpT | $\begin{gathered} V \\ (\mathrm{mag}) \end{gathered}$ | $\begin{aligned} & V-K_{s} \\ & (\mathrm{mag}) \end{aligned}$ | $\begin{gathered} \text { vsini } \\ (\mathrm{km} / \mathrm{sec}) \end{gathered}$ | binarity? ${ }^{\text {a }}$ | $\log \left(\mathrm{L}_{x} / \mathrm{L}_{\text {bol }}\right)$ | common names ${ }^{\text {b }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 8:37:47.0 | -52:52:12.4 | F5 | 9.65 | 1.14 | - | N | - | HD 73777 |
| 2 | 8:37:55.6 | -52:57:11.0 | G9 | 11.50 | 2.22 | - | N ? | -3.70 | VXR02a |
| 3 | 8:38:44.8 | -53:05:25.4 | B8 | 6.44 | -0.17 | - | Y | -5.99 | HD 73952,VXR04 |
| 4 | 8:38:55.7 | -52:57:51.7 | G2 | 10.29 | 1.61 | 34 | N | -4.47 | SHJM1,VXR05 |
| 5 | 8:38:58.8 | -53:19:12.7 | M3 | 13.77 | 3.92 | $<7$ | SB2 | -3.38 | VXR06a |
| 6 | 8:38:59.9 | -53:01:26.3 | F5 | 9.66 | 1.39 | 21.0 | N | -3.98 | VXR07 |
| 7 | 8:39:02.8 | -52:42:38.4 | K: | 11.28 | $2.48{ }^{\text {c }}$ | - | Y | - | HD 74009B |
| 8 | 8:39:03.4 | -52:42:39.7 | F3 | 8.78 | 0.98 | - | Y | $-3.80{ }^{\text {d }}$ | HD 74009A,VXR08 |
| 9 | 8:39:23.9 | -53:26:23.0 | B5 | 5.44 | -0.36 | - | N | - | HD 74071 |
| $10^{\text {e }}$ | 8:39:29.6 | -53:21:04.4 | M5 | 17.31 | 5.69 | - | Y? | - | PP07 |
| 11 | 8:39:38.8 | -53:10:07.2 | G: | 9.95 | 1.63 | - | N | -3.68 | VXR11,CD-52-2482 |
| 12 | 8:39:43.0 | -52:57:51.1 | F2 | 9.10 | 0.97 | - | N | <-5.14 | HD 74117 |
| 13 | 8:39:53.0 | -52:57:56.9 | K0 | 11.86 | 2.07 | 16 | N | -3.63 | SHJM6,VXR12 |
| 14 | 8:39:57.6 | -53:03:17.0 | B5IV | 5.17 | -0.36 | - | SB | $<-7.28$ | HD 74146 |
| 15 | 8:39:59.4 | -53:15:39.4 | A1p | 7.21 | 0.05 | - | SB | -4.90 | HD 74169,VXR13 |
| 16 | 8:40:01.6 | -52:42:12.6 | A7 | 8.48 | 0.55 | - | N | <-5.75 | HD 74145 |
| 17 | 8:40:06.2 | -53:38:06.9 | G0 | 10.41 | 1.51 | 47 | N | -3.59 | VXR14 |
| 18 | 8:40:16.2 | -52:56:29.2 | G9 | 11.84 | 2.24 | 22.0 | N | -3.25 | VXR16a |
| 19 | 8:40:17.5 | -53:00:55.4 | B7 | 5.55 | -0.34 | - | SB | $<-6.95$ | HD74196 |
| $20^{\text {f }}$ | 8:40:17.6 | -52:55:19.0 | B3IV | 3.59 | $-0.55^{\text {f }}$ | - | N | - | o Velorum, HD 74195 |
| 21 | 8:40:18.3 | -53:30:28.8 | K4 | 13.54 | 3.30 | 8 | N | -3.28 | VXR18a |
| 22 | 8:40:48.5 | -52:48:07.1 | A0 | 7.26 | 0.05 | - | SB | -4.92 | HD 74275,VXR21 |
| 23 | 8:40:49.1 | -53:37:45.4 | G1 | 11.15 | 1.88 | - | N | -3.27 | VXR22a |
| 24 | 8:41:10.0 | -52:54:10.6 | F6 | 9.85 | 1.22 | 43 | SB1? | -4.48 | HD 74340,VXR30 |
| 25 | 8:41:22.8 | -53:38:09.2 | F3 | 9.54 | 1.00 | - | N | - | HD74374 |
| 26 | 8:41:25.9 | -53:22:41.6 | K3e | 12.63 | 2.94 | 90 | SB? | -3.00 | SHJM3,VXR35a |
| 27 | 8:41:39.7 | -52:59:34.1 | K7.5 | 13.38 | 3.42 | 18 | $Y$ ? | -3.32 | SHJM8,VXR38a |
| 28 | 8:41:46.6 | -53:03:44.9 | A3 | 7.55 | 0.63 | - | N | - | HD74438 |
| 29 | 8:41:57.8 | -52:52:14.0 | K7.5 | 13.57 | 3.30 | <15 | N | -3.21 | SHJM9,VXR41 |
| 30 | 8:42:10.0 | -52:58:03.9 | A1 | 7.37 | 0.03 | - | N | $<-6.69$ | HD 74516 |
| 31 | 8:42:12.3 | -53:06:03.8 | F5 | 9.88 | 1.52 | 67: | N | -3.95 | VXR44 |
| 32 | 8:42:18.6 | -53:01:56.9 | M2e | 13.96 | 4.07 | 95 | Y | -3.41 | SHJM10,VXR47 |
| 33 | 8:42:19.0 | -53:06:00.3 | B9p | 5.48 | -0.33 | - | $Y$ ? | -6.67 | HD 74535 |
| 34 | 8:42:25.4 | -53:06:50.2 | B3IV | 4.82 | -0.44 | - | SB | -7.79 | HD 74560,VXR48 |

[^11]Table 4.2. Infrared Properties of IC 2391 Cluster Members with $24 \mu \mathrm{~m}$
Detections

| ID | $\begin{gathered} K_{s}-[24] \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[24]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} \sigma([24]) \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} 24 \mu \mathrm{~m} \text { flux } \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} \text { excess ratio }^{\mathrm{a}} \\ \text { (mag) } \end{gathered}$ | $\begin{gathered} 24 \mu \mathrm{~m} \\ \text { excess? } \end{gathered}$ | $\begin{gathered} 70 \mu \mathrm{~m} \text { flux }^{\mathrm{b}} \\ (\mathrm{mJy}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | -0.06 | 8.57 | 0.03 | 2.71 | 0.94 | N | $<63$ |
| 2 | 0.37 | 8.91 | 0.04 | 1.98 | 1.34 | N | $<82$ |
| 3 | -0.11 | 6.72 | 0.03 | 14.90 | 0.93 | N | <108 |
| 4 | 0.25 | 8.43 | 0.03 | 3.09 | 1.23 | Y | <88 |
| 5 | 0.14 | 9.71 | 0.04 | 0.95 | 0.86 | N | <102 |
| 6 | 0.07 | 8.20 | 0.03 | 3.83 | 1.05 | N | <100 |
| 7 | $-0.03^{\mathrm{c}}$ | 8.83 | 0.04 | 2.14 | 0.93 | N | <71 |
| 8 | 0.05 | 7.75 | 0.03 | 5.81 | 1.04 | N | $<52$ |
| 9 | -0.20 | 6.00 | 0.03 | 28.98 | 0.86 | N | <73 |
| 10 | 1.10 | 10.52 | 0.06 | 0.45 | 1.63 | Y | $<52$ |
| 11 | 0.07 | 8.25 | 0.03 | 3.67 | 1.04 | N | $<73$ |
| 12 | 0.14 | $7.99$ | 0.03 | 4.65 | 1.13 | N | $<52$ |
| 13 | 0.22 | 9.58 | 0.04 | 1.08 | 1.18 | Y | <148 |
| 14 | -0.18 | 5.71 | 0.03 | 37.92 | 0.88 | N | <109 |
| 15 | -0.08 | 7.24 | 0.03 | 9.28 | 0.95 | N | <94 |
| 16 | 0.61 | 7.32 | 0.03 | 8.59 | 1.77 | Y | <159 |
| 17 | 0.07 | 8.83 | 0.03 | 2.14 | 1.04 | N | $<75$ |
| 18 | 0.06 | 9.54 | 0.04 | 1.12 | 1.01 | N | <74 |
| 19 | -0.14 | 6.03 | 0.03 | 28.27 | 0.91 | N | <54 |
| $20^{\mathrm{d}}$ | $-0.08^{\mathrm{d}}$ | 4.22 | 0.03 | 149.05 | 0.97 | N | $<136$ |
| 21 | 0.12 | 10.12 | 0.05 | 0.65 | 0.99 | N | - |
| 22 | -0.10 | 7.31 | 0.03 | 8.70 | 0.93 | N | $<102$ |
| 23 | 0.03 | 9.25 | 0.03 | 1.46 | 0.99 | N | - |
| 24 | 0.43 | 8.20 | 0.03 | 3.84 | 1.47 | Y | <124 |
| 25 | 0.75 | 7.79 | 0.03 | 5.58 | 1.98 | Y | - |
| 26 | 0.26 | 9.44 | 0.04 | 1.23 | 1.18 | Y | <115 |
| 27 | 0.22 | 9.74 | 0.04 | 0.93 | 1.07 | N | $<93$ |
| 28 | -0.05 | 6.97 | 0.03 | 11.84 | 0.96 | N | $<67$ |
| 29 | 0.35 | 9.92 | 0.05 | 0.79 | 1.22 | Y | - |
| 30 | -0.11 | 7.44 | 0.03 | 7.70 | 0.93 | N | - |
| 31 | 0.03 | 8.34 | 0.03 | 3.37 | 1.00 | N | $<68$ |
| 32 | 0.30 | 9.59 | 0.04 | 1.07 | 0.96 | N | - |
| 33 | -0.10 | 5.91 | 0.03 | 31.57 | 0.94 | N | - |
| 34 | -0.20 | 5.47 | 0.03 | 47.48 | 0.87 | N | - |

[^12]as probable cluster members in the literature. All seven - ID 8, 10, 13, 21, 27, 29, and 32 - have photometry consistent with membership according to our first two criteria. ID 8 (HD 74009) is an F3 star whose proper motion we recalculated using additional catalogue points and now satisfies the third criterion. Using an 88-yr baseline, we also verified that ID 8 is part of a $5.5^{\prime \prime}$ binary whose companion, ID 7, is also detected in our $24 \mu \mathrm{~m}$ image. The companion independently satisfies the first two membership criteria but with large $V$ band uncertainty. We thus add ID 7 in addition to the original 26 sources. ID 10 (PP 07; Patten \& Pavlovsky, 1999) is an M5 dwarf that we discuss in more detail in §5.3.6. ID 13 (SHJM 6=VXR PSPC 12), ID 27 (SHJM 8=VXR PSPC 38a=VXR 17), and ID 29 (SHJM 9=VXR 41) (Stauffer et al., 1989; Patten \& Simon, 1996) all have evidence of youth through strong Li I detections ( $\lambda 6707 \AA$; Randich et al., 2001). ID 32 (SHJM 10=VXR 47; Stauffer et al., 1989; Patten \& Simon, 1996) is observed to be an M2e dwarf with a radial velocity within $1 \sigma$ of the cluster mean (Stauffer et al., 1997), Li abundance (Randich et al., 2001), and colors consistent with an early-M dwarf. However, its position on a CMD requires it to be a near-equal mass multiple system. Lastly, ID 21 (VXR PSPC 18a), has no measured proper motion but is X-ray active (Patten \& Simon, 1996), has youth signatures (Randich et al., 2001), and a radial velocity consistent with cluster membership (Stauffer et al., 1997). Thus we add these eight sources to raise our final sample size to 34 objects and include them in Tables 4.1 and 4.2.

Spectral types in Table 4.1 were obtained from the references previously mentioned or from SIMBAD; rotational velocities were obtained from Stauffer et al. $(1989,1997)$, and fractional X-ray luminosities $\left(\log \left[\mathrm{L}_{x} / \mathrm{L}_{b o l}\right]\right)$ were obtained from Patten \& Simon (1996). For completeness, we list in Appendix A three objects that are classified in the literature as cluster members but through this study are
shown to be unassociated. None of these sources had $24 \mu \mathrm{~m}$ excess.

### 4.3.2 Determining $24 \mu \mathrm{~m}$ Photospheric Colors

Our goal is to measure the fraction of IC 2391 cluster members possessing evidence of debris disks by measuring $24 \mu \mathrm{~m}$ flux densities in excess of their expected photospheric emission. We now establish a photospheric base-line emission using a $V-K_{s}$ vs $K_{s}-[24]$ color-color diagram to help identify these excess sources across a broad range of spectral types.

When the sources are all of similar distance and spectral type, a $K_{s}$ vs $K_{s}{ }^{-}$ [24] CMD can identify potential excesses empirically (see Fig. 3 in a Pleiades disk study by Stauffer et al., 2005). Even without knowing the exact photospheric color at $24 \mu \mathrm{~m}$, Stauffer et al. (2005), in consideration of their uncertainties and relative excesses, designate stars with $K_{s}-[24] \gtrsim 0.1$ as candidate debris disk sources. However, for a broader range in photospheric temperatures (color), results from Gautier et al. (2007) show that the $K_{s}-[24]$ photospheric color gradually reddens with cooler effective temperatures until abruptly turning redward for spectral types later than M0. We also see evidence of this behavior in a larger disk survey of the Pleiades conducted by Gorlova et al. (2006).

The $V-K_{s}$ color is a good proxy for spectral type. The two bands are sufficiently separated in wavelength space to trace temperatures/spectral types as well as to break degeneracies that beset near-infrared colors near the K-M spectral type transition. The $K_{s}$-[24] color is a very good diagnostic for mid-infrared excess since for stars earlier than $M$ dwarfs, it is only weakly dependent on stellar temperature with both bands in the Rayleigh-Jeans regime. Using the $K_{s}$-[24] as a mid-infrared excess diagnostic, however, requires the $K_{s}$ band to be photospheric. Near-infrared excess is a diagnostic for optically-thick primordial disks probing emission from active accretion at radii $\lesssim 0.1 \mathrm{AU}$. We find no evidence
for near-infrared excesses from $H-K_{s}$ colors in our sample. Furthermore, for stars older than 10 Myr , the inner-most regions of primordial disks have largely dissipated (Haisch, Lada, \& Lada, 2001). Thus we conclude cluster member emission at $K_{s}$ is photospheric and that significant $K_{s}$-[24] deviations from photospheric values imply the presence of a circumstellar component.

The lack of a large sample of cluster members with no apparent $24 \mu$ m excess in IC 2391 across a wide spectral type range makes establishing a pure empirical photospheric locus potentially inaccurate. There are only 16 apparently-nonexcess stars with $V-K_{s} \curvearrowright 3.0$. On the other hand, a mid-infrared investigation of the Pleiades by Gorlova et al. (2006) offers a large homogeneous $24 \mu \mathrm{~m}$ stellar sample of similar metallicity and distance as IC 2391 with only slightly older age. Gorlova et al. (2006) have identified 57 Pleiades members with good quality detections at $K_{s}$ and $24 \mu \mathrm{~m}$ and no evidence of mid-infrared excess. We plot these 57 stars with colors $0.05 \leq V-K_{s} \leq 3.0$ in Figure 4.3 to illustrate the relative tightness of the distribution. The age difference between IC 2391 and the Pleiades will have negligible effect on the intrinsic $K_{s}-[24]$ color with both wavelengths on the Rayleigh-Jeans side of the emission spectrum for the range of stars in which we are interested. The effect on the $V-K_{s}$ color is less than 0.1 mag according to a comparison of Siess, Dufour, \& Forestini (2000) tracks. This is not surprising as pre-main sequence stars at 50 Myr are already quite close to the main sequence. As we use the $K_{s}-[24]$ color as the primary diagnostic for mid-infrared excess, a $10 \%$ variation in $V-K_{s}$ or less will have very little effect on identifying excesses when using Figure 4.3. Hence, for the $K_{s}-[24] \sim 0$ regime ( $0.05 \leq V-K_{s} \leq 3.0$ ), we use the larger sample of Pleiades members with no apparent mid-infrared excess to construct an empirical photospheric locus of stars on a $V-K_{s}$ vs $K_{s}-[24]$ colorcolor diagram. This photospheric locus is applicable for spectral types from late-B


Figure 4.3 Dereddened $V-K_{s}$ vs $K_{s}$-[24] color-color diagram plotting 57 late-B to mid-K cluster members (solid squares) of the Pleiades open cluster possessing no apparent $24 \mu \mathrm{~m}$ excess (Stauffer et al., 2005; Gorlova et al., 2006). The linear fit to the data (central dashed line) with a $3 \sigma$ scatter of 0.15 mag (outer solid lines) for stars with colors between $0.05 \leq V-K_{s} \leq 3.0$ is described in Gorlova et al. (2006). We interpret the region within the $3 \sigma$ outer solid lines as the empirical photospheric locus for late-B to mid-K stars.
to mid-K stars.
To establish the photospheric locus for M dwarfs, we rely on the field M-dwarf survey of Gautier et al. (2007). We plot their points (small open circles) with matching $V$ band magnitudes in Figure 4.4. The photospheric colors indeed turn redward with increased slope for stars with $V-K_{s} \gtrsim 3.6$. We compare this locus with the predicted $V-K_{s}$ colors for 50 Myr stars (Siess, Dufour, \& Forestini, 2000) with the spectral type $/ K_{s}$-[24] relation from Gautier et al. (2007) by a (dashed line).


Figure 4.4 Dereddened $V-K_{s}$ vs $K_{s}-[24]$ color-color diagram plotting 31 members (filled circles) of the IC 2391 open cluster. The brightest star in the cluster, B3IV $o$ Velorum (ID 20), is omitted due to saturated $\mathrm{K}_{s}$ photometry. The dereddened Pleiades photospheric locus with its mean (dotted line) and $3 \sigma$ scatter (solid lines) from Figure 4.3 is overplotted. Sources redder than the $3 \sigma$ Pleiades relative excess threshold possess $K_{s}$-[24] flux ratios in excess of expected photospheric colors and are considered to be debris disk candidates (large open circle). To estimate the photospheric locus for stars with $V-K_{s}$ colors redder than the Pleiades locus ( $V-K_{s}>3.0$ ), we plot field M dwarfs (small open circles) from a $24 \mu \mathrm{~m}$ and $70 \mu \mathrm{~m}$ investigation by Gautier et al. (2007). We also plot the theoretical photospheric $V-K_{s}$ colors of 50 Myr stars (Siess, Dufour, \& Forestini, 2000) matched to a spectral type $/ K_{s}-[24]$ relation from the Gautier et al. M dwarf sample (dashed line). Both profiles, along with a few members from IC 2391, show a redward turn for photospheres of late-type stars near $V-K_{s} \sim 3.0$. ID numbers of some of the cluster members are shown. The mid-infrared excess of ID 2 may be associated with a background giant (see §5.3.4).

### 4.3.3 Sources with Apparent $24 \mu \mathrm{~m}$ Excess

Since the precision of the $24 \mu \mathrm{~m}$ photometry in the Pleiades dataset is very similar to ours, we adopt the Pleiades $3 \sigma$ relative excess threshold ( $\sigma=0.05 \mathrm{mag}$ ) as the criterion for thermal excess in our IC 2391 study. A cluster member whose $24 \mu \mathrm{~m}$ flux density exceeds its predicted photospheric emission at this wavelength by at least $15 \%$ is a debris disk candidate. We refer to the ratio of observed to predicted flux density as the $24 \mu \mathrm{~m}$ excess ratio and will discuss its evolution for FGK stars in $\S 5.4 .3$. We apply in Figure 4.4 this photospheric locus for A-K stars along with the empirical photospheric locus for M dwarfs to our IC 2391 sample. We uniformly deredden the stars using $E(B-V)=0.006$ and the IR reddening laws described in Cambrésy et al. (2002) (assuming $\mathrm{A}_{[24]} \sim 0$ ).

In the $V-K_{s} \leq 3.0$ regime in Figure 4.4, we identify seven debris disk candidates: ID $2,4,13,16,24,25$, and 26 . Of the three detected cluster M dwarfs, we observed only 1 obvious excess - the M5 dwarf ID 10 (discussed further in §5.3.6). For the color regime not fitted by our models $\left(3.0<V-K_{s}<3.6\right)$, we assume in Figure 4.4 a simple diagonal fit connecting the upper and lower regimes. This is consistent with the positions of late-type stars ID 5, 21, and 27 and results in one more candidate excess source, ID 29.

The images of the nine stars initially identified as debris disk candidates were visually inspected at $24 \mu \mathrm{~m}$ to ensure they match a point spread function and do not include potential contamination by heated cirrus or background sources. In addition the stars were analyzed in the higher-resolution, near-infared 2MASS images ${ }^{5}$ for elongation due to possible tight binaries. Only source ID 2 (VXR 02a, G9; Patten \& Simon, 1996) showed elongation in the $24 \mu \mathrm{~m}$ image, due to a faint source appearing $6.6^{\prime \prime}$ away. Patten \& Simon (1996) classify this faint companion

[^13]object as a K3V but its near-infrared colors and position on the cluster CMD are more consistent with a background K giant and hence it is possible that the $24 \mu \mathrm{~m}$ excess may be due to dust from an evolving background giant and not the cluster member ID 2. Therefore, we do not classify ID 2 as a debris disk candidate.

In total, we identify eight cluster members with evidence of debris disks - one A star, six FGK stars, and one M dwarf. We circle the eight in Figures 4.1 and 4.4 and indicate them as $24 \mu \mathrm{~m}$ excess objects with a " Y " in Table tbl-2.

The candidate debris disks presented here are the first observed in IC 2391. A report of possible $25 \mu \mathrm{~m}$ IRAS excesses around several of the cluster A and earlyF stars (Backman, Stauffer, \& Witteborn, 1991) is not confirmed. Six members (all B stars) have $12 \mu \mathrm{~m}$ IRAS detections, all of which are photospheric. None have IRAS detections at wavelengths $\geq 60 \mu \mathrm{~m}$. In addition, none of the members have been previously detected with ISO. We summarize the overall number and frequency of excess objects by spectral type in Table 4.3 and discuss their interpretation in §5.4.

The excess frequency of a sample is defined as the ratio of the number of excess sources to the total number of sources. We include in this ratio only those IC 2391 cluster members whose photospheres are detectable at $24 \mu \mathrm{~m}$. We define this minimum flux density sensitivity as the completeness limit of our sample, calculated at the turnover in the $K_{s}$ brightness distribution of all the sources in our MIPS image with $24 \mu \mathrm{~m}$ detection ( $K_{s}<9.9$ ). This brightness corresponds to spectral type $\sim$ K4 in IC 2391. Detections fainter than the completeness limit may be biased toward excesses.

While we identify 34 cluster members in our mosaic, eight are removed from our statistical analysis. Four have $K_{s}$ magnitudes fainter than our photospheric completeness level (ID 10, 21, 27, 29) and another two are binaries whose individ-

Table 4.3. Fraction of IC 2391 Cluster Members with $24 \mu \mathrm{~m}$ Excess

|  | \# of | \# of |  |
| :---: | :---: | :---: | :---: |
| Members in | Excess | Excess |  |
| Spectral Type | this Sample $^{\text {Stars }}$ | Frequency $^{\text {b }}$ |  |

${ }^{\text {a }}$ Excesses defined as sources with $K_{s}-[24]$ colors lying on or redward of the $3 \sigma$ Pleiades photospheric baseline shown in Figure 4.4. $24 \mu \mathrm{~m}$ excess fluxes are $\geq 15 \%$ above the mean photospheric flux as a function of spectral type.
${ }^{\mathrm{b}}$ Ratio of the number of excess stars to the total number of stars in a spectral bin. All sources included in the excess frequency have $24 \mu \mathrm{~m}$ sensitivity to the photospheric flux (spectral type $<\mathrm{K} 4$ ).
cSpectral types < B5 are removed from the excess frequency statistics due to possible free-free emission contamination.
${ }^{\mathrm{d}}$ All 3 systems are most likely binaries with integrated brightness sufficiently large to be detected at $24 \mu \mathrm{~m}$; one, however, has a very strong $24 \mu \mathrm{~m}$ excess. None of the $24 \mu \mathrm{~m}$ detections are sensitive to photospheric emission.
ual components are outside the completeness limit (ID 5 and 32). The last two, ID 20 and 34, are both B3IV stars. It is known that early B stars are sufficiently hot to emit free-free emission that can also contribute $24 \mu \mathrm{~m}$ flux (Chokshi \& Cohen, 1987). Hence, using a $15 \%$ threshold, we report an overall excess frequency for the cluster of $0.23_{-0.06}^{+0.10}(6 / 26$; excess frequency uncertainties are reported throughout this report as $1 \sigma$ binomial probability distributions; see Appendix in Burgasser et al., 2003a).

While there were no detections of IC 2391 cluster members with the MIPS $70 \mu \mathrm{~m}$ channel, we calculate upper flux limits at the $24 \mu \mathrm{~m}$ source positions using aperture photometry with a 1.83 pixel radius aperture and 1.927 aperture correction (STinyTim $70 \mu \mathrm{~m}$ PSF model; Gordon et al., in prep). The $70 \mu \mathrm{~m}$ upper limits are listed in Table 4.2.

