SEARCHING THE SOLAR NEIGHBORHOOD FOR PROTOPLANETARY DEBRIS DISKS: A SURVEY OF VEGA-LIKE SOURCES AND A DISCUSSION OF NEW DISK EXAMPLES

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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2001
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by

Robert Scott Fisher
This work is dedicated to my fellow inhabitants of 317, 135, 8, 2613, 139, and 1072A.
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Searching the Solar Neighborhood for Protoplanetary Debris Disks: A Survey of Vega-Like Sources and a Discussion of New Disk Examples

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Chairman: Charles M. Telesco
Major Department: Astronomy

Theory suggests that planets form in the dusty circumstellar disks associated with young stars. Many classes of stars exhibit excess infrared emission that is attributed to the dust grains in these disks. In this dissertation we present mid-IR (10 and 18 μm) imaging observations of a sample of almost forty Vega-like stars. These are stars that have mostly finished their pre-main-sequence evolution and are now close to, or already on the main sequence. Our imaging shows that most of these sources are unresolved at arcsecond resolution at 10 and 18 μm. We did however make the first detection of extended mid-IR emission for two stars; HD 141569 and HD 169142. We use our observations to investigate the properties of the mid-IR-emitting dust grains in these two resolved disks, and the unresolved disks of 22 of the survey sources using radiative equilibrium models. The results of our modeling show that the mid-IR emission from these disks traces the
position of grains that are 1 to 10 μm in diameter in the disks of these stars. The mid-IR-emitting grains orbit the stars at distances of tens of AU, similar to the size of the Solar system, and therefore trace the region of assumed planetary formation in these disks. Additionally, we place the survey stars into the H-R diagram, and use the characteristics of their infrared excess in conjunction with their positions to suggest a proposed evolutionary sequence for them. Finally, discuss the development, characterization, and support of the OSCIR camera system that was a fundamental aspect of the work presented in this dissertation.
CHAPTER 1
INTRODUCTION

This dissertation focuses on the study of circumstellar disks around main-sequence stars. The most fundamental question one can ask is, why is the study of disks important? There are two facets to the answer to that question. The first deals with star formation and the evolution of stellar objects during the initial stages of their lives. Current theories of star formation like that of Andre (1994) suggest that the formation of a circumstellar disk is necessary for the successful formation of a low or intermediate mass \((M < \sim 5 \, M_\odot)\) star. In this context, circumstellar disks are just one of a myriad of supporting players in the process of star formation, but an important one. The disks dissipate angular momentum from the system while bi-polar outflows remove excess gas and dust from the close stellar environment in the first few million years of its life. With the relative explosion of observations of circumstellar disks in the last 10 years, they now seem ubiquitous. Also important is the fact that planetary systems form from these disks. With the recent discovery of numerous exo-solar planets and planetary systems (Marcy and Butler 1996), understanding the formation and evolution of circumstellar disks is more important than ever. The research presented in this dissertation relates more to the second facet presented above. Our research is centered on the study of circumstellar disks around stars that are either in the very last stages of their pre-main-sequence (PMS) formation, or have already moved onto (or past) the zero-age-main-sequence (ZAMS) in the H-R diagram. These disks are the so-called “Vega-like,” or debris disks.
Figure 1-1: The spectral energy distribution (SED) of Vega. Solid line is a model atmosphere. Dotted line is a modified blackbody fit to the data with $T=73$ K and $Q(\lambda) \propto \lambda^{-1.1}$ Flux estimates from ISOPHOT and IRAS. Submillimeter fluxes from Zuckerman and Becklin (1993). Figure from Heinrichsen et al. (1998)

The IRAS satellite discovered the “Vega phenomenon” in 1984 when it was performing what was thought to be routine calibration observations of the photometric standard star, Vega. The surprising result returned by IRAS was that at all $\lambda > 12 \mu$m Vega exhibited levels of emission that were several times higher than what was predicted by model stellar atmosphere calculations. In Figure 1-1 we plot the SED of Vega to show the shape and extent of this excess emission. This excess emission was attributed to emission from dust grains in the vicinity of the star, presumably in the form of a disk.

Three more examples of this phenomenon were quickly discovered: $\alpha$ PsA, $\beta$ Pictoris, and $\epsilon$ Eri; and together with Vega they became the archetypes for this class of object (Aumann et al. 1984). Smith and Terrile (1984) proved the disk hypothesis with their
coronagraphic image of β Pictoris, which showed a nearly edge-on disk ($i > 80^\circ$) around the star with dimensions of 100s of AU. The publication of this image jumpstarted the field and the study of Vega-like disks has become one of the most heavily researched aspects in modern astronomy; since 1984 there have been almost 1700 papers published with the name “Beta Pictoris” in the title.

Since planets are thought to form in the dusty environments around stars, there seems to be a growing consensus that the Vega phenomenon is intimately connected with the occurrence of planetary systems. Indeed, we live inside our own Vega-like disk, the so-called Zodiacal “cloud” disk around the Sun. Many of the characteristics of the Vega-like disks are similar to our own dust disk, including the fact that the lifetime of dust in orbit around the archetypes is much shorter than the estimated age of the central stars. This means that the dust must be replenished in some manner, which hints at the existence of hidden planetary companions in the disks that could supply the system with fresh dust much like comets and asteroidal collisions do in the Solar system. In the last few years evidence has been accumulating for the existence of exo-solar planets in some Vega-like disks. High-resolution STIS images have revealed a warp in the disk of β Pictoris (Heap et al. 1997), and subsequent near-IR (2 µm) observations confirm that warp exists and suggest that a planet with a $-3^\circ$ inclination could cause it (Mouillet et al. 1997). In the mid-IR (5 to 30 µm) the disk of HR 4796A has been imaged at $-0.3''$ resolution by Telesco et al. (2000), Jayawardhana et al. (1998), and Koerner et al. (1998) showing evidence for an inner hole of approximately Solar system dimensions.

Our motivation for this dissertation is to characterize a number of these Vega-like disks in the mid-IR. To this end we used a modern mid-infrared camera system with large
aperture telescopes to conduct a survey of nearly 40 Vega-like stars in the mid-IR (10 and 18 μm). In the following chapters we discuss our survey results, and place the observed Vega-like sources into an evolutionary sequence. We also discuss two new disk examples that we resolved in the mid-IR for the first time.

In the remainder of this chapter we summarize the current paradigm of low and intermediate mass star formation and see that the formation of a circumstellar disk is most likely a requisite step in the process. We then contrast the disks we see around Vega-like stars with those around stars in earlier stages of formation, like the Herbig Ae/Be stars. We end the chapter with a statement of the dissertation project and list what we hope to add to the current status of Vega-like disk research.

**Star Formation and Disk Creation**

The formation of stars is the main way that material is removed from the interstellar medium. Star formation is also one of the main topics of study in modern infrared astronomy. The very first stage of star formation takes place in the cores of giant molecular clouds (GMCs). The evidence that star formation occurs in these clouds is strong. First and foremost, direct observation easily correlates regions of star formation with dark clouds in the sky, for example in the constellations of Taurus and Ophiuchus. Since the newly formed stars are by definition young, we believe that they have not yet had sufficient time to move away from their birthplaces. Additional evidence comes in the form of the correlation between the youngest stars known and the presence of molecular CO emission (Churchwell 1991). In fact, Churchwell (1991) shows that there is no place in the galaxy where active star formation is occurring where there is not
significant CO emission. Since CO is a major constituent of molecular clouds, it seems very reasonable to think that stars form out of the material in these GMCs. The earliest stage of the formation of a star is the fragmentation and collapse of part of a GMC. The passing of a galactic spiral density wave, or a close encounter with a nearby star may trigger the collapse. Whatever the trigger, the process of star formation is underway when a fragment of approximately $10^4$ AU “breaks-off” from the main cloud and starts its collapse. The luminosity associated with these “protostars” is at first derived from the gravitational energy associated with this collapse. At some point in this process there is enough luminosity associated with the protostar that it can be observed directly. We begin our more detailed discussion of star formation at this point following the work of Lada (1987) and Andre et al. (1993).

In Figure 1-2 we show the different stages in the evolutionary sequence of young stellar objects. On the right side of the figure there is a model spectral-energy-distribution (SED) of the source. The middle panels show a sketch of the system, and the left side lists relevant masses and timescales for each Class. A Class 0 source is the earliest observable stage of star formation. Class 0 sources are only visible in the millimeter regime or through the detection of CO spectrally. The dust shells surrounding these sources are still so dense they are optically thick to even mid and far-IR radiation. Because collimated CO outflows are often associated with Class 0 sources, it is believed that a centralized core has formed by this stage and that matter from the surrounding shell is actively accreting onto it. At this stage the shell is likely still more massive than the protostar at its core.
The flow of matter onto the protostar continues unabated past the transition into the Class I phase, which occurs on timescales of $\sim 10^5$ yr. At this point the formation of the protostar is almost complete, and it is now detectable through the infrared, down to perhaps 2 $\mu$m. There are still collimated outflows of molecular gas, for example CO, associated with Class I objects indicating that the inner regions of the shell are still being
accreted onto the protostar. The amount of material around the star is still large, upwards of 0.1 M\(_{\odot}\). Class I objects are also normally associated with extended millimeter continuum emission. Some form of disk has likely formed around the protostar at this stage.

By the time the system becomes a Class II source the millimeter continuum has become much more compact, and there is rarely any evidence for outflows associated with the source. The age of the system is now \(\sim 10^6\) yr and the mass of the optically thick disks associated with these sources is close to the minimum mass Solar nebula, \(\sim 0.01\) M\(_{\odot}\). At this stage the SED of the source is beginning to resemble that of a Herbig Ae/Be star with strong excess emission detected down to 2 \(\mu\)m or less. This is relevant to our work since it is believed that the Herbig Ae/Be stars are the progenitors of the Vega-like stars that we study in this dissertation. Indeed, some of the SEDs of our survey sources resemble those of the Class II objects shown in Figure 1-2, although most of our sources are clearly Class III, or later.

The Class III stars have thin disks associated with them and their SEDs are approaching those of normal stars. Depending on the mass of the star, Class III is reached in the few \(\times 10^6\) yr timescale. In this stage there is little evidence for active accretion onto the star and absorption lines are often seen in the spectra of these sources. The mass of the disks around Class III stars is low: around 0.003 M\(_{\odot}\); much less than that in Class II or earlier. It is around Class III sources that you find Vega-like disks. This connection between a Class III and a Vega-like source is beautifully illustrated by comparing the SED of the Class III source in Figure 1-2 with the SED of Vega in Figure 1-1.
Evolutionary Status of Vega-like Disks

As seen in the last section the Vega-like sources most resemble stars in the last stages of star formation. To more clearly define what a “Vega-like” system is we use the definition suggested by Lagrange et al. (2000). In their review they suggest the following criteria for defining a Vega-like system

- \( \frac{L_{\text{dust}}}{L_*} \ll 1 \)
- \( M_{(\text{dust+gas})} \ll 0.01 M_\odot \)
- Dust dynamics not controlled by gas ; \( M_{\text{gas}} \ll 10 M_{\text{dust}} \)
- grain destruction times less than age of star

The first criteria is set to make sure that a massive protostellar disk is not present around the star. Criteria 2 guarantees that the circumstellar material is optically thin. Criteria 3 makes sure that the dust is separated from any remnant gas left in the system and that the motion of the dust grains are Keplerian modified by radiative processes. This should exclude systems where dust is condensing in winds and jets. Criteria 4 that is crucial to the definition because it ensures that the dust around the source is not primordial. That is, the grains have been processed within the disk. It implies that the dust grains must be somehow replenished from larger objects. This is important since it implies that larger grains are present, and also hints at the existence of even larger, planetesimal sized bodies capable of sending the smaller bodies into collision-producing orbits (Lagrange et al. 2000).

There is also some issue with the name “main-sequence” being an integral part of the definition of a Vega-like system. The definition of Lagrange et al. (2000) above defines the class in terms of the physical state of the circumstellar matter, not the exact evolutionary state of the central star. The star itself may or may not have reached the
Table 1-1: Resolved Vega-like Disks

<table>
<thead>
<tr>
<th>Source Name</th>
<th>D(pc)</th>
<th>Spectral Type</th>
<th>Age (yr)</th>
<th>Disk Radius at Given Wavelength (AU)</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5 µm</td>
</tr>
<tr>
<td>ε Eri</td>
<td>3.2</td>
<td>K2V</td>
<td>(5-10)x10^8</td>
<td>--</td>
</tr>
<tr>
<td>α PsA</td>
<td>7.7</td>
<td>A3V</td>
<td>1-3x10^8</td>
<td>--</td>
</tr>
<tr>
<td>α Lyr</td>
<td>7.8</td>
<td>A0V</td>
<td>3x10^8</td>
<td>--</td>
</tr>
<tr>
<td>β Pictoris</td>
<td>19.3</td>
<td>A5V</td>
<td>1-2x10^7</td>
<td>800</td>
</tr>
<tr>
<td>HR 4796A</td>
<td>67.0</td>
<td>A5V</td>
<td>(8±3)x10^6</td>
<td>--</td>
</tr>
<tr>
<td>HD 141569</td>
<td>99.0</td>
<td>B9V</td>
<td>1x10^7</td>
<td>--</td>
</tr>
<tr>
<td>HD 169142</td>
<td>145.0</td>
<td>A5V</td>
<td>(3-5)x10^6</td>
<td>--</td>
</tr>
<tr>
<td>BC+31°643</td>
<td>330.0</td>
<td>B5V</td>
<td>10^6-10^7</td>
<td>&gt;1000</td>
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</tbody>
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† Estimates from this dissertation
‡ OSCIR estimate, see Telesco et al. (2000)

main sequence by the time its disk meets the above criteria. This is relevant to this dissertation since we have investigated a number of stars that seem to be transitioning from Class II to Class III. While the stars may not yet have reached the ZAMS, they clearly exhibit characteristics reminiscent of main-sequence stars. Lagrange et al. (2000) coined the term ‘old pre-main-sequence’ stars (OPMS) to describe these sources. They are an interesting class of object since they represent the transition between the pre-main-sequence stars of the star forming regions, and the main-sequence stars in the solar neighborhood.

Because the Vega-like disks are optically thin, tenuous structures, they are very difficult to detect. In the 17 years since Smith and Terrile (1984) published their watershed image of β Pictoris only seven other Vega-like disks have been directly imaged. In Table 1-1 we list the Vega-like disks that have been resolved at any wavelength. This is however, rapidly changing. New instruments coupled with large aperture telescopes are giving us the opportunity to detect more of these disks than ever before. This is made evident by the fact that 12 of the 14 size estimates in Table 1-1 have
been published in the last 4 years. In particular the latest generation of near and mid-IR instruments allows us to investigate this class of object as never before. The sub-arcsecond angular resolution achieved by the 8 to 10 m class telescopes lets us see down to a few AU from the stars in the closer of the sample sources, and the sensitivities of the latest generation mid-IR cameras give us the chance to detect fainter extended emission from these disks than ever before. This is one of the motivating factors behind this dissertation, to use the latest generation of infrared camera systems on the largest aperture telescopes to investigate the class of Vega-like source as a whole.

This work is unique in one important way. Investigating these disks in the mid-IR directly probes the region where planetary systems form in them. This work is complementary to research done in the near-IR, sub-mm, and mm regimes. At the longer wavelengths we are detecting the coldest dust in the systems, which has temperatures in the tens of Kelvin range. This cold dust also orbits hundreds of AU from the stars, much farther away than any known planetary companions. At the shorter wavelengths, the near-IR, we detect two different kinds of radiation. Some sources exhibit thermal emission from hot dust ($T = 1$ to 2000 K) very close (1 to 3 AU) to the stars (e.g., HD 169142; Chapter 4). Others like HD 141569 (Weinberger et al. 1999) and β Pictoris (Kalas & Jewitt 1995) are associated with near-IR radiation that is scattered from the dust in their disks. This scattered radiation is seen out to hundreds of AU in these two cases and is likely being scattered off the dust grains that are responsible for the far-IR/sub-mm/mm emission detected around these systems. The mid-IR forms a bridge between these two regimes. It can be said that the long wavelength emission comes from the “Kupier belts” and perhaps “Oort clouds” of the Vega-like sources, while the near-IR emission comes...
from the very inner parts of their disks. In this scheme the mid-IR emission would come from the Zodiacal dust of the Vega-like systems, most likely tracing the region where planets are forming, exactly where they formed in our own Solar System. For this reason these disks are important to study, for by answering questions about them as a class, we may well be able to answer outstanding questions about the formation and evolution of our own Earth. In the next section we outline the work presented here.

Outline of the Project

This dissertation is centered on mid-IR (10 and 18 μm) imaging of a large sample of Vega-like stars. We undertook this project with the hoping to characterize a number of disks at these wavelengths, and we succeeded by making the first detection of extended mid-IR emission around two stars, HD 141569 and HD 169142. We did not detect any extension around the remainder of the survey sample.

In Chapter 2 we discuss our sample, our observations of the survey sources, and the data reduction steps we used. Chapter 3 presents our conclusions about the survey as a whole and we place our sample sources into what may be an evolutionary sequence. In Chapter 4 we discuss the newly discovered disk around the star HD 169142, and investigate the properties of the dust in that disk through radiative equilibrium models. We present similar results for HD 141569 in Chapter 5. For HD 141569 we derive grain size estimates for the mid-IR-emitting grains, and compare our mid-IR images of this disk to near-IR images from HST. In Chapter 6 we present observations that "de"-resolve the source SAO 26804, a star previously thought to be associated with a Vega-like disk. We show that it is likely that SAO 26804 is a luminosity Class III star and not on the
main sequence. Chapter 7 discusses the OSCIR instrument and its role in this dissertation. We close with an Appendix on mid-IR observing and discuss the specialized techniques used in that wavelength regime.
CHAPTER 2
OBSERVATIONS AND DATA REDUCTION

We have used front-line infrared instrumentation and large aperture telescopes to survey approximately 40 Vega-like sources in the northern and southern sky. Most of the survey was conducted at the Blanco 4-meter telescope at the Cerro Tololo Inter-American Observatory (CTIO). Parts of the survey were also conducted at the NASA Infrared Telescope Facility (IRTF) and the W. M. Keck Observatory (Keck). The project centered on imaging each of the survey sources at 10 and 18 μm using the Observatory Spectrometer and Camera for the Infrared (OSCIR). The OSCIR system is discussed in detail in Chapter 7. For most of the sources our images are the first mid-IR observations of them since those of the IRAS satellite. A literature search for other mid-IR observations of our survey sources returned only two further studies. Fajardo-Acosta, Telesco, and Knacke (1993) imaged five of the sources at ~4” resolution, and Sylvester et al. (1996) presented mid-IR spectra of a dozen of the sources on our list. A small number of our sources have questionable classification, and have been included in studies of Herbig Ae/Be stars also. In particular, the studies of van den Ancker et al. (1998) and van den Ancker (2001) contain members of our sample. Although the stars in our survey have been studied in other wavelength regimes, our mid-IR imaging here represents the highest resolution mapping of these sources to date. Our observations typically have sub-arcsecond resolution limits with some as low as 0.3”. At the average distance of our survey stars (77 pc) at these resolutions we are tracing emission from dust that is tens of AUs from the star, a region where planetary systems are born and evolve. We cannot yet
directly detect any planets around these stars. However, we can detect the effects of hidden planets on the disks they inhabit. An example of this idea is the inner holes predicted by the SEDs of some of the sources. An inner hole with a diameter of approximately 50 AU was predicted in the disk of HR 4796A by Jura et al. (1998) and was then directly imaged by Jayawardhana et al. (1998), Koerner et al. (1998) and Telesco et al. (2000). Observing our survey sources in two mid-IR passbands also gives us the opportunity to investigate the physical properties of the mid-IR-emitting grains in these disks. Our 10 and 18 μm observations let us estimate the temperature of the grains; and investigate their composition, size and distance from the stars. We also comment on the dynamical properties of the grains and discuss the roles of Poynting-Robertson drag and radiation expulsion on the evolution of the grains. In the next sections we discuss or sample stars and describe how we reduced the data.

Source Lists

Our primary source list is that of Walker and Wolstencroft (1988) [hereafter WW]. One of the first searches of the IRAS database after the discovery of the four archetypes, WW is one of the primary lists of Vega-like sources used today. WW present a list of 34 sources that have characteristics similar to Vega and the other archetypes. Their selection criteria are shown below.

1. Sources must be associated with bright visual sources (SAO stars), but not with a well-known emission-line star.
2. Sources must have a 60 μm/100 μm flux density ratio similar to that of the prototypes. The range of the accepted ratios corresponds to black body temperatures of the dust from 60 to 150 K.
3. Sources must show evidence for extension in one of more of the IRAS bands in the IRAS Working Survey Database.
The 34 sources that met these criteria were separated by WW into four categories: the prototypes, section A, section B, and those associated with objects in the Gliese catalog. The prototypes are exactly that: α Lyra, α PsA, ε Eri, and β Pictoris. Section A contained the best candidates for disks similar to the prototypes. Sources were relegated to Section B if there was evidence for mass-loss or emission characteristics in their spectra. The sources associated with the Gliese catalog were separated from the others since they were not stringently required to meet Criteria #3, however, most of them were flagged as extended in the IRAS database. All of the sources in the Gliese category are also on the Vega-like list of Aumann (1985). WW calculated temperatures for the dust using the IRAS 25 and 60 μm fluxes to fit the dust emission with a blackbody curve. By using published B and V magnitudes to model the photosphere, WW plotted the SEDs of the sources. Their plots give us a first look at the amount of excess associated with each source, and we used them to help prioritize the sequence in which we observed the stars.

Our secondary lists are those of Sylvester et al. (1996) and Mannings and Barlow (1998). The Sylvester et al. (1996) list was particularly useful since their selection process was similar to what we had in mind for this project. They included objects on their list that maximized their chances of determining disk and grain parameters. Their sources are therefore bright in the infrared, relatively close to the Sun, and have large IR excesses associated with them. Their list contains a total of 24 sources, of which we observed 20 during our survey. The Sylvester et al. (1996) list does have some overlap with the WW list, with a total of 12 stars common to both. A useful facet of the Sylvester et al. (1996) research is that they presented mid-IR spectra for 11 of their sources taken with CGS3 on UKIRT. We used these spectra to help prioritize our observations, and to compare to our results on the disks of HD 141569 (Chapter 5) and HD 169142 (Chapter
4). The better defined SEDs of the star/disk systems in Sylvester et al. (1996) were also very useful in our source selection.

The third list we used to select our survey stars from is that of Mannings & Barlow (1998). Their method of source identification was based on the cross-correlation of the Michigan Catalog of Two-Dimensional Spectral Types with the IRAS Faint Source Survey Catalog. The Mannings and Barlow list contains some 60 new Vega-like sources not contained on either the Sylvester et al. (1996) or WW list. Our primary use of the Mannings and Barlow sample was to search for Vega-like stars at Southern declinations.