### 4.3.4 Contamination

With a relatively flat background and little cirrus emission, the most likely contaminant in IC 2391 is confusion from random line-of-sight positional overlap with distant optically-faint but infrared-bright galaxies and AGN, showing no sign of elongation in the MIPS image. What is the probability of such an accurate chance alignment? For example, with $\sim 2000$ extra-galactic sources per square degree at 0.5 mJy (Papovich et al., 2004), a flux less than our completeness limit but greater than our detection limit, the probability of a chance background source observed within $0.5^{\prime \prime}$ of a cluster member is $0.4 \%\left[\pi\left(0.5^{\prime 2} /\left(0.97 \times 60^{2}\right)\right) \times 2000 \times 32\right]$. Except for ID 10 and ID 29, the faintest excess sources, the remaining excess candidates are at least a factor of two brighter and the extragalactic contamination is significantly lower.

Additionally, we looked for positional offsets between our $24 \mu \mathrm{~m}$ excess sources and the corresponding 2MASS positions that could potentially indicate
fake excess emission from a superimposed object. The average offset between all our MIPS objects and 2MASS positions for members from Table 4.1 is $0.6^{\prime \prime}$. Except for ID 29, which is the second faintest excess candidate in the sample (and not included in our frequency statistics), the sources fall within a $1^{\prime \prime}$ circle centered on the $0.6^{\prime \prime}$ systematic offset on a $\Delta R A$ vs $\Delta$ Dec plane.

### 4.3.5 Debris Disk Correlations with Other Stellar Properties

Due to both its age and proximity, IC 2391 has been the subject of several rotational velocity and X-ray studies (Stauffer et al., 1989; Patten \& Simon, 1993, 1996; Stauffer et al., 1997; Simon \& Patten, 1998; Marino et al., 2005). To assess correlations between cluster members with and without evidence for debris disks with other stellar parameters, we matched the cluster members in Table 4.1 with information regarding binarity, rotation (vsini), and X-ray luminosity ( $\log \left[\mathrm{L}_{x} / \mathrm{L}_{b o l}\right]$ ) from the literature. As also observed by Stauffer et al. (2005) and Gorlova et al. (2006) in their investigations of the Pleiades, we find no clear correlations between $24 \mu \mathrm{~m}$ excess sources and any of these stellar properties.

### 4.3.6 An Interesting Possible Cluster Member: PP 7

ID 10 (PP 7; Patten \& Pavlovsky, 1999) is a spectroscopically measured M5 dwarf (Barrado y Navascués, Stauffer, \& Jayawardhana, 2004) with an observed $24 \mu \mathrm{~m}$ flux density approximately 1.6 times the predicted photospheric level. PP 7 is the faintest star in Table 4.1 to have a $24 \mu \mathrm{~m}$ detection and have an excess; however, it is 3 times above the MIPS $24 \mu \mathrm{~m}$ detection limit. Its positions in both near-infrared and optical CMDs (Figure 4.2), as well as in the near-infrared color-color diagram, are consistent with membership, but only as a nearly equal-mass binary system. The Na I doublet ( $\lambda 8200 \AA$ ) equivalent width and $\mathrm{H} \alpha$ emission line are consistent with a young, late M dwarf. Using five astrometric positions we have calculated
its proper motion to be $\mu_{\alpha} \cos \delta=-45.0 \pm 10.1 \mathrm{mas} / \mathrm{yr}, \mu_{\delta}=20.8 \pm 10.7 \mathrm{mas} / \mathrm{yr}$. Compared to IC 2391's mean motion (Robichon et al., 1999), PP 7 gives a kinematic $\chi^{2}$ of 3.9 for two degrees of freedom (i.e. $14 \%$ of bona fide cluster members should have proper motion values more deviant). Hence, PP 7 appears to be kinematically consistent with membership in IC 2391.

PP7 appears to possess, however, a lithium abundance anomaly. Barrado y Navascués, Stauffer, \& Jayawardhana (2004) report a weak Li measurement $(S / N \sim 3)$ in its spectrum despite the star being about 2 mag brighter than the empirical Li depletion boundary for the cluster at $K_{s}$. The possibility, as mentioned above, that the star may be an equal-mass binary brings it 0.75 mag closer to the cluster Li depletion boundary. While there exists the possibility that PP 7 is a very young, nearby star but unassociated with IC 2391, the simpler hypothesis may be that it is a cluster member whose Li has simply not burned as fast as other members of similar mass. A radial velocity measurement would most likely confirm membership. If proven to be a member, it would be only the fourth M dwarf older than 10 Myr known to have a mid-infrared or submillimeter excess (AU Mic, GJ182, 2MASS J08093547-4913033; Song et al., 2002; Liu et al., 2004; Young et al., 2004).

### 4.4 Disk Frequency of IC 2391 and Implications for Debris Disk Evolution

We find eight IC 2391 cluster members with spectral types between $A$ and M possessing $24 \mu \mathrm{~m}$ excess consistent with debris disks. There are two interesting aspects to our results: 1.) a possible dearth of $24 \mu \mathrm{~m}$ excess around A-type stars; and 2.) an abundance of $24 \mu \mathrm{~m}$ excess around FGK stars. We now discuss these results, put them in the context of stars in clusters of similar and different ages, and interpret the implications for debris disk evolution.

### 4.4.1 Dearth of Debris Disks Around Early-Type Stars in IC 2391?

Because of their high temperatures and luminosities, A stars are very efficient at illuminating the dust in debris disks, yet they are not so hot, as are early-B stars, that they excite gaseous disks that might masquerade as debris dust. Consequently, debris systems around A-type stars (B5-A9) have been studied particularly thoroughly. The largest surveys of this nature are Rieke et al. (2005) (266 stars) and Su et al. (2006) (160 stars) who used both Spitzer and IRAS observations to study debris disk frequencies and evolution. Their samples, composed of both cluster members and field objects, range in ages between 5 and 850 Myr and all the observations at $24-25 \mu \mathrm{~m}$ are sensitive to photospheric levels.

How does the debris disk frequency of A-type stars in IC 2391 compare to the larger surveys? To create a single robust sample to which we could compare our results, we combined the two samples of Rieke et al. and Su et al., removed the IRAS sources (which have larger scatter than the Spitzer data), used a common relative excess threshold criterion ( $\geq 15 \%$ ), and only considered sources with estimated ages $\geq 10 \mathrm{Myr}$. Whenever there was source duplication we used the more recent Su et al. $24 \mu \mathrm{~m}$ excess ratio results due to improved reduction procedures and fitting to theoretical photosphere models. The combined data set consists of 276 stars which we place in arbitrary age bins. For the $31-89 \mathrm{Myr}$ age bin, the excess frequency is $0.44_{-0.10}^{+0.12}(8 / 18)$. Thus, nearly half of the stars between 3189 Myr have evidence for debris disks. For the same B5-A9 spectral type range in IC 2391, we find an excess frequency of $0.10_{-0.03}^{+0.17}(1 / 10)$. If we use the binomial distribution where the probability of "success" is $0.44_{-0.10}^{+0.12}$, the probability that these two results are drawn from the same distribution is about $3 \%$.

There are three possibilities to explain this result: 1.) it may be just a statistical deviation, given the only moderate probability that the difference is significant;

Table 4.4. $24 \mu \mathrm{~m}$ Excess Frequencies of A-Type Stars from Spitzer/MIPS Surveys ${ }^{\text {a }}$

|  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Excess Frequency | Age (Myr) | Sample Size | Excess Frequency References |
| Up Cen Lupus | $0.44_{-0.11}^{+0.12}$ | $16 \pm 2$ | 16 | Su et al. (2006) |
| NGC 2547 | $0.44_{-0.10}^{+0.12}$ | $30 \pm 5$ | 18 | Young et al. (2004), Gorlova et al. (in prep) |
| IC 2391 | $\mathbf{0 . 1 0}+0.03$ | $50 \pm 5$ | $\mathbf{1 0}$ | This paper |
| M47 | $0.32_{-0.12}^{+0.10}$ | $80 \pm 20$ | 31 | Rieke et al. (2005) |
| Pleiades | $0.25_{-0.07}^{+0.12}$ | $115 \pm 20$ | 20 | Gorlova et al. (2006) |
| NGC 2516 | $0.25_{-0.05}^{+0.07}$ | $150 \pm 20$ | 51 | Rieke et al. (2005) |
| Hyades | $0.09_{-0.03}^{+0.16}$ | $625 \pm 50$ | 11 | Su et al. (2006) |

${ }^{\text {a }}$ A-type stars are defined here as stars with spectral type B5-A9; earlier B stars are omitted to minimize the possibility of $24 \mu \mathrm{~m}$ detection from gaseous disk free-free emission rather than from warm dust in a debris disk.
2.) it may signal that the simple smooth decay with age used to characterize debris disks as demonstrated by Rieke et al. (2005) is an oversimplification; or 3.) it might indicate that the cluster environment has influenced the debris disk evolution. The first possibility cannot be ruled out without observations of additional clusters at similar ages. Nevertheless, the latter two are worth exploring because it is of interest to see whether variations in the debris disk frequencies in clusters might be possible and what their causes might be.

How does this frequency compare to clusters of other ages? In Table 4.4 we list the excess frequencies from Spitzer $24 \mu \mathrm{~m}$ surveys of A-type stars from open clusters (and an OB association) with sample sizes $\geq 10$ and plot them in Figure 4.5. In each cluster, the same relative excess threshold of $15 \%$ above the predicted photospheric emission has been used. Age estimates and their uncertainties are obtained from references within those listed in Table 4.4.

The seven open clusters and the association closely follow the larger com-


Figure 4.5 Fraction of A-type stars (B5-A9) with $24 \mu \mathrm{~m}$ excess as a function of age. Plotted as filled circles are the excess frequencies from Spitzer/MIPS observed open clusters and a stellar association (data and references listed in Table 4.4). Also shown in open boxes are mean $24 \mu \mathrm{~m}$ excess frequencies from age bins (listed across the top of the Figure) from the combined MIPS-only surveys of Rieke et al. (2005) and Su et al. (2006). Error bars are $1 \sigma$ binomial distribution uncertainties and age uncertainties are taken from the cluster references in Table 4.4. In all cases a $15 \%$ relative excess threshold was used. Note that the IC 2391 excess frequency appears comparatively low for its age.
bined field and cluster sample. This is not unexpected with only the Pleiades and IC 2391 not already included in the larger combined sample. While the fraction of stars with debris disks for the other clusters matches the overall behavior of the entire sample, IC 2391's disk frequency appears disproportionately low. Since its behavior does not seem to be reflected in the other cluster results, it does not represent an overall departure from the smooth decline in activity. That is, there is no evidence in favor of our second hypothesis.

We now consider the third possibility, that the cluster environment might be responsible. Unlike the marginally smaller fraction of measured excesses found amongst the A-type stars in IC 2391, Figure 4.4 shows that excesses around the FGK stars appear to be more common. Is there a physical scenario that can explain the behavior of both stellar types?

Metallicity is not a likely issue in this case because IC 2391 has comparable metallicity ( $\mathrm{Fe} / \mathrm{H}=-0.03 \pm 0.07$; Randich et al., 2001) to other clusters with higher frequency of A-type excesses (ie. the Pleiades and M47; Nissen et al., 1988; Randich et al., 2001). In addition, a dependence of the incidence of excesses on metallicity has not been seen in solar analogs (Greaves, Fischer, \& Wyatt, 2006).

A hypothesis invoking mass segregation whereby the most massive stars settle towards the cluster center where stellar densities, and hence disk interactions, are highest does manage to explain why less-massive stars would have higher disk frequencies. However, theoretical simulations of the effects of primordial disk interactions in clusters the size of IC 2391 ( $\sim 100-200$ members) during the early period of gas dissipation predict low interaction rates (Adams et al., 2006). In addition, this phenomenon is not observed in other open clusters which should already have experienced mass segregation (such as the Pleiades and the Hyades).

Interestingly, Sagar \& Bhatt (1989), conducting a kinematic survey of proper motion data for eight clusters with ages ranging from 8 to 300 Myr , found IC 2391 to be the only cluster that showed mass dependence as a function of intrinsic proper motion dispersions. The higher mass stars in IC 2391 were measured to have lower velocity dispersions than the lower mass stars suggesting mass segregation. Their results, however, suffer from several observational uncertainties including low proper motion accuracies and incomplete IC 2391 cluster membership. Nevertheless, their claim is intriguing.

Another possibility centers on the photoevaporation of primordial disks. This process may be greatly accelerated around very luminous O stars (e.g. Hollenbach, Yorke, \& Johnstone, 2001). The formation of such a star in a cluster is subject to small number statistics (Elmegreen, 2004) and it is possible that some clusters would have subjected their members' primordial disks to this effect, while others would not. Given the short lifetimes of O stars, the direct traces of the star would have disappeared by the age of IC 2391. To account for the differences between the A-type and FGK stars in this cluster, however, requires that either mass segregation play a key role in timescales short enough to expose the A-type stars and their primordial disks to the UV radiation of O stars before significant planetesimal formation, or that photoevaporation is less efficient inwards (towards the star), at radii where $G$ stars radiate at 24 micron ( $\sim 5 \mathrm{AU}$ ). Theoretical models differ on whether photoevaporation could behave in this manner (Johnstone, Hollenback, \& Bally, 1998; Richling \& Yorke, 2000; Matsuyama, Johnstone, \& Murray, 2003; Throop \& Bally, 2005). Although relaxation timescales in clusters of the size of IC 2391 are short enough ( $\sim 1$ Myr; p. 190, Binney \& Tremaine, 1987) to support this hypothesis, the high primordial disk frequency $\sim 40 \%$ in NGC 2244 ( $\sim 2$ Myr), despite its including many O stars (Balog et al., in prep),
would argue against it.
In summary, although it would be interesting to search for some of the effects we have discussed in other clusters, none of them gives a solid explanation for the behavior of IC 2391. For the present, we need to assume that the lack of A-type star debris systems may just be due to statistics.

### 4.4.2 Abundance of Debris Disks Around Solar-Type Stars in IC 2391

Seven cluster members in IC 2391 with spectral types F to M show evidence of $24 \mu \mathrm{~m}$ excess. Considering just the spectral types within the completeness limit $(<\mathrm{K} 4)$ and a $24 \mu \mathrm{~m}$ relative excess threshold of $15 \%$, the excess frequency of FGK stars is $0.31_{-0.09}^{+0.13}(5 / 16)$. In fact, even around solar-type stars (F5-K7), the excess frequency is $\sim 0.31(4 / 13)$. Debris disks around solar-type stars in IC 2391 appear to be common.

Unlike the A-star surveys of Rieke et al. (2005) and Su et al. (2006), there is to date no comprehensive mid-infrared study in the literature of the fraction of solar-type stars with debris disks over a broad range of ages. We list the excess frequencies for known Spitzer $24 \mu$ m surveys sensitive to photospheric emissions of F, G, and possibly K stars in open clusters (and an OB association) in Table 4.5. Depending on distance, or target sample, the spectral type corresponding to the $24 \mu \mathrm{~m}$ completeness limit brightness varies in each cluster. We state any assumptions made in estimating the debris disk frequency of each cluster in Appendix B.

The evolution of the excess frequency of FGK stars is shown in Figure 4.6. The IC 2391 results fill an age gap in the previous studies between 30 and 100 Myr . The relatively large $24 \mu \mathrm{~m}$ excess frequency observed around FGK stars in IC 2391 ( $\sim 31 \%$ ) appears consistent for its age with an evolutionary decay model. There are two important results here: 1) the IC 2391 result implies that planetesi-

Table 4.5. $24 \mu \mathrm{~m}$ Excess Frequencies of FGK Stars from Spitzer/MIPS Surveys

|  | Excess Frequency | SpT Range | Age (Myr) | Sample Size | Excess Frequency References |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Sco Cen $^{\text {a }}$ | $0.40_{-0.08}^{+0.25}$ | G | $16 \pm 2$ | 35 | Chen et al. (2005) |
| NGC 2547 | $0.33_{-0.12}^{+0.08}$ | F | $30 \pm 5$ | 21 | Gorlova et al. (in prep) |
| IC 2391 | $0.31_{-0.09}^{+0.13}$ | F-K4 | $50 \pm 5$ | $\mathbf{1 6}$ | This paper |
| Pleiades | $0.09_{-0.06}^{+0.06}$ | F-K6 | $115 \pm 20$ | 53 | Stauffer et al. (2005); Gorlova et al. (2006) |
| Hyades | $0.00+0.03$ | G | $625 \pm 50$ | $51^{\mathrm{b}}$ | Cieza, Cochran, \& Paulson (2005) |
| Field stars | $0.03 \pm 0.02$ | F5-K5 | $4000^{\mathrm{c}}$ | 69 | Bryden et al. (2006) |

${ }^{\text {a }}$ Includes only stars from the subgroups Upper Centaurus Lupus and Lower Centaurus Crux.
${ }^{\mathrm{b}}$ Results are based on preliminary information from Cieza, Cochran, \& Paulson (2005), a conference poster. See Appendix for additional comments.
${ }^{\mathrm{c}}$ Median age of the sample
mals around solar-type stars are still undergoing frequent collisions in terrestrial planet-forming regions at $\sim 50 \mathrm{Myr}$ and 2 ) the fraction of FGK stars with $24 \mu \mathrm{~m}$ excess appears to decay similarly to the trend seen for A-type stars.

While the uncertainties in the excess frequencies of the youngest systems are considerable, Figure 4.6 clearly illustrates that planetesimal activity (collisions) within the terrestrial planet zones of FGK stars ( $\sim 1-5 \mathrm{AU}$ ) is common during at least the first 50 Myr . This is consistent with the epoch of terrestrial planet formation in our own Solar System (Kleine et al., 2002; Jacobsen, 2005). In fact, planetesimal systems around FGK stars continue being collisionally active even within the first few hundred million years. Several hundred million years later, however, mid-infrared excesses in the $\sim 1-5$ AU regions become rare. A survey of 69 nearby, solar-like field stars with median age $\sim 4 \mathrm{Gyr}$ found only two with $24 \mu \mathrm{~m}$ excess meeting or exceeding the $15 \%$ relative excess threshold (Bryden et al., 2006). Also, the evolutionary decays presented in Figure 4.6 are only aggregate behaviors; even at ages $\gtrsim 500 \mathrm{Myr}$ large episodic excesses, while quite rare, do appear (e.g. Beichman et al., 2005a). The rarity of large impacts in mature systems is consistent with both the models of Kenyon \& Bromley (2004a) and the


Figure 4.6 Fraction of stars with spectral types F, G, and/or K with $24 \mu \mathrm{~m}$ excess as a function of age. Plotted as filled circles are the excess frequencies of these stars from Spitzer/MIPS observed clusters and an association (references given in Table 4.5; additional comments are made in Appendix B). As a comparison, we also plot the mean $24 \mu \mathrm{~m}$ excess frequencies of A-type stars (open boxes) from the combined MIPS-only data of Rieke et al. (2005) and Su et al. (2006) as shown in Figure 4.5 (we connect the A-type points with a dashed line to help distinguish the two populations). In all cases, a $15 \%$ relative excess threshold was used. Vertical error bars are 1 -sigma binomial distribution uncertainties and age uncertainties are taken from the cluster references listed in Table 4.5. Despite probing different annular regions, the decline in the excess frequency of the FGK stars suggests a decline in the collision rate between planetesimals with stellar age similar to that of the more massive A-type stars.
cratering record of the terrestrial planets (Strom et al., 2005; Gomes et al., 2005). We illustrate this further in §5.4.3.

Combining with the results of Gorlova et al. (2006), the debris disk frequency around FGK stars follows a similar excess decay behavior as the more massive A-type stars. Despite the overall similarity of behavior, one could also conclude from Figure 4.6 that the FGK decay characteristic time scale appears shorter than that of the A-type stars. This is possibly, however, a luminosity effect rather than a mass-dependent effect (since the more luminous A-stars heat up larger annuli of dust to the levels detectable at $24 \mu \mathrm{~m}$ ). Until longer-wavelength observations can probe larger distances around FGK stars for evidence of cooler dust, we conclude from Figure 4.6 that debris disk evolution does not appear to be strongly dependent on stellar mass.

Infrared excesses may originate from cascading collisions among asteroidsized objects. However, some systems may be in a quiescent phase and not currently exhibit infrared excesses. In others, a wave of planet formation may have already passed through the regions probed at $24 \mu \mathrm{~m}(\sim 1-5 \mathrm{AU})$ and planetesimal collisions may be occurring undetected at larger distances (Kenyon \& Bromley, 2004b). This implies that the debris disk incidence reported here actually gives a lower limit to the fraction of stars possessing planetestimals or undergoing planetesimal formation. Since a third of the stars have significant planetesimal-collision-generated excess emission at $\sim 50 \mathrm{Myr}$, and the incidence of debris disks possibly rises at earlier ages, it is likely that planetesimals form around the majority of solar-like stars. However, even a more intriguing conclusion can be drawn if planetesimal collisions must be driven by gravitational perturbations from planet-sized objects, in which case it may be true that most primordial disks around solar-like stars evolve to form planetary systems.

### 4.4.3 The Evolution of $24 \mu \mathrm{~m}$ Excesses Around FGK Stars

Understanding how the $24 \mu \mathrm{~m}$ excess evolves over time around FGK stars may provide insights to the collision history in the terrestrial planet region. Taking luminosity differences into account, we now explore the evolution of the excess ratio, which we defined in $\S 5.3 .3$. The $24 \mu \mathrm{~m}$ excess ratios of FGK stars in our IC 2391 sample range between 0.9 and 2.0 with a median of 1.1. In Figure 4.7 we plot these results along with the excess ratios of FGK stars from the other clusters listed in Table 4.5 as a function of time. We also add two known solartype stars not members of clusters but with measured mid-infrared excesses HIP 8920 (300 Myr, G0V; Song et al., 2005) and HD 12039 (30 Myr, G3/5; Hines et al., 2006). The upper envelope of the excess ratios appears to decrease rapidly within the first $\sim 25 \mathrm{Myr}$ followed by a gentler decay with characteristic timescale of $\sim 100$ Myr. This early rapid decay may represent the final clearing of disks that are transitional between the primordial and debris stages. By several hundred million years, the mean $24 \mu \mathrm{~m}$ flux is close to photospheric.

Over-plotted onto Figure 4.7 are an inverse time (solid line) and an inverse time-squared (dashed line) decay. While more data at younger ages would better define the fit, the inverse time decay appears to best match the data's upper envelope at ages $\gtrsim 20 \mathrm{Myr}$. Larger inverse powers overestimate the number of large excesses observed at earlier times. An inverse time decay is qualitatively consistent with collisions being the dominant grain destruction mechanism (Dominik \& Decin, 2003). Chen et al. (2006) show that for a main sequence F5 star with dust mass between 0.001-1 Earth masses , the collision lifetimes for average-sized grains is always shorter than the Poynting-Robertson and corpuscular wind drag lifetimes at radial distances < 100 AU. Dominik \& Decin (2003) and Wyatt (2005) conclude that all observed debris disks are in the collision-dominated regime.


Figure $4.724 \mu \mathrm{~m}$ excess ratio vs age for FGK stars. The excess ratio is the measured flux density to that expected from the stellar photosphere alone; a value of 1 represents no excess (lower horizontal dotted line). The upper horizontal dotted line represents the 1.15 relative excess threshold used in this study. F0-F4 stars are shown as filled triangles while F5-K7 stars ("solar-like") appear as filled circles. The solid curve is an inverse time dependence and the dashed curve is inverse time-squared. All of the points have been observed with Spitzer at $24 \mu \mathrm{~m}$ and, with a few noted exceptions, are part of the disk investigations listed in Table 4.5. Additions are M47 data (Gorlova et al., 2004), the 30 Myr HD 12039 (Hines et al., 2006), and the 300 Myr HIP 8920 (Song et al., 2005). Omitted from this figure is HD 152404 from Upper Centaurus Lupus ( $\sim 17 \mathrm{Myr}$, F5V; Chen et al., 2005) with a reported excess ratio of 202 . The size of the excess coupled with its age suggests the possibility that the large excess may be due to a long-lived primordial disk. IC 2391's data are shown above its labelled age of 50 Myr .

The evolution of the observed excess ratios shown in Figure 4.7 may be best interpreted as the evolution of dust generation from planetesimal collisions around FGK stars. As planetesimals are gravitationally scattered out of planetary systems, grow into Moon-sized objects or larger, or are ground down and removed via Poynting-Robertson drag, their fewer numbers result in less frequent but occasionally powerful collisions producing copious amounts of dust. Observationally, this translates to a decreasing mean $24 \mu \mathrm{~m}$ flux excess ratio with occasional large outliers as shown in Figure 4.7. Potential examples of stars with excess appearing as spikes indicating that such collisions have occured recently (in the past ~ million years) in their planetary systems are 2M0735-1450 (80 Myr, F9; Gorlova et al., 2004), HIP 8920 (300 Myr, G0V; Song et al., 2005), and HD 69830 (2 Gyr, KO; Beichman et al., 2005a).

Based on the rarity of objects with evidence of recent collisions and the generally low incidence of $24 \mu \mathrm{~m}$ excess we draw a conclusion similar to that of Rieke et al. (2005): large collisions occur after the initial period of terrestrial planet formation as episodic, stochastic events. The general decay in the excess ratio may very well correspond to the decline of the collision frequency within the inner parts of a planetary system analogous to the asteroid belt of our own Solar System. The larger excess ratios observed at earlier periods may be very reminiscent of our understanding of events in the early Solar System, in which an early period ( $\lesssim 100 \mathrm{Myr}$ ) of frequent and catastrophic collisions (e.g., the birth of the Moon) was followed by a declining rate of planetesimal impacts followed by one last brief period of heavy bombardment $\sim 600-700 \mathrm{Myr}$ (Strom et al., 2005; Gomes et al., 2005).

The general behavior of the FGK stars in Figure 4.7 is remarkably similar to the corresponding figure for A-stars (Rieke et al., 2005). Besides the inverse-time
decay of the excess ratio and episodic outliers at ages older than about a hundred million years, Figure 4.7 also illustrates another similarity between the two populations - the fraction of stars that have no or little $24 \mu \mathrm{~m}$ excess at a given age. This phenomenon occurs even for the youngest FGK stars despite their overall higher probability of having mid-infrared excesses. Analogous to the previous conclusion from A-type star studies (Spangler et al., 2001; Decin et al., 2003; Rieke et al., 2005), this possibly points to a distribution of planet formation and clearing timescales even within young stellar clusters. Given the uniform behavior, the range of $24 \mu \mathrm{~m}$ excess measured over time should eventually provide quantitative constraints for theoretical models of planetary system evolution.

The results from numerical simulations investigating the evolution of dust generation from planetesimal collisions around solar-type stars by Kenyon \& Bromley (2005) show a qualitative similarity to the observed behavior in Figure 4.7. Kenyon \& Bromley (see their Fig. 4) show both a steady decline of the $24 \mu \mathrm{~m}$ excess ratio after $\sim 1 \mathrm{Myr}$ due to the depletion of colliding bodies and episodic large increases due to individual massive collisions. However, there are a number of observed behaviors where the simulations do not yet match. The characteristic timescales of the simulations appear shorter than what is observed. For example, at the age of the oldest subgroups in Scorpius-Centaurus ( $\sim 17 \mathrm{Myr}$ ), the simulations show $24 \mu \mathrm{~m}$ flux densities only 2-3 times photospheric as compared to the much larger ratios observed by Chen et al. (2005) and shown in Figure 4.7. This difference is independent of possible contamination by remnant primordial (or transition) disks in the Scorpius-Centaurus sample. In addition, there are no large excess ratios (spikes) greater than two after 50 Myr in the simulation results, unlike those of 2M0735-1450 and HIP 8920 shown in Figure 4.7. Lastly, at no time before a hundred million years in the simulation does the $24 \mu$ m excess ratio reach
unity. Any theory of debris disk evolution will have to account for those stars that show no $24 \mu \mathrm{~m}$ excess (within Spitzer's detection limits) at ages less than 100 Myr . This is an important observed phenomenon discussed earlier that occurs in stars across a broad range of spectral types and ages. Why some stars, in particular the youngest ( $\lesssim 30 \mathrm{Myr}$ ), have mid-infrared excesses and others do not is still without clear explanation.

Additional mid-infrared observations of intermediate-mass stars with known ages should help further constrain the time scales and behavior of the evolution of debris disks and, ultimately, of planetary system formation.

### 4.5 Conclusions

We have conducted a photometric survey for dusty debris disks in the $\sim 50 \mathrm{Myr}$ open cluster IC 2391 with the MIPS $24 \mu \mathrm{~m}$ channel on Spitzer. This wavelength probes regions $\sim 5$ to 30 AU around A-type stars and regions $\sim 1$ to 5 AU around FGK stars. Due to the cluster's proximity, fluxes of stars as late as spectral type $\sim K 4$ can be measured down to the photospheric level. Of the 34 cluster members detected, only $10_{-3}^{+17} \%(1 / 10)$ of the A-type stars had $24 \mu$ m flux densities $\geq 15 \%$ that of the photosphere. This is lower than the $31_{-9}^{+13} \%(5 / 16)$ frequency measured for FGK stars in the cluster as well as marginally lower than A-type stars located in other young clusters. However, it is possible that this difference simply reflects random statistical variations.

In comparison, $31_{-9}^{+13} \%$ of the FGK stars in IC 2391 have excesses. From their behavior, we find the following:

1. A high level of planetesimal activity (collisions) is still occurring in terrestrial planet regions ( $\sim 1-5 \mathrm{AU}$ ) at $\sim 50 \mathrm{Myr}$.
2. The fraction of FGK stars with $24 \mu \mathrm{~m}$ excesses decreases significantly on
timescales of $\sim 100 \mathrm{Myr}$. This decay over time corresponds to the observed decline of the frequency of collisions within the inner parts of these systems analogous to the asteroid belt of our own Solar System.
3. The decay and variation of $24 \mu \mathrm{~m}$ excess ratios around FGK stars is very similar to that measured around A-type stars. Despite an overall decaying excess ratio evolution, there are large fractions of young stars with no excess at the youngest ages and rare large excesses at older ages indicative of episodic and stochastic events.
4. Despite differences in luminosity and in the annuli probed at $24 \mu \mathrm{~m}$ between A-type and FGK stars, debris disk evolution does not appear to be strongly influenced by stellar mass (for this range of spectral type).

## CHAPTER 5

## Evidence for Protoplanetary Disk Evolution in the Young Open Stellar Cluster IC 2395

The content of this chapter consists of work in preparation of submittal to The Astrophysical Journal by Siegler, N., Balog, Z., Muzerolle, J., Young, E. T., Mamajek, E. E E Trilling, $D$.

We present preliminary results from an infrared imaging survey of the $\sim 6 \mathrm{Myr}$ open cluster IC 2395 using the IRAC and MIPS instruments on board the Spitzer Space Telescope. Our observations cover the wavelength range from 3.6 to $24 \mu \mathrm{~m}$ where we detect protoplanetary disk emission over a typical range of radii between $\sim 0.1$ to $\sim 10 \mathrm{AU}$ from the central star. We identify 49 Class II, 7 transition disk, and 11 debris disk candidates awaiting membership confirmation through future optical photometry and spectra. This result shows stars at different stages of disk evolution despite being relatively coeval. A candidate post-Herbig Ae star is also identified with photometric evidence of an inner hole. We show for the first time the evolution of the median IRAC infrared colors for classical T Tauri stars during the first $\sim 10 \mathrm{Myr}$ of protoplanetary disk lifetime and see a trend possibly consistent with grain growth and dust settling in the innermost disk region. These results form the basis of a future paper that will present for the first time the cluster's low-mass members and measure the circumstellar disk fractions.

### 5.1 Introduction

The Spitzer Space Telescope (Spitzer; Werner et al., 2004) has further improved our understanding of how protoplanetary disks form, evolve, and eventually dissipate. There is now sufficient evidence showing that by about 10 Myr the accretion of gas has largely ceased and most primordial disks have dissipated (eg. Haisch, Lada, \& Lada, 2001; Mamajek et al., 2004). In the wake of this dissipation, most stars have already formed planetesimals (Rieke et al., 2005; Siegler et al., 2007a). Their stochastic collisions form what are called "debris" disks. These regenerated disks of dust indirectly reveal the presence of possible planetary bodies which serve as the replenishing source of the dust (Lagrange et al. 2000, Dominik \& Decin 2003). The fraction of stars displaying evidence of debris appears to decrease with time but individual stars show episodic collisional events even at several hundred million years.

There is also building support that the transition from being an optically-thick accretion disk to an optically-thin debris disk occurs rapidly and the process occurs from the inside-out (eg. Skrutskie et al., 1990; Sicilia-Aguilar et al., 2005; Megeath et al., 2006; Currie et al., 2007). These "transition" disks appear to represent the process of clearing "caught in the act". The process driving this transition is still not clear. Planetesimal building and/or photoevaporation from the central star may play important roles. From the few transition disks identifed relative to the number of primordial and debris disks, it is believed that this transition occurs quite rapidly, on order of a few hundred thousand years (Skrutskie et al., 1990; Kenyon \& Hartmann, 1995; Simon \& Prato, 1995; Wolk \& Walter, 1996). Regardless of the mechanism, the result is a largely evacuated inner region accompanied by an optically-thick primordial disk at larger radii. The process and its timescale are crucial to our understanding of disk dissipation and planet for-
mation because they signal the end of accretion and gas in the disk. Any link between the transition disk's unique spectral energy diagrams (SEDs) and planet formation may advance the timescales in which planets form. This in turn may provide observational constraints to possible planet formation mechanism(s).

Infrared observations at wavelengths longward of about $2 \mu \mathrm{~m}$ are needed to study disk properties out beyond the innermost regions ( $\gtrsim 0.1 \mathrm{AU}$ ). Thermal flux densities observed above that expected from the stellar atmosphere point to thermal emission from heated dust. Observations at longer wavelengths from samples of stars of different ages can therefore probe the evolution of the dust. In conjunction with theoretical models, the signatures of dust first appear as large infrared excesses across all wavelengths as micron-sized particles coupled to the gas are heated from irridation and viscous transport, then as a decrease in thermal emission first from shorter wavelengths (possibly as dust grains grow and settle to the disk midplane, eg. Dullemond \& Dominik, 2005; D'Alessio et al., 2006), and finally, as thermal radiation at the longest infrared wavelengths from heated regenerated dust, the result of collisional cascades following planetesimal impacts.

The Infrared Array Camera (IRAC; Fazio et al., 2004) and Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al., 2004) are perfect tools for testing theories of disk evolution and planet formation. Their unprecedented sensitivity have allowed surveying a wide range of dust and photospheric emissions from a large number of distant stars. These instruments probe the inner disk dust emission out to $\sim 20 \mathrm{AU}$ and can cover large areas containing enough stars to allow the use of statistical methods.

The key time period to observe these processes appears to be within the first 10 Myr of a star's life, while gas is still present in the disk. Clusters are an ideal
laboratory for studying disk evolution as the stars are coeval to within a few million years, of similar and reliably measured distance, and numerous enough to have a wide range of masses and improved statistics. Unfortunately, there is a lack of appropriately aged young clusters within a kiloparsec. Even Spitzer has insufficient mid-infrared sensitivity to detect the photospheres from the lowest mass members in clusters further than $\sim 200 \mathrm{pc}$. Furthermore, the nearest young clusters are typically very young, around 1 Myr , or older than 10 Myr .

IC 2395 provides an important opportunity to study disk evolution in an age range $(5-10 \mathrm{Myr})$ that has to date been poorly probed. The cluster has a reported age of $6 \pm 2 \mathrm{Myr}$ and is $\sim 800 \pm 40 \mathrm{pc}$ away (Clariá et al., 2003). Despite its desirable age in the study of circumstellar disks, the cluster has been poorly studied. Clariá et al. (2003) conducted the largest photometric investigation of the cluster identifying candidate cluster members and estimating the cluster's age, distance, extinction, and angular size. Sensitive to a limiting magnitude of $V<15 \mathrm{mag}$, they identified 78 probable and possible members through $U B V$ photometry. There have also been several proper motion studies but none combined with photometric observations. We present here the first infrared investigation.

We have mounted an effort over the last few years to obtain $\sim 45$ square arcmin fields of deep optical ( $U B V R I$ ), mid-IR (3.6, 4.5, 5.8, $8.0 \mu \mathrm{~m}$ ), and far-IR $(24 \mu \mathrm{~m})$ photometry of IC 2395 as part of a larger Spitzer Guaranteed Time Observing (GTO) study of the evolution of protoplanetary disks. The IC 2395 analysis is ongoing, however, the results reported here, while preliminary, paint a rich and active picture of a cluster in transition, displaying simultaneous evidence of accreting primordial disks, transition disks, and debris disks.

### 5.2 Observations and Sample Selection

We have obtained near-infrared and mid-infrared photometry of IC 2395 with Spitzer using the four channels (3.6, 4.5,5.8, and $8.0 \mu \mathrm{~m}$ ) of IRAC and the $24 \mu \mathrm{~m}$ band of MIPS. $U B V$ photometry ( $V<15 \mathrm{mag}$ ) comes from Clariá et al. (2003).

### 5.2.1 Spitzer/IRAC

Observations of IC 2395 were obtained on 2003 December 20 with IRAC on Spitzer. IRAC is equipped with a four-channel camera with central wavelengths of approximately $3.6,4.5,5.8$, and $8.0 \mu \mathrm{~m}$ (Fazio et al., 2004). Each region was mapped in a $4 \times 3$ grid resulting in a $20^{\prime} \times 15^{\prime}$ field with coverage in all four IRAC wavelength bands. The 12 s high dynamic range mode was used to obtain two frames at each position, one with an exposure time of 0.4 s and the other 10.4 s . The map was repeated four times with small offsets, resulting in a total integration of $41.6 \mathrm{~s} \mathrm{pixel}^{-1}$ after co-adding the longer duration frames. The observations were processed with the SAO IRAC Pipeline and mosaics were created with a custom IDL program.

Source finding and photometry were performed using Gutermuth's Photvis version 1.08, which incorporates Landsman's IDLPHOT package into an interactive GUI (Landsman, 1993). We used an aperture radius of 2 pixels (2.4") for the photometry and a sky annulus extending from $2\left(2.4^{\prime \prime}\right)$ to 6 pixels $\left(7.2^{\prime \prime}\right)$ to measure the sky flux. Data calibration was performed with in-flight observations of IRAC standard stars and aperture corrections were determined for each band from observations of IRAC standard stars. The standard deviations returned by IDLPHOT include a contribution from $\sigma\left(\pi r^{2}\right)^{1 / 2}$ which is added in quadrature, where $r$ is the aperture radius in pixels and $\sigma$ is the standard deviation of the pixel values in the sky annulus. We adopted zero-point magnitudes (ZP) of 19.6642,
$18.9276,16.8468$, and 17.3909 in the [3.6], [4.5], [5.8], and [8.0] bands, respectively, where $[m]=-2.5 \log (\mathrm{DN} / \mathrm{s})+\mathrm{ZP}$.

In Figure 5.1 we show the central region of IC 2395 from all four IRAC channels. The shortest wavelength channel can reach the photosphere of all stars in the cluster. However, it also picks up many background stars. The progression to longer wavelengths culminating in the $8 \mu \mathrm{~m}$ image shows less sources and highlights more of the dust component in what we believe to be residual dust (and associated gas) from the nascent molecular cloud. The cirrus remnant observed at $8 \mu \mathrm{~m}$ is likely dominated by silicate dust with possibly some contribution from polycylic aromatic hydrocarbons (PAHs). The brightest source in all four fields is EP Velorum, a thermally pulsing, M6 asymptotic giant branch star (Kerschbaum \& Hron, 1994), unassociated with the cluster. A three-color composite image composed of IRAC wavelengths $3.6 \mu \mathrm{~m}$ (blue) and $8 \mu \mathrm{~m}$ (green) and MIPS $24 \mu \mathrm{~m}$ (red) is shown in Figure 5.2.

### 5.2.2 Spitzer/MIPS

IC 2395 was observed using MIPS on Spitzer on 2004 April 11 as part of a similar GTO program to study protoplanetary disks and dust evolution. MIPS is equipped with a three-channel camera with central wavelengths of approximately 24, 70, and $160 \mu \mathrm{~m}$ (Rieke et al., 2004). The longer wavelength channels are insensitive to stellar photospheric emissions at the distance of IC 2395 and no cluster stars were detected at $70 \mu \mathrm{~m}$ nor $160 \mu \mathrm{~m}$. This study is based on only the MIPS $24 \mu \mathrm{~m}$ channel.

The observations used the medium scan mode with half-array cross-scan offsets resulting in a total exposure time per pixel of 80 s . The images were processed using the MIPS instrument team Data Analysis Tool (Gordon et al., 2005), which calibrates the data, corrects distortions, and rejects cosmic rays during the


Figure $5.144^{\prime} \times 44^{\prime}$ mosaic images of the central region of IC 2395 taken with the Spitzer/IRAC camera, channels 1-4 ( $3.6 \mu \mathrm{~m}$ top left, $4.5 \mu \mathrm{~m}$ top right, $5.8 \mu \mathrm{~m}$ bottom left, and $8.0 \mu \mathrm{~m}$ bottom right). The brightest object in each field is Velorum EP, an M6 thermally-pulsing asymptotic giant branch star (Kerschbaum \& Hron, 1994), not associated with the cluster. What is believed to be the residual starforming molecular cloud is best observed in the $8 \mu \mathrm{~m}$ channel from reradiating silicate dust, likely heated from within.


Figure 5.2 Three color composite image of the central region of IC 2395 composed of IRAC wavelengths $3.6 \mu \mathrm{~m}$ (blue) and $8.0 \mu \mathrm{~m}$ (green) and MIPS $24 \mu \mathrm{~m}$ (red). Likely contributing to emission in the $8.0 \mu \mathrm{~m}$ channel are probable silicate grains and polyaromatic hydrocarbons, seen as the bright green areas.
coadding and mosaicking of individual frames. A column-dependent median subtraction routine was applied to remove any residual patterns from the individual images before combining them into the final $24 \mu \mathrm{~m}$ mosaic. Total area mapped was near a square degree $\left(89^{\prime} \times 40^{\prime}\right)$.

We measured the $24 \mu \mathrm{~m}$ flux density of individual sources using the standard PSF-fitting photometry routine allstar in the IRAF data reduction package daophot. We then applied an aperture correction of 1.73 to account for the flux density outside the aperture, as determined from the STinyTim $24 \mu \mathrm{~m}$ PSF model (Engelbracht et al., in prep). Finally, fluxes were converted into magnitudes referenced to the Vega spectrum using a zero-point for the [24] magnitude of 7.3 Jy (from the MIPS Data Handbook, v2.3). Typical $1 \sigma$ measurement uncertainties for the MIPS $24 \mu \mathrm{~m}$ fluxes are $50 \mu \mathrm{Jy}$ plus $\sim 5 \%$ uncertainty in the absolute calibration (Engelbracht et al., in prep). The two are independent of each other and dominated by the latter.

The $24 \mu \mathrm{~m}$ mosaic is displayed in Figure 5.3. The dust within the cirrus cloud just below the cluster center is likely to be illuminated by embedded stars. As explained in $\S$ 5.6.1, the MIPS image is sensitive to detecting the photospheres of $\sim$ A0 stars at the distance of IC 2395.

### 5.3 Cluster Membership

One of this study's overall goals is to characterize the type of circumstellar disks observed in the $\sim 6 \mathrm{Myr}$ old stellar cluster IC 2395 and measure the fraction of members possessing evidence of disks. This requires a list of bone fide cluster members. Associating stars to stellar clusters can be tricky business best requiring several observational criteria, all needing to be consistent with membership. The most confident membership designations are those that have photometric,


Figure 5.3 The central $89^{\prime} \times 40^{\prime}$ mosaic of the central region of IC 2395 taken with the MIPS $24 \mu \mathrm{~m}$ channel. Sources with disks are identified with symbols: crosses represent Class II candidates, open squares represent transition disk candidates, and open triangles represent debris disk candidates. The point source FWHM is $5.7^{\prime \prime}$ and the platescale is $1.25^{\prime \prime}$ / pixel. The image is displayed with a log stretch and epoch 2000 celestial coordinates.
kinematic, and spectroscopic measurements. In the case of IC 2395, no study has yet constructed a membership list based on all three criteria types. Clariá et al. (2003) conducted a $U B V$ investigation of the cluster's central $50^{\prime} \times 50^{\prime}$ region to a $V$ band limiting magnitude of 15 . They selected cluster members photometrically by examining the positions of the observed stars in $U B V$ color-magnitude (CM) and color-color (CC) diagrams with respect to the theoretical models of Lejeune \& Schaerer (2001). Stars lying no more than 0.75 mag above the zero-age main sequence (ZAMS) and deviating no more than 0.10 mag from the CC main sequence locus were classified as cluster members. Clariá et al. (2003) presented 61 sources meeting these photometric criteria; the positions of another 16 stars were somewhat ambiguous but retained as possible members.

A comparison of 21 of these cluster members to a proper-motion-selected list from Dias et al. (2001) showed very good agreement, however, the uncertainties in the mean proper motion survey are sufficiently large to make the comparison ineffective. Without a kinematic, spectroscopic, or near-infrared membership criterion to go along with the visible photometry, we believe that the Clariá et al. (2003) classification is insufficient for providing a robust list of bona fide cluster members. We improve on this in the next sections.

### 5.3.1 Mean Cluster Proper Motion

We add a kinematic criterion to the Clariá et al. (2003) photometric membership list by selecting on proper motion. There are multiple estimates of the mean proper motion of IC 2395 members and, unfortunately, some of the estimates are statistically inconsistent with one another. We re-estimated the mean proper motion using a "clean" sample of 14 B-type cluster members selected from Clariá et al. (2003). The NOMAD catalog from USNO (Zacharias et al., 2004b) provides the best available proper motion for each star (usually from Tycho-2 or Hippar-
cos; Perryman et al., 1997; Høg et al., 2000). Twelve of the 14 had proper motions with the exceptions being HD 74455 and HD 74436. The variance-weighted mean $\mu_{\alpha} \cos \delta$ and $\mu_{\delta}$ values were calculated and the $\chi^{2}$ of each value was calculated for the sample. One star, HD 74251, was rejected due to contributing (by far) the majority of the $\chi^{2}$ for both $\mu_{\alpha} \cos \delta$ and $\mu_{\delta}$. Further clipping, however, had negligible effect on the final proper motion, so we calculate the mean proper motion value for the remaining 11 B -stars as representative for the group:


 tively added that "basement" term in quadrature to derive our final uncertainty
 rors whether we calculate it as a true median (Gott et al., 2001), a Chauvenetcriterion clipped mean (Bevington \& Robinson, 1992), or an unweighted mean, so our choice of $\mu$ estimation matters little.

Our derived mean proper motion agrees well with most of the previously measured values as shown in Table 5.1 (Kharchenko et al., 2003, 2005; Loktin \& Beshenov, 2003; Dias et al., 2001, 2002; Baumgardt, Dettbarn, \& Wielen, 2000), but is severely at odds with the quoted values from Gulyaev \& Nesterov (1992) and Dias et al. (2006). The Dias et al. (2006) value is dominated by large numbers of faint UCAC2 stars with relatively large uncertainties and likely suffers from larger amounts of field star contamination. As we (and most other studies) do not agree with the mean proper motion estimated by Dias et al. (2006), we do not use their membership probabilities.

Table 5.1. Proper Motion Studies of IC 2395

| Survey | $\mu_{\alpha} \cos \delta$ <br> $\mathrm{mas} / \mathrm{yr}$ | Uncertainty <br> $\mathrm{mas} / \mathrm{yr}$ | $\mu_{\delta}$ <br> $\mathrm{mas} / \mathrm{yr}$ | Uncertainty <br> $\mathrm{mas} / \mathrm{yr}$ | Sample <br> size | Comments |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| Gulyaev \& Nesterov (1992) | +2.3 | 1.0 | -1.8 | 1.0 | 8 | Greater then $3 \sigma$ away from this paper's result. |
| Baumgardt, Dettbarn, \& Wielen (2000) | -3.6 | 0.6 | 2.2 | 0.5 | 1 |  |
| Dias et al. (2001) | -4.4 | 1.6 | 4.0 | 1.6 | 11 |  |
| Dias et al. (2002) | -4.37 | 1.73 | 4.05 | 1.73 | 14 |  |
| Loktin \& Beshenov (2003) | -4.86 | 0.33 | 3.48 | 0.23 | 33 |  |
| Kharchenko et al. (2003) | -4.21 | 0.63 | 1.73 | 0.63 | 12 |  |
| Kharchenko et al. (2005) | -4.34 | 0.38 | 2.42 | 0.35 | 15 |  |
| Dias et al. (2006) | -5.56 | 0.40 | 6.02 | 0.40 | 55 | Greater then 3 $\sigma$ away from this paper's result. |
| This Paper | -3.92 | 0.33 | 3.03 | 0.26 | 11 | 1 clipped; proper motion values used in this analysis. |
| This Paper | -3.60 | 0.36 | 2.69 | 0.28 | 10 | 2 clipped |

### 5.3.2 Revised Cluster Membership List

The 61 probable and 16 possible cluster members from Clariá et al. (2003) were selected for being consistent with theoretical optical CM and CC diagrams. We feel that satisfying just this photometric criteria is insufficient to confidentally designating membership. We take their sample and further select those objects meeting near-infrared photometric and proper motion criteria:

- object positions located within 0.1 mag of the stellar main sequence locus of a dereddened $\mathrm{J}-\mathrm{H}$ vs $\mathrm{H}-\mathrm{K}_{s}$ CC diagram (Figure 5.4),
- object positions lying above or near a dereddened $J$ vs $J-H$ ZAMS (Figure 5.5),
- proper motions within two sigma of our derived cluster mean, and
- proper motion uncertainties less than 5 mas $_{\text {yr }}{ }^{-1}$

All the Clariá et al. (2003) objects were consistent with the two near-infrared criteria. The third criteria was determined through a $\chi^{2}$ comparison to the mean cluster motion (as measured in $\S 5.3 .1$ and presented in Table 5.1) which includes the objects' proper motion uncertainty along with an assumed intrinsic velocity
 son, 1992). In equation form:

$$
\begin{equation*}
\chi^{2}=\left\{\frac{\left[\overline{\left(\mu_{\alpha} \cos \delta\right)^{\mathrm{cl}}}-\left(\mu_{\alpha} \cos \delta\right)^{*}\right]^{2}}{\left(\sigma_{\mathrm{int}, \mu_{\alpha} \cos \delta}\right)^{2}+\left(\sigma_{\mu_{\alpha} \cos \delta}^{*}\right)^{2}}\right\}+\left\{\frac{\left[\overline{\mu_{\delta}^{\mathrm{cl}}}-\mu_{\delta}^{*}\right]^{2}}{\left(\sigma_{\mathrm{int}, \mu_{\delta}}^{\mathrm{cc}}\right)^{2}+\left(\sigma_{\mu_{\delta}}^{*}\right)^{2}}\right\} \tag{5.1}
\end{equation*}
$$

where the superscript "cl" designates the cluster, the subscript "int" designates intrinsic, and the asterisk superscript designates individual stars. By selecting those sources with $\chi^{2} \leq 6$ and two degrees of freedom, we expect only $\approx 5 \%$ of bona fide cluster members to be rejected using this criterion $(\sim 2 \sigma)$.