In the decade between the publication of the Walker and Wolstencroft (1988) paper and the Mannings and Barlow (1998) list, significant work was done on the spectral classification of the Vega-like stars. In 1988 some of the sources on the WW list are listed as luminosity Class I, III or IV, and a few had no luminosity classification at all. Mannings and Barlow (1998) note that today only about half of the sources on the WW list sources are known to be on the main sequence. At first glance this seems to have a negative effect on the completeness of our survey; however, this is not detrimental to our purposes. An important part of our research is to place these sources into an overall evolutionary sequence. To start to piece together that sequence we need to see these sources in all stages of their evolution. This includes the time immediately before, and the time just after they are on the main sequence. It is therefore not unreasonable to make observations of PMS objects and post-main-sequence objects that meet the criteria of the Vega-like surveys to fill in the gaps in this evolutionary sequence we are trying to construct. As we see in Chapter 3, it is the fact that we made observations of sources with questionable classifications, and varying amounts of IR excess that allows us to put together such a sequence for our survey stars.
The sources we observed for our survey are listed in Table 2-1. In total we observed 36 sources at both 10 and 18 μm. Three other sources were only observed in one filter because of poor observing conditions. In Table 2-1 we present which list the objects came from and see that in total we observed 25 sources from Walker and Wolstencroft (1988); 9 unique sources from Sylvester et al. (1996); and 4 sources from Mannings and Barlow. One star used as part of the survey, HR 4796A (HD 109573), was not present on any of our source lists. We also list the equatorial coordinates (J2000), and distance to each source as listed in the Hipparcos database. Only 5 of our sample stars do not have a Hipparcos measured parallax, and therefore distance. Values of (B-V) for each star from the Tycho catalogs are also listed. Using these newly measured distances for the sources allowed us to calculate absolute magnitudes for the stars, a requirement in setting up our evolutionary sequence presented in Chapter 3.

**Instrumentation**

We used the OSCIR camera system exclusively for the observations in this dissertation. OSCIR is a mid-IR camera/spectrometer system built and operated by the University of Florida Infrared Astrophysics Group. The camera is built around a 128 x 128 pixel Si:As blocked-impurity-band (BIB) detector from Rockwell/Boeing. Chapter 7 more fully discusses the role of OSCIR in this dissertation. As noted previously we collected data for this research on the IRTF, CTIO 4m, and Keck II telescopes. Because of the different apertures of the telescopes some important characteristics of OSCIR changed as we moved from site to site. Table 2-2 lists the parameters and their values on each telescope. The survey was conducted using the standard “chop/nod” technique with chop frequencies of a few Hz and chop throws in the range of 10” to 30.” Appendix A
Table 2-1: Survey source data.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Spectral Class</th>
<th>Distance (pc)</th>
<th>RA(^a) (2000)</th>
<th>DEC(^a) (2000)</th>
<th>M(_v)</th>
<th>(B-V)(^b)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 432</td>
<td>F2IV</td>
<td>17</td>
<td>00 09 10.6</td>
<td>+59 08 59.2</td>
<td>1.2</td>
<td>0.38</td>
<td>WW</td>
</tr>
<tr>
<td>HD 8538</td>
<td>A5IV</td>
<td>30</td>
<td>01 25 48.9</td>
<td>+60 14 07.0</td>
<td>0.2</td>
<td>0.16</td>
<td>WW</td>
</tr>
<tr>
<td>HD 9672</td>
<td>A1V</td>
<td>61</td>
<td>01 34 37.7</td>
<td>-15 40 34.8</td>
<td>1.7</td>
<td>0.07</td>
<td>WW</td>
</tr>
<tr>
<td>HD 16908</td>
<td>B3V</td>
<td>113</td>
<td>02 43 27.1</td>
<td>+27 42 25.7</td>
<td>-0.6</td>
<td>-0.12</td>
<td>Syl96</td>
</tr>
<tr>
<td>HD 17848</td>
<td>A2V</td>
<td>51</td>
<td>02 49 01.7</td>
<td>-62 38 23.5</td>
<td>1.7</td>
<td>0.10</td>
<td>MB</td>
</tr>
<tr>
<td>HD 20010</td>
<td>F8IV</td>
<td>14</td>
<td>03 12 04.5</td>
<td>-28 59 45.7</td>
<td>3.1</td>
<td>0.54</td>
<td>WW</td>
</tr>
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<td>HD 22049</td>
<td>K2V</td>
<td>3</td>
<td>03 32 55.8</td>
<td>-09 27 29.4</td>
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<td>0.88</td>
<td>WW</td>
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<tr>
<td>HD 27290</td>
<td>F0V</td>
<td>20</td>
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<td>-51 29 11.9</td>
<td>2.7</td>
<td>0.31</td>
<td>WW</td>
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<tr>
<td>HD 34282</td>
<td>A0V</td>
<td>164</td>
<td>05 16 00.4</td>
<td>-09 48 35.4</td>
<td>3.8</td>
<td>0.30</td>
<td>Syl96</td>
</tr>
<tr>
<td>HD 34700</td>
<td>G0</td>
<td>1162</td>
<td>05 19 41.4</td>
<td>+05 38 42.7</td>
<td>-1.2</td>
<td>0.57</td>
<td>WW</td>
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<tr>
<td>HD 35187</td>
<td>A2V</td>
<td>150</td>
<td>05 24 01.1</td>
<td>+24 57 37.5</td>
<td>1.9</td>
<td>0.28</td>
<td>WW</td>
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<tr>
<td>HD 38678</td>
<td>A2V</td>
<td>22</td>
<td>05 46 57.3</td>
<td>-14 49 19.0</td>
<td>1.9</td>
<td>0.10</td>
<td>MB</td>
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<tr>
<td>HD 39060</td>
<td>A5V</td>
<td>19</td>
<td>05 47 17.0</td>
<td>-51 04 03.5</td>
<td>2.4</td>
<td>0.17</td>
<td>WW</td>
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<tr>
<td>HD 49662</td>
<td>B7IV</td>
<td>186</td>
<td>06 48 57.7</td>
<td>-15 08 41.0</td>
<td>-1.0</td>
<td>-0.10</td>
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<td>HD 74956</td>
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<td>0.04</td>
<td>WW</td>
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<tr>
<td>HD 98800</td>
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<td>47</td>
<td>11 22 05.2</td>
<td>-24 46 39.7</td>
<td>5.5</td>
<td>1.15</td>
<td>WW</td>
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<tr>
<td>HD 101584</td>
<td>F0I</td>
<td>813</td>
<td>11 40 58.8</td>
<td>-55 34 25.8</td>
<td>-2.6</td>
<td>0.37</td>
<td>WW</td>
</tr>
<tr>
<td>HD 102647</td>
<td>A3V</td>
<td>11</td>
<td>11 49 03.5</td>
<td>-55 34 25.8</td>
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<td>0.09</td>
<td>WW</td>
</tr>
<tr>
<td>HD 104237</td>
<td>A0</td>
<td>116</td>
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<td>-78 11 34.5</td>
<td>1.3</td>
<td>0.24</td>
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<td>HD 109573</td>
<td>A0V</td>
<td>67</td>
<td>12 36 01.0</td>
<td>-39 52 10.1</td>
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<td>0.00</td>
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<tr>
<td>HD 123160</td>
<td>G5V</td>
<td>16*</td>
<td>14 06 12.8</td>
<td>-11 49 57.8</td>
<td>7.6</td>
<td>1.50</td>
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<tr>
<td>HD 135344</td>
<td>A0V</td>
<td>40</td>
<td>15 15 48.4</td>
<td>-37 09 16.2</td>
<td>5.6</td>
<td>0.53</td>
<td>WW</td>
</tr>
<tr>
<td>HD 139614</td>
<td>A7V</td>
<td>157*</td>
<td>15 40 46.3</td>
<td>-42 29 53.5</td>
<td>3.0</td>
<td>0.25</td>
<td>Syl96</td>
</tr>
<tr>
<td>HD 139664</td>
<td>F5V</td>
<td>18</td>
<td>15 41 11.3</td>
<td>-44 39 40.3</td>
<td>3.4</td>
<td>0.41</td>
<td>WW</td>
</tr>
<tr>
<td>HD 141569</td>
<td>B9V</td>
<td>99</td>
<td>15 49 57.7</td>
<td>-03 55 16.3</td>
<td>2.1</td>
<td>0.10</td>
<td>WW</td>
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<tr>
<td>HD 142165</td>
<td>B5V</td>
<td>127</td>
<td>15 53 53.9</td>
<td>-24 31 59.3</td>
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<td>-0.01</td>
<td>MB</td>
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<tr>
<td>HD 142666</td>
<td>A8V</td>
<td>114*</td>
<td>15 56 40.0</td>
<td>-22 01 40.0</td>
<td>3.5</td>
<td>0.55</td>
<td>Syl96</td>
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<tr>
<td>HD 143006</td>
<td>G6</td>
<td>94</td>
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<td>0.75</td>
<td>WW</td>
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<tr>
<td>HD 144432</td>
<td>A9V</td>
<td>253</td>
<td>16 06 57.9</td>
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<td>0.75</td>
<td>Syl96</td>
</tr>
<tr>
<td>HD 155826</td>
<td>F7V</td>
<td>31</td>
<td>17 45 52.7</td>
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<td>WW</td>
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<td>HD 158643</td>
<td>A0V</td>
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<td>HD 163296</td>
<td>A1V</td>
<td>122</td>
<td>17 56 21.2</td>
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<td>1.4</td>
<td>0.09</td>
<td>MB</td>
</tr>
<tr>
<td>HD 169142</td>
<td>A5V</td>
<td>145*</td>
<td>18 24 29.7</td>
<td>-29 46 49.3</td>
<td>1.9</td>
<td>0.29</td>
<td>WW</td>
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<tr>
<td>HD 172167</td>
<td>A0V</td>
<td>8</td>
<td>18 36 56.3</td>
<td>+38 47 01.2</td>
<td>0.0</td>
<td>0.00</td>
<td>WW</td>
</tr>
<tr>
<td>HD 188037</td>
<td>A2</td>
<td>229*</td>
<td>19 52 30.0</td>
<td>+22 27 14.2</td>
<td>1.2</td>
<td>0.90</td>
<td>WW</td>
</tr>
<tr>
<td>HD 207129</td>
<td>G0V</td>
<td>16</td>
<td>21 45 01.1</td>
<td>-47 31 55.8</td>
<td>4.6</td>
<td>0.60</td>
<td>WW</td>
</tr>
<tr>
<td>HD 216956</td>
<td>A3V</td>
<td>25</td>
<td>22 54 53.5</td>
<td>-29 53 15.7</td>
<td>1.7</td>
<td>0.15</td>
<td>WW</td>
</tr>
<tr>
<td>HD 218396</td>
<td>A5V</td>
<td>40</td>
<td>23 07 28.7</td>
<td>+21 08 03.3</td>
<td>3.0</td>
<td>0.46</td>
<td>Syl96</td>
</tr>
<tr>
<td>HD 233517‡</td>
<td>K2</td>
<td>---</td>
<td>08 22 46.7</td>
<td>-34 27 06.0</td>
<td>---</td>
<td>1.20</td>
<td>WW</td>
</tr>
</tbody>
</table>

\(^a\) Spectral classifications from Mannings & Barlow (1999).
\(^b\) Data taken directly from the Hipparcos and/or Tycho catalogs.
\(^\dagger\) Ambiguous distance and absolute magnitude, see Chapter 6
\(^*\) Distance from Walker & Wolstencroft (1988) or Sylvester et al. (1996)
Table 2-2: OSCIR/Telescope Characteristics

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Aperture (m)</th>
<th>Focal Ratio</th>
<th>OSCIR Platescale (arcsec)</th>
<th>OSCIR Field of View (arcsec)</th>
<th>Chop Throw (arcsec)</th>
<th>Chop Freq. (Hz)</th>
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</thead>
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<tr>
<td>IRTF</td>
<td>3</td>
<td>F/35</td>
<td>0.223</td>
<td>29</td>
<td>30</td>
<td>3-5</td>
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<td>CTIO</td>
<td>4</td>
<td>F/30</td>
<td>0.184</td>
<td>23</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Keck</td>
<td>10</td>
<td>F/40</td>
<td>0.062</td>
<td>8</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

gives a thorough explanation of these standard mid-IR observing techniques and more fully describes why these observational parameters were chosen.

During the planning stages of the survey we decided to observe all of the sources in a consistent manner, with follow-up observations made when warranted. For the survey observations, we made deep N ($\lambda_c = 10.8 \mu m$, $\Delta \lambda = 5.2 \mu m$) and IHW18 ($\lambda_c = 18.2 \mu m$, $\Delta \lambda = 1.7 \mu m$) integrations with exposure times ranging from 10 to 20 minutes of chopped-integration (5 to 10 minutes on-source) in each filter. Due to the inherent inefficiencies of chop/nod observing the elapsed time during an observation is approximately a factor of three longer than the on-source time. We felt that this exposure time allowed us to efficiently use the allocated telescope time while giving us a good chance to detect any extended emission associated with the survey sources. Given these integration times the possibility exists of faint extended emission around some of the survey stars that we did not detect. However, to keep our dataset consistent we observed all of the sources in a coherent manner. Next we describe our observational technique used for the survey observations.
Observational Strategy

Observations for this work were made over a period of three years at the above mentioned telescopes. We followed a set observing strategy for each of the observations made. When observing a science source we also made a series of observations in support of the actual data on the Vega-like source itself. The sequence of observations made is as follows

1. Observation of photometric flux calibrator
2. Observation of a nearby point-spread-function (PSF) star
3. Observation of the science source
4. Observation of the PSF star

There was normally no need to observe a 'pointing' star for these observations as all of our science sources are visually bright and easily detected with a 3 m class telescope. We attempted to start each Vega-like sequence with observations of a photometric standard at both 10.8 and 18.2 μm, however, due to time constraints this was not always possible. Since we were trying to determine if the science sources were resolved or not, the observations of the PSF star were as critical as those of the science source. As illustrated in Figure 2-3 our determination of whether or not a science source was resolved is based in part on our comparison of scans through the science source and PSF star. To make as accurate a comparison as possible, during the data reduction process we always used the PSF observation that was taken closest in time to the science source observation. The data was reduced in this way to combat the temporal changes observed in the PSF of the various telescopes. In the next section we give an example of these changes. The PSF stars were chosen to be bright, nearby stars with no excess associated with them. By selecting K or M class stars with $m_v < 5$ we could normally find a suitable star to use within 10° of the science object. In some cases the PSF stars were up to 15° away. Our
chopped integration times for the PSF stars were 2 to 4 minutes (1 to 2 minutes on-source).

**Nightly Variation of the PSF**

During the planning stages of this work we attempted to form a viable observational program that took into account some of the obstacles we knew we would face. One of the problems we foresaw was the overall stability of the PSF of the telescope-camera system. Many factors including slumping of the telescope structure, changes in the ambient temperature in the dome, and issues with the mirror support systems, can contribute to the instability of the PSF of the system. On modern telescopes like Keck and Gemini, active control of the mirror surface mostly compensates for these effects. However, even with these systems in operation some changes in the PSF are evident. To illustrate this point we present Figure 2-1, which is a plot of scans through all of the PSF measurements taken with OSCIR on the night of 04 May 1999. On this particular night of observing at Keck II we obtained five measurements of the PSF at 10.8 μm, and three at 18.2 μm. Inspection of the figure shows the magnitude of PSF changes for the night clearly. Although it is somewhat difficult to distinguish the lines, the sequence of 10.8 μm measurements goes from the narrowest scan, made early in the evening, to the broadest, made close to dawn. The 18.2 μm PSF scans follow the same trend. This implies that the PSF of the telescope became markedly worse as the night went on, illustrating the reason why we used the PSF taken as closely as possible in time to our science observations.

Note however that even though there is significant difference in the shape of the PSFs within each filter throughout the night, the FWHM of the PSF is relatively unaffected by these differences. From best to worst case the FWHM of the PSF changed
Figure 2-1: Nightly variation of the point-spread-function (PSF) at 10.8 μm (left) and 18.2 μm (right). Plotted are scans through the five PSF measurements at 10.8 μm and the three measurements at 18.2 μm on the night of 04 May 1999, with OSCIR on Keck II. The earliest measurements of the night are the narrowest, later measurements were progressively broader.

by 0.15” at 10 μm and 0.11” at 18 μm. Similar analysis done for other nights show that these values are slightly higher than normal. For most nights the FWHM of the PSF was stable to within ~0.1” at Keck, and that is from the best to worst case on a night. The variations between sequential PSF measurements were lower than this, implying that the changes to the PSF were gradual, akin to a slow drift that occurred over the course of hours. This is encouraging since the PSF measurements we used to compare to our science sources were normally taken within 30 minutes of the end of the science source observation. Along with the PSF star measurements we also observed infrared standard stars to absolutely calibrate our data. In the next section we discuss our data reduction steps, including that calibration.
Data Reduction Steps

Over the course of making our survey observations we acquired a large amount of data. Including the PSF and standard star observations approximately 12 GB of data was amassed for this project. The sheer amount of data alone made the data reduction arduous and time consuming. The reason that the amount of raw data is so large is because the OSCIR data is saved in specialized 6-dimensional FITS files. This unusual data structure is required due to the chop/nod method of observing in the mid-IR (see Appendix A). Briefly, the OSCIR detector is readout approximately every 10 ms during normal observations. The data from the readouts is saved in buffers in a VME control crate on the back of the telescope. Once every 2 seconds the buffers are sent down a fiber optic cable connecting the VME crate and the control computer. Once the data is sent to the control computer it is written to disk in one of these 6d FITS files. The advantage of this is that the observer has access to the entire data stream of the observation after the fact. While this produces data files in the 20 to 50 MB range, having access to the data in 2 second quanta is an invaluable asset during the data reduction. All of the data reduction for this dissertation was done in IDL, using the "f6tools" to access the OSCIR 6d FITS files, and the "wtools" to reduce the data in a GUI environment.

Removal of Contaminated Data

One of the advantages of having access to the entire data stream is evidenced in the very first step of any OSCIR data reduction, the removal of contaminated data sets. The advantage is that we can remove data in 2 second increments without changing the overall quality of the data as a whole. The main reason that portions of the data stream must be removed is due to fluctuations in the background. As explained in Appendix A,
Figure 2-2: Background at 10.8 µm during an observation of HD 141569 at Keck II. Here we plot %well (a measure of how close to saturation the OSCIR detector is) vs. frame number for an observation of HD 141569 at Keck II. During the reduction process frame numbers 145 to 200 were removed due to the large background change.

Accurate removal of the background is paramount in mid-IR observations. Using the routine 'f6bstat' we produced plots for each survey star observation like the one shown in Figure 2-2 above. In this figure we plot '%well' as a function of frame number for an observation of the science source HD 141569 at Keck II. The quantity '%well' is a measure of the background seen by the OSCIR detector during each of its ~10 ms integrations. Experience has shown that an acceptable background variation is < 0.5% change in '%well'. In this case we therefore remove the frames between number 145 to 200 because of the large change in well during those readouts. This large change in '%well' was most likely due to a faint band of cirrus clouds moving through the field of
view of OSCIR. Once any contaminated frames are removed from the data we move onto the next step of the reduction, which is the creation of a single image from the individual frames in the 6d FITS file.

**Cross-Correlation of Images**

Once any contaminated frames are removed from the data, we have a series of so-called ‘sig’ frames to work with. These are the final products of a complete nod-cycle, a single 128 x 128 image that has the background from the sky and telescope fully removed. For our survey mode observations we typically had 10 to 15 of these ‘sig’ frames to work with for each filter.

For sources that are not bright enough to be seen in each individual ‘sig’ frame, we performed what is called a “straight-stack”. A straight-stack is the direct sum of all of the sig frames in an observation, no shift-and-add processing done to the data. Most of our sources were relatively bright in the mid-IR and were detected in the individual sig frames. For these sources we developed and used two IDL routines that use a chi-squared minimization kernel to cross correlate the images to find the best offsets between them before stacking them into a single image. We find that this helps remove any tracking errors or other systematic drifts in the data. Once the sig images are straight-stacked or cross-correlated we move to the next step of the reduction sequence, ensuring that the sky is zero-mean before we calibrate the image.

**Skyfit**

The skyfit routine is used to ensure that the off-source portions of the final image are zero-mean. Due to imprecise background removal during some of our observations
the final image from a 6d FITS file may have a non-zero mean sky. To correct for this we use the skyfit routine written by Drs. Jim De Buizer and Robert Piña. This routine allows you to mask any portion of the array, for example around your source, and then it fits the remaining, unmasked, background with a 2 dimensional polynomial surface of specified order typically 3,3 to ‘flatten’ the sky. This routine was used on all of our survey data with good success. Once we have a zero-mean sky image, we are ready to calibrate.

Calibration/Airmass Correction

Our science observations were absolutely calibrated by observing infrared standard stars as part of our observational sequence. In Table 2-2 we list the fifteen primary standards that we observed during the survey. We also present their assumed flux densities at 10.8 and 18.2 μm. For most of the standard stars we have model atmospheres from Cohen et al. (1999). The flux densities for these stars were calculated by integrating the models for the star through the passband of the OSCIR filters. We used the following relation to calculate the bandpass averaged flux density standard star flux density $F_\lambda$. 

$$
F_\lambda := \frac{\int_{\lambda_1}^{\lambda_2} F_V(\lambda) \cdot \frac{c}{\lambda^2} \cdot (T_{filter}(\lambda) \cdot T_{atran}(\lambda)) \, d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{c}{\lambda^2} \cdot (T_{filter}(\lambda) \cdot T_{atran}(\lambda)) \, d\lambda}
$$

where $T_{filter}$ and $T_{atran}$ are the transmission curves of the OSCIR filter and the atmosphere respectively. $\lambda_1$ and $\lambda_2$ are the wavelengths where the transmission of the filter drops to zero, and $c$ is the speed of light. On average we observed standards at both 10 and 18 μm.
3 or 4 times per night during the survey observations. Each of these data was reduced and a calibration (‘cal’) value that converts the instrumental units of ADU/sec into the physical units of mJy was calculated. The ‘cal’ value was then applied to the reduced science data to create maps in mJy/pixel.

We comment here on the uncertainties associated with the photometric calibration since they are the dominant uncertainties we dealt with for the survey observations. The effects of atmospheric transmission always dominate the photometric uncertainties in mid-IR. As Figure A-1 shows (see appendix A), the mid-IR atmospheric windows at 10 and 20 μm are riddled with atmospheric absorption features from water vapor, CO₂, and O₃. A variation in the column density of these species has a dramatic effect on the transparency of the atmosphere in the mid-IR. Indeed, it is these variations of the sky background that requires the use of chopping in the mid-IR.

Van der Bliek et al. (1996) measure short term variations in the atmospheric transmission of ~10% for the 10 μm window, and upwards of 15% in the 20 μm window. Looking at the calibration data directly related to our survey, which consists of >60 individual stellar observations, we find that the overall uncertainty in the absolute calibration is 10% at both 10.8 and 18.2 μm. The discrepancy with the van der Bliek et al. (1996) long wavelength conclusion is most likely related to the fact that our 18.2 μm filter has a bandpass on only Δλ = 1.7 μm; relatively narrow when compared to the broadband 20 μm filters discussed in their paper. We adopt ±10% uncertainties for all of our measured OSCIR flux densities.