Figure 5.4 Dereddened near-infrared CC diagram of IC 2395 cluster members (open circles) and possible members (open triangles). Plotted are theoretical main sequence (solid line) and giant (dashed line) branches from the Siess, Dufour, \& Forestini (2000) models. Stars have been dereddended using either $E(B-V)=0.09$ or actual extinction measurements from Clariá et al. (2003) and the reddening laws of Cambrésy et al. (2002). The reddening vector is shown in the upper right; typical photometric uncertainty is shown in upper left. All members are consistent with main-sequence-like colors after removing the likely giants and background sources. There are no obvious members displaying near-infrared excess within the natural variation of the photometry.


Figure 5.5 Dereddened $J$ versus $J-H$ CM diagram of IC 2395 (symbols same as Figure 5.4). Plotted solid line is the zero-age main sequence (ZAMS) from Lejeune \& Schaerer (2001) and pre-main sequence evolutionary tracks of Siess, Dufour, \& Forestini (2000) at 3 Myr (dashed line) and 10 Myr (dotted line) placed at the cluster's $3 \sigma$ upper limit distance ( 920 pc ). Typical photometric uncertainty shown in upper right corner. The object positions are consistent with a young cluster ( $\lesssim 15 \mathrm{Myr}$ ), however, the models appear to predict an age older than that predicted by the optical main-sequence turnoff of Clariá et al. (2003).

We establish the last criterion to reduce the chances that sources with relatively large uncertainties may unjustifiably possess low $\chi^{2}$ values. We selected a
 faintest objects ( $V \gtrsim 12$ ). The consequence of this criterion, however, is that at the distance of IC 2395, J-H inferred spectral types roughly later than mid-F are deselected. Consequently, in our effort to reduce interlopers, we have removed the faint cluster members and reduced both our sample size and mass range of a measured disk fraction. Incorporating later spectral types will require adding other criteria such as radial velocity, spectral classification, and youth spectral features. Spectroscopically-confirmed later-type members will be presented in our next paper (note: running the Clariá et al. (2003) members through the Radial Velocity and Astrometry Catalogue Karchenko, Piskunov, \& Scholz (2004) matched only two stars).

Our proper motion criteria retained 40 of the Clariá et al. (2003) sample of 61 probable cluster members. We examined the six sources that had $\chi^{2} \leq 6$ and uncertainties greater then 5 mas $\mathrm{yr}^{-1}$ and found that half of them had very inconsistent mean proper motions and were left deselected. The other three have mean proper motions within $1 \sigma$ of the cluster mean $\left(\chi^{2} \leq 1\right)$ and we reclassified them as possible cluster members. Another of the original 61 had no measured proper motion and was retained but also only as a possible member. We also examined the sources that had $\chi^{2} \geq 6$ and uncertainties less than $5{\text { mas } \mathrm{yr}^{-1} \text { to identify any }}^{2}$ sources that were potentially penalized for having abnormally small reported uncertainties ( $\leq 2{\text { mas } \mathrm{yr}^{-1} \text { ). Three were retained and reclassified as possible cluster }}_{\text {a }}$ members.

Of the original Clariá et al. (2003) sample of 16 possible cluster members, three were proper motion selected and hence upgraded to probable members. One
possible member had no measured proper motion and remains a possible member.

After having applied the additional membership criteria established at the beginning of this section, we end up with 43 probable cluster members and 14 possible members. As we shall discuss later in the chapter, we will argue that two of the possible members are probable members, raising the final reported number to 45 cluster members and 12 possible members. We list the final results in Tables 5.2 and 5.3 and show on an optical CM diagram in Figure 5.6. To examine the spatial distribution of the known cluster members listed in Tables 5.2 and 5.3, we overplot their positions onto a Digital Sky Survey visible image in Figure 5.7. The cluster center is clearly located near the brightest (and likely most massive) member, B 1.5 star HD 74455 (ID 21).

Table 5.2. General Characteristics of IC 2395 Probable Cluster Members

| ID | RA (2000) | Dec (2000) | SpT | $\begin{gathered} V \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} B-V \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} \mu_{\alpha} \cos \delta \\ (\mathrm{mas} / \mathrm{yr}) \end{gathered}$ | $\begin{gathered} \mu_{\delta} \\ (\mathrm{mas} / \mathrm{yr}) \end{gathered}$ | Other Designation ${ }^{\text {a }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 8:40:09.9 | -48:07:57.6 | - | 11.29 | 0.10 | $-3.4 \pm 2.9$ | $4.2 \pm 3.8$ | - |
| 2 | 8:40:46.8 | -48:12:42.8 | - | 9.60 | 0.05 | $-8.7 \pm 3.0$ | $-1.6 \pm 3.0$ | JW8, CD-474208 |
| 3 | 8:40:48.2 | -48:14:15.6 | - | 11.75 | 0.17 | $-6.1 \pm 2.3$ | $2.0 \pm 3.2$ | JW5, CD-474209 |
| 4 | 8:40:53.4 | -48:13:31.8 | B2IV | 6.96 | -0.16 | $-3.6 \pm 0.6$ | $2.2 \pm 0.4$ | JW2, HD74234 |
| 5 | 8:40:59.8 | -47:47:02.8 | - | 11.39 | 0.17 | $-4.6 \pm 2.1$ | $3.9 \pm 2.0$ | CD-474211 |
| 6 | 8:41:04.0 | -48:04:15.6 | - | 13.31 | 0.61 | $6.6 \pm 5.1$ | $5.8 \pm 5.1$ | - |
| 7 | 8:41:13.7 | -48:04:36.7 | - | 12.77 | 0.49 | $-7.2 \pm 3.6$ | $1.5 \pm 1.4$ | - |
| 8 | 8:41:35.3 | -47:57:51.3 | - | 11.12 | 0.09 | $-2.4 \pm 1.9$ | $2.4 \pm 1.4$ | CD-474225 |
| 9 | 8:41:35.8 | -48:04:24.1 | - | 11.30 | 0.12 | $-2.9 \pm 3.0$ | $0.5 \pm 1.4$ | L54 |
| 10 | 8:41:44.9 | -48:09:35.8 | - | 12.17 | 0.38 | $-4.6 \pm 2.2$ | $2.2 \pm 1.4$ | L51 |
| 11 | 8:41:50.5 | -48:09:17.6 | - | 13.20 | 0.45 | $1.7 \pm 3.0$ | $-1.7 \pm 2.7$ | L50 |
| 12 | 8:41:55.2 | -48:09:12.2 | - | 11.49 | 0.15 | $-6.0 \pm 1.4$ | $4.4 \pm 1.4$ | CD-474238 |
| 13 | 8:41:55.7 | -47:52:12.6 | B9/A0V | 9.84 | -0.02 | $-4.9 \pm 1.7$ | $5.1 \pm 1.8$ | HD74402 |
| 14 | 8:41:59.5 | -47:48:17.7 | B8V | 10.29 | -0.05 | $-4.6 \pm 1.3$ | $3.4 \pm 1.5$ | CD-474240 |
| 15 | 8:42:04.9 | -48:11:43.3 | - | 11.88 | 0.17 | $-4.3 \pm 1.4$ | $5.5 \pm 2.3$ | L49 |
| 16 | 8:42:07.5 | -48:14:40.9 | B3V | 8.23 | -0.06 | $-4.1 \pm 1.2$ | $4.4 \pm 1.5$ | L6, HD74436 |
| 17 | 8:42:09.5 | -48:20:56.1 | - | 12.68 | 0.44 | $-4.9 \pm 5.8$ | $8.1 \pm 5.8$ | - |
| 18 | 8:42:11.8 | -48:06:33.0 | - | 10.39 | 0.00 | $-3.4 \pm 1.4$ | $4.7 \pm 2.0$ | L43,CD-474247 |
| 19 | 8:42:14.3 | -48:06:55.9 | - | 11.28 | 0.09 | $-4.4 \pm 1.4$ | $4.0 \pm 1.4$ | CPD-472576, L44 |
| 20 | 8:42:14.4 | -48:27:09.2 | B5V | 9.46 | -0.04 | $-1.5 \pm 1.7$ | $0.8 \pm 1.2$ | HD74456 |
| 21 | 8:42:16.2 | -48:05:56.7 | B1.5Vn | 5.49 | -0.18 | $-3.8 \pm 0.9$ | $2.7 \pm 0.8$ | HD74455, $\mathrm{V}^{*} \mathrm{HX}$ Vel |
| 22 | 8:42:15.8 | -48:04:20.0 | - | 11.70 | 0.29 | $-2.2 \pm 3.2$ | $5.3 \pm 2.4$ | L18 |
| 23 | 8:42:17.8 | -48:03:53.1 | - | 10.74 | 0.03 | $-6.8 \pm 2.5$ | $1.1 \pm 1.4$ | L15, CD-474253 |
| 24 | 8:42:26.4 | -47:58:22.1 | - | 12.49 | 0.32 | $-4.6 \pm 1.4$ | $7.2 \pm 1.6$ | L20 |
| 25 | 8:42:30.1 | -47:59:17.9 | - | 13.29 | 0.63 | $-7.0 \pm 2.7$ | $8.7 \pm 2.5$ | - |
| 26 | 8:42:33.5 | -48:10:27.8 | - | 11.91 | 0.22 | $-5.9 \pm 2.3$ | $6.9 \pm 2.3$ | - |
| 27 | 8:42:35.2 | -47:55:47.4 | - | 11.02 | 0.06 | $-6.4 \pm 1.7$ | $3.7 \pm 1.4$ | CD-474260 |
| 28 | 8:42:34.8 | -48:09:48.9 | B2V | 7.27 | -0.16 | $-3.7 \pm 0.8$ | $2.9 \pm 0.7$ | L3, HD74531 |
| 29 | 8:42:36.5 | -48:04:30.9 | B3IV-V | 8.71 | -0.11 | $-5.3 \pm 1.7$ | $4.4 \pm 1.6$ | L8, HD74530 |
| 30 | 8:42:36.6 | -48:05:04.1 | - | 10.61 | 0.03 | -9.4 $\pm 2.7$ | $0.8 \pm 3.2$ | L34, CD-474262 |
| 31 | 8:42:37.0 | -48:08:12.3 | - | 11.56 | 0.12 | $-8.3 \pm 2.8$ | $4.7 \pm 1.7$ | L28, CD-474264 |
| 32 | 8:42:43.0 | -48:07:55.7 | - | 11.51 | 0.12 | $-4.0 \pm 1.6$ | $4.6 \pm 1.4$ | L29, CD-474267 |
| 33 | 8:42:42.4 | -48:06:27.2 | - | 11.17 | 0.10 | $-8.5 \pm 2.7$ | $5.4 \pm 1.7$ | L31, CD-474266 |
| 34 | 8:42:44.5 | -47:51:02.5 | - | 12.69 | 0.49 | $-9.3 \pm 2.5$ | $6.1 \pm 2.2$ | - |
| 35 | 8:42:46.4 | -48:05:25.5 | B9Ve | 9.49 | -0.03 | $-2.5 \pm 1.3$ | $1.7 \pm 1.7$ | L11, HD74559 ${ }^{\text {b }}$ |
| 36 | 8:42:47.9 | -48:13:31.9 | B6/8V | 9.25 | -0.09 | $-4.5 \pm 1.3$ | $1.9 \pm 1.9$ | L21, HD74581 |
| 37 | 8:42:48.0 | -48:13:40.4 | - | 9.93 | 0.02 | $-4.0 \pm 1.5$ | $-1.9 \pm 2.4$ | - |
| 38 | 8:42:53.1 | -48:07:41.2 | B3V | 8.66 | -0.03 | $-1.5 \pm 1.4$ | $3.8 \pm 1.2$ | L7, HD74580 |
| 39 | 8:43:00.2 | -48:13:06.6 | - | 10.42 | -0.02 | $-5.9 \pm 1.3$ | $4.8 \pm 1.3$ | L14, CD-474274 |
| 40 | 8:43:04.3 | -48:11:03.7 | B8V | 8.91 | -0.04 | $-6.0 \pm 0.9$ | $5.1 \pm 0.7$ | L9, HD74621 |
| 41 | 8:43:18.8 | -48:20:42.9 | B3V | 8.87 | -0.11 | $-5.7 \pm 1.3$ | $2.6 \pm 1.1$ | HD74662 |
| 42 | 8:43:29.1 | -48:02:54.9 | - | 10.99 | 0.04 | $-4.0 \pm 1.4$ | $3.1 \pm 1.5$ | CD-474286 |
| 43 | 8:43:41.3 | -48:09:33.1 | - | 12.84 | 0.48 | $-5.9 \pm 2.9$ | $2.6 \pm 2.6$ | - |
| 44 | 8:44:07.8 | -48:01:14.6 | - | 11.80 | 0.18 | $-4.9 \pm 1.8$ | $4.4 \pm 2.8$ | CD-474298 |

Table 5.2-Continued


### 5.4 Results and Analysis

The key result of this chapter is the identification of candidate IC 2395 cluster members that posses evidence of circumstellar disks. These candidates will provide the basis of a future investigation which will add optical, spectroscopic, and kinematic information to broaden cluster membership to less massive stars.

The disk candidates identified here derive from two samples: A) upper main sequence members originating from the Clariá et al. (2003) study (Tables 5.2 and 5.3) and B) objects that appear in all four IRAC channels and are consistent with membership. These objects are presented here for the first time using Spitzer photometry.

### 5.4.1 Identifying Stars and Protostars with Circumstellar Disks

We match the celestial coordinates of the probable cluster members presented in Tables 5.2 and 5.3 to those from the Two Micron All-Sky Survey (2MASS; Cutri et al., 2003), IRAC (this work), and MIPS (this work) photometry. We used a $5^{\prime \prime}$ separation threshold to match the probable cluster members to the 2MASS objects and retained the near-infrared celestial coordinates. Each match was individually confirmed spatially and with respect to the photometry. Subsequent


Figure 5.6 Dereddened $V$ versus $B-V$ CM diagram placed at the mean distance of the cluster; symbols same as Figure 5.5. Photometry is obtained from Clariá et al. (2003). Plotted left to right are the ZAMS, $3 \mathrm{Myr}, 10 \mathrm{Myr}$, and 30 Myr main sequence turnoff isochrones (Lejeune \& Schaerer, 2001). Typical uncertainties are shown just below the reddening vector. Turnoff isochrones suggest a young cluster but the technique may be overly dependent on the brightest member.


Figure 5.7 A $45^{\prime} \times 45^{\prime}$ image of IC 2395 taken with the Digital Sky Survey POSS1 red plate. Green open boxes are cluster members; red open circles are possible members. Image grey color is inverted. Cluster members bunch around the cluster center near the B 1.5 star HD 74455 (ID 21).

Table 5.3. General Characteristics of IC 2395 Possible Cluster Members

| ID | RA (2000) | Dec (2000) | SpT | $\begin{gathered} V \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} B-V \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} \mu_{\alpha} \cos \delta \\ (\mathrm{mas} / \mathrm{yr}) \end{gathered}$ | $\begin{gathered} \mu_{\delta} \\ (\mathrm{mas} / \mathrm{yr}) \end{gathered}$ | Other Designation ${ }^{\text {a }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 46 | 8:40:18.9 | -48:29:43.4 | - | 11.30 | 0.16 | $-8.1 \pm 1.4$ | $5.7 \pm 1.4$ | CD-484010 |
| 47 | 8:40:25.6 | -48:22:48.1 | - | 12.96 | 0.56 | $-13.7 \pm 5.8$ | $12.7 \pm 5.8$ | - |
| 48 | 8:41:19.2 | -48:13:04.2 | - | 14.32 | 0.68 |  |  | - |
| 49 | 8:41:30.4 | -47:58:41.5 | B9IV | 9.92 | -0.04 | $-1.2 \pm 2.1$ | $6.7 \pm 1.3$ | L57,HD74338 |
| 50 | 8:41:37.3 | -48:20:47.8 | - | 13.03 | 0.64 | $-8.0 \pm 5.8$ | $7.2 \pm 5.8$ | - |
| 51 | 8:42:08.2 | -48:13:16.5 | - | 13.12 | 0.58 | $-6.1 \pm 5.8$ | $2.8 \pm 5.8$ | - |
| 52 | 8:42:12.9 | -48:09:34.5 | - | 13.60 | 0.66 | . . |  | - |
| 53 | 8:42:39.5 | -48:23:59.8 | - | 13.13 | 0.68 | $-6.3 \pm 5.8$ | $-1.8 \pm 5.8$ | - |
| 54 | 8:42:42.1 | -48:05:17.0 | - | 11.07 | 0.15 | $-8.7 \pm 1.7$ | $1.3 \pm 1.4$ | L33,CD-474265 |
| 55 | 8:42:47.2 | -48:08:04.2 | - | 12.69 | 0.54 | $-9.1 \pm 5.1$ | $13.3 \pm 5.1$ | L26 |
| 56 | 8:43:06.5 | -48:18:16.2 | - | 14.52 | 0.70 | $-6.9 \pm 5.9$ | $5.3 \pm 5.8$ | - |
| 57 | 8:44:11.4 | -48:10:44.4 | - | 13.06 | 0.62 | $-8.0 \pm 5.8$ | $1.1 \pm 5.8$ | - |
| ${ }^{\text {a }} \mathrm{CD}$ or CPD $=$ photographic plates from the Annals of the Cape Observatory, $\mathrm{L}=$ Lynga, $\mathrm{HD}=$ Henry Draper |  |  |  |  |  |  |  |  |
| Not uncer motio | - (i) Celest <br> nties describ erived in § | coordinates a within; (iii) 1 is $\mu_{\alpha} \cos \delta$ | from 2M <br> per mo $3.9 \pm 0 .$ | SS; (ii) sp <br> ons from <br> as/yr an | tral type <br> OMAD; $\mu_{\delta}=3.0$ | nd optical charias et $0.4 \mathrm{mas} / \mathrm{yr} .$ | tometry fro 2004b); (iv) | Clariá et al. (2003): <br> ean cluster prop |

2MASS matches to the Spitzer sources used a $3^{\prime \prime}$ distance threshold. We present the matched results in Tables 5.4 and 5.5. Several of the original Clariá et al. (2003) objects are outside the IRAC and MIPS images' field of view and a handful are incomplete in the IRAC detections.

Table 5.4. 2MASS, IRAC, and MIPS Photometry for IC 2395 Probable Cluster

## Members

| ID | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} K_{s} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[3.6]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[4.5]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[5.8]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{aligned} & {[8.0]} \\ & (\mathrm{mag}) \end{aligned}$ | $\begin{aligned} & {[24.0]} \\ & (\mathrm{mag}) \end{aligned}$ | Comment |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | $10.93 \pm 0.02$ | $10.89 \pm 0.02$ | $10.87 \pm 0.02$ | ... | ... | ... | ... | ... |  |
| 2 | $9.27 \pm 0.03$ | $9.21 \pm 0.02$ | $9.20 \pm 0.02$ | $9.34 \pm 0.01$ | $9.25 \pm 0.01$ | $9.27 \pm 0.01$ | $9.17 \pm 0.01$ | $7.60 \pm 0.05$ | transition disk candidate |
| 3 | $11.30 \pm 0.02$ | $11.25 \pm 0.02$ | $11.21 \pm 0.02$ | ... | ... | ... | ... | ... |  |
| 4 | $7.21 \pm 0.02$ | $7.28 \pm 0.04$ | $7.32 \pm 0.03$ | $7.44 \pm 0.01$ | $7.43 \pm 0.01$ | $7.49 \pm 0.01$ | $7.44 \pm 0.01$ | $7.21 \pm 0.04$ |  |
| 5 | $10.90 \pm 0.02$ | $10.73 \pm 0.02$ | $10.70 \pm 0.02$ | ... | ... | ... | ... | $10.35 \pm 0.06$ |  |
| 6 | $12.12 \pm 0.03$ | $11.80 \pm 0.03$ | $11.77 \pm 0.03$ | $11.69 \pm 0.01$ | $11.75 \pm 0.01$ | $11.64 \pm 0.03$ | $11.53 \pm 0.04$ | $9.90 \pm 0.05$ | transition disk candidate |
| 7 | $11.68 \pm 0.02$ | $11.50 \pm 0.02$ | $11.40 \pm 0.02$ | $11.37 \pm 0.02$ | $11.38 \pm 0.02$ | $11.30 \pm 0.02$ | $11.28 \pm 0.02$ | ... |  |
| 8 | $10.77 \pm 0.02$ | $10.78 \pm 0.02$ | $10.72 \pm 0.02$ | $10.73 \pm 0.01$ | $10.76 \pm 0.01$ | $10.76 \pm 0.01$ | $10.71 \pm 0.02$ | $9.99 \pm 0.05$ | debris disk candidate |
| 9 | $10.80 \pm 0.02$ | $10.69 \pm 0.02$ | $10.66 \pm 0.02$ | $10.70 \pm 0.01$ | $10.68 \pm 0.01$ | $10.66 \pm 0.01$ | $10.60 \pm 0.02$ | ... |  |
| 10 | $11.28 \pm 0.02$ | $11.17 \pm 0.02$ | $11.06 \pm 0.02$ | $11.07 \pm 0.06$ | $11.07 \pm 0.07$ | ... | $10.97 \pm 0.03$ | ... |  |
| 11 | $11.97 \pm 0.02$ | $11.81 \pm 0.02$ | $11.74 \pm 0.02$ | $11.83 \pm 0.01$ | ... | ... | ... | ... |  |
| 12 | $10.96 \pm 0.02$ | $10.94 \pm 0.03$ | $10.87 \pm 0.03$ | ... | $10.87 \pm 0.01$ | $10.86 \pm 0.02$ | $10.86 \pm 0.03$ | ... |  |
| 13 | $9.73 \pm 0.02$ | $9.77 \pm 0.02$ | $9.72 \pm 0.02$ | $9.81 \pm 0.03$ | $9.77 \pm 0.01$ | ... | $9.74 \pm 0.01$ | $9.25 \pm 0.04$ | debris disk candidate |
| 14 | $10.23 \pm 0.02^{\text {a }}$ | $10.31 \pm 0.03$ | $10.29 \pm 0.02$ | $10.36 \pm 0.01$ | $10.38 \pm 0.01$ | ... | ... | $9.40 \pm 0.04$ | debris disk candidate, binary? |
| 15 | $11.39 \pm 0.03$ | $11.28 \pm 0.02$ | $11.23 \pm 0.02$ | $11.25 \pm 0.01$ | $11.26 \pm 0.01$ | ... | ... | $10.33 \pm 0.08$ | debris disk candidate |
| 16 | $8.21 \pm 0.02$ | $8.17 \pm 0.02$ | $8.19 \pm 0.03$ | $8.31 \pm 0.01$ | $8.27 \pm 0.01$ | $8.23 \pm 0.01$ | $8.18 \pm 0.01$ | $8.15 \pm 0.03$ |  |
| 17 | $11.67 \pm 0.03$ | $11.45 \pm 0.03$ | $11.39 \pm 0.02$ | $11.40 \pm 0.01$ | $11.34 \pm 0.01$ | $11.40 \pm 0.02$ | $11.26 \pm 0.03$ | $8.89 \pm 0.04$ | transition disk candidate |
| 18 | $10.21 \pm 0.03$ | $10.07 \pm 0.02$ | $10.03 \pm 0.02$ | $10.05 \pm 0.01$ | $10.08 \pm 0.01$ | $10.13 \pm 0.01$ | ... | ... |  |
| 19 | $11.02 \pm 0.03$ | $10.98 \pm 0.02$ | $10.96 \pm 0.02$ | $10.82 \pm 0.01$ | $10.69 \pm 0.01$ | $10.51 \pm 0.01$ | $9.95 \pm 0.01$ | $6.86 \pm 0.03$ | HAe candidate |
| 20 | $9.27 \pm 0.02$ | $9.17 \pm 0.02$ | $9.12 \pm 0.02$ | $9.16 \pm 0.01$ | $9.14 \pm 0.01$ | $9.13 \pm 0.01$ | $9.12 \pm 0.01$ | $8.90 \pm 0.04$ |  |
| 21 | $5.81 \pm 0.02$ | $5.90 \pm 0.02$ | $5.92 \pm 0.02$ | $6.03 \pm 0.01$ | $6.04 \pm 0.01$ | $6.10 \pm 0.01$ | $6.08 \pm 0.01$ | $6.06 \pm 0.03$ |  |
| 22 | $11.12 \pm 0.03$ | $10.95 \pm 0.02$ | $10.90 \pm 0.02$ | $10.91 \pm 0.01$ | $10.87 \pm 0.01$ | ... | ... | $8.43 \pm 0.03$ | transition disk candidate |
| 23 | $10.50 \pm 0.02$ | $10.43 \pm 0.02$ | $10.42 \pm 0.02$ | $10.43 \pm 0.01$ | $10.41 \pm 0.01$ | $10.40 \pm 0.01$ | $10.38 \pm 0.02$ | $9.96 \pm 0.06$ | debris disk candidate |
| 24 | $11.68 \pm 0.03$ | $11.62 \pm 0.03$ | $11.54 \pm 0.03$ | $11.59 \pm 0.01$ | ... | $11.47 \pm 0.02$ | ... | ... |  |
| 25 | $11.98 \pm 0.02$ | $11.73 \pm 0.02$ | $11.62 \pm 0.02$ | $11.60 \pm 0.01$ | $11.73 \pm 0.01$ | $11.57 \pm 0.02$ | $11.82 \pm 0.03$ | ... |  |
| 26 | $11.39 \pm 0.03$ | $11.28 \pm 0.02$ | $11.21 \pm 0.02$ | $11.24 \pm 0.01$ | $11.24 \pm 0.01$ | $11.23 \pm 0.02$ | $11.22 \pm 0.03$ | ... |  |
| 27 | $10.74 \pm 0.03$ | $10.77 \pm 0.02$ | $10.74 \pm 0.02$ | $10.74 \pm 0.01$ | $10.77 \pm 0.01$ | $10.79 \pm 0.01$ | ... | $9.66 \pm 0.04$ | debris disk candidate |
| 28 | $7.54 \pm 0.02$ | $7.61 \pm 0.03$ | $7.66 \pm 0.02$ | $7.75 \pm 0.01$ | $7.79 \pm 0.01$ | $7.81 \pm 0.01$ | $7.79 \pm 0.01$ | $7.88 \pm 0.03$ |  |
| 29 | $8.89 \pm 0.02$ | $8.94 \pm 0.02$ | $8.96 \pm 0.02$ | $9.13 \pm 0.01$ | $8.96 \pm 0.01$ | $9.10 \pm 0.01$ | $9.02 \pm 0.01$ | $8.40 \pm 0.05$ | debris disk candidate |
| 30 | $10.47 \pm 0.03$ | $10.41 \pm 0.02$ | $10.37 \pm 0.02$ | $10.43 \pm 0.01$ | $10.41 \pm 0.01$ | $10.47 \pm 0.01$ | $10.29 \pm 0.02$ | $8.27 \pm 0.03$ | transition disk candidate |

Unlike near-infrared (eg. $J H K$ ) emission from young stars, the IRAC and MIPS channels can detect a significant fraction of thermal emission from circumstellar material over the stellar photosphere. Recent studies of young star forming regions have shown that infrared photometry using Spitzer is efficient in identifying young stars in their earliest evolutionary phases (eg. Allen et al., 2004; Megeath et al., 2004; Hartmann et al., 2005; Sicilia-Aguilar et al., 2006; Megeath et al., 2006; Lada et al., 2006; Allen et al., 2007; Wang \& Looney, 2007). For the youngest systems, these studies have distinguished deeply embedded protostars (Class I) from accreting T-Tauri-like stars (Class II) from "normal" stars (Class III) using placement on IRAC CC diagrams (eg. [3.6]-[4.5] versus [5.8]-[8.0]). In addition, the CC diagrams that combine IRAC and MIPS bands, for example [3.6][4.5] versus [8.0]-[24] and [3.6]-[5.8] versus [8.0]-[24], are also efficient in identifying young stars, especially for stars with significant inner holes (for example, Sicilia-Aguilar et al., 2006; Muzerolle et al., 2007).

The most significant risk in using the longer wavelength Spitzer channels for identifying stars and protostars is extinction due to line-of-sight sources, thermal dust continuum from the residual natal molecular cloud, or emission from polycylic aromatic hydrocarbon molecules (PAHs, which contribute strongly at $8 \mu \mathrm{~m}$ ). While IC 2395 appears to have little overall extinction at short wavelengths (E(B$V) \sim 0.09 \mathrm{mag}$ ), PAH emission near the residual cloud must be considered (see Figure 5.1). Hence, observing with MIPS/24 $\mu \mathrm{m}$ where the effect of extinction is much less, can be very useful in identifying transition and debris disks.

For our sample consisting of only the objects common to all four IRAC channels, in which there are 3644 sources. We conservatively select those sources on or above the ZAMS of Lejeune \& Schaerer (2001) in the near-infrared CM diagram previously shown in Figure 5.5. The sample is further reduced by removing

Table 5.4-Continued

| ID | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} K_{s} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[3.6]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[4.5]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[5.8]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[8.0]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{aligned} & {[24.0]} \\ & (\mathrm{mag}) \end{aligned}$ | Comment |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 31 | $11.22 \pm 0.02$ | $11.16 \pm 0.02$ | $11.13 \pm 0.02$ | $11.15 \pm 0.01$ | $11.11 \pm 0.01$ | $11.13 \pm 0.02$ | $11.19 \pm 0.04$ | ... |  |
| 32 | $11.18 \pm 0.02$ | $11.09 \pm 0.02$ | $11.08 \pm 0.02$ | $11.06 \pm 0.01$ | $11.04 \pm 0.01$ | $11.03 \pm 0.02$ | $11.12 \pm 0.04$ | ... |  |
| 33 | $10.82 \pm 0.02$ | $10.84 \pm 0.02$ | $10.78 \pm 0.02$ | $10.80 \pm 0.01$ | $10.79 \pm 0.01$ | $10.82 \pm 0.01$ | $10.71 \pm 0.02$ | ... |  |
| 34 | $11.53 \pm 0.03$ | $11.25 \pm 0.03$ | $11.14 \pm 0.03$ | $11.10 \pm 0.01$ | $11.08 \pm 0.01$ | $11.12 \pm 0.02$ | $11.01 \pm 0.03$ | ... |  |
| 35 | $9.33 \pm 0.03$ | $9.30 \pm 0.03^{\mathrm{b}}$ | $9.27 \pm 0.03^{\mathrm{b}}$ | $9.33 \pm 0.01$ | $9.23 \pm 0.01$ | $9.20 \pm 0.01$ | $8.97 \pm 0.01$ | $7.81 \pm 0.03$ | binary,transition disk candidate |
| 36 | $9.33 \pm 0.03$ | $9.33 \pm 0.04$ | $9.35 \pm 0.02$ | $9.45 \pm 0.01$ | $9.46 \pm 0.01$ | $9.51 \pm 0.01$ | $9.45 \pm 0.01$ | ... |  |
| 37 | $9.77 \pm 0.02$ | $9.75 \pm 0.02$ | $9.76 \pm 0.02$ | $9.85 \pm 0.01$ | ... | $9.83 \pm 0.01$ | $9.89 \pm 0.02$ | ... |  |
| 38 | $8.52 \pm 0.02$ | $8.49 \pm 0.04$ | $8.46 \pm 0.02$ | $8.49 \pm 0.03$ | $8.58 \pm 0.03$ | $8.52 \pm 0.04$ | $8.46 \pm 0.03$ | $8.05 \pm 0.05$ | debris disk candidate |
| 39 | $10.21 \pm 0.02$ | $10.17 \pm 0.02$ | $10.14 \pm 0.02$ | $10.21 \pm 0.01$ | ... | $10.13 \pm 0.01$ | $10.17 \pm 0.02$ | ... |  |
| 40 | $8.88 \pm 0.02$ | $8.88 \pm 0.02$ | $8.89 \pm 0.02$ | $8.93 \pm 0.01$ | $9.00 \pm 0.01$ | $8.94 \pm 0.01$ | $8.93 \pm 0.01$ | $8.93 \pm 0.04$ |  |
| 41 | $8.90 \pm 0.04$ | $8.95 \pm 0.02$ | $8.95 \pm 0.02$ | $9.13 \pm 0.01$ | $9.06 \pm 0.01$ | $9.05 \pm 0.01$ | ... | $8.91 \pm 0.04$ |  |
| 42 | $10.62 \pm 0.02$ | $10.58 \pm 0.02$ | $10.53 \pm 0.02$ | $10.50 \pm 0.01$ | $10.44 \pm 0.01$ | $10.46 \pm 0.01$ | $10.43 \pm 0.02$ | $10.06 \pm 0.05$ | debris disk candidate |
| 43 | $11.79 \pm 0.03$ | $11.59 \pm 0.02$ | $11.49 \pm 0.02$ | $11.51 \pm 0.01$ | $11.48 \pm 0.01$ | $11.53 \pm 0.02$ | $11.41 \pm 0.03$ | $9.52 \pm 0.04$ | transition disk candidate |
| 44 | $11.10 \pm 0.02$ | $11.08 \pm 0.02$ | $11.01 \pm 0.02$ | $11.01 \pm 0.01$ | $11.01 \pm 0.01$ | $10.99 \pm 0.02$ | $10.93 \pm 0.03$ | ... |  |
| 45 | $11.03 \pm 0.02$ | $10.92 \pm 0.02$ | $10.92 \pm 0.02$ | ... | ... | ... | ... | $10.31 \pm 0.06$ | debris disk candidate |

a $J$-band appears inconsistent with $H$ and $K_{s}$ off, binary?
${ }^{\mathrm{b}} H$ and $K_{s}$ photometry flagged due to elongation from nearby source.
Note. - Those sources with no detections in any of the four IRAC channels are Clariá et al. (2003) objects imaged outside the IRAC field of view.

Table 5.5. 2MASS, IRAC, and MIPS Photometry for IC 2395 Possible Cluster Members

| ID | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} K_{s} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[3.6]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[4.5]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[5.8]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[8.0]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{aligned} & {[24.0]} \\ & (\mathrm{mag}) \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 46 | $10.86 \pm 0.02$ | $10.84 \pm 0.02$ | $10.81 \pm 0.02$ | ... | ... | ... | ... | ... |
| 47 | $11.81 \pm 0.02$ | $11.47 \pm 0.02$ | $11.41 \pm 0.02$ | ... | ... | $\ldots$ | ... |  |
| 48 | $12.88 \pm 0.02$ | $12.55 \pm 0.02$ | $12.47 \pm 0.03$ | $12.39 \pm 0.02$ | $12.38 \pm 0.02$ | ... | $12.35 \pm 0.05$ |  |
| 49 | $9.90 \pm 0.02$ | $9.91 \pm 0.02$ | $9.90 \pm 0.02$ | ... | $9.96 \pm 0.01$ | $10.01 \pm 0.01$ | $9.94 \pm 0.01$ | $9.78 \pm 0.04$ |
| 50 | $11.64 \pm 0.02$ | $11.32 \pm 0.02$ | $11.22 \pm 0.02$ | $11.20 \pm 0.01$ | $11.20 \pm 0.01$ | $11.22 \pm 0.02$ | $11.15 \pm 0.03$ | $11.04 \pm 0.10$ |
| 51 | $11.91 \pm 0.03$ | $11.62 \pm 0.03$ | $11.57 \pm 0.03$ | $11.53 \pm 0.01$ | $11.54 \pm 0.01$ | $11.59 \pm 0.03$ | $11.52 \pm 0.04$ | ... |
| 52 | $12.25 \pm 0.03$ | $11.88 \pm 0.02$ | $11.83 \pm 0.02$ | $11.76 \pm 0.01$ | $11.77 \pm 0.01$ | $11.73 \pm 0.03$ | $11.74 \pm 0.03$ | ... |
| 53 | $11.66 \pm 0.02$ | $11.38 \pm 0.02$ | $11.28 \pm 0.02$ | $11.25 \pm 0.01$ | $11.29 \pm 0.01$ | $11.26 \pm 0.02$ | ... | ... |
| 54 | $10.60 \pm 0.03$ | $10.37 \pm 0.02$ | $10.30 \pm 0.02$ | $10.29 \pm 0.01$ | $10.29 \pm 0.01$ | $10.30 \pm 0.01$ | $10.20 \pm 0.01$ | ... |
| 55 | $11.58 \pm 0.02$ | $11.33 \pm 0.02$ | $11.29 \pm 0.02$ | ... | $11.25 \pm 0.01$ | $11.22 \pm 0.02$ | $11.22 \pm 0.05$ | ... |
| 56 | $12.72 \pm 0.02$ | $12.36 \pm 0.02$ | $12.24 \pm 0.02$ | $12.39 \pm 0.01$ | ... | $12.38 \pm 0.04$ | $12.33 \pm 0.05$ | $\cdots$ |
| 57 | $11.86 \pm 0.03$ | $11.56 \pm 0.03$ | $11.44 \pm 0.03$ | $11.44 \pm 0.01$ | $11.42 \pm 0.01$ | ... | $11.40 \pm 0.04$ |  |

Note. - Those sources with no detections in any of the four IRAC channels are Clariá et al. (2003) objects imaged outside the IRAC field of view.
sources which lie in an extragalactic locus on an IRAC CM diagram (Eisenhardt et al., 2004) (see Figure 5.8). These two infrared selection criteria reduced the number of sources to 2662 . We can be reasonably confident that any of the sources in this sample showing infrared excess in the IRAC and/or MIPS bands and consistent with near-infrared CM and CC diagrams are likely members. Those cluster members not showing infrared excess will have to await classification until our future report which will make use of acquired deep visible photometry and spectra for the classification of lower-mass members.

### 5.4.1.1 Class II Objects

Class II objects are pre-main sequence stars characterized by SEDs with photospheric emission at visible wavelengths up to about $2 \mu \mathrm{~m}$ followed by a flat or gradually decreasing slopes at longer wavelengths (eg. Lada \& Wilking, 1984; Lada, 1987). The mid-infrared emission is believed to arise from heated dust in


Figure 5.8 IRAC CM diagram [3.6] versus [3.6]-[4.5]; symbols same as Figure 5.5. We use the dotted box from Eisenhardt et al. (2004) to identify the locus of typical background galaxies and remove the sources within from our sample. Typical photometric uncertainties are shown in the upper right.
an optically-thick, gas-rich primordial disk. In some cases, there is an ultraviolet excess component of the SED signaling radiation emitted from an accretion shock onto the star's surface (Muzerolle et al., 2003). All Class II objects include classical T Tauri stars (CTTSs) and Herbig AeBe (HAeBe) stars. Their existence within a cluster, especially in large numbers, implies stellar ages of less than about 10 Myr (eg. Haisch, Lada, \& Lada, 2001; Mamajek et al., 2004; Hillenbrand, 2005). Stars older than this age have typically dissipated their primorial gas (eg. Pascucci et al., 2006).

While this chapter's results do not yet include additional diagnostics to confirm their status as CTTSs (eg. H $\alpha, U$-band excess, SEDs), Class II objects in other regions appear to lie in a characteristic IRAC CC locus (Allen et al., 2004; Hartmann et al., 2005). Due to these longer wavelengths less affected by extinction, the color locus is quite reliable when compared to spectroscopically-confirmed CTTSs (eg. Hartmann et al., 2005; Sicilia-Aguilar et al., 2006). Theoretical models from D'Alessio et al. $(2005,2006)$ which include well-mixed dust and gas along with a range of mass accretion rates reproduce the empirical IRAC CC locus well. In their models, the colors become bluer as the mass accretion rate decreases suggesting a color evolution. Other physical parameters, however, also effect CTTS colors such as luminosity, inclination, and dust properties.

In Figure 5.9 we plot our sample of 2662 objects onto the IRAC CC diagram and classify the sources that lie in the D'Alessio et al. (2006) predicted CC locus (dashed box) as Class II candidates. For comparison, we plot a dotted box containing nearly all the CTTSs identified in an IRAC study of the $\sim 1$ Myr Taurus star-forming region (Hartmann et al., 2005). Because in this chapter we are only interested in identifying objects with disks (infrared excesses), we select only the sources that fall in the Class II locus and the remaining red sources clearly outside
the main concentration near $(0,0)$. We then removed those sources that lie on the giant sequence of the near-infrared CC diagram (eg. Figure 5.5) or have apparent extragalactic near-infrared colors (Figure 5.8). This leaves 49 candidate Class II objects which we list in Table 5.6.


Figure 5.9 IRAC CC diagram. The plotted points are all the sources that were detected in all four IRAC channels, lie above the IC 2395 near-infrared ZAMS, and do not possess typical galaxy colors (Figure 5.8). The cluster members and possible members are shown as (open circles) and (open triangles), respectively. The vast majority of sources shown have pure photospheric colors and are found near $(0,0)$. The dashed box represents the predicted locus of Class II objects (D'Alessio et al., 2005, 2006) and the dotted box encloses the Class II objects identified in an investigation of $\sim 1$ Myr objects in Taurus (Hartmann et al., 2005). Typical photometric uncertainty of the candidate Class II objects is shown in the upper left.

Table 5.6. 2MASS, IRAC, and MIPS Photometry for Class II Candidates in IC 2395

| ID | RA (2000) | Dec (2000) | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} K_{s} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[3.6]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[4.5]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[5.8]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[8.0]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{aligned} & {[24.0]} \\ & (\mathrm{mag}) \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 58 | 8:40:16.8 | -48:02:53.3 | $15.39 \pm 0.05$ | $14.74 \pm 0.06$ | $14.34 \pm 0.09$ | $13.74 \pm 0.02$ | $13.45 \pm 0.02$ | $13.26 \pm 0.05$ | $12.53 \pm 0.05$ |  |
| 59 | 8:40:21.1 | -48:04:08.8 |  | $\ldots$ |  | $15.23 \pm 0.05$ | $15.03 \pm 0.04$ | $14.83 \pm 0.17$ | $13.95 \pm 0.12$ |  |
| 60 | 8:40:32.0 | -48:09:14.2 | $15.07 \pm 0.05$ | $14.31 \pm 0.05$ | $13.81 \pm 0.05$ | $13.28 \pm 0.03$ | $13.13 \pm 0.02$ | $13.09 \pm 0.05$ | $12.33 \pm 0.05$ | . $\cdot$ |
| 61 | 8:40:54.6 | -47:53:42.3 | $14.85 \pm 0.03$ | $14.23 \pm 0.05$ | $13.96 \pm 0.06$ | $13.43 \pm 0.02$ | $13.24 \pm 0.03$ | $13.03 \pm 0.06$ | $12.52 \pm 0.06$ | $9.84 \pm 0.04$ |
| 62 | 8:40:57.7 | -47:57:42.2 | $14.52 \pm 0.03$ | $13.66 \pm 0.04$ | $13.22 \pm 0.04$ | $12.54 \pm 0.01$ | $12.33 \pm 0.02$ | $12.22 \pm 0.03$ | $11.61 \pm 0.03$ | $8.51 \pm 0.03$ |
| 63 | 8:40:58.3 | -47:53:15.6 | $15.12 \pm 0.04$ | $14.47 \pm 0.05$ | $14.07 \pm 0.06$ | $13.94 \pm 0.02$ | $13.72 \pm 0.02$ | $13.61 \pm 0.07$ | $12.96 \pm 0.06$ | $9.18 \pm 0.04$ |
| 64 | 8:41:32.3 | -48:20:27.8 | . . . | . . | . . . | $16.11 \pm 0.25$ | $15.74 \pm 0.23$ | $14.71 \pm 0.21$ | $13.91 \pm 0.16$ | ... |
| 65 | 8:41:41.6 | -48:12:09.0 | . $\cdot$ | . . | . $\cdot$ | $14.29 \pm 0.03$ | $14.08 \pm 0.03$ | $13.86 \pm 0.08$ | $13.30 \pm 0.07$ | $\ldots$ |
| 66 | 8:41:57.4 | -47:53:18.7 | $14.59 \pm 0.04$ | $13.92 \pm 0.04$ | $13.58 \pm 0.05$ | $13.26 \pm 0.02$ | $13.07 \pm 0.02$ | $12.90 \pm 0.04$ | $12.35 \pm 0.04$ | . . |
| 67 | 8:41:59.9 | -48:17:44.2 | $15.52 \pm 0.05$ | $14.86 \pm 0.06$ | $14.54 \pm 0.08$ | $14.17 \pm 0.02$ | $13.87 \pm 0.02$ | $13.61 \pm 0.07$ | $12.93 \pm 0.08$ | $9.70 \pm 0.04$ |
| 68 | 8:42:00.2 | -48:23:17.8 | $15.60 \pm 0.06$ | $14.92 \pm 0.09$ | $14.49 \pm 0.09$ | $13.50 \pm 0.02$ | $13.03 \pm 0.02$ | $12.91 \pm 0.04$ | $12.45 \pm 0.04$ |  |
| 69 | 8:42:05.4 | -48:09:18.4 | $13.35 \pm 0.06$ | $12.42 \pm 0.05$ | $11.93 \pm 0.03$ | $11.39 \pm 0.01$ | $11.10 \pm 0.01$ | $10.96 \pm 0.02$ | $10.23 \pm 0.02$ | $7.53 \pm 0.03$ |
| 70 | 8:42:05.4 | -48:10:44.4 | $15.83 \pm 0.08$ | $15.04 \pm 0.10$ | $14.62 \pm 0.11$ | $13.78 \pm 0.05$ | $13.38 \pm 0.04$ | $13.19 \pm 0.05$ | $12.66 \pm 0.06$ |  |
| 71 | 8:42:06.8 | -48:10:13.9 | $15.83 \pm 0.07$ | $14.95 \pm 0.07$ | $14.60 \pm 0.10$ | $14.16 \pm 0.04$ | $13.79 \pm 0.07$ | $13.85 \pm 0.11$ | $13.25 \pm 0.10$ |  |
| 72 | 8:42:09.3 | -48:04:55.2 | $16.10 \pm 0.09$ | $15.37 \pm 0.10$ | $15.03 \pm 0.13$ | $14.23 \pm 0.05$ | $14.03 \pm 0.04$ | $13.59 \pm 0.09$ | $13.11 \pm 0.08$ |  |
| 73 | 8:42:12.0 | -48:14:34.9 | $15.82 \pm 0.11$ | $14.98 \pm 0.12$ | $14.59 \pm 0.12$ | $14.35 \pm 0.09$ | $14.10 \pm 0.08$ | $14.07 \pm 0.13$ | $13.03 \pm 0.08$ | $10.12 \pm 0.05$ |
| 74 | 8:42:14.4 | -48:04:31.6 |  |  |  | $13.42 \pm 0.03$ | $13.20 \pm 0.04$ | $13.20 \pm 0.07$ | $12.18 \pm 0.06$ |  |
| 75 | 8:42:15.5 | -48:04:49.3 | $15.74 \pm 0.06$ | $14.97 \pm 0.10$ | $14.51 \pm 0.08$ | $14.02 \pm 0.04$ | $13.69 \pm 0.03$ | $13.52 \pm 0.07$ | $13.07 \pm 0.08$ |  |
| 76 | 8:42:17.2 | -48:14:54.5 | $15.68 \pm 0.06$ | $15.04 \pm 0.06$ | $14.71 \pm 0.10$ | $14.31 \pm 0.02$ | $14.08 \pm 0.03$ | $13.86 \pm 0.08$ | $13.14 \pm 0.10$ | $\cdots$ |
| 77 | 8:42:19.3 | -48:01:24.9 | $15.74 \pm 0.06$ | $14.90 \pm 0.06$ | $14.21 \pm 0.09$ | $14.09 \pm 0.02$ | $13.65 \pm 0.02$ | $13.32 \pm 0.06$ | $12.76 \pm 0.06$ | $10.11 \pm 0.05$ |
| 78 | 8:42:19.8 | -48:01:45.3 | . . ${ }^{\text {a }}$ | $\cdots$ | $\cdots$ | $14.68 \pm 0.04$ | $14.30 \pm 0.04$ | $14.16 \pm 0.09$ | $13.60 \pm 0.10$ | . . . |
| 79 | 8:42:21.9 | -48:03:25.1 | $15.74 \pm 0.06$ | $14.99 \pm 0.08$ | $14.50 \pm 0.09$ | $13.69 \pm 0.04$ | $13.34 \pm 0.03$ | $13.03 \pm 0.06$ | $12.48 \pm 0.06$ | $\ldots$ |
| 80 | 8:42:22.9 | -48:29:08.1 | $16.61 \pm 0.14$ | $15.76 \pm 0.19$ | $14.80 \pm 0.13$ | $14.22 \pm 0.04$ | $14.09 \pm 0.04$ | $14.32 \pm 0.11$ | $13.63 \pm 0.16$ |  |
| 81 | 8:42:24.5 | -48:06:30.2 | $16.05 \pm 0.07$ | $15.28 \pm 0.09$ | $14.88 \pm 0.13$ | $13.45 \pm 0.02$ | $12.91 \pm 0.02$ | $12.52 \pm 0.04$ | $11.82 \pm 0.03$ | $8.73 \pm 0.03$ |
| 82 | 8:42:25.6 | -48:16:20.8 | ... | ... | . . . | $13.99 \pm 0.04$ | $13.89 \pm 0.03$ | $13.69 \pm 0.08$ | $12.91 \pm 0.08$ |  |
| 83 | 8:42:27.4 | -48:08:58.5 | $15.35 \pm 0.05$ | $14.75 \pm 0.06$ | $14.44 \pm 0.09$ | $13.86 \pm 0.03$ | $13.62 \pm 0.03$ | $13.58 \pm 0.08$ | $12.95 \pm 0.10$ | . . |
| 84 | 8:42:29.4 | -48:05:40.6 | $13.19 \pm 0.04$ | $12.38 \pm 0.04$ | $11.94 \pm 0.03$ | $11.03 \pm 0.01$ | $10.62 \pm 0.01$ | $10.26 \pm 0.01$ | $9.84 \pm 0.01$ | $7.28 \pm 0.03$ |
| 85 | 8:42:31.7 | -47:46:38.2 | . . | $\cdots$ | . $\cdot$ | $16.22 \pm 0.08$ | $15.85 \pm 0.08$ | $14.15 \pm 0.11$ | $13.71 \pm 0.12$ | $9.15 \pm 0.04$ |
| 86 | 8:42:33.6 | -48:12:47.3 | $15.08 \pm 0.04$ | $14.24 \pm 0.05$ | $13.88 \pm 0.06$ | $13.43 \pm 0.02$ | $13.19 \pm 0.02$ | $12.96 \pm 0.04$ | $12.49 \pm 0.06$ | $10.12 \pm 0.06$ |
| 87 | 8:42:38.2 | -48:26:40.4 | $15.44 \pm 0.07$ | $14.64 \pm 0.08$ | $14.36 \pm 0.09$ | $14.35 \pm 0.05$ | $14.20 \pm 0.10$ | $15.32 \pm 0.35$ | $14.62 \pm 0.34$ |  |

### 5.4.1.2 Transition Disks

Transition disks are primordial disks with inner holes - characterized by nearly evacuated inner regions and optically-thick outer regions. They show strictly photospheric emission out to around $6 \mu \mathrm{~m}$ and little to no $8 \mu \mathrm{~m}$ excess followed by a strong $24 \mu \mathrm{~m}$ signal (well investigated examples are TW Hya and CoKu Tau 4; Calvet et al., 2002; Uchida et al., 2004; Forrest et al., 2004; D'Alessio et al., 2005). Observationally, the evacuated inner region should correspond to little to no [3.6]-[4.5] excess color and a significant [8.0]-[24.0] excess. The mechanism(s) responsible for producing the evacuated inner regions remain somewhat uncertain. Previous studies have invoked the presence of a planet (Rice et al., 2003; Quillen et al., 2004), dust evolution (Wilner et al., 2005), or photoevaporation (Hollenbach, Yorke, \& Johnstone, 2001; Alexander, Clarke \& Pringle, 2006; Goto et al., 2006) to explain the observed "holes".