The airmass corrections in the mid-IR are generally small. Under good sky conditions, a rule-of-thumb measure for the airmass correction in the N-band (10.8 μm) is ~0.02 mag/airmass. Even so, we attempted to perform airmass corrections for all of our
Table 2-2: Standard Star Flux Densities

<table>
<thead>
<tr>
<th>Standard Star</th>
<th>10.8 µm (N-Band)</th>
<th>18.2 µm (IHW18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>α Lyr</td>
<td>37.8</td>
<td>11.9</td>
</tr>
<tr>
<td>α CMa</td>
<td>130.7</td>
<td>41.1</td>
</tr>
<tr>
<td>α CrB</td>
<td>5.0</td>
<td>1.8</td>
</tr>
<tr>
<td>α Boo</td>
<td>682.7</td>
<td>219.1</td>
</tr>
<tr>
<td>α Hya</td>
<td>125.2</td>
<td>41.5</td>
</tr>
<tr>
<td>α Tau</td>
<td>600.6</td>
<td>200.1</td>
</tr>
<tr>
<td>β And</td>
<td>245.9</td>
<td>83.9</td>
</tr>
<tr>
<td>β Gem</td>
<td>115.5</td>
<td>37.0</td>
</tr>
<tr>
<td>β Gru</td>
<td>906.0</td>
<td>323.1</td>
</tr>
<tr>
<td>β Peg</td>
<td>352.1</td>
<td>122.2</td>
</tr>
<tr>
<td>γ Aql</td>
<td>77.2</td>
<td>25.6</td>
</tr>
<tr>
<td>γ Cru</td>
<td>833.9</td>
<td>286.7</td>
</tr>
<tr>
<td>γ Ret</td>
<td>72.6</td>
<td>28.7</td>
</tr>
<tr>
<td>λ Vel</td>
<td>194.6</td>
<td>69.4</td>
</tr>
<tr>
<td>μ UMa</td>
<td>99.1</td>
<td>33.9</td>
</tr>
</tbody>
</table>

† Values are bandpass-averaged flux densities calculated by integrating Kurucz models of each star through the OSCIR filter bands also taking into account the detector QE, and atmospheric transmission. All other values come from the CTIO standard list.

Survey data by using the observations of the photometric calibrators over a range of airmass. At times this was impossible due to insufficient standard star observations, or obviously contaminated standard data where there was no trend at all evident in the cal values. When there was sufficient data of good quality available we used a linear regression of log(cal) vs. airmass to correct the science observations for airmass. These corrections rarely made a more than 5% change in the flux estimate for a survey source, well within the 10% photometric errors assigned to our OSCIR photometry.
Flat-field Correction

Figure 7-6 shows an image of the OSCIR detector under uniform illumination in the N-band (10.8 μm). There are approximately 10 hot pixels distributed across the array that have significantly different response than the others. There are also about 10 dead pixels. Overall the uniformity of the detector is very good, however there is a small amount of vignetting in the lower right corner of the array. The response of the array is generally very flat though, the flat-filed varies < 5% across the array. All of the structure seen in Figure 7-6 is ‘fixed-pattern’ and is removed during the chop-nod process. Because of the flat response of the array, no flat filed corrections were applied to the survey data.

Photometry

The last step in the reduction was to conduct aperture photometry on the science sources to estimate their brightness at 10.8 and 18.2 μm. We used two methods to perform the photometry on the survey stars. The first is an automated routine, which estimates the sky background, and automatically grows an aperture around a point source until the increase in flux obtained is less then or equal to the measured noise in the background contained within the annulus bounded by the last two apertures. This routine works very well for strongly detected sources and was used for the photometry for 75% of the survey data. We also used this routine when we manually reduced standard star data, or obtained flux estimates for PSF stars. For faint sources we used a manual aperture for the photometry. For consistency, all manual apertures used had a radius \( r = 2". \) The measurement errors associated with the photometry (i.e. \( \sigma_{pix}(N_{pix})^{1/2} \)) were always dominated by the 10% photometric error for all survey sources. Our observed
color corrected OSCIR flux density estimates for the survey sources are presented in Table 3-1. In Chapter 3 we also discuss the removal of the stellar photosphere from those values to calculate a values for the excess emission from the circumstellar dust.

**Color Correction**

Flux density estimates for objects observed through wide bandpass infrared filters need to have a correction applied to them called a 'color correction'. This is particularly true of the OSCIR N-band filter that has a bandpass of 5.2 μm. The color correction must be applied since the spectral shapes of the flux calibration star and science object are different through the bandpass of the filter. Because stellar temperatures are high (> 5000 K), the SED of a calibration star peaks well short of the mid-IR and its SED is on the Raleigh-Jeans tail through the OSCIR filters. For our science sources though, this is not be the case. For our science targets we are observing dust that has a temperature in the hundreds of Kelvin. Because of this the SED of the science source may be peaking, or has not yet peaked, in the mid-IR which means that its spectral shape through the passband of the OSCIR filters is different than that of the calibration star. This is an issue because we prefer to discuss monochromatic flux densities in the mid-IR, and since the calibration star and science objects have different SEDs through the filter, any monochromatic flux density given is dependent on the spectral shape of the source through the passband. Since we also make the assumption that the SEDs of our science objects follow a modified blackbody function \( F_ν = (1 - e^{-ν}) \times B_ν(T) \) through the passband. The color correction term is applied to scale that function to give us the correct in-band flux for the science source.
We outline the procedure for this correction below starting with the definition of the effective wavelength of the N-band filter ($\lambda_{\text{eff}}$). Since the OSCIR detector is a photon counter for these purposes $\lambda_{\text{eff}}$ is defined in terms of the photon with the average energy in the bandpass.

The color correction factor assumes that the ratio of instrumental counts for the calibration star (ADU$^s$) to that of the program object (ADU$^p$) is equal to the ratio of number of photons detected from the calibration star ($N_{\gamma}^s$) to the program source ($N_{\gamma}^p$). This equality is shown below in equation 1.

$$\frac{\text{ADU}^p}{\text{ADU}^s} = \frac{N_{\gamma}^p}{N_{\gamma}^s}$$  \hspace{1cm} (1)

the number of photons a source will generate through a bandpass is

$$N = \int Q_{\text{sys}} F_{\nu} dv$$  \hspace{1cm} (2)

Where $F_{\nu}$ is the flux density of the source with temperature $T$ and optical depth $\tau_{\nu}$ and is defined as

$$F_{\nu} = (1 - e^{-\tau_{\nu}}) \cdot \Omega \cdot B_{\nu}(T)$$  \hspace{1cm} (3)

We also define the 'quantum efficiency' of the system as

$$Q_{\text{sys}} := \text{T}_\text{filter}(\lambda) \cdot \text{T}_\text{atran}(\lambda) \cdot \text{QE}(\lambda)$$
where this relation takes into account the QE of the OSCIR detector, the atmospheric transmission, and the transmission of the OSCIR filter. Substituting (3) into (2) gives

\[ N := \Omega \cdot \int \frac{Q_{sys} \left( 1 - e^{-\tau_v} \right) B_{V}(T)}{h \nu} \, dv \]  \hspace{0.5cm} (4)

If we are given a monochromatic flux density of the source at some frequency, \( F_{\nu_0} \) using equation (3) and solving for \( \Omega \) we can define the following relation

\[ \Omega := \frac{F_{\nu_0}}{\left( 1 - e^{-\tau_{\nu_0}} \right) B_{\nu_0}(T)} \]  \hspace{0.5cm} (5)

substituting equation (5) into (4) gives

\[ N := \frac{F_{\nu_0}}{\left( 1 - e^{-\tau_{\nu_0}} \right) B_{\nu_0}(T)} \cdot \int \frac{Q_{sys} \left( 1 - e^{-\tau} \right) B_{V}(T)}{h \nu} \, dv \]  \hspace{0.5cm} (6)

which is an expression for the number of photons produced by a source with flux density \( F_{\nu} \) through the passband of the filter. Recalling equation (1)

\[
\frac{ADU^p}{ADU^s} = \frac{N_{\gamma^p}}{N_{\gamma^s}}
\]

we can use equation (6) to relate the number of photons received from the program source \( (N_{\gamma^p}) \) to the counts measured from the program source \( (ADU^p) \) and the number of counts measured from the calibration star \( (ADU^s) \). First solving (1) for \( (N_{\gamma^p}) \) and then substituting in expressions for the number of photons received from the star and program source from (6) gives
the absence of the \((1 - e^{-\tau})\) terms on the right hand side of equation (7) is due to the fact that the calibration star is assumed to be a simple blackbody. We can now solve (7) for the flux density of the program object at \(v_0\), \((F_{vo}^p)\)

\[
\frac{F_{vo}^p}{(1 - e^{-\tau_{vo}}) \cdot B_{vo}(T^p)} = \left[ \int Q_{sys} \frac{(1 - e^{-\tau_{vo}}) \cdot B_{vo}(T^p)}{\text{ADU}} \, dv \right] \cdot \frac{\text{ADU}_w}{\text{ADU}_s} \cdot \left[ \int \frac{B_{vo}(T^s)}{Q_{sys} \cdot \frac{1}{hv}} \, dv \right]
\]

\( (7) \)

In equation (8) we have equated the flux density of the program source at the monochromatic frequency \(v_0\) to three known quantities, \(\text{ADU}_w^p\), \(F_{vo}^s\), and \(\text{ADU}_s^p\). The first term on the right hand side of (8) is the measured instrumental counts of the program source. The second term is simply the ratio of the given flux density of the calibration star at \(v_0\) the measured instrumental counts for the calibration star. This is the “cal” value mentioned in the calibration section. The third term is the color correction term. It is this factor that is applied to the data to account for the different spectral shapes of the calibration star and program object through the bandpass of the filters.

To color correct our fluxes we used a program written for MATHCAD. Using our raw 10 and 18 \(\mu\)m flux density estimates as a starting point the code iterates to simultaneously solve for \(T\), \(\tau\), and color correction. All of our flux density estimates
presented in this dissertation are color corrected. For the sample as a whole the mean color correction for our broad band 10.8 μm flux density estimates was approximately 13%. The 18 μm estimates had a mean correction of ~3%. The 18 μm value is lower due to the much narrower passband of the 18 μm filter. Color corrections for 10.8 μm (N-band) fluxes on the order of 15 to 20% are consistent with the work of Hanner et al. (1984).

Resolved or Unresolved: The Question

Perhaps the most fundamental question we attempted to answer in this dissertation is, are our sample Vega-like sources resolved? For the most part, the answer to that question is no. We find that ~90% of our survey sources are unresolved at both 10.8 and 18.2 μm. However, in this section we only discuss how we answered the question of resolution. The full results of the survey are presented in Chapter 3.

Our primary method of determining whether or not a survey source was extended was close inspection of the reduced data by eye. We found early on in the reduction of the survey data that the eye is the best detector for faint extended emission near bright stellar sources. This is especially true when the data is reduced with the latest generation of data reduction software. The ability to scale and color data in a point-and-click environment is a very powerful tool at our disposal and we used it to the fullest extent we could during this project. For each of our survey sources we carefully studied the data as closely as possible by eye to look for hints of extended emission near the science sources. Visual comparison of the science sources and PSF stars was also performed for each survey source.
Figure 2-3: Scans of a resolved (a & c) and unresolved source (b & d). (a and c) Scans of HD 151469 and PSF star at 10.8 μm and 18.2 μm respectively. HD 141569 is the solid line, the PSF star is dashed. The dotted line is a Gaussian fit to the data. (b and d) Scan of HD 16908 at 10.8 μm (b) and 18.2 μm (d). 18.2 μm data for HD 16908 and PSF star have a 2-pixel (0.12" FWHM) Gaussian smooth applied to boost the signal to noise of the HD 16908 detection.

Another way we investigated the data to try to answer the question of resolution was through scans (i.e. line-cuts) through the science objects and corresponding PSF stars. We find the best way to visualize the data in this form is through plots like Figure 2-3. In Figure 2-3 we show scans that are representative of a resolved and unresolved source. The resolved source (panel a & c) is HD 141569 which we observed at Keck II in 1999 May. This source is discussed in detail in Chapter 5. We contrast HD 141569 with a representative unresolved source, HD 16908. Also observed at Keck, the HD 16908 data has the same resolution as the HD 141569 observations.
One immediately sees the differences in the two sets of panels. HD 141569 is clearly broader than the PSF star at both 10.8 and 18.2 μm while the HD 16908 and PSF star scans lie on top of each other. It is the extended emission of HD 141569 that causes this broadening of its scan with respect to the PSF star. Close inspection of panel (a) shows that there is significant extended emission from HD 141569 detected out to a radius of ~1". At 18.2 μm the noise in the source scan prevents a determination of the exact extent of the extended emission, however, even with the relatively low signal-to-noise of the HD 141569 18.2 μm data the difference in width of it and the PSF star is easily distinguishable in panel (c). Images of HD 141569 also exhibit a ‘fuzziness’ that is not present when observing a true point source. This effect is difficult to describe, but it is very evident when looking at the data on a monitor.

The scans of HD 16908 are representative of the unresolved sources in the survey. There is virtually no difference in the FWHM measurements of HD 16908 and the PSF star at either 10.8 or 18.2 μm. There is also no evidence for faint extended emission at the lowest levels of panels (b) and (d). Using these scans in conjunction with an in depth inspection by eye, we can confidently conclude that HD 16908 is unresolved at this angular scale at both 10.8 and 18.2 μm. In the next chapter we move onto the discussion of our survey data.
CHAPTER 3
SURVEY DISCUSSION

In this chapter we discuss our survey data. We do not give further details on the mechanics of making the survey, rather we discuss our overall interpretations of the data. In the first sections of this chapter we present size limits on the disks of the unresolved sources, and give our derived grain parameters for their dust. We then compare the unresolved survey sources to \( \beta \) Pictoris and HR 4796A, and show that if the survey stars were at the distance of \( \beta \) Pictoris (19 pc) about 50% would still have been unresolved in our observations. This comparison allows us to answer the question of whether the unresolved sources are unusual as compared to archetypal disk examples, and gives us an idea of how the unresolved sources fit into the Vega-like class.

In the later sections we discuss trends seen in the data and show how they can be used to form a probable evolutionary sequence for Vega-like stars. By breaking the survey sources into three classes and using the H-R diagram, we can graphically see how these stars may be evolving. We bring in evidence that supports such a sequence in the form of the SEDs of the star/disk system and relate the evolution of those SEDs to the evolution of the disks around the stars. Using one of the sub-classes as a pivot point, we see how one group of stars is likely still moving onto the ZAMS, while the majority of them have already made it there and are now moving across the main-sequence in the middle stages of their lives. In general we have incorporated ideas that are already well represented in the literature into our survey discussion while adding our own ideas to the
overall evolutionary scheme. We start the chapter with the presentation of our disk size estimates and a discussion of their implications.

**Disk Sizes**

Perhaps the most fundamental piece of information we can gain from our observations are size estimates for the mid-IR-emitting region of the disk around each of the survey stars. Once we have these estimates we can then compare them to the disks of the archetypal Vega-like stars to piece together a more complete picture of the scale sizes of this type of disk. As was mentioned in Chapter 1, the majority of our survey sources are unresolved at both 10 and 18 μm. In fact, we observe 34 out of 38 sources as unresolved within the uncertainties associated with our observations. Only HR 4796A, HD 169142 (Chapter 4), HD 141569 (Chapter 5), and possibly 49 Ceti were resolved during the survey.

Since over 88% of the sources are unresolved we can only place upper limits on the size of their disks in the mid-IR. We do this by using the observed FWHM of the emission as the limiting size of the mid-IR-emitting region of the disk. Using this limiting size in conjunction with distance estimates to the stars allows us to translate the size into physical units. Since most of our Vega-like sample stars are have distances < 200 pc, and are bright in the visible, most of them were observed with the Hipparcos satellite. Indeed, we have Hipparcos measured parallaxes, and therefore distances, for all but 5 of the stars in our sample. As we will see later in the chapter the fact that we have accurate distances for most of the stars is one of the main reasons that we can put these stars into an
evolutionary sequence. For now we use the distance estimates to help us place limits on the size of disks associated with the unresolved sources in the sample.

Our limiting disk sizes are listed in the last column of Table 3-1. For each star in the survey we present the observed upper limit on the diameter of its disk. Although using the observed FWHM to limit the disk size is the least constraining method, for the majority of the sources these limits are the tightest existing constraints on the size of their disks in the mid-IR. For sources that are resolved we list approximate limits on the sizes of their mid-IR-emitting regions (denoted with ‘=‘ in the limiting size column). Our size estimates for these disks are only approximate since there may be faint extended emission from the disk that we did not detect in our survey-mode observations. An observational program centered on deep mid-IR imaging of these systems will more accurately define the limits of emission for these four disks. Many of the sources have not been observed in the mid-IR since IRAS, and those that have been observed were mostly observed with single element detectors or at low spatial resolution. Walker and Heinrichsen (2000) observed nine of the sample with ISO, but only at 60 and 90 μm and at relatively low spatial resolution. The only other observations of a significant number of the survey stars is that of Sylvester et al. (1996), in which mid-IR spectra of 12 of the sources were presented, but no imaging.

Table 3-1 also lists our color corrected observed flux densities of the survey sources at 10.8 and 18.2 μm. The flux densities presented in Table 3-1 are the sum of the photospheric emission of the star and the thermal emission from the circumstellar dust. We present these values here in this manner so that they can be directly compared to other observations. For our analysis of the dust properties we remove the stellar
### Table 3-1: Observed Properties of the Survey Sources

<table>
<thead>
<tr>
<th>Source Name</th>
<th>$F_{10.8\mu m}$ (Jy)</th>
<th>$F_{18.2\mu m}$ (Jy)</th>
<th>IRAS 12 $\mu m$ (Jy)</th>
<th>IRAS 25 $\mu m$ (Jy)</th>
<th>IRAS 60 $\mu m$ (Jy)</th>
<th>IRAS 100 $\mu m$ (Jy)</th>
<th>Limiting Size (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 432</td>
<td>13.5</td>
<td>3.59</td>
<td>11.7</td>
<td>2.87</td>
<td>1.00</td>
<td>&lt;12.7</td>
<td>16</td>
</tr>
<tr>
<td>HD 8538</td>
<td>5.69</td>
<td>1.42</td>
<td>4.96</td>
<td>1.14</td>
<td>0.35</td>
<td>&lt;6.09</td>
<td>27</td>
</tr>
<tr>
<td>HD 9672</td>
<td>0.36</td>
<td>0.14</td>
<td>0.33</td>
<td>0.38</td>
<td>2.02</td>
<td>1.88</td>
<td>≈150</td>
</tr>
<tr>
<td>HD 16908</td>
<td>0.45</td>
<td>0.09</td>
<td>0.38</td>
<td>0.41L</td>
<td>0.36</td>
<td>&lt;1.87</td>
<td>31</td>
</tr>
<tr>
<td>HD 17848</td>
<td>0.25</td>
<td>0.23L</td>
<td>0.46</td>
<td>0.25L</td>
<td>&lt;0.40</td>
<td>&lt;1.00</td>
<td>51</td>
</tr>
<tr>
<td>HD 20010</td>
<td>3.09</td>
<td>0.77</td>
<td>2.85</td>
<td>0.74</td>
<td>0.23</td>
<td>&lt;1.00</td>
<td>14</td>
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<td>&lt;1.00</td>
<td>20</td>
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<td>HD 34282</td>
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<td>0.32</td>
<td>0.70</td>
<td>1.63</td>
<td>10.8</td>
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<td>173</td>
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<td>HD 34700</td>
<td>0.48</td>
<td>1.40</td>
<td>0.57</td>
<td>4.42</td>
<td>14.1</td>
<td>9.38</td>
<td>900</td>
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<tr>
<td>HD 35187</td>
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<td>6.02</td>
<td>5.39</td>
<td>11.5</td>
<td>7.95</td>
<td>5.00</td>
<td>200</td>
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<td>HD 38678</td>
<td>1.80</td>
<td>0.63</td>
<td>2.12</td>
<td>1.15</td>
<td>&lt;0.53</td>
<td>&lt;1.00</td>
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<tr>
<td>HD 49662</td>
<td>0.19</td>
<td>0.13L</td>
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<td>1.62</td>
<td>4.60</td>
<td>5.68</td>
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<td>HD 74956</td>
<td>8.08</td>
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<td>1.99</td>
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<td>9.44</td>
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<td>HD 101584</td>
<td>96.5</td>
<td>113.0</td>
<td>92.6</td>
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<td>179</td>
<td>99.1</td>
<td>800</td>
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<td>2.70</td>
<td>5.26</td>
<td>1.75</td>
<td>1.02</td>
<td>&lt;1.00</td>
<td>10</td>
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<td>22.7</td>
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<td>9.21</td>
<td>115</td>
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<td>0.91</td>
<td>0.45</td>
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<td>7.36</td>
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<td>≈200</td>
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<td>0.60</td>
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<td>3.11</td>
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<td>HD 135344</td>
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<td>1.57</td>
<td>6.91</td>
<td>25.6</td>
<td>25.7</td>
<td>60</td>
</tr>
<tr>
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<td>8.05</td>
<td>4.11</td>
<td>18.14</td>
<td>19.3</td>
<td>13.9</td>
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<td>0.61L</td>
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<td>0.59</td>
<td>&lt;1.00</td>
<td>15</td>
</tr>
<tr>
<td>HD 141569</td>
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<td>0.65</td>
<td>0.53</td>
<td>1.82</td>
<td>5.54</td>
<td>3.48</td>
<td>≈200</td>
</tr>
<tr>
<td>HD 142165</td>
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<td>0.06L</td>
<td>0.25L</td>
<td>0.34</td>
<td>&lt;2.77</td>
<td>&lt;11.6</td>
<td>40</td>
</tr>
<tr>
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<td>9.10</td>
<td>8.67</td>
<td>11.5</td>
<td>7.23</td>
<td>5.46</td>
<td>35</td>
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<tr>
<td>HD 143006</td>
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<td>1.92</td>
<td>0.87</td>
<td>3.06</td>
<td>6.57</td>
<td>4.82</td>
<td>50</td>
</tr>
<tr>
<td>HD 144432</td>
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<td>7.62</td>
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<td>HD 155826</td>
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<td>4.12</td>
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<td>1.06</td>
<td>&lt;5.97</td>
<td>65</td>
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<tr>
<td>HD 163296</td>
<td>26.3</td>
<td>17.4</td>
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<td>28.2</td>
<td>&lt;40.6</td>
<td>60</td>
</tr>
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<td>2.95</td>
<td>18.4</td>
<td>29.5</td>
<td>23.4</td>
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<td>113</td>
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<td>0.23</td>
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<td>12</td>
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<td>&lt;2.59</td>
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<td>3.43</td>
<td>7.60</td>
<td>5.10</td>
<td>--</td>
</tr>
</tbody>
</table>

We adopt 10% errors on the OSCIR photometry at 10.8 and 18.2 $\mu m$.

* Denotes source with near-IR excess as listed by Sylvester et al. (1996)

L in flux column denotes upper limit used in temperature and optical depth calculation.
contribution from the observed flux density. This procedure and our results are discussed in the next section. For the few sources that we did not detect at either 10.8 or 18.2 μm, we list a 3σ upper limit in the appropriate column in Table 3-1. These limits were calculated using an aperture with radius = 1.22(λ/D). Table 3-1 also lists the IRAS 60 and 100 μm flux density estimates from the IRAS Point Source Catalog v2.0 in for each source. At these longer wavelengths these is negligible contribution to the flux from the star, it is comprised entirely of thermal emission from the circumstellar dust. All of the sources in our sample have significant excess emission at these long wavelengths, and the IRAS fluxes are included to give a more complete picture of the magnitude of the excesses associated with each star. In Table 3-1 we also mark the nine systems that exhibit near-IR excess. As we will see, these nine systems form one of the three subclasses we define when discussing our proposed evolutionary sequence for the survey sources. In the next section we explain the procedure for removing the stellar contribution to the flux density estimates presented in Table 3-1. This is necessary since this procedure directly bears on which sources we could accurately model.

**Photosphere Removal**

As mentioned above the flux density estimates presented in Table 3-1 contain both emission from the photosphere of the star and the thermal emission from the grains in its disk. Since we are trying to investigate the properties of the dust, we must separate these two contributions so we know as accurately as possible how much radiation the grains themselves emit at 10.8 and 18.2 μm. While this procedure is straightforward, the uncertainties associated with both the predictions of the photospheric emission and our
observed flux density estimates have consequences on the final results. The procedure we used to calculate the photospheric contribution of each star to our observed flux density estimate is outlined below.

1. Use a published value or spectral type of the star to find the effective temperature of its photosphere ($T_{\text{eff}}$).
2. Model the SED of the stellar photosphere as a blackbody function with temperature $T_{\text{eff}}$, and normalize the blackbody function to observed 2.2 μm (K-band) values.
3. Use the blackbody function to predict the fluxes emitted at 10.8 and 18.2 μm for each $T_{\text{eff}}$. Then form the ratios ($F_{10.8\mu m}/F_{2.2\mu m}$) and ($F_{18.2\mu m}/F_{2.2\mu m}$) as a function of $T_{\text{eff}}$.
4. Multiply the observed 2.2 μm flux value by the correct ratios to predict the photospheric flux at 10.8 and 18.2 μm.
5. Subtract the predicted flux estimates from our observed estimates, which leaves only the contribution of the dust, defined as the excess emission.

Two questions immediately come to mind concerning this procedure: (1) is it legitimate to use the ratios ($F_{10.8\mu m}/F_{2.2\mu m}$) and ($F_{18.2\mu m}/F_{2.2\mu m}$) in the calculation and (2) is the assumption the photosphere behaves as a blackbody accurate enough? In short, the answer to both is yes. As illustrated in Figure 3-1 in the mid-IR we are working on the Raleigh-Jeans tail of the blackbody distribution for even the coolest stars in our sample (~5000 K), and the stellar photospheres follow the well-known $v^2$ falloff in this regime. Close inspection of the 5000 K curve in Figure 3-1 shows there is slight deviation from Raleigh-Jeans falloff at 2.2 μm, but this is a relatively small discrepancy, and only applies to one of our survey sources. We address the second question by plotting three quantities in Figure 3-2, the near and mid-IR portion a blackbody function with $T = 10000$ K, a model atmosphere for Vega from Cohen (1995), and flux density estimates for Vega from OSCIR observations. All three curves have been normalized to unity at 2.2
Figure 3-1: Blackbody plots for temperatures that bracket the effective temperatures ($T_{\text{eff}}$) of the stars in our Vega-like sample. Our spectral types of our sample stars range from a B3V (19000 K) to K2V (5010 K). The mean $T_{\text{eff}}$ of the sample is 8500 K. The vertical dotted lines denote 2.2, 10.8, and 18.2 μm (from left to right).

μm. For the OSCIR observations we have also plotted error bars that mark the ±10% uncertainty in their values. Both the model atmosphere and the blackbody line lie well within the photometric uncertainties associated with our OSCIR observations. The close correlation of all three plots in Figure 3-2 illustrates that for the relatively hot temperatures of the intermediate mass stars in our sample the approximation of the stellar photospheric emission as a blackbody function is robust.

We used this method to remove the stellar contribution from our observed flux estimates for all of the stars in our sample. For star/disk systems where the mid-IR flux comes primarily from the dust emission the procedure is sound. However, for a subset of
Figure 3-2: Comparison of OSCIR data, 10000 K blackbody function, and model atmosphere data for Vega. Error bars on OSCIR data are ±10% and represent the uncertainly in our measured flux values.

seventeen of the survey stars this procedure returns negative excesses at either 10.8 or 18.2 µm clearly not a legitimate result. We believe that these non-physical results are primarily due to the ±10% uncertainties in our OSCIR flux estimates. Since the determination of the magnitude of the excess is directly related to our observed mid-IR flux estimates, any uncertainty in those estimates translates directly into uncertainties in our estimates of the excesses. For these seventeen sources the amount of their mid-IR excess is within our observational uncertainties, and we therefore cannot calculate the amount of excess they exhibit. Because of this, we are forced to remove these seventeen stars from our analysis of the disk grain properties.
Clearly this has a dramatic effect on the results of our survey. Because of this issue we have only modeled the grains associated with 22 of the observed systems, or 56% of our sample. However, we use the fact that some stars exhibit little or no excess in the mid-IR in the discussion of our proposed evolutionary sequence presented later in this chapter. Indeed, these sources with little or no mid-IR excess form one of the three subclasses we divide our survey into and represent the last stage of our proposed sequence.

We do have robust estimates for the 10.8 and 18.2 μm excesses of the remaining 22 survey sources and we present them in Table 3-2. Listed by HD number, we present our excess estimates in units of flux density, and as a percentage of our observed flux estimate. A literature search and use of the SIMBAD database gave the spectral types for each of the sources in the table. We also list the effective (\(T_{\text{eff}}\)) we used for each star in our calculations of the excess. The majority of these values were taken from Allen (2000), while others were taken from the literature, in particular Dunkin, Barlow, and Ryan (1997b).

One important conclusion that we can infer from Table 3-2 is that although our sample is biased toward stars of A-type, within the sample there is no apparent correlation between spectral type and amount of mid-IR excess. This is supported by the literature where it has been found that at least 15% of nearby field stars of all spectral types between A to K have circumstellar dust systems like those associated with our sample (Lagrange, Backman, & Artymowicz 2000). We also see that percentage wise there is varying amounts of 10.8 μm excess associated with our sample stars. The excesses of twelve stars in Table 3-2 accounts for more than 95% of the observed 10.8μm flux, seven of the stars have intermediate values of 10.8 μm excess (between 10 to
Table 3-2: Excess Characteristics of the Survey Sources

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Sp. Type</th>
<th>$T_{\text{eff}}$</th>
<th>10.8 μm Excess (Jy)</th>
<th>% Excess (10.8 μm)</th>
<th>18.2 μm Excess (Jy)</th>
<th>% Excess (18.2 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 9672</td>
<td>A1V</td>
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<td>1.3</td>
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<td>98.6</td>
<td>0.31</td>
<td>99.2</td>
</tr>
<tr>
<td>HD 34700</td>
<td>G0</td>
<td>5930</td>
<td>0.37</td>
<td>88.8</td>
<td>1.34</td>
<td>98.8</td>
</tr>
<tr>
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<td>A2V *</td>
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<td>3.08</td>
<td>98.2</td>
<td>5.78</td>
<td>99.7</td>
</tr>
<tr>
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<td>0.13</td>
<td>7.2</td>
<td>0.05</td>
<td>7.7</td>
</tr>
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<td>4.05</td>
<td>88.0</td>
</tr>
<tr>
<td>HD 98800</td>
<td>K2V *</td>
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<td>79.8</td>
<td>4.82</td>
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<td>1.90</td>
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<td>0.32</td>
<td>72.6</td>
<td>1.90</td>
<td>97.7</td>
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</table>

* In sp. Type column denotes multiple star system  
† Ambiguous classification, see Chapter 6

95%), and three stars have little 10.8 μm excess (< 10%). Coupled with the seventeen sources that have no measurable excess and are not listed in Table 3-2 there are twenty stars that exhibit <10% excess at 10.8 μm. This is our first look at the three sub-classes we break the survey into with regards to our proposed evolutionary sequence. As we will
see, the amount of the 10.8 μm excess exhibited by a star/disk pair is a good indicator of
the evolutionary state of the system.

Now that we have our best estimate at the values for the emission from the dust
around the stars in the survey we can proceed with our investigation of the properties of
that dust. In the following sections we discuss our modeling of these mid-IR-emitting
grains and present the results of that modeling.

**Grain Models**

In this section we discuss the properties of the radiative equilibrium models we
used to analyze our mid-IR data. The core of the model code used was developed by
members of the University of Florida Dust Dynamics Group. In particular, the version of
the code used in our analysis was written by Dr. Mark Wyatt. We begin this section with
a high-level overview of the operation of the modeling code, then present results for one
of the survey sources, HD 141569. Using the HD 141569 results as an example, we
describe the model output and show how it relates directly to the physical parameters of
the grains we are studying.

Before we discuss the operation of the modeling code, we need to address what
assumptions were made about the grains. The most fundamental assumption made is in
regards to the composition of the dust. For the models presented in this dissertation we
assume that the disk particles are comprised of the astronomical silicates of Draine and
Lee (1984) and Laor and Draine (1993). There is evidence for particles with this
composition in both interplanetary dust particles gathered high in the Earth’s atmosphere
(Leinert and Grün 1990), and in disks similar to those studied here. Sylvester et al. (1996)
presented mid-IR spectra of 13 sources in our survey and definitively detected silicates in seven of them. Other significant detections of silicate materials in Vega-like disks are those in the archetypal Vega-like source β Pictoris (Telesco and Knacke 1991), and in the source 51 Oph (Fajardo-Acosta, Telesco, & Knacke 1993).

We also make the assumptions that the model particles have a density $\rho = 2.5 \text{ g cm}^{-3}$, and that they are spherical. We make the assumption about the density since ‘astronomical silicates’ is not a physical material and its measured density is undefined. The value of $2.5 \text{ g cm}^{-3}$ is used since it is representative of interplanetary dust particles (Gustafson 1994). With regards to the assumption about the shape of the grains, one must first realize that the methods for calculating the optical constants for grains are limited. Rigorous solutions for light scattering from particles are only available for spherical grains, using Mie theory, and infinite cylinders, as described in Bohren & Huffman (1983). New solutions for more complicated aggregate particles have recently become available (Xu & Gustafson 1999), but these methods are computationally intensive, and beyond the scope of the modeling presented here. Recent advances in the work on the composition and structure of particles in circumstellar disks has shown that these assumptions likely oversimplify the grains (e.g. Gustafson 1994), however, this sort of analysis provides a good starting point for more detailed models which incorporate more complex grain structures. In a following section we discuss the limitations of our models, and touch on how different compositions and/or grain morphology changes our results.

Using the optical constants for astronomical silicates from Laor and Draine (1993) our radiative equilibrium models use Mie theory to calculate the absorption coefficients ($Q_{abs}$) of different sized particles at different distances from the central star.
Once we know how efficiently a particle of a given size (diameter, D) emits and absorbs radiation we can work out what its temperature will be at any distance from the star (r) by iteratively solving the equation from Gustafson (1994):

\[
T(D,r) = \left( \frac{<Q_{\text{abs}}>_T / <Q_{\text{abs}}>_T}{1/4} \right) \times T_{bb} \quad (1)
\]

Where \(<Q_{\text{abs}}>_T\) is the absorption efficiency of the grain averaged over the stellar spectrum (which has been approximated by a blackbody with temperature \(T_\star\)) and \(<Q_{\text{abs}}>_T(D, r)\) is the same quantity averaged over a blackbody spectrum of temperature \(T\). \(T_{bb}\) is the equilibrium temperature of the grain in degrees Kelvin if it were a blackbody and is given by:

\[
T_{bb} = 278 \times r^{1/2} \times (L_\star/L_\odot)^{1/4} \quad (2)
\]

where \(r\) is the distance of the grain from the star in AU and \(L_\star\) is the stars luminosity in units of \(L_\odot = 3.9 \times 10^{33} \text{ erg sec}^{-1}\).

We can also calculate the thermal emission from the dust received at the Earth at a given wavelength. In the optically thin case, which we assume for our survey sources, this can be written as:

\[
F_\nu(\lambda, D, r) = Q_{\text{abs}}(\lambda, D) \times \Omega(D) \times B_\nu(\lambda, T(D, r)) \quad (3)
\]

where \(Q_{\text{abs}}(\lambda, D)\) is the grains efficiency as a function of wavelength and diameter, \(\Omega(D)\) is the solid angle subtended by the grain at the Earth, and \(B_\nu(\lambda, T(D, r))\) is the Planck function for the temperature of the grain. Using the luminosity and effective temperature of the stars along with the assumed optical properties of the grains, our models use equations (1) and (2) to calculate temperatures for grains of different sizes at varying distances from the stars.
Figure 3-3: Model temperature calculations for spherical Mie particles 10 to 50 AU from HD 141569. The shape to the temperature curves is due to the changes in the values of the grain emission and absorption efficiencies. The shading marks the three regions described in the text.

To show an example of our model temperature calculations in Figure 3-3 we plot the calculated temperature against grain diameter for particles between 10 to 50 AU from the star HD 141569, a source that we resolved at Keck II (see Chapter 5). We see that grains at these distances reach temperatures of 150 to 250 K. This is the temperature range we derive for the majority of the survey sources that have well defined excess values, and is one of the conclusions of our work. That is, the mid-IR excess emission from Vega-like sources traces material that is at temperatures between 150 to 300 K.

Once we have calculated the temperature of the grains as a function of distance from the star and diameter $T(D,r)$ we can use equation (3) in conjunction with the grain
efficiencies to calculate the amount of emission from a grain as a function of wavelength, $F_v(\lambda, D, r)$. In Figure 3-4 we plot the emitted flux density per unit solid angle (i.e. specific intensity) at 10.8 and 18.2 $\mu$m for grains near HD 141569. This is the quantity

$$Q_{abs}(\lambda, D) \times B_v[\lambda, T(D, r)]$$

from the right hand side of equation (3) and has units of Jy/ster. This is the first point in the modeling process where we have output that is in terms of physical units which is important since we need to compare our model output to our observations.

To make the direct comparison between our models and observations we form the ratio of the two plots shown in Figure 3-4 by dividing the 10.8 $\mu$m curves by the corresponding 18.2 $\mu$m ones. The resulting flux-ratio plot is shown in Figure 3-5. The plotted curves represent the flux ratio predicted for a particle of a given size at a given distance from the star. The horizontal line plotted in Figure 3-5 marks the observed flux ratio of the excess emission associated with HD 141569. It is where this horizontal line intersects the model curves that returns a particle size at a given distance from the star.
Figure 3-5: Flux density ratio plot for HD 141569. The curved lines represent the flux density ratio emitted by model grains between 10 to 50 AU from HD 141569. The horizontal line marks our observed (10.8 μm/18.2 μm) flux ratio. The intersection of the model curves and horizontal line returns grain sizes at the given distance from the star that are consistent with our observations.

that is consistent with our observed flux ratio. Note that there is a double-valued solution for grains at 30 AU from the star. For most of the survey source model results we see this behavior where two different values of the diameter for a particle at a given distance give the same flux ratio. This results from the fact that the temperature of the particle depends on the particle size, which in turn depends on the ratio of the absorption and emission efficiencies. Since we cannot distinguish between the two values, we use the largest consistent size to place an upper limit on the diameter of the mid-IR-emitting grains in the disks.
It is the interaction of the absorption and emission efficiencies of the grain that causes the shape of the curves in Figures 3-3, 3-4, and 3-5. This 'S' shape is characteristic of our models, and is seen to some extent in all of the results for the survey sources. This is because it is ultimately the absorption and emission efficiencies that determine the equilibrium temperature of the grain with respect to the radiation field. The temperature of the grains then determines the amount of emission at a given wavelength (Figure 3-4), and the ratio of the emission at two wavelengths is how we connect the models to the observations (Figure 3-5). Therefore, the effects of the varying efficiencies are seen directly in all of the various model outputs. This is not surprising since these are radiative equilibrium models, which means that the interaction of the grains with radiation is the most fundamental physical process with which we are dealing.

To discuss the reasons behind this characteristic 'S' shape of the curves we will use Figure 3-3 as an example. We divide the figure into the regions represented by the three shades of gray where each of the regions defines a regime where certain interactions between the grain efficiencies are determining the shape of the model output curves. At the leftmost side of the plot the grains have a diameter of 0.01 μm, similar to the wavelength of UV radiation. At this point the small grains do not effectively absorb the stellar radiation and have relatively low temperatures. As you move from the leftmost side of the plot through region I to larger grain sizes, both the absorption and emission efficiencies increase; however, the absorption efficiency increases more quickly than the emission efficiency and we see a rise in grain temperature. At the boundary of regions I & II the absorption efficiency reaches a maximum resulting in the maximum grain temperature for a given distance from the star. As we move through region II toward
region III the absorption efficiency of the grains stays relatively constant but the emission efficiency increases which results in cooler temperatures for the grains. Near the boundary of regions II & III the grain temperatures actually dip below the blackbody temperature for grains at a given distance from the star. This seemingly incongruous result stems from the fact that for grains with D=20 μm their emission efficiency can go up as high as 2 due to emission in silicate resonances and they become super efficient emitters (Wyatt et al. 1999). In region III we move out of the regime where they grains are super emitters and their temperature climbs back up toward the blackbody temperature for grains at that distance from the star. The same overall shape can be seen in the curves in Figures 3-4 and 3-5. We have shaded these figures similarly to illustrate the three regions. The effects of the changing efficiencies are especially evident in Figure 3-4 since there we are looking at the quantity \( Q_{\text{abs}}(\lambda, D) \times B_\nu[\lambda, T(D, r)] \) and the variations in \( Q_{\text{abs}} \) directly change the shape of the plots.

**Color Temperatures and Optical Depths**

We can also use equation (3) to calculate a value for the mid-IR optical depth of the material around the survey sources. If we use our size limits in Table 3-1 to calculate a value for the solid angle (\( \Omega(D) \)) subtended by the entire mid-IR-emitting region, and note that \( Q_{\text{abs}} \propto \tau_\nu \) through the relation:

\[
\tau = \pi(D/2)^2 \times Q_{\text{abs}} \times n_d \times L \quad (4)
\]

where \( \pi(D/2)^2 \) is the cross sectional area of a grain with diameter \( D \), \( n_d \) is the number density of the grains along the line of sight, and \( L \) is the line-of-sight path length we can then solve for a consistent \( T, \tau \) pair. Using our observations at the two different
wavelengths (10.8 and 18.2 \(\mu m\)) and equation (3) we then have two equations and two unknowns for the temperature and \(\tau\) for the mid-IR-emitting dust:

\[
F_{10.8 \mu m} = \Omega \times \tau_{10.8} \times B_{\nu}[10.8 \mu m, T] \quad (5)
\]

and

\[
F_{18.2 \mu m} = \Omega \times \tau_{18.2} \times B_{\nu}[18.2 \mu m, T] \quad (6)
\]

We can then solve these equations iteratively for the color temperature of the dust, \(T\), and the corresponding depth of the dust, \(\tau\). To absolutely scale the optical depth we use \(\lambda_\tau = 9.7 \mu m\) as our reference wavelength. The resulting color temperatures and optical depths are listed in Table 3-3. There is good agreement between this method of temperature calculation and the grain temperatures returned by the modeling code. If we calculate the average grain temperatures returned by the models for each source, and compare that temperature to the calculated color temperature for the same source the mean difference between the two methods is < 30 K for the survey as a whole.

We next investigate the dynamical properties of the thermally emitting grains using our models. A particles radiation pressure efficiency (Qpr) can be calculated from its optical constants using Mie theory. Qpr is related to its absorption and scattering efficiencies through the relation

\[
Q_{pr} = Q_{abs} + Q_{sca} (1 - \langle \cos \theta \rangle)
\]

where the \(\langle \cos \theta \rangle\) term accounts for the fact that radiation is scattered asymmetrically from the particles (Wyatt et al 1999). Once we have Qpr calculated we can consider the ratio of the radiation forces acting on the particle to the gravitational forces as a function of particle diameter. This ratio, called \(\beta\) is given by the relation below
Figure 3-6: The quantity $\beta$ as a function of grain diameter for particles near HD 141569. Horizontal line marks a value of 1. Particles with $\beta > 1$ will be removed from the system on hyperbolic orbits in $< 10^4$ yr.

\[
\beta(D) = \frac{C}{\rho D} <Qpr>_T \left( \frac{L_*}{L_\odot} \right) \left( \frac{M_*}{M_\odot} \right) \tag{7}
\]

where $C = 1.15 \times 10^{-3}$ kg m$^{-2}$, $\rho$ is the particle density, $D$ is the particle diameter, and

\[
<Qpr>_T = \int Qpr(D,\lambda) F_\lambda \, d\lambda / \int F_\lambda \, d\lambda
\]

is the particle’s radiation pressure efficiency averaged over the stellar spectrum with assumed temperature $T_*$ (Wyatt et al. 1999). By calculating $\beta$ as a function of particle diameter, we can determine what sized particles will be removed from the system through radiation expulsion. Particles with $\beta > 1$ will be removed from the system by radiation expulsion on very short timescales. On average, the time for removal for the survey stars is $<10^4$ yr. Figure 3-6 shows $\beta(D)$ for HD 141569. The horizontal line marks $\beta = 1$. Using Figure 3-6 we see that for HD 141569 all particles smaller than $D = 5 \mu$m have $\beta > 1$ and will be removed from the system quickly. We can therefore make the claim that grains
with D < 5 μm are likely not primordial, and have been replenished by some mechanism. The determination of whether or not the mid-IR-emitting grains in the survey disks is an important conclusion of the modeling since the presence of “second-generation” dust in these disks places them firmly in the Vega-like class (Lagrange et al. 2000). Plots similar to Figure 3-6 for all the modeled survey sources allow us to set a limit on the minimum size of grains that would not be removed from the system through radiation expulsion. These “β-Limiting” sizes are given in the last column of Table 3-3. To reiterate, all grains smaller than the ‘β Limiting’ size (i.e. the blow-out size) will be removed from the system by radiation expulsion.