Due to the relatively small number observed their lifetimes have been estimated to be on order of a few hundred thousand years (Skrutskie et al., 1990; Kenyon \& Hartmann, 1995; Simon \& Prato, 1995; Wolk \& Walter, 1996), a small fraction of the overall disk lifetime. It is quite possible that transition disks are the rapid evolutionary stage all gas-rich, primordial disks pass through on their way to the gas-less, potentially planetesimal-rich disk. Alternatively, transition disks may point to a separate class of disk that has experienced a different evolutionary path, perhaps dictated by a different set of initial conditions. Regardless of the mechanism, their detections likely set the timescales for the accretion phase and disk dissipation. If the objects' ages can be well defined, they then provide important upper age limits for gas giant planet formation timescales.

In Figure 5.10 (top) we plot the 186 sources that are detected in all four IRAC channels and $24 \mu \mathrm{~m}$ (filled squares) onto an IRAC/MIPS CC diagram. The dotted

Table 5.6-Continued

| ID | RA (2000) | Dec (2000) | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} K_{s} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[3.6]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[4.5]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[5.8]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[8.0]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{aligned} & {[24.0]} \\ & (\mathrm{mag}) \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 88 | 8:42:42.5 | -47:57:23.5 |  |  |  | $15.13 \pm 0.04$ | $14.79 \pm 0.04$ | $14.07 \pm 0.10$ | $13.05 \pm 0.07$ | $9.37 \pm 0.04$ |
| 89 | 8:42:44.8 | -48:01:00.0 | $14.42 \pm 0.04$ | $13.69 \pm 0.04$ | $13.21 \pm 0.04$ | $12.61 \pm 0.02$ | $12.27 \pm 0.02$ | $12.02 \pm 0.03$ | $11.16 \pm 0.03$ | $8.30 \pm 0.03$ |
| 90 | 8:42:46.6 | -48:16:25.3 | $14.65 \pm 0.04$ | $13.96 \pm 0.05$ | $13.74 \pm 0.05$ | $13.32 \pm 0.02$ | $13.11 \pm 0.03$ | $12.96 \pm 0.05$ | $12.41 \pm 0.08$ | . . . |
| 91 | 8:42:47.0 | -48:29:22.5 | $14.55 \pm 0.03$ | $13.89 \pm 0.04$ | $13.71 \pm 0.05$ | $13.44 \pm 0.02$ | $13.32 \pm 0.02$ | $13.57 \pm 0.07$ | $13.16 \pm 0.09$ | $\ldots$ |
| 92 | 8:42:48.1 | -48:08:58.6 | $15.37 \pm 0.06$ | $14.65 \pm 0.06$ | $14.47 \pm 0.08$ | $14.22 \pm 0.02$ | $14.06 \pm 0.03$ | $13.90 \pm 0.11$ | $13.24 \pm 0.24$ | $\ldots$ |
| 93 | 8:42:52.4 | -48:02:29.3 | $15.75 \pm 0.07$ | $14.99 \pm 0.08$ | $14.68 \pm 0.10$ | $14.41 \pm 0.04$ | $14.28 \pm 0.04$ | $14.39 \pm 0.16$ | $13.94 \pm 0.15$ | $\ldots$ |
| 94 | 8:42:54.4 | -48:08:40.3 | $14.41 \pm 0.03$ | $13.72 \pm 0.04$ | $13.46 \pm 0.04$ | $13.10 \pm 0.01$ | $12.86 \pm 0.01$ | $12.56 \pm 0.04$ | $12.02 \pm 0.10$ |  |
| 95 | 8:42:54.7 | -48:07:38.3 | $13.68 \pm 0.05$ | $12.81 \pm 0.05$ | $12.37 \pm 0.05$ | $11.68 \pm 0.01$ | $11.13 \pm 0.01$ | $10.72 \pm 0.02$ | $9.86 \pm 0.02$ | $\ldots$ |
| 96 | 8:42:55.6 | -48:02:22.7 | $15.53 \pm 0.05$ | $14.88 \pm 0.07$ | $14.51 \pm 0.10$ | $14.14 \pm 0.03$ | $13.87 \pm 0.03$ | $13.83 \pm 0.08$ | $13.09 \pm 0.07$ | $\ldots$ |
| 97 | 8:42:57.5 | -48:07:01.6 | . . . |  |  | $14.08 \pm 0.08$ | $13.91 \pm 0.09$ | $13.67 \pm 0.13$ | $12.95 \pm 0.14$ |  |
| 98 | 8:42:58.4 | -48:13:21.5 | $14.33 \pm 0.02$ | $13.53 \pm 0.04$ | $13.17 \pm 0.04$ | $12.57 \pm 0.02$ | $12.39 \pm 0.02$ | $11.92 \pm 0.03$ | $11.24 \pm 0.03$ | $8.93 \pm 0.05$ |
| 99 | 8:42:58.8 | -48:08:04.7 | $15.04 \pm 0.04$ | $14.41 \pm 0.05$ | $14.00 \pm 0.07$ | $13.72 \pm 0.03$ | $13.43 \pm 0.04$ | $13.56 \pm 0.12$ | $12.55 \pm 0.19$ | ... |
| 100 | 8:42:58.9 | -48:06:00.7 | $16.60 \pm 0.15$ |  |  | $14.80 \pm 0.06$ | $14.63 \pm 0.06$ | $14.18 \pm 0.11$ | $13.56 \pm 0.10$ | $\ldots$ |
| 101 | 8:43:6.9 | -47:59:46.2 | $14.99 \pm 0.04$ | $14.35 \pm 0.07$ | $14.06 \pm 0.07$ | $13.67 \pm 0.03$ | $13.50 \pm 0.04$ | $13.36 \pm 0.07$ | $12.80 \pm 0.08$ | $9.13 \pm 0.04$ |
| 102 | 8:43:7.0 | -48:14:59.6 | $15.57 \pm 0.06$ | $14.90 \pm 0.09$ | $14.69 \pm 0.10$ | $13.88 \pm 0.04$ | $13.57 \pm 0.06$ | $13.56 \pm 0.10$ | $12.98 \pm 0.10$ | . . |
| 103 | 8:43:10.0 | -48:09:26.2 | $16.04 \pm 0.08$ | $15.19 \pm 0.09$ | $14.75 \pm 0.10$ | $14.47 \pm 0.03$ | $14.30 \pm 0.03$ | $14.24 \pm 0.14$ | $13.61 \pm 0.26$ | $\ldots$ |
| 104 | 8:43:17.1 | -48:10:26.3 | $14.98 \pm 0.05$ | $14.36 \pm 0.08$ | $14.14 \pm 0.09$ | $14.01 \pm 0.05$ | $13.87 \pm 0.05$ | $13.94 \pm 0.16$ | $13.03 \pm 0.23$ | $\ldots$ |
| 105 | 8:43:45.4 | -48:12:20.8 | $15.77 \pm 0.07$ | $14.88 \pm 0.08$ | $14.42 \pm 0.09$ | $14.48 \pm 0.03$ | $14.36 \pm 0.03$ | $14.40 \pm 0.13$ | $13.86 \pm 0.16$ |  |
| 106 | 8:44:1.8 | -48:08:55.3 | $16.33 \pm 0.11$ | $15.55 \pm 0.14$ | $15.25 \pm 0.18$ | $14.84 \pm 0.03$ | $14.69 \pm 0.04$ | $14.59 \pm 0.14$ | $14.18 \pm 0.18$ |  |

Note. - (i) 2MASS celestial coordinates are used; (ii) All of the Class II candidates are likely members but none are part of the original Clariá et al. (2003) sample.
box represents the locus of colors, [3.6]-[4.5] $<0.1$ and $[8.0]-[24.0]>1.5$, consistent with the transition disk properties. The near-photospheric shorter wavelength colors imply a lack of dust near the star and the significant excess at longer wavelengths implies a residual optically-thick, primordial disk. The sources lying within this locus we therefore classify as transition disk candidates. As with Class II candidates, we remove those sources that lie on the giant sequence of the near-infrared CC diagram (shown in Figure 5.4) or have apparent extragalactic near-infrared colors (Figure 5.8). We list the surviving seven transition disk candidates in Table 5.7.

In Figure 5.10 (bottom) we confirm that the number of transition disk candidates does not change when we use a slightly larger baseline on the ordinate axis, [3.6]-[5.6] instead of [3.6]-[4.5], demonstrating indeed that the excess does not "turn on" till longer wavelengths. Also, since IRAC's $8 \mu \mathrm{~m}$ channel is very sensitive to silicate and PAH emission, this effect could bluen the [8.0]-[24.0] color, potentially underestimating the number of transition disks identified. We confirm that none of the slightly blueward sources are consistent with cluster membership.

### 5.4.1.3 Debris Disks

Debris disks represent the final evolutionary state of circumstellar disks. By this stage, the primordial gas has fully dissipated and dust grains have grown sufficiently to have created planetesimals and perhaps even planetary mass objects. Evidence of cratering on all the terrestrial planets and many of the moons in our own Solar System point to a past that included frequent and massive collisions. It is quite plausible that these collisions generated ejecta that escaped the gravitational well of the parent bodies, collided with other orbiting solid objects creating a collisional cascade, and resulting in a dusty, gasless disk. When heated by the


Figure 5.10 (top) Spitzer [3.6]-[5.8] versus [8.0]-[24.0] CC diagram. Symbols shown are cluster members (open circles), possible members (open triangles), and sources with $2 \mathrm{MASS} / \mathrm{IRAC} / 24 \mu \mathrm{~m}$ matches (filled squares). The plotted dotted box represents the transition disk locus. Typical uncertainty of the Class II candidates are shown in the upper left. (bottom) Spitzer [3.6]-[4.5] versus [8.0]-[24.0] CC diagram. Symbols are the same as the top figure. There is consistency between the number of transition disk candidates identifed between the two figures. Transition disk candidate ID 22 is missing in the Figure due to no $8 \mu \mathrm{~m}$ detection.

Table 5.7. 2MASS, IRAC, and MIPS Photometry for Transition Disk Candidates
in IC 2395

| ID | RA (2000) | Dec (2000) | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} K_{s} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[3.6]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[4.5]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{aligned} & {[5.8]} \\ & (\mathrm{mag}) \end{aligned}$ | $\begin{aligned} & {[8.0]} \\ & (\mathrm{mag}) \end{aligned}$ | $\begin{aligned} & {[24.0]} \\ & (\mathrm{mag}) \end{aligned}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 2 | 8:40:46.8 | -48:12:42.8 | $9.28 \pm 0.03$ | $9.21 \pm 0.02$ | $9.20 \pm 0.02$ | $9.34 \pm 0.00$ | $9.25 \pm 0.00$ | $9.27 \pm 0.00$ | $9.17 \pm 0.01$ | $7.59 \pm 0.05$ | cluster member |
| 6 | 8:41:04.0 | -48:04:15.6 | $12.12 \pm 0.03$ | $11.80 \pm 0.03$ | $11.77 \pm 0.03$ | $11.69 \pm 0.01$ | $11.75 \pm 0.01$ | $11.64 \pm 0.03$ | $11.53 \pm 0.04$ | $9.90 \pm 0.05$ | cluster member |
| 17 | 8:42:09.5 | -48:20:56.1 | $11.67 \pm 0.03$ | $11.45 \pm 0.03$ | $11.39 \pm 0.02$ | $11.40 \pm 0.01$ | $11.34 \pm 0.01$ | $11.40 \pm 0.02$ | $11.26 \pm 0.03$ | $8.89 \pm 0.04$ | cluster member |
| 22 | 8:42:15.8 | -48:04:20.0 | $11.12 \pm 0.03$ | $10.95 \pm 0.02$ | $10.90 \pm 0.02$ | $10.91 \pm 0.00$ | $10.87 \pm 0.01$ | ... | . . | $8.43 \pm 0.03$ | cluster member |
| 30 | 8:42:36.6 | -48:05:04.1 | $10.47 \pm 0.03$ | $10.41 \pm 0.02$ | $10.37 \pm 0.02$ | $10.43 \pm 0.00$ | $10.41 \pm 0.00$ | $10.47 \pm 0.01$ | $10.29 \pm 0.02$ | $8.27 \pm 0.03$ | cluster member |
| 113 | 8:43:38.1 | -48:08:40.7 | $12.74 \pm 0.03$ | $12.15 \pm 0.02$ | $12.00 \pm 0.02$ | $11.95 \pm 0.01$ | $11.93 \pm 0.01$ | $11.93 \pm 0.03$ | $11.86 \pm 0.04$ | $9.52 \pm 0.05$ | likely member |
| 43 | 8:43:41.4 | -48:09:33.1 | $11.79 \pm 0.03$ | $11.59 \pm 0.02$ | $11.49 \pm 0.02$ | $11.51 \pm 0.01$ | $11.48 \pm 0.01$ | $11.53 \pm 0.02$ | $11.41 \pm 0.03$ | $9.52 \pm 0.04$ | cluster member |

Note. - 2MASS celestial coordinates are used except for ID 110 where IRAC coordinates are used.
central star, the dust reradiates in the mid-infrared.
In Figure 5.11 we plot the 186 sources that are detected in all four IRAC channels and $24 \mu \mathrm{~m}$ onto a $J-H$ versus $K_{s}-[24]$ CC diagram. For Class III sources that have lost their primordial disks, the $J-H$ is a good proxy for spectral type, while the $K_{s}-[24]$ provides a sufficiently long baseline to detect thermal dust emission in the mid-infrared. Lacking large numbers of bona-fide cluster members to determine an empirical main sequence, we conservatively classify debris disks candidates (filled triangles) as those sources with $K_{s}$-[24] flux densities $>30 \%$ ( $\sim 0.3 \mathrm{mag}$ ) above expected photospheric emission $\left(K_{s}-[24] \approx 0\right)$ but less than 1.5 mag. This color locus is typical of observed debris disks in older clusters (eg. Gorlova et al., 2006; Siegler et al., 2007a). The classification criterion of debris disks will be improved in a subsequent paper where fractional luminosities, SED comparisons, and disk modelling will be used.

One of the sources labeled in Figure 5.11, ID 35, is near this locus and has a relatively large $K_{s}-[24](1.5 \mathrm{mag})$. However, there is a close companion observed in the $K_{s}$ band that may be contributing to its mid-infrared flux. We tentatively classify this source as a debris disk candidate but it will require further investigation.

We list the eleven debris disk candidates in Table 5.8. As expected, none of the debris disk candidates have IRAC band excesses.

### 5.4.1.4 Other Color-Color Diagrams: A Consistency Check

In this study, we have used flux densities from the near-infrared ( $J H K_{s}$ ), the four IRAC channels, and the MIPS $24 \mu \mathrm{~m}$ band and various flux ratios to identify probable and possible cluster members, Class II, transition, and debris disk candidates. Using our knowledge of disk characteristics, here we examine the consistency of the candidate selections across different color combinations.


Figure 5.11 Dereddened $J-H$ versus $K_{s}$-[24.0] CC diagram. Plotted are cluster members open circles, possible members open triangles, Class II candidates filled circles, evolved giants and foreground stars unrelated to the cluster open squares, transitional disk candidates filled squares, and debris disk candidates filled triangles. Typical uncertainty of the Class II candidates are shown in the upper right. We designate the locus of debris disks as those sources with $0.3 \leq K_{s^{-}}$ [24.0] $<1.5$ mag. ID 19 is the candidate HAe star.

Table 5.8. 2MASS, IRAC, and MIPS Photometry for Debris Disk Candidates in
IC 2395

| ID | RA (2000) | Dec (2000) | $\begin{gathered} J \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} H \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} K_{s} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[3.6]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[4.5]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} {[5.8]} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{aligned} & {[8.0]} \\ & (\mathrm{mag}) \end{aligned}$ | $\begin{aligned} & {[24.0]} \\ & (\mathrm{mag}) \end{aligned}$ | Comments |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 8 | 8:41:35.3 | -47:57:51.3 | $10.77 \pm 0.02$ | $10.78 \pm 0.02$ | $10.72 \pm 0.02$ | $10.73 \pm 0.02$ | $10.76 \pm 0.01$ | $10.77 \pm 0.01$ | $10.70 \pm 0.02$ | $9.99 \pm 0.05$ | cluster member |
| 13 | 8:41:55.7 | -47:52:12.6 | $9.73 \pm 0.02$ | $9.77 \pm 0.02$ | $9.72 \pm 0.02$ | $9.81 \pm 0.02$ | $9.77 \pm 0.02$ | $\ldots$ | $9.74 \pm 0.01$ | $9.25 \pm 0.04$ | cluster member |
| 14 | 8:41:59.5 | -47:48:17.7 | $10.23 \pm 0.02$ | $10.31 \pm 0.03$ | $10.29 \pm 0.02$ | $10.36 \pm 0.00$ | $10.38 \pm 0.00$ | ... | ... | $9.40 \pm 0.04$ | cluster member |
| 15 | 8:42:04.9 | -48:11:43.3 | $11.39 \pm 0.03$ | $11.28 \pm 0.02$ | $11.23 \pm 0.02$ | $11.25 \pm 0.01$ | $11.26 \pm 0.01$ | ... | ... | $10.33 \pm 0.08$ | cluster member |
| 23 | 8:42:17.8 | -48:03:53.1 | $10.51 \pm 0.02$ | $10.43 \pm 0.02$ | $10.42 \pm 0.02$ | $10.43 \pm 0.02$ | $10.41 \pm 0.02$ | $10.40 \pm 0.01$ | $10.38 \pm 0.02$ | $9.96 \pm 0.06$ | cluster member |
| 27 | 8:42:35.2 | -47:55:47.4 | $10.74 \pm 0.03$ | $10.77 \pm 0.02$ | $10.74 \pm 0.02$ | $10.74 \pm 0.02$ | $10.77 \pm 0.01$ | $10.79 \pm 0.01$ | ... | $9.66 \pm 0.04$ | cluster member |
| 29 | 8:42:36.5 | -48:04:30.9 | $8.89 \pm 0.02$ | $8.94 \pm 0.02$ | $8.96 \pm 0.02$ | $9.13 \pm 0.02$ | $8.96 \pm 0.01$ | $9.10 \pm 0.00$ | $9.02 \pm 0.01$ | $8.40 \pm 0.05$ | cluster member |
| 35 | 8:42:46.4 | -48:05:25.5 | $9.33 \pm 0.03$ | $9.30 \pm 0.03$ | $9.27 \pm 0.03$ | $9.33 \pm 0.00$ | $9.23 \pm 0.00$ | $9.20 \pm 0.01$ | $8.97 \pm 0.01$ | $7.81 \pm 0.03$ | cluster member, likely binary |
| 38 | 8:42:53.1 | -48:07:41.2 | $8.52 \pm 0.02$ | $8.49 \pm 0.04$ | $8.46 \pm 0.02$ | $8.49 \pm 0.02$ | $8.58 \pm 0.02$ | $8.52 \pm 0.02$ | $8.46 \pm 0.02$ | $8.05 \pm 0.05$ | cluster member |
| 42 | 8:43:29.1 | -48:02:54.9 | $10.62 \pm 0.02$ | $10.58 \pm 0.03$ | $10.53 \pm 0.02$ | $10.50 \pm 0.02$ | $10.44 \pm 0.02$ | $10.46 \pm 0.01$ | $10.43 \pm 0.02$ | $10.06 \pm 0.04$ | cluster member |
| 45 | 8:44:26.6 | -48:27:05.7 | $11.03 \pm 0.02$ | $10.92 \pm 0.02$ | $10.92 \pm 0.02$ | ... | ... | ... | ... | $10.31 \pm 0.06$ | cluster member |

Note. - 2MASS celestial coordinates are used

The $J-H$ versus $K_{s}$-[24] CC diagram (Figure 5.11), which we used to identify the debris disk candidates, is also a useful consistency check for our disk classifications. All the objects in the Figure with large $K_{s}-[24]$ excesses (greater than 3.5 mag ) and with estimated spectral type later than K dwarfs ( $J-H \geq 0.5 \mathrm{mag}$ ) correspond to Class II candidates, as identified via the IRAC CC diagram (Figure 5.9). In fact, these large $K_{s}$-[24.0] excess objects make up all the Class II candidates with $24 \mu \mathrm{~m}$ detections identified using the IRAC CC diagram. All but one of the Class II candidates with $24 \mu \mathrm{~m}$ detections have estimated spectral types later then G9, suggesting that the more massive stars lose their primordial disks faster than lower mass stars, an observation also noted by others (eg. Carpenter et al., 2006).

None of the objects in Figure 5.11 with $J-H \geq 0.5 \mathrm{mag}$ and $K_{s}-[24]<2$ appear to be members of IC 2395. This is not surprising since most have near-infrared colors consistent with giants. Dwarfs with these J-H colors (corresponding to masses less than about $1.4 \mathrm{M}_{\odot}$ ) would be too faint to have detectable photospheres at $24 \mu \mathrm{~m}$ at the distance of the cluster. They are more likely foreground objects. To illustrate this further, we plot these objects on the near-infrared CM diagram in Figure 5.12 as open boxes. They all lie far above the young isochrones and disk candidates (filled symbols).

The transition disk candidates which we identified from the [8.0]-[24] color all have $K_{s}-[24]$ excesses greater than 1.5 mag , consistent with optically thick outer regions (Figure 5.11). In Figure 5.12, all but one of the transition disk candidates are F/G type stars. The fact that there are no low-mass candidates is likely due to $24 \mu \mathrm{~m}$ sensitivity at the distance of the cluster. Sensitivity at $24 \mu \mathrm{~m}$ plays an even more limiting role in our debris disk candidate selection, all of which are B- and A-type stars.

Figure 5.13 shows all the disk candidates plotted on the near-infrared CC dia-


Figure 5.12 All the disk candidates (filled symbols) plotted onto the dereddened $J$ versus $J$ - $H$ CM diagram (symbols as in Figure 5.11). We also show the sources consistent with giant or foreground stars as open squares confirming their nonmembership. The ZAMS extending to the higher mass stars is from the models of Lejeune \& Schaerer (2001) solid curve and the three curves represented by broken lines are from left to right, ZAMS, 10 Myr , and 3 Myr isochrones from Siess, Dufour, \& Forestini (2000). Only one of the candidate Class II objects (located near $J \sim 11$ ) is earlier than a K-type star likely due to faster disk dissipation rates for earlier-type stars. Alternatively, only early-type stars have transition and debris disk detections but this result is likely due to $24 \mu \mathrm{~m}$ sensitivity.
gram. As a sanity check we find that all the candidate Class II objects lie either in the near-infrared CTTS locus (dotted lines) of Meyer, Calvet, \& Hillenbrand (1997) or the main sequence branch. The CTTS locus is created by simply plotting the upper and lower $3 \sigma$ slope and ordinate intercept uncertainties. All the transition disk candidates (filled squares) lie on the main sequence branch as expected.

Lastly, we plot in Figure 5.14 all the disk candidates and cluster members from our two samples on the IRAC CC diagram. As expected, all the debris and transition disk candidates occupy the region near ( 0,0 ). ID 82 has a relatively large $8 \mu \mathrm{~m}$ flux density and is likely a Class II object (no $24 \mu \mathrm{~m}$ detection) despite being slightly outside the Class II locus. We note the one cluster member (ID19) within the locus as a possible HAe star. ID 19 is either a Class II A star, based on its IRAC colors (Figure 5.14), or a transition disk with a higher [5.8]-[8.0] excess than typical transition disks. The object does not lie on the HAeBe near-infrared locus of Hernandez et al. (2005) and has a $K_{s}$-[24] excess less than typical HAe stars (Hernandez et al., 2006). Hence we tentatively classify ID 19 as a HAe candidate with a small inner gap.

### 5.4.2 Contamination?

The most likely contaminant in our classification of disks (infared excesses) is confusion from random line-of-sight positional overlap with distant opticallyfaint but infrared-bright galaxies, planetary nebule, and AGN showing no sign of elongation in the 2MASS image. What is the probability of such an accurate chance alignment? The effects of these contaminations are usually small (Megeath et al., 2004; Gutermuth et al., 2007). For example, with ~2000 extragalactic sources per square degree at 0.5 mJy (Papovich et al., 2004), a flux less than our completeness limit but greater than our detection limit, the probability of a chance background source observed within $0.5^{\prime \prime}$ of a cluster member is $0.4 \%$


Figure 5.13 Dereddened near-infrared CC diagram as in Figure 5.4 but now with all our disk candidates plotted (symbols defined in Figure 5.10). All the Class II candidates lie in the CTTS near-infrared locus (dotted lines; Meyer, Calvet, $\mathcal{E}$ Hillenbrand, 1997) or near the main sequence locus. Typical uncertainty of the Class II candidates are shown in the upper left.
$\left[\pi\left(0.5^{\prime 2} /\left(0.97 \times 60^{2}\right)\right) \times 2000 \times 32\right]$.

### 5.4.3 Cluster Age

Estimating the age of a young open cluster by fitting theoretical pre-mainsequence models to upper-main-sequence stars (spectral types $B$ and $A$ ) can be unreliable. Small photometric errors, especially associated to the stars defining the main-sequence turn-off, can translate into large errors in age and there are substantial uncertainties in the pre-main-sequence evolution for these intermediate-mass stars.

IC 2395's age of $6 \pm 2$ Myr was estimated by Clariá et al. (2003) who fit several theoretical turn-off isochrones of various metallicity using the models of Lejeune \& Schaerer (2001). They weighted the three brightest cluster members and examined different solar metal abundance assumptions. In actuality, their best fit was largely dependent on the position of a single member - the brightest probable member of the cluster, HD 74455 (ID 21, $\mathrm{V}^{*} \mathrm{HX}$ Vel). In addition, this star is listed in the catalog of Blue Stragglers in Open Clusters (Ahumda \& Lapasset, 1995). We redid their CM diagram with our new revised cluster membership list and their derived individual extinction values and can only conclude from Figure 5.6 that the cluster appears young, less than 15 Myr .

We offer perhaps the more persuasive evidence for youth from the large number of CTT-like objects identified in Figures 5.13 and 5.14. The cluster is almost certainly less than 10 Myr based on the rarity of older CTTSs (eg. Haisch, Lada, \& Lada, 2001; Mamajek et al., 2004). In addition, the cluster is also very likely older than 2-3 Myr with no Class I sources identified in the IRAC CC diagram of Figure 5.9 (all the sources redward of the Class II box plotted were determined to be inconsistent with membership; see IRAC CC diagram locus for Class 0 and I sources in Muzerolle et al., 2004). Hence we conclude that the open cluster

IC 2395 is indeed young and likely between $4-10 \mathrm{Myr}$.
In a follow-up paper, we will present evidence for active accretion from broad $\mathrm{H} \alpha$ emission and U-band excesses further supporting the photometric evidence for the cluster's youth. A large population of bona-fide members, particularly lower mass, will also help constrain the cluster's age.

### 5.5 Evidence of Circumstellar Disk Evolution

One of this investigation's overall goals is to identify sources with circumstellar disks and measure the timescales of disk evolution. By observing stellar clusters, there should be significant coeval sources of similar composition, distance, and environment to make the results statistically meaningful. Many of this study's goals, however, will have to wait for the remainder of our data analysis. We now comment on some of this study's early results.

### 5.5.1 Circumstellar Disks and High Mass Stars

Of the 45 bona-fide cluster members listed in Table 5.2, 18 have evidence of infrared excess attributed to circumstellar disks; none of the 12 "possible" members are disk candidates. The disk breakdown of these members is 7 transition disks and 11 debris disks. What fraction of these cluster members have circumstellar disks? To answer this we must determine the completeness of our sample. Of the 22 A and B stars in Table 5.2, as classified from optical spectra or nearinfrared colors, only one appears to still possess its primordial disk ( $\sim 5 \%$ ). This small fracion is not unexpected considering most Herbig AeBe stars dissipate their disks within $\sim 5 \mathrm{Myr}$ (Hernandez et al., 2005). For example, while $\sim 10 \%$ of the most massive stars in the $\sim 3 \mathrm{Myr} \sigma$ Orionis open cluster still have primordial disks (Hernandez et al., 2007), none were found in the $\sim 5 \mathrm{Myr}$ Orion OB1b and ~ 10 Myr OB1a Associations (Hernandez et al., 2006).


Figure 5.14 IRAC CC plot of all the disk candidates and cluster members from our two samples (symbols same as Figure 5.10). The overplotted boxes are the predicted IRAC colors for Class II stars of different accretion rates by the models of D'Alessio et al. (2006) (dashed box) compared to empirical results from a study of CTTS in Taurus (Hartmann et al., 2005) (dotted box). Object ID 82 is a likely Class II object rather than a transition disk based on its relatively large flux at $8 \mu \mathrm{~m}$. Typical uncertainty of the Class II candidates are shown in the upper left corner.

In order to quantify the fraction of transition and debris disks among the A and B stars, a source must have been detected at $24 \mu \mathrm{~m}$ and meet the photometric requirements discussed in $\S$ 5.4. The $24 \mu \mathrm{~m}$ completeness limit of our samples correspond to those cluster members whose photospheres are detectable at $24 \mu \mathrm{~m}$. We define this minimum flux density sensitivity as the turnover in the [24] brightness distribution of all the sources in our MIPS image ([24] $<9.9 \mathrm{mag}$ ). Since $K_{s}$ is approximately the same as [24] for photospheric emission for early type stars (eg. Gorlova et al., 2006; Siegler et al., 2007a), the [24] brightness limit corresponds to spectral type $\sim$ A0 in IC 2395. Detections of fainter sources at $24 \mu \mathrm{~m}$ will almost certainly be biased toward those with infrared excesses.

In addition, we remove from our disk fraction calculation those stars with spectral types earlier than B5 due to their possible "extruded" disks. It is known that early-B stars may form gaseous disks "extruded" from the star due to its fast rotation and X-ray emission (Chokshi \& Cohen, 1987). These stars are sufficiently hot to produce free-free emission on the surface of the gaseous disk that can contribute to the $24 \mu \mathrm{~m}$ flux density and masquerade as thermally re-emitting debris dust. Hence when considering disk fractions, we remove all the cluster members from our sample that have spectral types or near-infrared colors earlier than B5.

Only five stars from our sample of 45 meet this dual requirement of photospheric sensitivity at $24 \mu \mathrm{~m}$ and no extruded disks (ID 13, 14, 20, 35, 40). ID 13 and 14 have infrared excesses consistent with debris disks while the excess associated with ID 35 may be related to a tight companion as discussed in $\S$ 5.4.1. ID 20 has a $K_{s}-[24]=0.22 \mathrm{mag}$, falling just below our conservative 0.30 mag cutoff for debris disks. The statistics are too small to broadly interpret these results but the high disk fraction ( $\_40 \%$ ) are consistent with IC 2395's young age. In comparison, the $\sim 2-3$ Myr old open cluster IC 348 has about half of its members possessing disks
(50 $\pm 6 \%$; Lada et al., 2006).
The number statistics will be more meaningful when the analysis of the spectral and deep visible photometry components of this investigation are completed. At that time we will also compare the disk fraction results of lower mass stars with those from other open clusters.

### 5.5.2 Evolution of the IRAC Colors

From observations and analysis at submillimeter and millimeter wavelengths (eg. Testi et al., 2003) to the mid-infrared (eg. van Boekel et al., 2003; Furlan et al., 2006), there is now sufficient observational evidence that dust grains in circumstellar disks have evolved from that seen in the interstellar medium. However, the exact process and characteristic timescales during which incremental growth occurs, from submicron- to millimeter- to kilometer-sized objects, ultimately leading to planet-mass objects, are still not well known. The question of timescales is critical to our understanding of planet formation because there is little remnant gas in a star's primordial disk after more than about 10 Myr (eg. Pascucci et al., 2006). During this relatively short time period, grain growth must be sufficiently efficient to create several Earth-mass objects to serve as the core of future gas-giant planets.

Theories of dust evolution predict grain-grain interactions increase with decreasing orbital period (Hayashi, Nakazawa, \& Nakagawa, 1985; Wiedenschilling, 1997). Higher velocity Keplerian orbits permit more frequent collisions and agglomeration capable of forming larger bodies faster than in outer regions so that models that include grain growth and consequent settling to the disk midplane satisfy requirements for shorter timescales in the inner disk (but outside the dust sublimation radius).

In Figure 5.15 we reproduce a simulated SED from one of the fiducial disk
models of D'Alessio et al. (2006) to illustrate the flux contributions from a CTTS to the four IRAC channels. Their models incorporate depleted distributions of dust typical of the interstellar medium in the upper disk layers along with larger sized particles near the disk mid-plane, isotropic scattering, and irradiation of the inner rim by the central star (excluding accretion shock heating). According to the model, the IRAC colors are largely effected by the extant radiation from the inner edge or rim of the disk. This rim, located at the dust destruction radius ( $T \sim 1400 \mathrm{~K}$ ), is believed to be slightly enlarged or puffed due to direct irradiation of small dust grains in the disk's surface mainly by the central star (Natta et al., 2001; Muzerolle et al., 2003).

According to the SED model shown in Figure 5.15, the emission from the heated dust within the rim is the dominant excess flux contributor at $K$ band and the two shortest IRAC wavelengths ( 3.6 and $4.5 \mu \mathrm{~m}$ ). At the longer IRAC wavelengths ( 5.8 and $8.0 \mu \mathrm{~m}$ ), the flux contributions arrive from both the rim and disk in similar amounts. The D'Alessio et al. (2006) models predict the irradiated rim to decrease in scale height as the opacity to the incident radiation decreases. This is consistent with the processes of grain growth and settling to the disk midplane.

If grain growth and dust settling is really the dominant process of primordial disk evolution, then this suggests an "inside-out" reduction of dust opacity and flattening of the flared primordial disk. We would therefore expect the IRAC colors, [3.6]-[4.5] and [5.8]-[8.0], to become bluer over time eventually reaching photospheric values (near 0,0). Furthermore, [3.6]-[4.5] should decrease to zero more quickly than [5.8]-[8.0].

In a disk investigation of the $\sim 4$ Myr open cluster Trumpler 37, Sicilia-Aguilar et al. (2006) first observed the median IRAC [3.6]-[4.5] and [5.8]-[8.0] colors of


Figure 5.15 A simulated SED of a CTTS reproduced from a fiducial model from D'Alessio et al. (2006). The model includes ISM dust, isotropic scattering, and dust settling. Flux contributions from the photosphere (short-dash-long-dashed line), the inner "puffed" rim (dotted line), and the disk (dashed line) are shown individually; the composite SED is represented by the solid line. The four IRAC channels are overplotted illustrating that the two shorter wavelength channels are dominated by excess flux from the irradiated inner edge while the latter two longer wavelength channels receive flux excess almost equally between the rim and the disk.

CTTSs to be bluer than those of the $\sim 1$ Myr Taurus association (Hartmann et al., 2005). How do the median IRAC colors of the $\sim 6 \mathrm{Myr}$ IC 2395 Class II objects compare? The median [3.6]-[4.5] and [5.8]-[8.0] colors of the 49 identified Class II candidates listed in Table 5.6 is 0.24 and 0.62 mag, respectively. IC 2395's median IRAC colors are lower still than these two younger clusters.

In Figure 5.16 we plot the median IRAC colors of Class II objects from several young stellar groups with ages ranging from $\sim 1$ to 7 Myr . In addition to Taurus, Trumpler 37, and IC 2395¹, we include recent Spitzer results from the NGC 2068 ( $\sim 2$ Myr, Kevin Flaherty, priv communication), IC 348 ( $\sim 2-3$ Myr; Lada et al., 2006), NGC 2244 ( $\sim 3$ Myr; Balog et al., 2007), and $\eta$ Chameleontis association ( $\sim 5-9$ Myr; Megeath et al., 2006) surveys. Together they show the evolution of the IRAC colors of Class II objects during timescales commensurate with primordial disk lifetimes.

The analysis does not include groups older than about 10 Myr because by this age there are not enough Class II objects in older clusters and associations to make a reliable statistical measuremement. The horizontal error bars in Figure 5.16 reflect the uncertainties in the cluster ages and the vertical bars represent the photometric uncertainties in the colors. The dotted vertical lines on the right side represent the median $1 \sigma$ dispersion in the colors from the groups represented.

To be consistent in our handling of each stellar group, we only considered those sources whose colors lie in the D'Alessio et al. (2006) theoretical CTTS locus shown in Figure 5.9. This locus is used because it matches very well with the empirical data (eg. Allen et al., 2004; Hartmann et al., 2005), relies only on IRAC photometry, and is less affected by extinction. This locus is likely to be conserva-

[^14]

Figure 5.16 Evolution of the IRAC colors for Class II objects. We plot the median [3.6]-[4.5] colors in filled circles and the median [5.8]-[8.0] colors in filled triangles for objects whose colors fall within the Class II IRAC CC locus (Allen et al., 2004; Hartmann et al., 2005). The unreddened colors of the included stellar groups are taken from the literature (see $\S 5.5 .2$ for references). The horizontal solid lines represent reported age uncertainties while the vertical solid lines represent the median photometric uncertainty per group. The two vertical dotted lines on the right are median $1 \sigma$ color dispersions from the groups. Both median colors appear to become bluer with time, consistent with dust settling in the inner regions of the primordial disk. The large dispersions point to other likely effects driving primordial disk evolution besides age. The number of Class II objects associated with the each labelled cluster from left to right is: $41,46,59,290,53,35,6$.
tive in identifying CTTS as a few may lie just blueward of the locus amongst the weak TTSs and Class III objects, and hence go uncounted (eg. Trumpler 37 study by Sicilia-Aguilar et al., 2006).

Figure 5.16 is a preliminary result showing a possible decrease in the two IRAC colors with age. A further analysis of several effects inherent in each survey - observational biases, extinction, cluster membership, and completion limits is required to determine if the trends actually exist. The clusters and associations in these surveys differ in distance and hence the stellar mass ranges probed. This is potentially quite important since there appears to be a mass-dependent effect in disk lifetime. Both Taurus (Hartmann et al., 2005) and IC 348 (Lada et al., 2006) show higher primordial disk fractions for the later $K$ and $M$ dwarfs than G-type stars. We have also seen in our IC 2395 investigation all but one of the candidate Class II objects have near-infrared colors consistent with K and M dwarfs. For the most distant groups, it is precisely this lower-mass population that is likely to remain undetected. Thus an accurate comparsion would require similar probed mass ranges, however, it is not clear what effect on the IRAC colors the missing low-mass population would have. Removing 35 Class II objects with spectral types M5 and later from the IC 348 analysis had little effect on the median colors (note, at the age of this cluster, these are substellar objects).

If an actual general trend in Figure 5.16 is still observed even after observational biases are considered, we point out two possible observational behaviors related to disk evolution. The first is a general decrease in the median infrared excesses over time; the second is the relatively large dispersion of colors per age. The former is an age-dependent effect while the latter may be less so.

### 5.5.2.1 Decrease in the Median Infrared Excess Over Time

The observed general decrease in the median IRAC color excess over time is consistent with either grain growth or grain settling occuring in the disk atmosphere, or possibly both. It is quite reasonable to expect that the innermost dust grains, at the dust sublimation distance near the inner rim, should be among the first grains to agglomerate and grow into larger objects because of more frequent interactions due to higher Keplerian velocities (eg. Wiedenschilling, 1997). Because larger grains have smaller absorption efficiencies, they will reradiate less, resulting in less excess emission as compared to smaller grains. Hence, the process of grain growth could be observable as an age-dependent decrease in the IRAC colors.

Alternatively, grain removal from the disk atmosphere, without necessarily first agglomerating, would also result in reduced opacity simply due to less emitters. Again, this could be observed as a decrease in IRAC colors in the inner disk region. Turbulence certainly can play a role in removing and circulating grains in the upper atmosphere (eg. Ciesla et al., 2007). However, it is hard to explain any mechanism that removes small grains from disk atmosphere that does not lead to either their replenishment or in their growth. Dullemond \& Dominik (2005) suggest that perhaps after a rapid planetesimal formation period, high-velocity collisions are fragmenting at a rate comparable to grain growth. Turbulence related to accretion may then repopulate the disk surface with grains from the midplane (van Boekel et al., 2003) as well as play a role in extending the lifetime of small grains (eg. Ciesla et al., 2007).

Sicilia-Aguilar et al. (2007) support the process of dust settling with time from spectral observations of very pristine silicate features in a sample of 10 Myr old stars. This is in contrast to the larger grains $(\sim 5-6 \mu \mathrm{~m})$ found only among stars
less than about 2 Myr. They argue that the older stars already experienced dust settling to the disk mid-plane leaving behind only (or replenishing) the smallest and unprocessed grains in the disk atmosphere. They speculate that the dust grains in the younger stars, on the other hand, may be in the process of agglomerating. We find this result intriguing but acknowledge the difficulty in assigning ages for individual objects and their small sample sizes. More objects are needed, especially at older ages.

### 5.5.2.2 Large Color Dispersion Per Age

Figure 5.16 also shows a considerable amount of scatter in the colors of individual Class II objects within each group (vertical dotted lines). The size of the respective dispersions argue for less-age dependent drivers. D'Alessio et al. (2006) show the effects of accretion rates, an age-dependent process, having an important effect on the IRAC colors. However, other differences such as stellar mass may also lead to different rates of disk dissipation. As discussed earlier, more massive stars appear to remove their primordial disks on faster timescales than less massive stars. In addition, the variations in the initial conditions of the collapsing, rotating molecular cloud core may be important in accounting for variations in the original disk mass, size, angular momentum, and turbulence. For example, two coeval stars of the same stellar and disk mass but differing sizes may have different surface densities. If the disk dissipation rate is dependent on surface density, then the effect on the IRAC colors may be as important as other dissipation mechanisms such as grain growth and settling.

Perhaps the wide color dispersion in the IRAC bands per age shown in Figure 5.16 reflects the wide variation of disk evolutionary states observed at all ages. For reasons still not clear, stars of similar age and mass may be at different stages of disk evolution. Even at about 1 Myr , some stars appear to have already
dissipated their inner primordial disks (Hartmann et al., 2005; Flaherty et al., 2007). Our preliminary IC 2395 analysis is a good example of this dispersion showing many cluster members with no apparent disks, some with evolved debris disks, and some with optically thick or transitional disks. Similar disk diversity is observed among the candidate disk objects.

Figure 5.16 also suggests that the processes of grain growth and settling are still occuring at $\sim 7 \mathrm{Myr}$, despite arguments that grains grow to sizes greater than about $10 \mu \mathrm{~m}$ and rapidly settle to the disk midplane ( $10^{3}-10^{5} \mathrm{yr}$; eg. Wiedenschilling, 1997; van Boekel et al., 2003; Dullemond \& Dominik, 2005). So why are there near-infrared and IRAC excesses corresponding to primordial disks at subAU radii still observed around stars older than a million years? Reconciling the observations would require small grains at the disk surface be replenished while some grain growth is occuring. The replenishing by fragmentation hypothesis of Dullemond \& Dominik (2005) discussed earlier may support this.

Finally, we note that the decrease in IRAC colors observed in Figure 5.16 is not applicable to any individual star but rather to an ensemble. The simple evolutionary scenario in which grains grow from sub-micron sized grains to kilometersized planetesimals over a period of a few million years is likely more complicated. The bottom line is age does not appear to be the only effect driving disk evolution and there is not likely an absolute, evolutionary timescale regulating the transition from primordial to debris disks. Both observations from Figure 5.16 are consistent with a model of grain growth and settling in the inner disk. However, trying to disentangle all the competing effects in disk evolution related to these results is very difficult. At minimum, the evolutionary trend in Figure 5.16 provide another observational constraint in the overall theory of primordial disk evolution.

### 5.6 Future Work

- Short and deep optical photometry in $U B V R I$ bands have been obtained with the CTIO 4-m telescope which will help identify additional cluster members, particularly low-mass. We have already obtained nine $15^{\prime} \times 15^{\prime}$ fields similar to the angular area observed with Spitzer images. One set targets the brightest members of the cluster ( $V \lesssim 13 \mathrm{mag}$ ) and a second set targets the faintest members ( $V \lesssim 21 \mathrm{mag}$ ). $U$-band photometry in particular will be useful to identify those members still accreting as well as their mass accretion rates.
- Intermediate optical spectroscopy has already been obtained with the CTIO 4-m telescope and Magellan $6.5-\mathrm{m}$ telescope to measure youth diagnostics such as Li and $\mathrm{H} \alpha$ and determine spectral classification to help identify additional cluster members. High resolution spectra have also been obtained for a number of targets to resolve the $\mathrm{H} \alpha$ emission line and measure radial velocities for earlier spectral types lacking youth diagnostics.
- With an increased cluster membership extending to lower mass objects, we will quantify the fraction of members still possessing primordial disks and what fraction are still accreting. We will also measure the fraction of members with evidence of transition disks and address if there is a preferred timeline for their formation. The relationship between disk fraction as a function of stellar mass will be examined.
- The creation of SEDs will assist in differentiating between the different types of disks discovered in this investigation as well as identify those objects containing gaps, possibly due to planet formation.
- The identification of more lower-mass members through deep optical photometry and spectra will better constrain the cluster's age by fitting the lower-main-sequence cluster members to more numerous lower-mass members and better performing theoretical models. This is important in understanding the timescales around many of the processes discussed in this chapter.
- Removing the biases inherent in the evolution of the IRAC colors shown in Figure 5.16 will show if the IRAC colors do evolve over time. Extending the infrared baseline to $24 \mu \mathrm{~m}$ would reveal if the trend continues and if the model of outward evacuation is the correct one. Measuring accretion rates at several ages will also tell us if its relevant importance in the observed IRAC color evolution.
- Obtaining IRS spectra for a subsample of the CTTS and transition disks in IC 2395 will allow for the examination of the $10 \mu \mathrm{~m}$ silicate feature. We would be able to analyze the composition and size of the warm photospheric silicate grains by fitting the feature and study the possible correlations between the silicate characteristics and the stellar and disk properties such as age, SED slope, accretion rate, spectral type.


### 5.7 Conclusions

This chapter presents preliminary results from an ongoing study of the $\sim 6 \mathrm{Myr}$ old open cluster IC 2395. The main result to date are:

- Preliminary lists of candidate Class II objects (49), transition disk (7), and debris disks (11) are presented. A Herbig Ae candidate with an inner gap is also identified.
- From the relatively large number of Class II candidates and transition disks identified in this investigation, a young cluster age is well supported. However, from isochrone fitting we can only estimate the cluster age to lie between $\sim 4-10$ Myr. We await enlargening the cluster membership to lower masses to better constrain the overall age.
- A decline in the median IRAC colors is consistent with a process of grain growth and settling in the innermost region of Class II objects which continues past $\sim 6 \mathrm{Myr}$. However, the trend, if true, may be an optical debth effect leading to the overall flattening of the disk surface.


## CHAPTER 6

## CONCLUSIONS AND Future Directions

I end with a summary of this dissertation's key conclusions and place them in an overall context of star and planet formation and evolution.

### 6.1 Multiplicity of Very-Low-Mass Stars

We used AO in the near-infrared to obtain high-spatial-resolution observations of 36 nearby M6-M7.5 field dwarf stars (Siegler et al., 2005). Five of these targets were observed for the first time to have near-equal mass companions. Considering instrument sensitivity effects, empirical separation and mass ratio distributions, and the Malmquist bias, we concluded that the binary multiplicity fraction of M6-M7.5 field stars is $9_{-3}^{+4} \%$ at separations between $\sim 3-300 \mathrm{AU}$ and mass ratios greater than about 0.5 . This fraction, along with the separation and mass ratio distributions between the components, are consistent with what has been measured by our group for late-M dwarfs as well as studies by others of $L$ and $T$ dwarfs (Close et al., 2003; Burgasser et al., 2007).

High-resolution imaging studies of VLM binary stars show a clear difference in properties from slightly more massive and intermediate-mass stars. We compared 87 known VLM binary systems found in the literature to more massive stars. Within the sensitivities of our and others' studies (separations greater than about 3 AU and mass ratios greater than about 0.5 ), we conclude that with respect to more massive binary systems, VLM binaries are:

- rarer (binary frequency $7-15 \%$ ); versus $\sim 40 \%$ for early-M dwarfs and $\sim 50 \%$ for G dwarfs,
- tighter ( $89 \%$ have projected separations less than 20 AU ; distribution peaks at or below $\sim 3-10 \mathrm{AU}$ ); versus more broadly peaked distributions for more massive dwarfs (early-M dwarfs: 4-30 AU, G dwarfs: around 30 AU ),
- and more frequently in near-equal mass configurations ( $76 \%$ have $\mathrm{q} \geq 0.8$ ); versus a very broad distribution peaking around 0.6-0.7 for FGK stars.