Another dynamical property we investigate is the lifetime of the disk particles with respect to Poynting-Robertson drag (P-R drag). Once we have calculated β(D) we use the following relation to calculate the P-R drag lifetimes of the grains as a function of diameter.

\[ t_{PR}(D) = 400(M_\odot/M_\star)(r^2/β(D)) \]

where r is the distance of the grain from the star in AU. Using the upper limits for grain diameter and distance from the star, we calculate a maximum P-R drag lifetime for the mid-IR-emitting grains in each disk. This maximum value represents the longest time any mid-IR-emitting grains would survive in the disk before spiraling into the star. If the grains are smaller than our upper limit, or closer to the star, their P-R drag lifetimes would be less than this value. We list the calculated maximum values for the survey stars in Table 3-3. The longest P-R drag lifetime in the survey is 3\times10^6 yr, for grains near HD 9672. Although it is not certain, we suspect that all of the survey sources are older than this value. It therefore seems likely that the mid-IR-emitting grains in these disks
Table 3-3: Derived Grain Parameters

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Mid-IR Color Temp. (K)</th>
<th>$\tau_{\text{mid-IR}}$</th>
<th>Grain size upper limit ((\mu)m)</th>
<th>Grain Distance Upper Limit (AU)</th>
<th>Max. P-R Drag Lifetime (yr)</th>
<th>$\beta$-Limiting size ((\mu)m)</th>
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<tr>
<td>HD 9672</td>
<td>107</td>
<td>6.30E-03</td>
<td>7.00</td>
<td>111.0</td>
<td>3.0E+06</td>
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<tr>
<td>HD 34282</td>
<td>375</td>
<td>3.80E-05</td>
<td>10.00</td>
<td>10.0</td>
<td>3.0E+04</td>
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<td>HD 34700</td>
<td>165</td>
<td>5.60E-03</td>
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<td>9.0E+05</td>
<td>0.9</td>
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<td>HD 35187</td>
<td>211</td>
<td>9.90E-02</td>
<td>5.00</td>
<td>31.0</td>
<td>3.0E+05</td>
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<tr>
<td>HD 38678</td>
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<td>2.80E-06</td>
<td>4.00</td>
<td>5.0</td>
<td>5.0E+03</td>
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</tr>
<tr>
<td>HD 39060</td>
<td>171</td>
<td>6.80E-02</td>
<td>4.00</td>
<td>31.0</td>
<td>5.0E+05</td>
<td>3.5</td>
</tr>
<tr>
<td>HD 98800*</td>
<td>157</td>
<td>1.84E-01</td>
<td>2.50</td>
<td>5.0</td>
<td>2.0E+05</td>
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<tr>
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<td>7.00</td>
<td>630.0</td>
<td>1.0E+05</td>
<td>&gt;100</td>
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<tr>
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<td>8.00</td>
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<td>15.00</td>
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<td>HD 139614</td>
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<td>2.0E+05</td>
<td>3.5</td>
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<td>4.5</td>
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<td>4.0</td>
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<td>2.5</td>
</tr>
<tr>
<td>HD 155826</td>
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<td>1.0E+05</td>
<td>1.5</td>
</tr>
<tr>
<td>HD 158643</td>
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<td>13.0</td>
<td>5.0E+04</td>
<td>9.0</td>
</tr>
<tr>
<td>HD 163296</td>
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<td>3.00</td>
<td>13.0</td>
<td>5.0E+04</td>
<td>6.0</td>
</tr>
<tr>
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<td>9.60E-02</td>
<td>4.00</td>
<td>30.0</td>
<td>4.0E+05</td>
<td>3.0</td>
</tr>
<tr>
<td>HD 188037</td>
<td>410</td>
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<td>6.00</td>
<td>5.0</td>
<td>9.0E+03</td>
<td>5.0</td>
</tr>
<tr>
<td>HD 233517</td>
<td>142</td>
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<td>10.00</td>
<td>81.0</td>
<td>1.0E+06</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Mean values:
- 232 K
- 0.042
- 6 \(\mu\)m
- 25 AU
- 4.4E+05 yr
- 6.0 \(\mu\)m

* $\beta < 1$ for all grain sizes

are not primordial material and have been replenished in some way. One method of replenishment is through the collisions of larger bodies in the disks. Replenishment of material in this manner is apparently occurring in the archetypal Vega-like disks of both $\beta$ Pictoris (Artymowicz 1997), and HR 4796A (Wyatt et al. 1999; Telesco et al. 2000).
The last row of Table 3-3 contains the mean values of each of the quantities listed in the table. We calculate these numbers simply to give an idea of the properties of these disks in the broadest sense. Certainly these values are only useful as benchmarks for the survey sources, however, it is interesting to compare them with values from other Vega-like disks. In particular the mean upper limit to the mid-IR-emitting grains size is very consistent with the grain sizes in other Vega-like disks. Similar modeling of the HR 4796A disk by Wyatt et al. (1999) and Telesco et al. (2000) shows that the grains in that disk are approximately 2 μm in diameter. Mid-IR aperture photometry of β Pictoris implies there are 1 to 3 μm grains in that archetypal disk (Telesco et al. 1988; Telesco & Knacke 1991; Aitken et al. 1993). Vega itself is also reported to have 1 to 10 μm grains as the dominant population in its disk (Van der Bliek, Prusti, & Walters 1994).

The fact that our estimated grain sizes for the 22 survey sources we studied have mid-IR-emitting grains that are similar in size to the archetypes is one of the main conclusions of our work. In fact, the mid-IR emission detected around this class of source is tracing this size range of grains in their disks. This is more or less expected since this is thermal emission from the dust we are detecting and the dust grains emit most effectively when their size is comparable to the wavelength of the radiation they are emitting. In the next section we continue with our comparison of the survey sources to some of the archetypes.

**Scale Size Comparison**

An obvious question to ask is, would the unresolved sources be resolved if they were at the distances of β Pictoris or HR 4796A? The average distance of the modeled
survey sources is 95 pc, while β Pictoris is at 19 pc, and HR 4796A is at 67 pc. To answer this question we ‘moved’ the unresolved sources to the distances to those archetypes and calculated what their model predicted size would be. In this analysis we assume that the maximum extent of the mid-IR-emitting grains from the stars is given by the upper limits returned by our models, which are listed in Table 3-3. Using these values in conjunction with the distance estimates for the stars given in Table 2-1 we can
calculate a predicted angular size for each of the disks. We then scaled those predicted sizes to what they would be at the distances of β Pictoris and HR 4796A. These predicted and scaled sizes are listed in Table 3-4. Assuming that we are using an 8 to 10 m class telescope to make the observations, by analogy with HD 169142 (Chapter 4), we set the threshold of detection at an angular size 0.7". While this limit is somewhat arbitrary, our experience with the survey data has shown that this is about the limit at which a face-on disk source can be distinguished from PSF measurements. This represents a worst-case scenario though since edge-on disks may be detectable at smaller angular scales.

What we see is that for the most part the predicted disk sizes at the real distances of the stars are in the tenths of arcsecond range, below the current limit of detectability. This changes somewhat when we move the survey stars to the distance of the archetypes. At the distance of β Pictoris, the closer of the two, we predict that we could have resolved twelve, or 54% of the disks. This seems to imply that it is only an observational limitation that prevents us from resolving them. This is clearly a very rough way to estimate the detectability of these sources. However, it does give us a starting point for the planning of more in-depth observational programs.

Conversely, Table 3-4 shows that if we move the two archetypes to the distances of the survey sources, we would be able to resolve both the disks of both β Pictoris and HR 4796 at effectively all the distances of the survey stars. This implies that the disks of the unresolved sources have a smaller scale size than the archetypes. While the cause of this scale size discrepancy is still not fully understood one idea that may explain it deals with the size of the mid-IR-emitting grains in the disks. If the grains in the β Pictoris and HR 4796 disk are smaller than those in the disks of the unresolved sources, they will be
detected farther from the stars since smaller grains in equilibrium with a radiation field are hotter than larger ones at a given distance from the star. If the grains in the unresolved disks are larger than those in the archetypes, even by a factor of a few in diameter, they will have to orbit their parent stars within a few AU for a late A-type star to emit strongly in the mid-IR. This idea is supported by the results presented in Table 3-3 where we see the model results imply that the grains around most of the unresolved sources orbit within ~20 AU of their stars and have diameters of ~6 μm. Compared to the ~2 to 3 μm diameter grain in the β Pictoris and HR 4796 disks, the larger grains size may account for the unresolved nature of some of the survey sources. The idea that the mid-IR-emitting grains in the disks of the unresolved sources are larger also has implications for the evolutionary status of those disks, and therefore the stars. Since it is believed that the grains in these disks grow through aggregation, disks with larger grains in them are likely older than those with small grains. In a later section of this chapter we investigate the evolutionary status of these sources in detail, and propose an evolutionary sequence for our survey sources.

Here we touch on two limitations of our modeling that are related to the basic assumptions we made about the composition and morphology of the grains. Obviously, the dust grains may not be simple Mie spheres. For example, the zodiacal particles in our solar system seem to have a much more complex “bird’s nest” structure. The “bird’s nest” like appearance of these grains occurs because the grain itself is actually an aggregate of tens or hundreds of smaller particles that have stuck together through collisions (Gustafson 1994). As noted, we have assumed that the observed grains are solid and spherical. However, if the grains are actually aggregates and complex in
appearance ("fluffy"), our overall conclusions about particle lifetimes are not significantly changed. Gustafson (1994) points out that Mie calculations for homogeneous spheres consistently underestimate the value of $\beta$ for aggregated dust models by a factor of two. For our survey sources, this means that even larger particles would have $\beta > 1$, and would be expelled from the star/disk systems in a short time. Since the P-R drag lifetime of a particle is proportional to $\beta^{-1}$ (Wyatt et al. 1999), the larger value of $\beta$ for a grain of a given size would drive its P-R drag lifetime down, implying that the grain would spiral in to the star in a shorter time. We therefore see that if the grains in the disks of the survey sources are porous or fluffy, it does not change our overall conclusion that most of them are second-generation grains, perhaps collision fragments.

The modeling presented here has shown that the mid-IR-emitting grains in the disks of the survey sources are on the order of a few microns in diameter, similar to the grains in the archetypal disks of $\beta$ Pictoris, Vega, and HR 4796. It has shown that these grains orbit at distances of tens to a hundred AU from the central stars, and have temperatures in the range of 150 to 250 K. Considerations of the dynamical properties of the grains like their P-R drag lifetime and the parameter $\beta$ imply that these grains are likely not primordial, and have been replenished by some mechanism. We also present rough calculations which show that about half of the disks could possibly resolved at the distance of $\beta$ Pictoris, but that the dust lies too close to the other half of the sources to be seen even at this relatively close distance of 19 pc. The main conclusion that we draw from our models is that the mid-IR properties of the survey sources are, in fact, similar to those of the archetypes. The fact that the mid-IR-emitting grains in the survey disks are
probably replenished places them firmly into the debris disk class, and the similarity in their grain sizes, temperatures, and distances from the central stars to those of the archetypes implies that they are at a similar evolutionary state. In the following sections we expand on this idea of source evolution and present an evolutionary sequence for the survey stars.

A Proposed Evolutionary Sequence

In this section we present an evolutionary sequence we have constructed for our survey sources using the properties of their mid-IR excesses in conjunction with the characteristics of the stars. The idea that the Herbig Ae/Be stars are the progenitors of the Vega-like stars is well represented in the literature (cf. Lagrange et al. 2000; van den Ancker et al. 1998). Trends seen in the characteristics of properties of disks also support such an evolution. For example, Holland et al. (1998) sees a strong trend of decreasing disk mass with age. Their Figure 2 clearly shows that the mass of the dust associated with Herbig Ae/Be stars is orders of magnitudes greater than that in the tenuous disks in our sample (Holland et al. 1998). More relevant to the discussion of our evolutionary sequence is the trend seen in the evolution of the spectral energy distributions (SED) of sources with associated circumstellar dust. Below we discuss how this idea is directly related to our survey sources.

SED Evolution

For a graphical representation of what SED evolution looks like we reintroduce the scheme of Andre (1994) in Figure 3-7. This figure shows how the SED of a star/disk
Figure 3-7: SED evolution of a star/disk system moving onto the ZAMS. Most of our survey sources fall into Class III, but a small number of them exhibit some characteristics of a Class II source. Using our survey sources we refine the Class III group here by subdividing it into three smaller parts.

system evolves during the first few Myr of its existence. The most important trend to notice in regards to our proposed additions to this sequence is how the overall amount of excess emission decreases as the system evolves. That is, as the system evolves, less of the overall infrared luminosity comes from the circumstellar dust, and the SED of the system approaches that of the star itself, a simple blackbody curve. By the time the
source can be classified as Class III in this scheme the dust associated with the star has become optically thin and only contributes a fraction of the overall system luminosity. The low optical depths we derived for them in Table 3-3 support the idea that the dust around our survey stars is optically thin. As we will see, a subset of our survey stars have SEDs that have characteristics of an object transitioning from Class II to Class III. However, the majority of our survey stars can be classified as true Class III objects.

To introduce our survey sources into the context of this sequence we present Figure 3-8. In this figure we show three examples of SEDs of sources in our survey. In the top panel we show the SED of HD 143006. Note the strong near-IR excess associated with this source. We suggest that the presence of such an excess can be taken as a sign of relative youth within the survey sources. This excess comes from dust that is close to the star, within a couple AU in the case of HD 143006. The fact that there is dust so close to the star implies that the processing of the inner disk has yet to commence. Indeed, the last stages of active accretion may still be occurring in this system. Nine of our survey sources exhibit excess emission in the near-IR, and these nine star/disk systems form the first of three sub-groups we break our survey sources into. We name this sub-class "Class IIIa" since the SED of these sources is similar to that of a source that has just evolved into Class III in the Andre (1994) scheme. The middle panel of Figure 3-8 shows the SED of HD 141569, a source that falls into our second sub-class (named Class IIIb). Along with HD 141569, the other three members of this group represent an intermediate stage of evolution within our survey. The four sources in Class IIIb exhibit no near-IR excess, however they all have well defined excesses in the mid-IR. Processing of the inner disk regions is most likely still ongoing in these sources. Interestingly, three out of...
Figure 3-8: SED evolution within our survey. (top) SED of HD 143006. Note the strong near-IR excess associated with this source. (middle) SED of HD 141569. This source represents an intermediate evolutionary step. There is no near-IR excess associate with this star. (bottom) SED of HD 142764, a source that represents the last stage of evolution within our survey. No near-IR or mid-IR excess is associated with this star.
the four sources in Class IIIb have been resolved in the mid-IR. The bottom panel of Figure 3-8 shows the SED of HD 142764, a source representative of the last of the three sub-groups, Class IIIc. HD 142764 and the other sources in this group exhibit no excess emission in the near-IR, and little or none in the mid-IR either, indicative of them being the most evolved. By the time a star/disk system evolved to this point, processing of the inner portions of the disk has taken place, and a central hole has formed leading to the paucity of excess IR emission. In the next section we discuss the three sub-classes in more detail, and show how each group is tied together by common characteristics.

Class IIIa: The near-IR Nine

The first sub-class we discuss is the group that represents the earliest stage in the evolutionary sequence. Class IIIa contains nine of our survey sources that have a common trait in that they all exhibit significant near-IR excess. Because of this the SEDs of these sources all resemble that of HD 143006 (Figure 3-8 top), which exhibits a strong near-IR excess as seen in Figure 3-8. Listed in Sylvester et al. (1996) we see that the nine sources have an average of 0.6 mag of excess at 1.7 μm, and 1.1 mag of excess at 2.2 μm. Sylvester et al. (1996) also calculated blackbody fits to the near-IR excesses of the sources and found that grain temperatures in the range of 1500 to 2000 K fit the excess well. In our own analysis of these sources we find that the Class IIIa stars exhibit 7 out of the top 10 highest mid-IR optical depths (see Table 3-3). The fact that these stars have near-IR excess, and relatively high optical depths makes them similar to Herbig Ae/Be stars, and they are therefore most likely young. Indeed, at least 3 of the 9 Class IIIa stars show hydrogen emission lines in their spectra (Sylvester et al. 1996), another sign of
Figure 3-9: SED of HD 169142 with $(\lambda)^{-4/3}$ plotted for comparison. The diamonds are flux estimates for HD 169142 from Sylvester et al. (1996). Squares are our OSCIR fluxes. The solid line is a blackbody function with $T_{\text{eff}} = 8400$ K. The dashed line follows the relation $F(\lambda) \propto (\lambda)^{-4/3}$.

youth as compared to the other survey sources. Since it seems these sources are the youngest in our survey, we use these sources as the starting point in our evolutionary sequence.

One of the main distinctions between Class II and Class III sources is whether their disk is optically thick or thin. Class II sources have optically thick disks, while those associated with Class III stars are optically thin. As noted by Hillenbrand et al. (1992) one of the most powerful diagnostics of a circumstellar disk is its SED in the near-IR $(1 \ \mu m < \lambda < 2.2 \ \mu m)$. Objects with flat, optically thick disks have SEDs that follow a $\lambda^{-4/3}$ falloff wavelength. This fact gives us a criterion we can employ to place our survey sources into the correct class. We know that any optically thick disks will follow that
functional relationship, and would belong in Class II. A steeper than $\lambda^{-4/3}$ falloff in
indicative of emission from an optically thin disk, and warrant a Class III designation of
any source whose SED follows this trend. To answer the question of whether the sources
we designate as Class IIIa are actually Class II sources we present Figure 3-9. In this
figure we plot the SED of one of the Class IIIa sources, HD 169142. Its SED is
representative of all nine of the Class IIIa sources showing a strong near-IR excess
beginning at approximately $\lambda = 1.4 \text{\mu m}$. HD 169142 is an A5 V star with a $T_{\text{eff}} = 8400 \text{ K}$
(Dunkin, Barlow, & Ryan 1997) and we plot a blackbody function with this temperature
as a model photosphere in the figure. Also plotted is a dashed line designating a $\lambda^{-4/3}$
falloff with wavelength. Inspection of the figure shows that in the near-IR regime, which
is bracketed by the two vertical lines, the SED of HD 169142 has a much steeper falloff
than $\lambda^{-4/3}$. This implies that HD 169142 and the other eight sources with similar SEDs are
likely to have optically thin disks, and should rightfully be classified as Class IIIa objects.

Class IIIb: ZAMS Sources

The next step in our sequence brings us to Class IIIb. The four sources in this
class do not exhibit any near-IR excess, implying that they are somewhat older than the
Class IIIa stars. These stars do have a common trait though, they all have low
luminosities for their colors, which places them very near the ZAMS in the H-R diagram
(Jura et al. 1998). Interestingly, 3 out of the 4 sources (β Pictoris, HR 4796A, and HD
141569) in this class have been resolved in the mid-IR.

With respect to how these sources fit into the evolutionary sequence, we can ask
the question: how young are they? Luckily, for this sub-class we have an answer for that
question. One of the Class IIIb members is HR 4796A, which has a well-constrained age of 8 ± 3 Myr (Stauffer et al. 1995). Recent work by Barrado y Navascues et al. (1999) uses Hipparcos data and evolutionary tracks to estimate the age of the archetype β Pictoris at 20 ± 10 Myr, similar to the age of HR 4796A. The third resolved source, HD 141569 has no published age values. However, we show in Chapter 5 that it is likely a source that is transitioning from the Herbig Ae/Be class to the Vega-like class. Lagrange et al. (2000) coin the term "old-pre-main-sequence" star when describing HD 141569, indicating that it is more or less finished with its PMS evolution and is approaching the ZAMS. The age estimates for HR 4796A and β Pictoris, along with their position on the ZAMS seem to imply that these stars are relatively young, perhaps 10 to 30 Myr old. Since it seems that they are finished with their PMS evolution, we suggest that they are older than the Class IIIa sources, and form the second step in our sequence.

Class IIIc: Post - ZAMS Sources

The last sub-group in our sequence is Class IIIc. The remaining twenty-six stars in our survey fall into this class. They represent sources that are the most evolved and have most likely already moved onto and then off of the ZAMS and are now crossing the main sequence in the middle stage of their lives. Class IIIc sources show no near-IR excess, and little if any mid-IR excess. In fact, all of the sources that we could not model due to uncertain excess determination fall into Class IIIc. None of the sources in this class exhibit any signatures of youth, like emission lines in their spectra. We take the paucity of near and mid-IR excess coupled with the lack of any signatures of youth to mean that these are the most evolved sources in the sample. In reality, these sources could likely
Table 3-5: Evolutionary Class characteristics

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Shortest Excess Wavelength (µm)</th>
<th>Age (Myr)</th>
<th>H-R Diagram Position</th>
<th>Class Characteristics</th>
</tr>
</thead>
</table>
| Class IIIa | 1.2 to 1.7                      | < 10      | Pre-ZAMS             | - Hα emission in spectra  
- Li seen in source spectra  
- Strong near-IR excess |
| Class IIIb | 10 - 20                         | 10 to 20  | ZAMS                 | - no near-IR excess  
- strong mid-IR excess  
- Good age estimates |
| Class IIIc | > 20                            | > 20      | Post-ZAMS            | - little or no mid-IR excess  
- no signatures of youth |

form a new class, “Class IV” in the schemes of Andre (1994) and Hillenbrand et al. (1992). A class that would represent sources already on the main sequence, completely finished with the formation and PMS evolution.

In Table 3-5 we summarize the characteristics of the new sub-groups. To quantify the idea of SED evolution we list the wavelengths at which the excess ‘turns-on’ for each class and show that it increases with age. We also list approximate ages for each of the groups and their corresponding position in the H-R diagram. Finally, we comment on some of the common characteristics for each of the sub-classes that we use to tie each group together. In the next and final section of this chapter we use the H-R diagram to graphically illustrate our proposed evolutionary sequence.
Survey Sources in the HR Diagram

It is useful to investigate the position of our survey sources in the H-R diagram. Such an investigation allows us to graphically see how the survey fits into the overall scheme of stellar evolution, and it gives us another way to present our evolutionary sequence. For this purpose we use a H-R diagram comprised of \approx 41000 stars taken from the Hipparcos database (Perryman et al. 1995). We have Hipparcos measured distances for 90% of the stars in our survey, and we use them in conjunction with their Tycho measured B-V values to place them in the diagram as shown in Figure 3-10. For most of the sources this is the first time their newly measured distances have been used to place them in the diagram. In fact, this is the first time ever that Hipparcos and Tycho data has been used in conjunction with a significant number of Vega-like stars to illustrate their position in such a diagram. Inspection of Figure 3-10 shows that several interloping giants made their way into the survey, one in particular, SAO 26804, is discussed in detail in Chapter 6. However, generally the sources are on, or near the main sequence.