Both the separation (Figure 2.8) and mass ratio (Figure 2.9) distributions imply possible evolutionary processes. The subsample of binaries less than 10 Myr (shaded regions), while now only twelve in number, appear to have distinctly broader distributions. While only $11 \%$ of the field VLM binaries have separations greater than $15 \mathrm{AU}, 50 \%$ of the young subsample have wider separations. A likely hypothesis explaining the differences between VLM binaries and more massive binaries as well as the age distribution differences invokes dynamical interactions.

### 6.2 Evolution of Debris Disks Around Solar-Like Stars

Using the MIPS instrument on the Spitzer telescope we have measured the $24 \mu \mathrm{~m}$ flux densities of a sample of IC 2391 cluster members in order to identify sources with mid-infrared excess typical of debris disks (Siegler et al., 2007a). The best explanation for these mid-infrared excesses are micron-sized dust grains heated by ultraviolet and visible light from the central star and reradiating at longer wavelengths. Because dissipation mechanisms are predicted to remove the dust on timescales much less than a million years, the dust must be regenerated.

One of the key results in our mid-infrared investigation of the 50 Myr old open cluster IC 2391 is that about $30 \%$ of the F-K members have evidence of debris disks. Placing this result in context of other clusters and associations both younger and older, we observe an evolutionary decay in the fraction of stars with
$24 \mu \mathrm{~m}$ excess (consistent with debris disks) on timescales near 100 Myr (Figures 4.6 and 4.7). Nearly $60 \%$ of the youngest stars in the Figures, members of the $\sim 16-17$ Myr old regions of Scorpius Centaurus, have evidence of debris disks while those several hundred million years and older report less than $3 \%$. Collectively, these results infer that the number of collisions decreases over time, similar to what we believe occurred in the early Solar System (eg. Strom et al., 2005). The reduction in collisions further suggests a reduction in the number of colliders of which there may be several explanations - ejected out of the stellar system due to kinematic interactions, agglomerated into larger bodies, ablated due to collisions and dragged into the star due to Poynting-Robertson drag or forced out to due to radiation pressure, or lastly, obtained collision-free orbits.

While the evolution of typical debris disks around solar-like stars appears to gently decay on timescales near 100 Myr , Figures 4.6 and 4.7 show that there are large fractions of stars with no excess at even the youngest ages. For some reason, perhaps embedded in their initial formation conditions (rotation, magnetic fields, disk mass density, disk turbulence, environment), some stars have either shedded any evidence of dust, arrived at a quiescent stage, or never formed planetesimals to collide. Regardless of the mechanism, these results show substantial intrinsic differences between stars even of similar ages.

An interesting behavior of disk evolution observed in the Figure 4.7 is that large mid-infrared excesses around individual stars occur at ages when most stars show no excess. There appears to be no favorite time or regularity in these excess "spikes" leading us to conclude that large collisions around solar-like stars occur even after the initial period of terrestrial planet formation as episodic, stochastic events. Perhaps our own Solar System's Late Heavy Bombardment stands as such an example 700-800 Myr after the Sun's formation.

This chapter's results, along with those of (Rieke et al., 2005, debris disks around A-type stars), may be among the most significant from the Spitzer disk investigations - the formation of planetesimals around late-B to early-K stars appears to be a universal process of star formation. From the moment giant molecular clouds begin to form, the formation of rocky bodies, anywhere between pebble and kilometer-sized objects, is most likey assured. However, the Galaxy's most populous members, M dwarfs, have not yet been probed at young ages for evidence of debris disks. Their less massive disks and lower stellar luminosities pose detection challenges, especially for the younger objects that are typically further away. But as shown in this dissertation and elsewhere, we have evidence consistent with grain growth in the young T Tauri stars suggesting that even in primordial disks, the process of planetesimal formation is underway.

### 6.3 Evolution of Primordial Disks

In Chapter 5 we presented preliminary results from the first infrared investigation of the poorly-studied, $\sim 6 \mathrm{Myr}$ old open cluster IC 2395 (Siegler et al., in preparation). Using empirical photometric loci from both color-color and colormagnitude diagrams, we identified probable and possible cluster members as well as candidate circumstellar disks at different stages of disk evolution - primordial, transition, and debris. The fact that even coeval stars of the same spectral type show variations in disk evolution supports suggestions from other investigators that age is not the primary driver in the disk dissipation rate for T Tauri stars. Other processes possibly playing a role are the initial conditions imprinted in the original fragmenting cloud core and variations in the environmental conditions or interactions in the natal cluster. In addition, only one massive star (spectral type A) had evidence of an optically-thick disk supporting the idea
that primordial disk lifetimes are overall shorter for these types of stars.
We also present for the first time a median IRAC color-color evolution diagram (Figure 5.16) consisting of Class II objects from clusters and associations younger than 10 Myr . Preliminary interpretation suggests a downward trend in excess color with age consistent with grain growth and dust settling in the inner $\sim 0.2 \mathrm{AU}$ of circumstellar disks. However, grain growth without settling is also a possibility resulting in an optical debth effect. The relativley large color dispersions per age bin again suggest a range of initial conditions within circumstellar disks. Furthermore, the fact that these inner regions are still populated with micron-sized dust at ages $\sim 5-10 \mathrm{Myr}$ supports the idea of planetesimal collisions even at the youngest ages. One possibility is that these collisions fragment and repopulate the inner disk surface with micron-sized dust grains even as others are growing into larger bodies.

### 6.4 On the Question of Planets

In many ways this dissertation has also been about planets - do they exist around VLM stars? How common are they around more massive stars? How do terrestrial planets form? Like the metaphorical blind men each individually investigating a section of an elephant, my own scientific inquiries have explored different, but narrow, aspects on the questions of planets. I take the opportunity here to look at the implications this research has had on planet detection - both direct and indirect.

### 6.4.0.3 Multiplicity of Very-Low-Mass Stars

In our multiplicity studies we used large aperture mirrors along with optics that counter the blurring effects introduced by the Earth's atmosphere to resolve potential faint companions. These companions were in most cases VLM stars but
in at least five of our discovered systems (Freed, Close, \& Siegler, 2003; Close et al., 2002b; Siegler et al., 2007b; Close et al., 2007) the companions had predicted masses less than 80 Jupiters and are all certainly brown dwarfs. But why were no planetary-mass objects discovered ( $\lesssim 12$ Jupiter masses)?

As shown in Figure 2.3, our near-infrared surveys, totalling nearly 90 VLM stars ( $\left.\lesssim 0.1 \mathrm{M}_{\odot}\right)$, were typically sensitive to companions about 11 mag fainter than the target at angular separations of about $1.5^{\prime \prime}$. According to the models of Burrows, Sudarsky, \& Lunine (2003), the contrast was sufficient to have detected gigayear-old, 10-12 Jupiter-mass objects. Similar results are arrived at using other evolutionary models (eg. Baraffe et al., 1998). This suggests that either the models are overluminous at these ages or massive planets are unlikely to exist around VLM stars at semi-major axes larger than 20-30 AU. At gigayear ages, however, the models appear well constrained. More likely, our null result has placed an observational constraint on the presence of planets around VLM stars in the form of upper mass limits and semi-major axes - it is unlikely that 10-12 Jupiter-mass objects orbit VLM stars at semi-major axes greater than about 20-30 AU. These objects may be orbiting undetected nearer the star or less massive objects may be orbiting undetected at semi-major axes greater than about 20-30 AU (Figure 6.1).

The lack of detected very massive planets at 20-30 AU distances around VLM stars points perhaps to the lack of material in the natal primordial disks. If we assume that typical $0.1 \mathrm{M}_{\odot} \mathrm{T}$ Tauri stars have disks roughly $10 \%$ of their stellar mass, then a late-M dwarf would only be expected to contain about 10 Jupiter masses worth of gas and dust. It is therefore highly unlikely that planet formation is sufficiently efficient to form 10-12 Jupiter-mass planets around these late-type stars, at any distance. Our null result supports this assumption.

Our null result also supports the hypothesis that planetary mass objects


Figure 6.1 Orbital radius - mass distribution. The blue stars are all extra-solar planets and the red stars are our own Solar System's planets. The blue-shaded region represents the sensitivity of the radial velocity planet surveys while the general sensitivity of our direct-imaging VLM survey is represented by the redshaded region. The two planet-finding techniques are mutually complementary. As shown, only one planet-mass companion has been discovered via direct imaging (2MASS 1207b; Chauvin et al., 2004, 2005). Nature rarely forms several-Jupiter-mass planets at distances greater than $\sim 20$ AU around VLM stars. The blue stars located outside the shaded regions represent those extra-solar planets discovered by other techniques such as planetary-transits or gravitational lensing (credit: Daniel Apai).
formed from fragmenting molecular cloud cores near VLM stars are also very unlikely. Two exceptions are 2M 1207A, a brown dwarf with a bound $\sim 5-10$ Jupiter mass companion (2M1207B; Chauvin et al., 2004, 2005; Subhanjoy et al., 2007) and Ophiuchus 11A, a brown dwarf with an 8-19 Jupiter mass companion (Ophiuchus 11B; Close et al., 2007). These two systems demonstrate that several-Jupiter-mass planets are possible, however, around low-mass substellar objects.
6.4.0.4 The Evolution of Circumstellar Disks - Grain Growth and Collisions But all is not lost. Several indirect planet detection techniques, led by radial velocity, transiting, and microlensing studies, have now led to evidence for 223 extrasolar gas giant planets in 183 systems. While mid-infrared excess disk studies have not directly identified planets, these debris disk studies offer potentially indirect signposts of terrestrial planetary systems. Our results from Chapter 5 are consistent with the hypothesis of grain growth and dust settling occuring in the inner disk regions ( $\lesssim 0.2 \mathrm{AU}$ ) early in the T Tauri stage (less than $\sim 1 \mathrm{Myr}$ ). Results from Chapter 4 point to the ejecta from larger planetesimal collisions experiencing collisional cascades around most solar-like stars (in regions $\sim 1-5 \mathrm{AU}$ away). Together, these results are consistent with models predicting that planetesimals form through agglomeration and over time collide with other planetesimals. Hence the detection of heated dust infers at minimum the presence of planetesimal parent bodies slightly larger than those inferred from mid-infrared detection - perhaps a few hundred microns.

The origin of the collisional cascades may very well be linked to the presence of planets. Kenyon \& Bromley (2005) argue that the collisional cascades themselves may be initiated by gravitational perturbations sufficiently large to stir up a planetesimal belt. The perturbations may originate from the effect Mars-sized objects have on other objects within the same annular region or from a massive
collision with another similar-sized or larger object (like the Earth-Moon formation; Strom et al., 2005). An even larger perturbation may occur as a result of gas giant migration as that proposed to have initiated the Late Heavy Bombardment in our own Solar System. The simulations of Gomes et al. (2005) attribute the migration of giant planets to destabilizing the Kuiper and Asteroid belts causing a massive delivery of planetesimals to the inner Solar System.

### 6.5 Future Directions

Along with defining dark matter and dark energy, I believe the quest to learn about extrasolar planets - their frequency and characteristics, their formation mechanisms, and their possibilities of harboring life - are the key challenges in modern astronomy. More than 180 planetary systems have now been discovered through ground-based observations. Despite such success, our knowledge of other planetary systems is still very rudimentary, largely dominated by the instrumental biases of the radial velocity technique - indirect detection of mostly gas giants orbiting their stars at distances much less than 6 AU.

Just as our comprehension of the Cosmos improved when Galileo picked up a spyglass, the next big steps forward will come when we will commit to building even larger aperture mirrors both on the ground and in space. However, no single instrument or technique is capable of finding all planetary system components around stars of all ages. Instead, I believe our understanding of other planetary systems will require an integrated suite of ground- and space-based missions that will use complementary instrumentation and techniques to explore the majority of planetary-discovery-phase space. Four fundamental techniques will be used to determine the architecture of planetary systems: radial velocity measurements, astrometry, transit observations, and direct imaging.

Characterizing the frequency and distribution of planets will begin with broadening our understanding of the distribution and properties of gas giant planets. Over the next 5 years, ground-based imaging will continue making advances in probing lower-mass and more-widely-separated gas giants. Interferometers such as the Keck Interferometer (KI), Very Large Telescope Interferometer (VLTI), and Large Binocular Telecope Interferometer (LBTI) will probe new planetary phase spaces with high-spatial-resolution and high-contrast-nulling imaging along with high-precision astrometry of the nearest stars. AO imagery from these ground-based telescopes as well as new "extreme" AO planet finder coronagraphic instruments coming on line such as the Gemini Planet Imager and the ESO Sphere will image young Jupiters directly. We will finally have spectral observations of these giant planets which will help us understand their chemical composition and physical structure. Collectively, these observations will determine the abundance of gas giants and the relationship between stellar properties (eg mass, metallicity, and binarity) with the properties of their giant planets (eg. mass and orbital parameters) for the nearest planetary systems.

Our own research studying stellar (and substellar) multiplicity will benefit from these advancements improving investigations in both separation and dynamic range space. With the benefits provided by LGS AO, we have just begun targeting young, VLM stars building support for the important effects of kinematic interactions on the evolution of binary properties. There may even be some headway into the effect the environment plays in the evolution of these properties as more VLM stars and brown dwarfs are investigated in young star-forming regions. My research of circumstellar disks will largely benefit with a larger sample of better resolved systems as these new telescopes (including the Atacama Large Millimeter Array, scheduled for $\sim 2014$ ) are likely to reveal ripples and gaps in
debris disks that will help locate the presence of perturbing planets. In the process, the link between gas giants and debris disks may be empirically established. Spectral analysis of resolved disks may also indicate how and where dust grains are processed within disks.

The large ground-based telescopes will set the stage for more advanced telescope searches in space. In the following decade, the James Webb Space Telescope (JWST) with a 6 m aperture mirror, will use enhanced mid-infrared sensitivity and angular resolution to continue studying planetary debris disks with a 6.5fold improvement in angular resolution over Spitzer's. While JWST will not be capable of detecting 5 Gyr old Jupiters at 5 AU , its near and mid-infrared cameras may find young Jupiters around nearby young stars. Around the nearest main sequence stars, JWST may even detect directly a handful of old, cold Jupiters.

The detection of terrestrial planets, where we believe life has the best chance of commencing and evolving, will have to await, however, for future space-borne telescopes (Figure 6.2). Transiting and astrometric surveys, free of the Earth's atmosphere, with sufficient sensitivity, will be capable of detecting Earth-mass planets (eg. COROT and Kepler, 100 ppm at $5 \sigma$ and Space Interferometer Mission PlanetQuest (SIM PlanetQuest, $1 \mu \mathrm{mas}$ ), respectively). Their direct detection and spectral analysis, however, will require unprecedented dynamic range ( $10^{-10}$ in the visible) and angular resolution (better than 50 mas ), enabling the first studies of the planetary atmospheres and habitability of other worlds (eg. Terrestrial Planet Finder).

So we end as we have begun, the key to solving astronomy's next unsolved secrets will rely on advanced technologies. I look forward to the next chapter of my own career where I hope to play a role defining and prioritizing the next gen-


Figure 6.2 Several NASA slated ground and space missions targeting the direct imaging of extrasolar planets (Source: NASA).
eration of astronomy objectives and planning their subsequent space missions.

## Appendix A

## Literature Stars Inconsistent with Membership in Cluster IC 2391

The following sources are classified in the literature as possible or probable cluster members, but we conclude from this investigation that their properties are inconsistent with membership.

## VXR PSPC 31

Source at $084111.0-523146.0$ is 0.47 mag below IC 2391 single-star sequence in Figure 4.2. In addition, both the Tycho-2 and UCAC2 proper motions exclude it as a member with high significance ( $\chi^{2} / \nu \simeq 42 / 2$ ). In addition, colors and spectral type indicate evidence of reddening which is inconsistent with the overall cluster reddening. Despite evidence of youth (Randich et al., 2001), the source is likely to be a young background object rather than a cluster member.

## HD 74517

Tycho-2 proper motion is well-constrained but largely inconsistent with the Robichon et al. (1999) cluster mean $\left(\chi^{2} / \nu \simeq 320 / 2\right)$. The nearly zero proper motion suggests that the source is likely to be an interloping A star rather than a cluster member.

## HD 74665

The proper motion is known to high accuracy and the Hipparcos, Tycho-2, and UCAC2 proper motions exclude the star as a kinematic member: ( $\chi^{2} / \nu \simeq 115 / 2$, $81 / 2,107 / 2$, respectively). Source is likely an interloping A star rather than a cluster member.

## Appendix B

## Comments on Debris Disk Evolution in Individual Open Clusters

## Scorpius-Centaurus OB association ( $16-17 \mathrm{Myr}, 132 \pm 14 \mathrm{pc}$ )

Chen et al. (2005) have described a survey for excesses in this association's two oldest subgroups, Upper Centaurus Lupus ( $\sim 17 \mathrm{Myr}$ ) and Lower Centaurus Crux ( $\sim 16 \mathrm{Myr}$ ). Initial results show a $24 \mu \mathrm{~m}$ excess frequency of $\sim 40 \%(14 / 35$ using a relative excess threshold $\geq 1.15$, private communication Christine Chen). Chen et al. state that the frequency could potentially be $40 \%$ higher if presumed interlopers are identified and removed from their proper motion selected sample. The large reported upper error bar in Table ?? is due to basing the uncertainty on this possible contamination. Age estimates are from Mamajek et al. (2004); distance is reported as typical stellar distances from the 3 subgroups (Chen et al., 2005).

Regarding the A-type stars in Upper Centaurus Lupus observed at $24 \mu \mathrm{~m}$ with Spitzer by Su et al. (2006), we used a 15\% threshold in determining the number of excess sources so as to be consistent in our treatment of all the surveys. Su et al. (2006), however, with improved photometry and Kurucz photospheric model fitting have reduced the threshold to $6 \%$ for the Spitzer A-type stars in their sample. Consequently, they measure an excess frequency of $56 \%(9 / 16)$ rather than the $44 \%(7 / 16)$ we report in Table 4.4 and shown in Figure 4.5.

NGC 2547 ( $\mathbf{3 0} \pm \mathbf{5} \mathbf{~ M y r , ~} \mathbf{4 5 0} \pm \mathbf{4 5} \mathbf{~ p c}$ )
Using the Pleiades photospheric locus as the relative excess threshold and a larger list of cluster members, Gorlova et al. (in prep) have improved upon the number of sources with $24 \mu \mathrm{~m}$ detections from Young et al. (2004) to now include F stars. M47 ( $80 \pm 20 \mathrm{Myr}, 450 \pm 50 \mathrm{pc}$ )

The scatter of the $K_{s}-[24]$ color for FGK stars is relatively large with some sources appearing blue-ward of the Pleiades photospheric locus. While there were both F and G stars detected in the $24 \mu \mathrm{~m}$ investigation of M47 (Gorlova et al., 2004), the photometry was obtained during the Spitzer early checkout period during telescope commissioning and data analysis techniques were still being optimized. Consequently, identifying excess sources among the FGK stars with a $15 \%$ threshold cannot yet be done with great confidence and hence we do not use the cluster in our evolution analysis of FGK disk frequencies.

While we do not utilize the photometry of the solar-like stars in determining a debris disk frequency, we include M47 data in the excess ratio evolution (Figure 4.7) since we are interested in the range of excesses rather than the frequency. Hyades $(625 \pm 50 \mathrm{Myr}, 46.3 \pm 0.3 \mathrm{pc})$

We include unpublished preliminary MIPS $/ 24 \mu$ m results of the 625 Myr Hyades open cluster (conference poster; Cieza, Cochran, \& Paulson, 2005) who report no sources with excess ratios clearly above $\sim 25 \%$. At the $15 \%$ level, there is evidence for one borderline excess source from a re-reduction of the public Hyades $24 \mu \mathrm{~m}$ data during this investigation. Age estimate is from Perryman et al. (1998).

## Pleiades ( $\mathbf{1 1 5} \pm \mathbf{2 0}$ Myr, $\mathbf{1 3 5} \pm \mathbf{3 p c})$

Fifty-three members of the Pleiades with spectral types between B8 to K6 have been analyzed by Stauffer et al. (2005) and Gorlova et al. (2006) identifying five with evidence of debris disks. References for cluster age and distance are taken from those within Gorlova et al. (2006).

## Field stars

Targeting 69 older, nearby field solar-type stars with median age $\sim 4$ Gyr, Bryden et al. (2006) only found 2 objects with $24 \mu$ m excess $\geq 15 \%$ above the photosphere.

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[^0]:    ${ }^{1}$ The sampling source may be the science target when it is sufficiently bright. Otherwise, a bright nearby star may suffice. Chapter III deals with the case when neither option is sufficient

[^1]:    and laser beacons are required.
    ${ }^{2}$ Imperfect corrections are also due to non-common path errors within the optical train leading to dynamic, scattered light appearing at the focal plane, also known as super speckles. Super speckles actually also limit the detection of faint objects at close angular separations. We discuss this further in Chapter II.

[^2]:    ${ }^{3}$ The ratio between the masses of the individual binaries; ratio is never greater than 1 .

[^3]:    ${ }^{4} 82$ Moon masses per Earth mass.

[^4]:    ${ }^{1}$ http://www.eso.org/instruments/naco/inst/naos.html
    ${ }^{2}$ Generally defined as objects with spectral types later than M6 (T ${ }_{\text {eff }} \lesssim 2700$ K); Kirkpatrick, Henry, \& Simons (1995); Dahn et al. (2002).

[^5]:    ${ }^{3}$ IRAF is distributed by the NOAO, which is operated by the AURA, Inc., under cooperative agreement with the NSF.

[^6]:    ${ }^{4}$ See also Cruz et al. (2004); Burgasser et al. (2005); Liu et al. (2006); Reid et al. (2006).

[^7]:    ${ }^{5}$ The Archive lists all the VLM binary systems reported in refereed journals, defined as binaries with total estimated mass less than $\sim 0.2 \mathrm{M}_{\odot}$. This mass limit is arbitrary and corresponds to binary M6 field dwarfs (slightly earlier spectral types for younger objects). The website is maintained by Nick Siegler at http:/ / paperclip.as.arizona.edu/ ~nsiegler/VLM binaries

[^8]:    ${ }^{1}$ http://www.nofs.navy.mil/data/fchpix
    ${ }^{2}$ for catalog details and references see http:/ /www.nofs.navy.mil/nomad/nomad readme.html

[^9]:    ${ }^{3}\left(\mu_{\alpha} \cos \delta=-25.06 \pm 0.25 \mathrm{mas} / \mathrm{yr}, \mu_{\delta}=22.7 \pm 0.22 \mathrm{mas} / \mathrm{yr}\right.$; Robichon et al., 1999)

[^10]:    ${ }^{4}$ http://www.noao.edu/noao/staff/cprosser

[^11]:    ${ }^{\text {a }}$ SB: spectroscopic binary, SB1: single-line spectroscopic binary, SB2: double-line spectroscopic binary.
    ${ }^{\mathrm{b}}$ VXR: Patten \& Simon (1996), SHJM: Stauffer et al. (1989), PP: Patten \& Pavlovsky (1999)
    ${ }^{c}\left(K_{s}\right)_{2 M A S S}$ derived from $\left(K_{s}\right)_{\text {Denis }}$ and $\left(\mathrm{J}-K_{s}\right)_{\text {Denis }}$ using the Carpenter (2001) transformation relation.
    ${ }^{\mathrm{d}}$ X-ray measurements from Patten \& Simon (1996) include emission from both ID 7 and 8
    ${ }^{e}$ Li abundance potentially inconsistent with membership; see discussion in §5.3.6
    ${ }^{\mathrm{f}}$ The reported 2 MASS $\mathrm{K}_{s}$ photometry is flagged due to saturation. We do not include this source in any of the figures using $\mathrm{K}_{s}$ nor is it included in the excess frequency calculations due to its early spectral type.

[^12]:    ${ }^{\text {a }}$ Ratio of observed $24 \mu \mathrm{~m}$ flux density to the predicted photospheric flux density at $24 \mu \mathrm{~m}$.
    ${ }^{\mathrm{b}}$ Upper limits; the $24 \mu \mathrm{~m}$ and $70 \mu \mathrm{~m}$ mosaicks cover slightly different areas of the sky and hence some $24 \mu \mathrm{~m}$ detections do not have $70 \mu \mathrm{~m}$ upper limit measurements.
    ${ }^{\mathrm{c}}\left(K_{s}\right)_{2 M A S S}$ derived from $\left(K_{s}\right)_{\text {Denis }}$ and $\left(\mathrm{J}-K_{s}\right)_{\text {Denis }}$ using the Carpenter (2001) transformation relation.
    ${ }^{d}$ The reported 2 MASS $K_{s}$ photometry is flagged due to saturation. We do not include this source in any of the figures using $\mathrm{K}_{s}$.

[^13]:    ${ }^{5}$ http:/ /irsa.ipac.caltech.edu/applications/2MASS/IM/

[^14]:    ${ }^{1}$ In the case of IC 2395, we calculated the median colors from only the sources with [5.8] brighter than 13.6 mag so as to be consistent with the other samples. Uncertainties, especially for the longer IRAC color are higher due to a larger population of fainter objects whose membership is not yet confirmed.