While it is instructive to see the whole survey in the diagram, the real value of this kind of presentation comes into view when we discuss our proposed evolutionary sequence. We present the sequence as a series of three panels in Figure 3-11. In Figure 3-11a we show our so-called Class IIIa sources. These represent the youngest of our survey sources, and we propose that they are still moving onto the ZAMS. In Figure 3-11b we show our Class IIIb stars. These are the sources that have relatively well defined ages at \approx 10 Myr. Notice that we can now see that they all have low luminosities for their colors, as reported by Jura et al. (1998). Since they are very close to the ZAMS we use them as a useful fiducial point in the sequence. These sources are somewhat of a fulcrum point,
Figure 3-10: The Vega-like survey sources in the H-R diagram. This figure shows the sources of the survey plotted in a HR diagram comprised of ~41000 stars from the Hipparcos catalog. The four squares are the position of the disks that have been resolved in the mid-IR, β Pictoris, HR 4796A, HD 141569, and 49 Ceti. The arrow is a reddening vector. Hipparcos data from Perryman et al. (1995).
Figure 3-11: Three steps in an evolutionary sequence on the H-R diagram. (a) Step 1: Class IIIa sources, stars moving onto the ZAMS. (b) Step 2: Class IIIb sources, stars which are on the ZAMS. (c) Step 3: Class IIIc sources, stars moving away from the ZAMS.

about which the other stars in the survey pivot. On one side of the fulcrum are the Class IIIa sources, which are younger and still moving onto the ZAMS. On the other side, we have the Class IIIc sources that are most likely older and have already reached and moved off of the ZAMS.

To investigate the timescales involved with the first stage of this sequence, we present Figures 3-12, and 3-13. In Figure 3-12 we have plotted the Class IIIa and IIIb stars in the H-R diagram with the PMS evolutionary tracks of Palla and Stahler (1993) overlaid. Using the tracks we determine age estimates for the Class IIIa sources in the range of 3 to 10 Myr, consistent with them being younger than the Class IIIb stars. Indeed, the Class IIIb stars lie at the end of the PMS tracks while the Class IIIa sources look to be still following them onto the ZAMS. The isochrones of Iben (1965) agree with the age estimates given by the PMS tracks. In Figure 3-13 we see that most of the Class IIIa sources lie between the 3 Myr and 10 Myr isochrones.
Figure 3-12: H-R Diagram with the PMS evolutionary tracks for intermediate mass stars of Palla and Stahler (1993) overlaid. The stellar birth line is the dotted line. The mass associated with each evolutionary track is given on the left in units of $M_\odot$. Tick marks on each track correspond to the times listed in the legend. Age estimates for these sources are in the 3 to 10 Myr range.
Figure 3-13: H-R Diagram with the isochrones of Iben (1965) overlaid. Also plotted are the Class IIIa and Class IIIb stars. Class IIIa (circles) and Class IIIb (squares) stars are plotted for comparison. The times to reach each isochrone is given on the left side of each.
As noted by Lagrange et al. (2000) a problem with using this method for age estimates is that isochrones are normally bi-valued. That is, under normal circumstances you cannot distinguish between a source moving onto the ZAMS and one evolving away from it. Our sequence eliminates this issue since we use the shape and apparent evolution of the SED of a source to determine whether or not is moving onto or away from the ZAMS. Hence, we believe our method solves this problem for our survey.

That is in essence the extent of our proposed sequence. By sub dividing the survey into three sub-classes we have come to one of the main conclusions of this work. That is that we feel the evolution of the SEDs of the sources, coupled with the positions of the sources in the H-R diagram is strong evidence that Vega-like sources in our sample evolve in this manner. In the next chapters we move to talking about individual survey sources. Chapter 4 discusses the face-on disk of HD 169142, Chapter 5 presents our work on HD 141569, and in Chapter 6 we present results that ‘de’-resolve the source SAO 26804. In Chapter 7 we discuss the OSCIR camera system and its important role in this dissertation.
CHAPTER 4
THE FACE-ON DISK OF HD 169142

In this chapter we present Keck imaging of the source HD 169142. Our images show the source to be resolved at both 10 and 18 μm with strongly detected extended emission seen in the form of a seemingly face-on disk with diameter approximately equal to 1.2". At a distance of 145 pc (Sylvester et al. 1996) this corresponds to a radial extent for the mid-IR emitting dust of ~85 AU, which is very similar to the size of the mid-IR emitting regions of the archetype β Pictoris and the source HD 141569 (Lagage & Pantin 1994; Fisher et al. 2000). Although we have a high degree of confidence in our detection of extended emission associated with the source, we have no significant spatial information on the distribution of the dust itself. This is primarily due to the fact that it is extremely difficult to accurately remove the contribution of the star from the central region of the emission. As we will discuss, the photospheric contribution to the total flux of the source is minimal, however, the spatial deconvolution of that flux from the image itself is not an easy task due to the relatively low signal-to-noise of the outer regions of the extended emission. We can however use the global characteristics of the disk to infer some of its properties. Using our images we place strong limits on the size of the extended emission and show that the orientation of the disk is nearly face-on.

We also use our observations to model the mid-IR emitting dust as silicate Mie spheres and determine a characteristic size and temperature for the grains. Since we have no little spatial information on the grain distribution, we use our images to derive 'global' dust parameters. We then use our derived grain parameters to discuss the possible
Table 4-1: Characteristics of HD 169142

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Type</td>
<td>A5 Ve†</td>
</tr>
<tr>
<td>Distance</td>
<td>145 pc‡</td>
</tr>
<tr>
<td>(B – V)</td>
<td>0.29‡</td>
</tr>
<tr>
<td>Mv</td>
<td>2.3‡</td>
</tr>
<tr>
<td>v sin(i)</td>
<td>55 ± 2 km/sec‡</td>
</tr>
<tr>
<td>T_{eff}</td>
<td>8400 K†</td>
</tr>
<tr>
<td>log g</td>
<td>4.2†</td>
</tr>
<tr>
<td>M/M\odot</td>
<td>2.0§</td>
</tr>
<tr>
<td>L/L\odot</td>
<td>14§</td>
</tr>
<tr>
<td>R/R\odot</td>
<td>1.7§</td>
</tr>
</tbody>
</table>

† Dunkin, Barlow, & Ryan (1997), ‡ Sylvester et al. (1996), § Allen (2000)

origin, and eventual fate, of the grains in the disk of this star. We also place HD 169142 into an emerging evolutionary sequence for this class of source and discuss how it may be a bridge between the well-known class of Herbig Ae/Be stars and the Vega-like sources.

Accurate stellar parameters are needed to confidently model the grains near HD 169142 and to interpret our new mid-IR images of the source. A literature search gives the relevant characteristics of HD 169142 listed in Table 4-1 above. Note that HD 169142 was originally classified as a B9 V source in the list of Walker and Wolstencroft (1988) but has since been re-classified as A5 V using high resolution optical spectroscopy (Dunkin, Barlow, & Ryan 1997). Recent photometry has also refined the rotation speed of the source and polarimetry of the source and has revealed that the source exhibits variable polarization in the near-IR (Dunkin, Barlow and Ryan 1997). These facts are important to our discussion since they give us clues to the nature of the circumstellar disk. In the rest of the chapter we present our new observations, discuss the results of our modeling of the grains in the disk, and comment on the evolutionary status of HD 169142.
As we hinted at, the evolutionary status of HD 169142 is still very much in question. It has been classified as a Vega-like star by many authors including both Walker and Wolstencroft (1988) and Sylvester et al. (1996). However, HD 169142 is also a member of various Herbig star lists like those of Malfait et al. (1998) and Corporon & Lagrange (1999). The reason that HD 169142 is on both kinds of lists is because it is one of several stars in our survey sample that exhibit characteristics of both a Herbig star and a Vega-like source. HD 169142 meets two of criteria to be defined as a Herbig star by having a spectral class earlier than F0 and exhibiting single peaked Balmer emission line profiles. HD 169142 also has HeI [λ 5876] in emission (Dunkin, Barlow, and Ryan 1997), a fact that is relevant to its evolutionary status. The star does exhibit some Vega-like characteristics though. In particular, both the existence of the large mid and far-IR excess, and its characteristic shape are very similar to those of other Vega-like sources.

We believe that the possible transitional nature of HD 169142 is evident in its spectral energy distribution (SED), which is shown in Figure 4-1. The optical-to-mm SED shows that the source exhibits a large excess for all \( \lambda > 1.7 \mu m \). First discovered by IRAS, the excess peaks between 30 to 40 \( \mu m \), which is very similar to the SEDs of all of the Vega-like archetypes. Observations by Sylvester et al. (1996) revealed a strong near-IR excess associated with the source in the H (1.7 \( \mu m \)) and K bands (2.2 \( \mu m \)) where they measure an excess of 0.4 and 0.8 mag in the H and K bands respectively. The excess becomes more pronounced at longer wavelengths and reaches 1.7 mag in the M-band (\( \lambda_{cen} = 4.8 \mu m \)) (Sylvester et al. 1996). As we discuss in the observation section, the excess is very pronounced in the mid-IR. In fact, the photosphere of the central star
Figure 4-1: SED of HD 169142. The solid line is a model photosphere the points are observed fluxes. The IR excess of HD 169142 is seen at all wavelengths > 1.7 μm. The near-IR excess can be interpreted as a sign of youth since it implies there is hot material very close to the star and that the inner disk region has yet to be processed or cleared. SED from Sylvester et al. (1996)

only accounts for a couple percent of the total flux at 10.8 μm, and an order of magnitude less than that at 18.2 μm.

Using the IRAS long wavelength data as a diagnostic Walker & Wolstencroft (1988) assigned a temperature of $T = 115$ K to the circumstellar dust around HD 169142. As we will see this value is low compared to the temperature we derive from our mid-IR data ($T \approx 175$ K). This is not an unexpected result though since Walker & Wolstencroft fit the 25 and 60 μm fluxes in the SED, while we use 10 and 18 μm data.
Mid-Infrared Observations at Keck

We observed HD 169142 as part of our Vega-like survey at the Keck II telescope in 1999 May using OSCIR. On the night of 03 May 1999 UT we first detected the extended emission associated with the source in the N-band ($\lambda_0 = 10.8 \mu m, \Delta \lambda = 5.2 \mu m$) and IHW18 ($\lambda_0 = 18.2 \mu m, \Delta \lambda = 1.7 \mu m$) filters. Our observing sequence consisted of first observing an 18 $\mu m$ PSF star (\alpha Boo). Then we observed HD 169142 for 20 minutes chopped integration (10-min on-source) at 10.8 and 18.2 $\mu m$. After the science observations we observed a 10 $\mu m$ PSF star (19 Sgr). Observations of an infrared photometric standard to absolutely calibrate the HD 169142 data finished the observing sequence (\alpha Boo, and \gamma Aql). For the HD 169142 observations a Boo was used as the 18 mm PSF star since the chosen star was not bright enough to give a good signal-to-noise detection in a reasonable integration time.

On Keck OSCIR the 128 x 128 pixel detector of OSCIR has a plate scale of 0.062"/pixel which gives a field of view of 7.9" x 7.9". The observations were made using standard chop/nod techniques with an 8" chopper throw in declination. The Keck autoguider system was used for all of the Keck observations. We estimate that there is ~1 pixel (~0.06" on Keck) of "guiding jitter" inherent in any OSCIR observations made while using it. On the Keck run in 1999 May the weather was non-photometric with thin, but uniform, light cirrus clouds present during the night that HD 169142 was observed. During post-processing of the data, chopped image pairs that were obviously compromised by the cirrus were discarded. However, there is still some uncertainty in the photometry of the source and the standard stars, which we take to be $\pm 10\%$. This
translates into the major component of the uncertainties associated with our flux estimates.

Measurements of the full-widths at half maximum (FWHM) intensities of comparison stars were approximately 0.45" and 0.49" at 10.8 and 18.2 μm, respectively. Quadratic subtraction of the diffraction limits (λ/D) of 0.22" at 10.8 μm and 0.37" at 18.2 μm from these values from implies seeing of ~0.3 to 0.4" in the 10 to 20 μm spectral region. It is our experience that these values are typical for non-photometric nights on Mauna Kea.

Our measured flux estimates of HD 169142 contain both the thermal emission from the circumstellar grains, and emission directly from the photosphere of the central star. To calculate the amount of photospheric emission the star emits in the mid-IR we normalized the J-band (λcen = 1.22 μm) flux estimate of Sylvester et al. (1996) to that of a blackbody function with effective temperature, Teff = 8400 K. We then predicted that the photospheric contribution to the 10.8 μm flux density is 41 mJy, or 1.7%. At 18.2 μm, the photosphere only accounts for 0.2% (14 mJy) of the observed flux. Our photosphere-subtracted flux estimates for HD 169142 are: 2283 ± 228 mJy at 10.8 μm, and 7187 ± 718 mJy at 18.2 μm. These flux estimates are in agreement with those of Sylvester et al. (1996). The 10.8 μm point is also consistent with the IRAS PSC 12 μm value of 2.95 Jy, however our 18 μm point is low compared to the IRAS 25 μm estimate of 18.4 Jy. Even accounting for the spectral shape of the dust SED in this regime the IRAS point seems to overestimate the flux from the source. The IRAS 25 μm point also lies above the overall level of the CGS3 spectrum of HD 169142 presented in Sylvester et al. (1996). We can only speculate as to the reason for this and an obvious hypothesis is contamination of the
IRAS beam. Since it is the ratio of the fluxes \(F_{10.8}/F_{18.2}\) that lets us place an upper limit to the grain sizes in our modeling, we believe the non-photometric quality of the sky will not fundamentally change our modeling results.

**HD 169142 Source Size**

In this section we present our new mid-IR observations of HD 169142. These observations represent the highest resolution mid-IR images currently possible. We measured a FWHM for HD 169142 of 0.57" at 10.8 μm, and 0.62" at 18.2 μm. Measured FWHM values of the PSF stars are 0.45" at 10.8 μm, and 0.48" at 18.2 μm. Subtracting these values quadratically from the HD 169142 data gives an inherent source size of 0.35" at 10.8 μm and 0.39" at 18.2 μm. Interestingly, these values match the peaks of the intensity of the residual emission of the disk. Our mid-IR data is presented in Figure 4-2 in the form of normalized radial scans along the cardinal directions through HD 169142 and a nearby PSF star (19 Sgr). Also plotted in each of the panels is the residual emission in the scan direction. Each of the scans through the source and PSF star was normalized to have a maximum of one and the peaks of the scans were aligned. The residuals were then calculated by differencing the two scans. An inherent assumption in this method is that the star sits in the exact center of the emission, and therefore the exact center of the disk. Recent work on the disk of HR 4796A by Wyatt et al. (1999) has shown that this may not be true. In that work they introduce the concept of “pericenter glow” where the long term perturbation of a disk by an object in orbit inside or outside the disk may shift the disk with respect to its central star (Wyatt et al. 1999).
Figure 4-2: Normalized scans through HD 169142 and a nearby PSF star. In all plots HD 169142 is the solid line, the PSF star is the dashed line. The dotted line is the residual emission, which is the difference of the source scan and the PSF scan. The four panels are as follows: (a) 10.8 μm – north-south direction. (b) 10.8 μm – east-west direction. (c) 18.2 μm – north-south direction. (d) 18.2 μm – east-west direction.

In the case of our HD 169142 data small (1 pixel) changes in the position of the PSF star scan with respect to the source scan produced significant changes in the shape of the residual emission, but under no circumstances could we make the residuals disappear. We therefore are confident that the residual emission is present, even within a couple tenths of an arcsecond from the peak of the emission, but we cannot say confidently say anything about the structure of the residuals. The scans in Figure 4-2 are our best estimate at the alignment of the source and PSF star, and therefore our best estimate at the residuals. The residuals are present in scans through the source at any position angle at
approximately the same level of brightness, which is consistent with the disk being almost face-on to our line of sight. Additionally, the overall shape of the residuals stays relatively constant with scan position angle. The approximate face-on orientation of the disk is also evident in our images. Both the images of the source and of the residuals are close to circular although there is a slight asymmetry in the outermost region of the 18.2 μm residuals. This asymmetry is detected at a very low level and may well be an artifact of the PSF removal. In a later section we discuss other evidence that predicts that the disk should be face-on.

The difference in the widths of HD 169142 and the PSF star is very evident at both 10.8 and 18.2 μm. Careful inspection of Figure 4-2, especially panels b and c shows that HD 169142 is broader than the PSF star even in the very core of the scans. We interpret this as meaning that there is excess emission from the dust coming from very close to the central source. We see evidence for dust emission within 0.2” in the scans and images, and it probably reaches in closer to the central source than that. This interpretation is supported by the fact that HD 169142 exhibits a near-IR excess since such an excess is caused by hot dust at temperatures of 500 to 1000 K. Calculations show that blackbody grains need to be within a couple of AU of the star to reach these temperatures. The fact that there may be dust this close to the star also has implications for the evolutionary status of the disk that we address in a later section.

Modeling of Characteristic Grain Parameters

Here we present and discuss our modeling of the grains in the HD 169142 disk. We can use our observations at two wavelengths to estimate basic parameters of the mid-
IR-emitting grains in the disk such as their temperature and approximate size. To derive these properties we make an assumption about the composition of the grains.

To address the question of the composition of the mid-IR-emitting grains in the disk of HD 169142 we present the spectra shown in Figure 4-3. Here we see two moderate resolution spectra of the source that give complete wavelength coverage of the thermal infrared region. The top panel of Figure 4-3 is an ISO-SWS spectrum reproduced
from Walker & Heinrichsen (2000). The bottom panel is a CGS3 spectrum of HD 169142 from Sylvester et al. (1996). In these spectra we see compelling evidence that there are both silicate grains and polycyclic aromatic hydrocarbons (PAHs) present in the disk. The features seen between 7 and 9 µm, and the sharp peak at 11.3 µm are normally attributed to PAH grains. In fact, HD 169142 was the first Vega-like source to have these features detected in its 10 µm spectrum (Sylvester et al. 1994). Also present in the HD 169142 spectrum is a broad silicate feature that dominates the 20 µm region, which is caused by the stretching of Si:O bonds in the silicate molecules. Another clue to the existence of silicate disk material is the fact that optical spectroscopy has shown that HD 169142 has a large under abundance in both Si and Mg. HD 169142 is deficient by 0.86 dex in Si, and 0.56 dex in Mg as compared to the Sun (Dunkin, Barlow, & Ryan 1997). These values are by far the lowest abundance of these elements of any star in the 13 Vega-like sources studied by Dunkin, Barlow, & Ryan (1997). Dunkin, Barlow, & Ryan (1997) suggests that the photospheric depletions of these elements is indicative of the material residing in circumstellar grains, and indeed the presence of the 20 µm silicate feature seems to support this hypothesis.

These results imply that there are at least two different grain populations in the disk. This has consequences for our modeling of the grains since our models assume that the grains are composed of the astronomical silicates of Draine and Lee (1984). However, since we are working with the global flux estimates of the source it is impossible to decouple the emission of the silicate grains from that of the PAHs. To deal with this we treat the PAH emission as a ‘contamination’ and run the models assuming that it
contributes varying amounts to the total 10.8 \textmu m flux. Below we discuss our models and this process in detail.

Model Results

Before we discuss the results of our modeling we introduce the model itself and synopsize its operation. The University of Florida Dust Dynamics group developed our model initially to work on the zodiacal dust of the Solar system. We have used these thermal equilibrium models to analyze similar data on the disk of HR 4796A (Telesco et al. 2000; Wyatt et al. 1999) and HD 141569 (Fisher et al. 2000; chapter 5). Our models assume the grains are spherical Mie particles composed of the astronomical silicates of Draine and Lee (1984) with a density $\rho = 2.5$ g cm$^{-3}$.

The results presented there we first need to discuss the operation of our models. The primary inputs to the modeling code are the optical constants of the grains, and the characteristics of the grain heating source. In this case the only heating source is HD 169142 itself and we use the data in Table 4-1 as our inputs. We also input a distance to the source, a vector of grain sizes (diameters in \textmu m) we want the code to model, and a vector of wavelengths we want the code to calculate fluxes for. Our models then start with the optical constants of astronomical silicates (Draine and Lee 1984) and use Mie theory to calculate the absorption efficiencies ($Q_{\text{abs}}$) for different sized particles and different wavelengths. Once we know how efficiently a particle of a given size absorbs and emits radiation, we can calculate what its temperature would be at a given distance from the star. To do this we use the effective temperature of the star to work out the stellar spectrum, and the luminosity of the star to work out the equilibrium temperature of
the particle. Both the luminosity and effective temperature of the star are inputs into the model. Once we know the temperature of the particle and its absorption efficiency \((Q_{abs})\) we know how much radiation it will emit at any given wavelength, we can write this as: \(Q_{abs}B_v(T)\), where \(B_v(T)\) is the Planck function for the temperature of the particle. We can then plot \(Q_{abs}B_v(T)\) for different sized particles at different distances from the star for a given wavelength. These plots are shown in the top two panels of Figure 4-4. Since our observations give us the ratio of the fluxes the grains emit at 10.8 and 18.2 \(\mu\)m, we can directly compare the model output with our observations by forming the ratio of the output at the two wavelengths. That is, the ratio of the \(Q_{abs}B_v(T)\) plots at the two wavelengths (the top two panels of Figure 4-4) is just the ratio of the flux densities emitted by the particle in the two wavebands. The large panel in Figure 4-4 is the result of taking the ratio of the top two panels. A point on these resulting curves is the flux ratio expected for a particle of a given size at a given distance from the star. Also plotted on this panel is a horizontal line marked 0% that represents our observed excess flux ratio. The 50% and 75% lines plotted assume that amount of contamination of the 10.8 \(\mu\)m flux by non-silicate grains. Once we have this plot, we can immediately read off our model results by looking for where the horizontal line intersects the model output curves. It is where the curves and the line intersect that returns a grain size and distance from the source that is consistent with our observed flux ratio.

**Grain Sizes and Temperatures**

To get an accurate grain size estimate for the mid-IR emitting dust in the disk we match the model output for grains of different sizes at different distances from HD
Figure 4-4: Model output for grains 10 to 50 AU from HD 169142 assuming they are spherical Mie particles composed of astronomical silicates. (top left) Grain emission at 10.8 \( \mu m \). (top right) Grain emission at 18.2 \( \mu m \). (bottom) Flux density ratio plots for grains near HD 169142. The horizontal line marked 0\% denotes our observed flux ratio. Other lines plotted assume 50\% and 75\% contamination of the N-band flux by non-silicate grains. The points where these lines intersect the flux ratio curves represent grain sizes and distances from the source that are consistent with our observations.
169142 to the observed mid-IR flux ratio \((F_{10.8\mu m}/F_{18.2\mu m})\). However, since there is evidence that there is strong PAH emission between 7 and 9 \(\mu m\) and at 11.3 \(\mu m\) in the spectra of HD 169142 we cannot simply assume that all of the N-band (10.8 \(\mu m\)) emission we detect comes from silicate grains. To try to account for this contamination of our 10.8 \(\mu m\) flux estimate we ran three sets of models. Each run assumed that non-silicate grains (i.e. PAHs) contributed a different amount of the observed 10.8 \(\mu m\) flux. To get a feel for how strongly this contamination would change our results we ran models assuming 0\%, 50\% and 75\% of the 10.8 \(\mu m\) flux came from the PAH grains. Sylvester et al. (1996) roughly estimate that up to 50\% of the flux in the 10 \(\mu m\) region is emitted by the carbonaceous PAH grains (Sylvester et al. 1997). The grain sizes consistent with our observations assuming 50\% non-silicate 10.8 \(\mu m\) emission range from grains with diameter \(d = 6 \mu m\) 10 AU from the central star, to \(d = 0.3 \mu m\) grains 45 AU from the source. Note that the contamination of our 10.8 \(\mu m\) flux estimate by PAH emission does not dramatically change our results. Even with 75\% contamination, which is almost assuredly higher than the true amount, our grain size estimates change by less than a factor of two.

Our results are very consistent with the grain sizes in other Vega-like disks. Similar modeling of the HR 4796A disk by Wyatt et al. (1999) and Telesco et al. (2000) shows that the grains in that disk are approximately 2 \(\mu m\) in diameter. Mid-IR aperture photometry of \(\beta\) Pictoris implies there are 1 to 3 \(\mu m\) grains in that archetypal disk (Telesco et al. 1988; Telesco & Knacke 1991; Aitken et al. 1993). Vega itself is reported to have 1 to 10 \(\mu m\) grains as the dominant population in its disk (Van der Bliek, Prusti, & Walters 1994). In Chapter 5 we present results on the disk of HD 141569 where we find
the mid-IR-emitting grains are of 2 μm in size and orbit HD 141569 at similar distances. This is a very interesting result when you consider the fact that we now have estimates for the size of the mid-IR-emitting grains in at least five resolved Vega-like disks and they are all in the 1 to 10 μm range. These size estimates are very similar to those we derive for sources observed in our Vega-like survey (Chapter 3). Combining the results of the five resolved cases with those of the ~35 unresolved sources seems to uncover the trend that mid-IR emission detected around this class of source traces the location of 1 to 10 μm grains in the disks. This trend is not surprising though since this is thermal emission from the dust we are detecting, and the dust grains emit most effectively when their size is comparable to the wavelength of the radiation they are emitting.

In addition to a size estimate our observations and modeling allows us to calculate the temperature of the mid-IR-emitting grains. Using the luminosity and effective temperature of the central star (see Table 4-1) along with the optical properties of the grains we can calculate temperatures for grains of different sizes at varying distances from HD 169142. Figure 4-5 shows our model temperature output. For 6 μm grains 10 AU from the star the model returns a temperature of $T = 160$ K. For the 0.3 μm grains at 45 AU we get a temperature $T = 140$ K. These temperatures agree well with those for mid-IR-emitting grains in other resolved Vega-like disks. We derive a temperature of $T = 170$ K for the grains about 30 AU from the source in the disk of HD 141569 (Fisher et al. 2000) and work by Wyatt et al. (1999) and Telesco et al. (2000) places a temperature of $T = 120$ K on the mid-IR-emitting grains in the disk of HR 4796A.

We can also use our observations to calculate a value for the optical depth of the mid-IR-emitting material. Using the observed radius of the extended emission (~0.62") to
Figure 4-5: Model grain temperatures near HD 169142. (top) Grain temperature as a function of size and distance from the star. Distances calculated at 10 AU intervals from 10 to 100 AU. (bottom) Grain temperature vs. distance from source. In the bottom panel we see the familiar $T \propto R^{-1/2}$ shape to the curves, although the curves do not exactly follow this relation as we are not treating them as blackbodies.

calculate the solid angle subtended by the source, we derive a mid-IR color temperature for the grains of $T_{\text{mid-IR}} = 173$ K with a corresponding optical depth $\tau_{\text{mid-IR}} = 0.096$. These results are encouraging for two reasons. Firstly, this relatively simple calculation returns a temperature for the grains that is consistent with the more detailed models. Secondly, our derived optical depth measurement of 0.096 is very close to the value of 0.088 presented by Sylvester et al. (1996) for HD 169142. This value of the optical depth is
interesting since it is higher than that of the Vega-like archetypes, but low compared to a Herbig Ae/Be star. The classical Vega-like archetypes have τ values on the order of $10^{-3}$ to $10^{-5}$ (Artymowicz 1997) while the Herbig sources generally have values in the 0.01 to 0.5 (or higher) range (van den Ancker 1998). We interpret the intermediate τ value of HD 169142 as evidence that it is in fact an object in transition from one class to the other. The idea that the fractional luminosity of a disk changes as it evolves is not new. Both Holland et al. (1998) and Barrado y Navascutes et al. (1999) see a trend of decreasing ($L_{IR}/L_*$) with respect to age of the disk and HD 169142 fits well into the trends seen in figures in both of those works.

The effects of radiation on the particles in the disk can be investigated by considering the ratio of the radiation force to the gravitational force felt by a grain. This ratio, called β, allows us to determine how these forces act on a particle of a given size and give clues to the eventual fate of such grains. β can be calculated as a function of grain radius (a) from the following relation (Augereau et al. 1999; Artymowicz 1988):

$$β = 3 L_*/<Q_{PR}(a)> / 16 \pi G M_* c \rho a$$

where a is the grain radius, $<Q_{PR}(a)>$ is the radiation pressure efficiency for the grain averaged over the stellar spectrum for a given grain size. $L_*$ and $M_*$ are the luminosity and mass of the central star, and ρ is the assumed mass density of the grain. Using the stellar parameters in Table 4-1 and assuming the grains are silicate Mie spheres with ρ = 2.5 g cm$^{-3}$ we calculate the values of β shown in the top panel of Figure 4-6. Grains with $β > 1$ will be removed from the system on unbound, hyperbolic orbits (Wyatt et al. 1999). In the case of HD 169142 these grains are removed on essentially free-fall timescale, which is $< 10^4$ yr for the mid-IR-emitting grains in the disk. It can also be noted that
grains with $0.1 < \beta < 0.5$ will have their space motion significantly effected by
the radiation field and will most likely be on very eccentric orbits (Augereau et al. 1999).

Another force that effects the grains Poynting-Robertson drag (P-R drag). Once we know $\beta$ we can calculate the effects of this force on particles of varying sizes. Using the relation for $t_{PR}$ from Wyatt et al. (1999):

\begin{equation}
\frac{F_{\text{rad}}}{F_{\text{grav}}} = \beta
\end{equation}
we use our derived $\beta$ values to plot the P-R drag lifetimes of grains in the disk of HD 169142 in the bottom panel of Figure 4-6. For 0.3 $\mu$m grains 45 AU from the central star we calculate a P-R drag lifetime of $t_{PR} \sim 10^5$ yr, for 6 $\mu$m grains 10 AU from the source this time is $t_{PR} \sim 5 \times 10^4$ yr. One immediately sees that the P-R drag lifetime of our derived grain sizes is small when compared to the presumed lifetime of the central star ($> 3 \times 10^6$ yr). Because the removal process happens on a timescale that is much less than the apparent age of the source (3 to 10 Myr) we believe that the mid-IR-emitting grains are not primordial and have been replenished by some mechanism. One replenishment mechanism is through collisions of larger bodies as is apparently the case for $\beta$ Pictoris (Artymowicz 1997), and HR 4796A (Telesco et al. 1999; Wyatt et al. 1999). The idea that there is processed or “second-generation” dust in the disk of HD 169142 is important since that is one of the basic characteristics of a Vega-like disk. Whether or not these grains are truly ‘debris’ from collisions remains to be seen, but the existence of processed grains in the disk is strong evidence that HD 169142 is a Vega-like source.

In Table 4-2 we summarize the properties for the mid-IR-emitting grains near HD 169142. Comparison with Table 2-2 shows that the grain properties for HD 169142 fit well with the derived values for the survey sources. HD 169142 does distinguish itself by being one of the brighter sources in the mid-IR, even at its distance of 145 pc. This may well have contributed to our detection of the extended emission around the source. For comparison we also list the temperature of the dust derived from the 25 and 60 $\mu$m IRAS data by Walker and Wolstencroft (1988). In the next section we discuss other data that
Table 4-2: Summary of HD 169142 grain properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{10.8 \mu m}$</td>
<td>$2283 \pm 228$ mJy</td>
</tr>
<tr>
<td>$F_{18.2 \mu m}$</td>
<td>$7187 \pm 718$ mJy</td>
</tr>
<tr>
<td>$\tau_{\text{mid-IR}}$</td>
<td>0.096</td>
</tr>
<tr>
<td>$\beta_{\text{mid-IR}}$</td>
<td>$&gt; 1$</td>
</tr>
<tr>
<td>$T_{\text{mid-IR}}$</td>
<td>170 K</td>
</tr>
<tr>
<td>$T_{\text{model}}$ (K)</td>
<td>140 to 160</td>
</tr>
<tr>
<td>$D_{\text{model}}$ ($\mu m$)</td>
<td>0.3 to 6</td>
</tr>
<tr>
<td>$R_{\text{model}}$ (AU)</td>
<td>10 to 45</td>
</tr>
<tr>
<td>$t_{\text{PR}}$ (yr)</td>
<td>$5 \times 10^4$ to $10^5$</td>
</tr>
<tr>
<td>$T_{\text{WW}}$ (K)</td>
<td>115 K</td>
</tr>
</tbody>
</table>

$^\dagger$ Observed flux density; $^\ddagger$ Walker & Wolstencroft (1988); $^\dagger$ Assumes 50% contamination of N-band flux estimate by PAH grains, $^\ddagger$ $\beta = 0.7$ for 6 $\mu m$ grains.

gives clues about the orientation of the disk and we try to put HD 169142 into a newly proposed evolutionary scheme for this type of source.

**Discussion and Conclusions**

**Disk Orientation**

HD 169142 has been studied as both a Herbig star and a Vega-like star since the discovery of its excess by IRAS in 1984 and some of this work revealed clues to the orientation of the disk associated with the star. In light of our detection of what we believe to be is a nearly face-on disk around the source we summarize this previous work here and show how it strengthens our detection.

Since we believe that any circumstellar disk will form in the equatorial plane of the star, one of the most fundamental observations that can be made is of the rotational velocity of the source. We can then correlate the measured velocity with an assumed disk orientation. Sources that have high rotational velocities are most likely seen close to
“equator – on” and their disks would therefore probably be close to edge-on. An example of this is the archetype β Pictoris which has a measured $v \cdot \sin(i) = 139$ km/sec and a disk inclination of $> 80^\circ$ (Backman & Paresce 1993). The source HD 141569 also has a high rotational velocity (~155 km/sec) and a close to edge-on disk resolved in both the near and mid-IR (Weinberger et al. 1999; Fisher et al. 2000). Conversely, Vega-like sources that have low rotational velocities should have disks that are face-on. An example of this situation is Vega itself which has $v \cdot \sin(i) = 15$ km/sec (Backman & Paresce 1993) and an almost face-on disk that has been resolved in the sub-mm by Holland et al. (1998).

Another of the archetypes, η Eri, also has a resolved sub-mm disk that is close to circular, and most likely face-on (Greaves et al. 1998) and a very low $v \cdot \sin(i)$ value of ~2 km/sec (Saar and Osten 1997). In their discovery paper Greaves et al. (1998) note that the appearance of the disk is consistent with inclination estimates of the stellar pole. We therefore know of at least four examples, including three archetypal sources, where the orientation of the disk can be roughly estimated from the rotational velocity of the central star.

We believe the disk of HD 169142 also fits into this trend. While the mean value of $v \cdot \sin(i)$ for A5 V stars is ~125 km/sec (Backman & Paresce 1993), HD 169142 has a measured rotational velocity of $v \sin(i) = 55 \pm 2$ km/sec (Dunkin, Barlow, & Ryan 1997a). Dunkin, Barlow, & Ryan (1997b) note that HD 169142 has the next to lowest $v \cdot \sin(i)$ of all of the Vega-like stars in their sample and suggested that we may be viewing this star close to pole-on. This would imply that we should see the disk of HD 169142 close to face-on.
Another piece of evidence that supports a face-on disk orientation is seen in optical spectra of HD 169142. Dunkin, Barlow, and Ryan (1997b) obtained high-resolution optical spectra in the regions around the lines of Hα, Na I D, and Ca II K for a sample of 9 Vega-like stars with spectral classes ranging from B9.5 to A9. Their sample included both HD 169142 and HD 141569 (see Chapter 5). In regards to the Hα emission of these sources they find that two show no emission lines, four show double-peaked emission structure, two show a single-peaked profile, and one source has a strong P Cyg profile in its line. HD 139614, which is another of our Vega-like survey sources, and HD 169142 are the two sources in the Dunkin, Barlow, & Ryan survey that shows a strong single-peaked Hα profile (Dunkin, Barlow, & Ryan 1997b). We address this facet of the Hα emission again in the next section. It is interesting to note that the two stars in the Dunkin, Barlow, & Ryan sample that exhibit single-peaked Balmer emission-line profiles also have the lowest v·sin(i) values of the sample and they both show Si depletion in their spectra (Dunkin, Barlow, & Ryan 1997). Both of these facts, the low rotational velocity, and the single peaked nature of the Hα emission suggest that they are being seen closer to pole-on than the other stars in the sample. It is not clear how he chemical abundance is related to disk orientation, but these facts give some idea as to the expected orientation of the HD 169142 disk.

Evolutionary Status

In this section we discuss the evolutionary status of HD 169142 and place in into the context of a broader evolutionary scheme. We propose that HD 169142 is a young source and present evidence that it is most likely still moving across the main-sequence
toward the ZAMS. We are hesitant to call HD 169142 a pre-main-sequence source because this implies that the source is a Herbig Ae/Be star. We do not believe that HD 169142 fully fits into the Herbig class, even though it does exhibit some Herbig-like characteristics. In their recent review of Vega-like sources Lagrange et al. (2000) coin the term “old-pre-main-sequence” (OPMS) sources, which are sources that have more or less finished their PMS evolution and are now moving into the main-sequence phase of their lives. We believe that HD 169142 is an excellent example of just such a source.

One possible signature of the youth of HD 169142 was discovered in the high-resolution optical spectra of Dunkin, Barlow, & Ryan (1997). Along with single-peaked Hα emission they also detected emission in the line of He I λ5786. In fact, emission in this line was detected for both single-peaked Hα sources in their sample (HD 169142 and HD 139614) while absorption was detected for the double-peaked Hα stars (HD 35187, HD 142666, & HD 158643).

There is no significant He I absorption or emission predicted to be present in the photospheric spectra of A-type stars (Bohm & Catala 1995). However, the presence of the He I λ5786 emission in the case of HD 169142 can be interpreted as a signature of ongoing accretion in the system. One suggestion for the presence of this emission is that the origin of the He I emission is at the interface of a boundary layer between the central star and the accretion disk. In their models of T-Tauri stars Hartmann, Hewett, & Calvet (1994) propose that material is funneled from the surface of the innermost parts of the disk along the magnetic field lines of the star to elevated latitudes in both hemispheres of the central source. One of the predictions of their models is that double-peaked Balmer line emission should come from systems that are closer to pole-on than edge-on, while
the single-peaked Hα emission should come from edge-on systems (Hartmann, Hewett, 
& Calvet 1994). This is exactly opposite of what we see here. Even though the details of
the interactions have yet to be uncovered, it seems likely that the presence of the He I
λ5786 emission in HD 169142 is tracing phenomena occurring in the innermost regions
of the star-disk system. We interpret the possible active accretion in the system as a clear
signature of its youth.

Another powerful diagnostic that we use to investigate the evolutionary state, and
age, of HD 169142 is the H-R diagram. In Figure 4-7 and 4-8 we place HD 169142
(square) and the other eight sources in our Vega-like survey that exhibit near-IR excess
into the H-R diagram. The diagram itself consists of ~41,000 stars from the Hipparcos
database (Perryman et al. 1995) and shows a well defined main-sequence as well as a
fully populated giant branch. In Figure 4-7 we have the pre-main-sequence evolutionary
tracks for intermediate mass stars from Palla and Stahler (1993) overlaid onto the
diagram. In Figure 4-8 the isochrones of Iben (1965) are plotted on the diagram along
with HD 169142 and the other sources.

Since we believe that the evidence strongly suggests that HD 169142 is an OPMS
object transitioning between the Herbig stars and the Vega-likes, we suggest that it is at a
point in its evolution where it is moving across the main-sequence onto the ZAMS. Given
that its mass estimate is M* = 2.0 M☉ it is encouraging that inspection of Figure 4-7
shows that the source lies very close to the 2.0 M☉ track. The evolutionary tracks also
give us an age estimate for the source by using the legend seen in the lower left part of
Figure 4-7. The ticks along the tracks correspond to the ages listed in the legend. If HD
169142 is following the 2.0 M☉ track then we can estimate its age as 3 to 10 Myr. The 3
Figure 4-7: Position of HD 169142 in the H-R diagram (square). HD 169142 and the eight other sources in our Vega-like survey with near-IR excesses (our Class IIIa stars) are plotted here on an H-R diagram of 41,000 stars from the Hipparcos catalog. Overlaid are the evolutionary tracks of Palla & Stahler (1993) for intermediate mass stars. From the rightmost track the corresponding masses of the stars are: 0.6, 1.0, 1.5, 2.0, 2.5, 3.0 $M_\odot$. Tick marks on the track correspond to the times lists in the legend. Hipparcos data from Perryman et al. (1995).
Figure 4-8: Position of HD 169142 (square) and other sources with near-IR excess (Class IIIb) in the H-R diagram with the isochrones of Iben (1966) overlaid. The time-constant loci were derived as described in Iben (1965). The times appropriate for each locus are given above each in yr.

to 10 Myr age estimate for HD 169142 is substantiated by Figure 4-8. Here we have plotted the isochrones of Iben (1965) onto the same H-R diagram as Figure 4-7. One immediately sees that HD 169142 (square) falls between the $3 \times 10^6$ and $6 \times 10^6$ yr isochrones.

We believe that the accretion hypothesis to account for the He I emission and the position of HD 169142 in the H-R diagram is very strong evidence that it is a young source, and most likely moving into the Vega-like class from the Herbig category. This is
a very interesting time in the evolution of these sources since we believe that it is this
during this time, when the sources are in the 1 to 10 Myr age range, that the active
formation of planetesimals will start to clear out the inner regions of these disks
(Jayawardhana et al. 1998). Because of the presence of the near-IR excess, it is probably
true that this process has only just started, if it has started at all.

Conclusions

Our conclusions about the disk of HD 169142 can be summarized as follows:

1. We find HD 169142 to be resolved in the mid-IR at both 10.8 and 18.2 μm.
   Images obtained with OSCIR on Keck II reveal what appears to be a nearly
   face-on disk with a mid-IR emitting region with diameter ~175 AU. This is
   larger than, but similar to the size of the mid-IR-emitting region in the
   archetypal disk of β Pictoris and the disk of HD 141569. Due to uncertain
   removal of the central source no information of the morphology of the disk is
   available.

2. Modeling of the circumstellar grains as spherical Mie particles gives an upper
   limit of 6 μm on the diameter of the mid-IR emitting grains. We also calculate
   a lower limit of 175 K for the temperature of those grains. The models also
   return a maximum value for the distance of the grains from the central source
   of ~50 AU. Since we strongly detect extended emission from the source at
   greater distances we invoke a two-component theory of dust composition
   where the emission seen at distances > 50 AU from the star comes from small
transiently heated grains, most likely polycyclic aromatic hydrocarbons (PAHs). This hypothesis is supported by near and mid-IR spectra of HD 169142 that show strong features at several wavelengths that are attributed to PAH grains.

3. We also place HD 169142 into an emerging evolutionary sequence using the H-R diagram. We argue that HD 169142 is a source that is transitioning from the Herbig Ae/Be stage of its evolution to a classical Vega-like source. The source clearly exhibits characteristics of both classes and its position in the H-R diagram is indicative of it moving onto the ZAMS. The existence of a strong near-IR excess and evidence for active accretion imply that the source is young enough that the inner region of its disk has yet to be processed or cleared by planetesimal formation. By analogy with HR 4796A, this places a loose upper limit of \(~10^7\) yrs on the age of HD 169142. The evolutionary tracks for intermediate mass PMS stars of Palla and Stahler (1993) and the isochrones of Iben et al. (1965) can be used to estimate the age of the source at 3 to 10 Myr, consistent with the HR 4796A analogy.
CHAPTER 5
KECK IMAGING OF HD 141569

This chapter presents new mid-IR observations of the Vega-like star HD 141569 (B9.5Ve). The status of HD 141569 is, in fact, ambiguous. It is classified as a Vega-like star by some authors (e.g. Sylvester et al. 1996) but as a Herbig Ae/Be star by others (e.g. Van den Ancker et al. 1998). The fact that HD 141569 exhibits characteristics of both a pre-main-sequence and a main sequence object suggests that it may be a transitional star (Van den Ancker et al. 1998). For example, HD 141569 fulfills 3 of the 4 criteria for a Herbig Ae/Be star put forth by Herbig in his original paper (Herbig 1960). It has a spectral type earlier than F0, there are emission lines present in its spectrum (i.e., Hα and O I at 7772 and 8446 Å), and it is associated with a relatively bright reflection nebula. By themselves these facts suggest that the source is a member of this class of object.

However, the Paschen series is not in emission in HD 141569, which is unusual for a Herbig Ae/Be star (Andrillat, Jaschek & Jaschek 1990). In addition, HD 141569 exhibits no measurable photometric variation, whereas most (> 65%) Herbig Ae/Be stars show variations with amplitude > 0.05 mag (Alvarez & Schuster 1981; Schuster & Guichard 1984). Finally, the ratio of infrared to stellar luminosities for HD 141569 is 8x10^{-3} (Sylvester et al. 1996), comparable to the value ~3x10^{-3} for the prototype Vega-like star β Pictoris but low for a Herbig Ae/Be star. These counter-arguments make it difficult to classify HD 141569 as a Herbig Ae/Be star, but they are consistent with its being more evolved, possibly more than 10^7 years old (Van den Ancker et al. 1998).
Table 5-1: Characteristics of HD 141569

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Type</td>
<td>B9.5 Ve</td>
</tr>
<tr>
<td>Distance</td>
<td>$99^{+9.3}_{-9}$ (pc)</td>
</tr>
<tr>
<td>log($L_*/L_\odot$)</td>
<td>$1.35^{+0.08}_{-0.07}$</td>
</tr>
<tr>
<td>Mass</td>
<td>$2.3 M_\odot$</td>
</tr>
<tr>
<td>log(age)</td>
<td>$&gt; 7.0$ (yr)</td>
</tr>
<tr>
<td>log($T_{\text{eff}}$)</td>
<td>4.00</td>
</tr>
<tr>
<td>$v \sin(i)$</td>
<td>$236 \pm 9$ (km/s)</td>
</tr>
</tbody>
</table>

---

$a$ Data from Van den Ancker et al. (1998). $b$ Data from Dunkin, Barlow and Ryan (1997a).

The possible transitional nature of HD 141569 is reflected in its position in the HR diagram. HD 141569 has a Hipparcos measured distance of 99 pc, and Tycho magnitudes that transform to give (B-V) = 0.078 (Sahu et al. 1998). If we assume that the (B-V) color is indicative of interstellar reddening, HD 141569 has an absolute magnitude $M_v = 1.6$ (Weinberger et al. 1999). We can place HD 141569 onto the HR diagram as shown in Figure 5-1, which is reproduced from Jura et al. (1998). One clearly sees that HD 141569 lies on, or very close to the ZAMS consistent with its being young (Jura et al. 1998). Interestingly, in the HR diagram HD 141569 lies between two other Vega-like stars that have well resolved disks in the optical and/or infrared, β Pictoris and HR 4796A. The position of 49 Ceti in the HR diagram is also plotted in Figure 5-1. 49 Ceti was tentatively resolved at 18 μm during our Vega-like survey. If follow-up observations do confirm this, we may be seeing the beginnings of a trend which we can use to search for other resolved sources by their position in the HR diagram. In the following sections we present the results of our imaging of HD141569 at the Keck II telescope using OSCIR. We then use the observed source size and flux density estimates.
to investigate the properties of the dust around the source and we compare our results to recent NICMOS observations of HD 141569 made by Weinberger et al. (1999). We summarize our conclusions at the end of the chapter.

**Observations**

Mid-IR observations of HD 141569 using OSCIR were obtained on four separate observing runs between 1998 May 15 and 1999 August 30. We first detected the extended emission surrounding HD 141569 at Keck II on 1998 May 14 and 15.
Subsequent observations made at Keck II and at the CTIO Blanco 4-m telescope were used to obtain more accurate flux estimates for the source. All of the observations discussed here were made using the OSCIR system.

HD 141569 was observed on two separate occasions at Keck II. All observations were made using standard chop/nod techniques with an 8" chopper throw in declination. Images of HD 141569 were obtained in the N-band ($\lambda_0 = 10.8 \ \mu$m, $\Delta \lambda = 5.2 \ \mu$m) and in the IHW18 band ($\lambda_0 = 18.2 \ \mu$m, $\Delta \lambda = 1.7 \ \mu$m). The Keck autoguider system was used for all of the Keck observations. On both Keck runs (1998 May and 1999 May) the weather was marginal with light cirrus clouds present during the nights HD 141569 was observed. During post-processing of the data, chopped image pairs that were obviously compromised by the cirrus were discarded. However, there is still some uncertainty in the photometry of the source and the standard stars, which we take to be ± 10%. For most of the observations this translates into the major component of the uncertainties associated with the flux estimates.

Despite the cirrus, the seeing during the HD 141569 observations was very good. Measurements of the full-widths at half maximum (FWHM) intensities of comparison stars were approximately 0.32" and 0.42" at 10.8 and 18.2 $\mu$m, respectively. Quadratic subtraction of the diffraction limits ($\lambda/D$) of 0.22" at 10.8 $\mu$m and 0.37" at 18.2 $\mu$m from these values from implies seeing of ~0.2-0.3" in the 10 to 20 $\mu$m spectral region.

On the CTIO Blanco 4-m telescope, OSCIR has a plate scale of 0.18" per pixel, with an array field of view of 23" x 23". Images of HD 141569 were obtained between 1999 February 28 and March 2 and again on 1999 August 26 in the N and IHW18 filters at CTIO to assist in the flux calibration of the Keck images. We used the standard
Table 5-2: OSCIR observations of HD 141569

<table>
<thead>
<tr>
<th>Date</th>
<th>Wavelength (µm)</th>
<th>Flux (mJy)(^a)(^b)</th>
<th>Int. Time (sec)(^c)</th>
<th>Standard Stars</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 May 1998</td>
<td>18.2</td>
<td>723 ± 79</td>
<td>348</td>
<td>α Boo, α CrB, Vega</td>
<td>Keck</td>
</tr>
<tr>
<td>15 May 1998</td>
<td>18.2</td>
<td>554 ± 29</td>
<td>261</td>
<td>α CrB, α Sco, γ Aql</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>10.8</td>
<td>325 ± 19</td>
<td>239</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>01 Mar 1999</td>
<td>18.2</td>
<td>613 ± 134</td>
<td>601</td>
<td>α Sco, γ Ret, λ Vel</td>
<td>CTIO</td>
</tr>
<tr>
<td></td>
<td>10.8</td>
<td>317 ± 35</td>
<td>450</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>02 Mar 1999</td>
<td>18.2</td>
<td>528 ± 160</td>
<td>601</td>
<td>α Sco, λ Vel</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>10.8</td>
<td>260 ± 28</td>
<td>601</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>01 May 1999</td>
<td>18.2</td>
<td>695 ± 78</td>
<td>206</td>
<td>η Sgr, µ UMa</td>
<td>Keck</td>
</tr>
<tr>
<td></td>
<td>10.8</td>
<td>429 ± 45</td>
<td>160</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

\(^a\) The fluxes were obtained by centering a r = 2'' aperture on the source.
\(^b\) The errors listed with these flux estimates contain both the statistical measurement errors and the errors in calibration. In all cases they are dominated by the ± 10% uncertainty in the reproducibility of the standard star fluxes caused by non-photometric sky conditions.
\(^c\) The integration times listed correspond only to that half of the chopper cycle for which the source itself (and not the reference sky position) was projected onto the detector.

Our OSCIR measurements are 68% and 58% of the Sylvester estimates at 10.8 and 18.2 µm.
\( \mu m \) respectively. However, the ratio of the fluxes \( F_{10.8}/F_{18.2} \) presented here is very consistent with the Sylvester et al. (1996) flux ratio. As we will see in a later section it is primarily the flux ratio \( F_{10.8}/F_{18.2} \) that allows us to place an upper limit on the size of the mid-IR emitting grains around HD 141569.

In addition to the emission from the dust, the measured fluxes contain mid-IR radiation emitted by the photosphere of the central star. To remove this photospheric emission, we estimated the mid-IR flux densities of HD 141569 (B9.5 Ve) by normalizing the spectral energy distribution of Vega (A0 V) to the K-band (2.2 \( \mu m \)) flux density of HD 141569 measured by Sylvester et al. (1996). This method implies a photospheric flux density of 72 mJy at 10.8 \( \mu m \) (22% of the total flux at this wavelength). At 18.2 \( \mu m \), the photosphere emits 23 mJy (4% of the total flux). The photosphere-subtracted, variance-weighted flux estimates and associated errors are: 246 \( \pm \) 16 mJy at 10.8 \( \mu m \) and 623 \( \pm \) 35 mJy at 18.2 \( \mu m \).

**Source Size**

In Figure 5-2 we present contour plots of HD 141569 at 10.8 and 18.2 \( \mu m \) and a nearby comparison star (HD 146051) observed to measure the point-spread-function (PSF). At each wavelength, the lowest contour plotted for the PSF star represents the same brightness relative to the peak as that plotted for the program star. Panels a-b of Figure 5-2 compare HD 141569 and the PSF at 10.8 \( \mu m \), and panels c-d compare HD 141569 and the PSF at 18.2 \( \mu m \). The extended emission from HD 141569 is evident as an elongation of the source in Figures 5-2a and c at PA = 355° \( \pm \) 10°. The diameter of the lowest contour along the major axis of the emission in Figure 1a is \( \sim \)2.2” which
Figure 5-2: Images of HD 141569 and a point-spread-function (PSF) star. North is up and east is to the left. The contour plots have been smoothed using a Gaussian filter with FWHM = \( \lambda/D \). (4 and 6 pixels for 10.8 and 18.2 \( \mu \)m respectively). In all panels, the lowest contour is about 4 times the smoothed noise. (a) 10.8 \( \mu \)m image of HD 141569 with logarithmic contours (mJy/arcsec\(^2\)) spaced at 14, 21.1, 31.9, 48.2, 72.8, 109.9, 165.9, 250.6, 378.4, 571.4. The source has a measured FWHM = 0.56" (b) Plot of the PSF star at 10.8 \( \mu \)m normalized to 100 at peak. Logarithmic contours here are spaced at the same percentage levels as panel in (a): 2.4, 3.6, 5.5, 8.3, 12.5, 18.9, 28.6, 43.1, 65.1, 98.4. FWHM = 0.44" (c) 18.2 \( \mu \)m image of HD 141569 with contours (mJy/arcsec\(^2\)) spaced linearly at 50, 113, 177, 241, 305, 369, 433, 497, 561, 625. FWHM = 0.85" (d) Normalized plot of the PSF star HD 146051 at 18.2 \( \mu \)m. Linear contour levels here are spaced at the same percentage levels as panel in (c): 8, 18, ..., 98 with 10 unit steps. FWHM = 0.57".
corresponds to ~215 AU. In Figure 1c we see that the maximum extent of the lowest contour at 18.2 μm is ~2.0" (~198 AU) which is about 90% the size of the 10 μm emission. Therefore, the same population of grains may be emit most or all of the extended emission at both 10 and 18 μm.

In Figure 5-3 we present normalized scans through both HD 141569 and the PSF star. The differences in the widths of the source and the PSF star are clearly evident. Quadratic deconvolution of the source with the PSF gives FWHM sizes of 34 AU at 10 μm and 62 AU at 18 μm for the extended emission near the star. Compared to the full extent of the mid-IR emitting size of the disk represented by the lowest contours in Figure 5-2, the relatively small values of the dust FWHM sizes suggest that the mid-IR emission is sharply peaked close to the star, with much lower-level extended emission farther out. Inspection of Figures 5-3a and c shows a noticeable difference in the source profile along the major axis at the two different wavelengths. While this difference can be attributed to a temperature gradient in the mid-IR emitting dust, it could also be related to different dust components dominating the emission in the two passbands. A mid-IR spectrum of HD 141569 by Sylvester et al. (1996) shows that there is strong emission in the 7.7 μm “PAH” band and somewhat weaker emission in the 11.3 μm “PAH” band. Our broadband (Δλ = 5.1 μm) flux measurement at 10.8 μm includes a contribution from this PAH emission. Below, we estimate what effect the presence of this PAH emission could have on our conclusions.

The overall size of the emission around HD 141569, a radial extent of 100 AU at both 10.8 and 18.2 μm, is comparable to the sizes of the mid-IR emitting regions of both the archetype Vega-like source β Pic (A5V), and HR 4796A (A0V). Lagage & Pantin
Figure 5-3: Scans through HD 41569 and the PSF star. In all plots, HD 141569 is the solid line, and the PSF star is the dashed line. A gaussian fit to the HD 141569 data is shown as the dotted line. (a) Scan through the major axis (PA = 175°) of HD 141569 at 10.8 μm. (b) Scan through the minor axis of HD 141569 at 10.8 μm. (c) Major axis (PA = 175°) scan at 18.2 μm. (d) Minor axis scan at 18.2 μm.

(1994) measured 10 μm emission from β Pictoris out to 100 AU from the central star. Recent observations of the disk around HR 4796A show that it too emits both 10 and 18 μm radiation out to a distance of 95 AU (Telesco et al. 2000). Our estimates of the source size are consistent with similar mid-IR images of the source presented by Silverstone et al. (1999).
Dust Temperature and Grain Size

We can use our observations at two wavelengths to estimate the temperature and size of the grains responsible for the mid-IR emission. With assumptions about the composition of the grains and the dependence of the grain emission efficiency on wavelength, we can calculate a temperature of the dust. Since the emission efficiency of a dust particle depends on its size, a smaller grain in equilibrium with the radiation field will be hotter. The calculated temperature then provides a basis for estimating the size of the particles emitting the radiation.

We can estimate an upper limit on the size of the mid-IR emitting grains by assuming that all of the 18.2 μm radiation comes from the same region around the star as the 10.8 μm flux. Quadratic subtraction of the PSF from the source at 10.8 μm gives a FWHM value of 34 AU. Since the emission at 10.8 μm at distances greater than this is at a very low level, we can say that a significant fraction of the 10.8 μm emitting dust orbits within 20 AU of the star. This provides a lower limit on the dust temperature and therefore an upper limit on the grain size. To proceed further, we use a model developed by the University of Florida Dust Dynamics Group. This modeling technique was used to analyze similar data on the circumstellar disk around HR 4796A (Wyatt et al. 1999; Telesco et al. 2000). The model assumes that the grains that are spherical Mie particles composed of astronomical silicates (Draine & Lee 1984) with density $\rho = 2.5$ g/cm$^3$.

The temperature of the dust particles determines the observed flux ratio, and we estimate the grain size by matching the observed flux ratio to the flux ratio calculated for grains of different diameters located at a distance of 20 AU from the star. The results of the model show that spherical Mie particles composed of astronomical silicates with a
temperature ~170 K and a diameter of 2 μm fit the observed mid-IR flux ratio. More detailed models of HD 141569 produced by Sylvester & Skinner (1996) indicate a comparable value for the upper limit to the characteristic grain size.

Modeling of the disk of HR 4796A in Wyatt et al. (1999) and Telesco et al. (2000) shows that, with the assumption that they are spherical Mie particles, the mid-infrared emitting dust grains in that disk are also approximately 2 μm in size. Mid-IR aperture photometry and spectrophotometric observations of β Pictoris (Telesco et al. 1988; Telesco & Knacke 1991; Aitken et al. 1993) implies the presence of 1 – 3 μm grains in that disk. Van der Bliek et al. (1994) re-analyzed the IRAS data on Vega and proposed that the dominant grains in that archetypal disk are on the order of 1 - 10 μm in size.

The mid-IR spectrum of HD 141569 by Sylvester et al. (1996) shows that there is emission in the mid-IR “PAH” bands that contributes to our 10.8 μm flux estimate. To investigate how our deduced grain size estimates change due to this contamination we ran the models assuming that none, 50% and 75% of the 10.8 μm flux was emitted by PAH grains. Our grain size estimates ranged from 2 μm (no contamination) to 5 μm (75% contamination). Even with most of the flux coming from the PAH grains the derived grain sizes estimates are consistent with those in other debris disks.

The fact the HD 141569 may have dust of this size has important implications for our understanding of the evolution of the disk. By considering the ratio of the radiation force to the gravitational force on a particle (called β) we can investigate the effects of the stellar radiation on these particles. As summarized in Artymowicz (1988):

$$\beta \propto \frac{Q_p}{(L_*/M_*) / R \rho}$$
where R is the particle radius, \( \rho \) is its density, \( \langle Q_{pr} \rangle \) is the radiation pressure efficiency averaged across the stellar spectral energy distribution, and \( L*/M* \) is the ratio of the stellar luminosity and mass. Using the stellar parameters for HD 141569 from Table 5-1 we have calculated \( \beta \) as a function of particle size for astronomical silicate Mie spheres with density, \( \rho = 2.5 \text{ g/cm}^3 \). For 2 \( \mu \text{m} \) diameter particles, we infer a value of \( \beta \approx 3 \).

Particles with \( \beta > 1 \) are on unbound, hyperbolic orbits and will be removed from the system in a very short time. In the case of HD 141569 this is on the order of a few hundred to a thousand years, depending on where in the disk the high \( \beta \) particles were formed. The models show that the value of \( \beta \) remains above unity for particles smaller than 5 \( \mu \text{m} \) in diameter. Consequently, we conclude that the mid-IR emitting particles will be removed from the system very quickly even if our upper limit underestimates the grain size by a factor of two or more. Since the removal time of the grains from the disk is much less than the assumed age of the system (\( > 10^7 \text{ yr} \)), we conclude that the mid-IR emitting grains are not primordial, and have been replenished through some mechanism. One possible scenario for the replenishment of these particles is through collisions of larger bodies, as is apparently the case for \( \beta \) Pictoris (Artymowicz 1997) and HR 4796A (Wyatt et al. 1999; Telesco et al. 2000).

**Comparison to NICMOS Images**

Weinberger et al. (1999) made coronagraphic observations of HD 141569 at 1.1 \( \mu \text{m} \) with NICMOS. They used a 0.6" diameter spot, but instrumental effects rendered data
within 0.9" of the central star unusable. Their images show what appears to be an almost face-on circumstellar disk. The near-IR flux, which is probably light from the star scattered by dust in the disk, extends out to a radius of ~4" (400 AU) (Weinberger et al 1999). The position angle of the major axis of the near-IR disk is equal to that of the mid-IR emission. The NICMOS image also shows evidence for a gap in the dust at a radius of ~ 2.5". As suggested by Weinberger et al. (1999), one way to form such a gap is by the gravitational influence of a planetary companion to the star.

Figure 5-4 shows the OSCIR 18.2 μm contours overlaid onto the 1.1 μm NICMOS image. The thermal emission arises much closer to the star than the near-IR flux. In fact, nearly all of the detected mid-IR emission comes from within the region blocked by the coronagraphic spot. Except for circumstances in which the transient heating of small grains can cause abnormally high temperatures far away from a heating source, we expect grains farther away from a source to be cooler. Since we estimate that the mid-IR emitting grains have a characteristic temperature of ~170 K, we therefore expect the grains seen in the near-IR image to be cooler than that. In their compilation of Vega-like sources Walker & Wolstencroft (1988) fit a 95 K blackbody to the far-IR (25 and 60 μm) IRAS fluxes for this source. However, the 12 μm IRAS point was conspicuously high compared to the otherwise good fit. This implies that there may be a second population of dust at a temperature higher than 95 K that is responsible for the 12 μm excess in the source. The mid-IR contours in Figure 5-4 probably indicate the location of those warmer grains.

The OSCIR & NICMOS data shown in Figure 5-4 may be direct observational evidence for two separate populations of dust grains. The inner, warmer grains which
emit the mid-IR (10 and 18 μm) radiation, and the more distant grains that are responsible for the scattered near-IR flux seen in the NICMOS image and the far-IR (60 and 100 μm) emission detected by IRAS. The strong PAH emission seen in the spectrum of this source (Sylvester 1996) indicate that this proposed ‘inner population’ cannot simply be warm silicates. The PAH grains in the innermost regions of the disk may

Figure 5-4: NICMOS image and OSCIR contours of HD 141569. 18.2 μm contours over a 1.1 μm image from Weinberger et al. (1999). Contours (in mJy arcsec-2) are spaced linearly at 50, 113, 177, 241, 305, 369, 433, 497, 561, and 625. The lowest contour level is about 4 times the smoothed noise. The mid-IR contours were registered to the stellar position in the near-IR image.
indeed be mixed with silicates, for which there is not yet direct evidence. Even if the mid-IR emitting grains were blackbodies, they would contribute a very tiny fraction of the 60 and 100 μm excess (41 and 7 mJy respectively), and, therefore the longer wavelength excess must come from other grains. This situation is similar to that for β Pictoris where the mid-IR emission comes from a relatively small inner region of the total disk. Images in the visible and near-IR by Burrows & Krist (1995), Kalas and Jewitt (1995) and Smith and Terrile (1984) show that the disk around β Pictoris extends out to at least a radius of 10” (~200 AU) from the star in the near-IR and much farther than that in the visible.

Conclusions About the Disk of HD 141569

1. Our mid-IR images made with OSCIR on Keck show extended emission around the B9.5 Vega-like star HD 141569 at 10.8 and 18.2 μm. The emission is detected out to a radius of ~1” (100 AU) at both wavelengths. Since the emitting regions at both wavelengths are of comparable size, the same population of dust may emit both the 10.8 and 18.2 μm radiation. The size of the mid-IR emitting region of this system is comparable to those of HR 4796A and the archetype Vega-like source β Pictoris.

2. We use the 10.8 and 18.2 μm images to place a lower limit of 170 K on the temperature and an upper limit of 2 μm on the diameter of the dust grains responsible for the mid-IR emission if they are Mie spheres composed of astronomical silicates.
3. The value of $\beta$, the ratio of the radiation force to the gravitational force on a particle, for these particles is $\sim 3$. Particles with a value of $\beta > 1$ are on unbound, hyperbolic orbits and will be removed from the system on a very short time scale. In the case of HD 141569 the removal takes place in a few hundred years. We therefore conclude that, if they are silicate Mie spheres, the grains responsible for the mid-IR emission are not primordial. They have been replenished by some mechanism, perhaps through collisions of larger bodies, as is also apparently the case for HR 4796A.

The large extent of this disk, its orientation, and its relatively high surface brightness make this source an excellent choice for further study. With only a few examples of this class of disk known, the disk of HD 141569 will most likely be studied intensely for the foreseeable future. In particular, deep mid-IR imaging with a telescope such as Gemini would allow us to try to detect any thermal emission even farther away from the central star. The symmetric PSF of Gemini would make removal of the emission from the central much easier, thus giving us a better chance of seeing structure in the disk. Instruments that are now being built to be used on the new class of 8-10 meter telescopes are being equipped with suites of narrowband mid-IR filters which will be extremely valuable in the study of the "PAH" bands and emission features. By imaging sources like HD 141569 with filters that are in and out of these features, we will be able to map where the emission from these molecules are and better model the particle distribution in these disks.
CHAPTER 6
SAO 26804: A QUESTION OF CLASSIFICATION

This chapter discusses Keck observations of the source SAO 26804. The unusual nature of SAO 26804 (HD 233517) was first recognized by the IRAS satellite when it detected a large IR excess at all wavelengths longer than 12 \( \mu m \) for the source. The characteristics of the excess fit the criteria of Walker and Wolstencroft (1988) [WW], and they included the object on their list of Vega-like sources. Indeed, SAO 26804 looks like an excellent disk candidate. The overall brightness of the source and the shape of its SED both seem to imply there is a large amount of dust around the source. Additionally, SAO 26804 has one of the highest [12] - [25] colors in the sample of WW, and the source was marked as extended at 25, 60, and 100 \( \mu m \) in the IRAS Working Survey Database (WW).

The nature of the excess, its overall magnitude, and the evidence for extension made SAO 26804 an excellent candidate for further observation. Sylvester et al. (1996) included SAO 26804 in their follow-up survey of the WW sources and observed the source from the optical to the millimeter. Skinner et al. (1995) also observed SAO 26804 from the near-IR to the millimeter filling in gaps in the Sylvester et al. (1996) observations, and presented a 10 \( \mu m \) (N-band) image of the source that shows what appears to be a highly inclined disk surrounding the star.

About the same time the Skinner et al. (1995) result was published, a paper by Zuckerman et al. (1995) presented a list of 92 luminosity class III stars with far-IR excess emission. Although SAO 26804 was not included in the this original list of sources, the Zuckerman et al. (1995) paper was perhaps the first to discuss the idea of a class of giant
stars with dust *orbiting* them. Fekel et al. (1996) presented evidence that SAO 26804 is in fact a member of the luminosity class III stars with far-IR excesses. The luminosity class III designation is at odds with the work of Miroshnichenko et al. (1996) who argue that SAO 26804 is in fact a dwarf star (luminosity class V), but with a later spectral type (K5-K7) than that assumed by Skinner et al. (1995) and Sylvester et al. (1996). In 1999, we added our own follow-up observations to the study of the source when we imaged SAO 26804 as part of our Vega-like survey at Keck.

### The Detection and Non-detection of the SAO 26804 Disk

#### Previous Observations

The first infrared observations of SAO 26804 were made with the IRAS satellite. The source was marked as extended in the three long wavelength IRAS bands (25, 60, and 100 \( \mu \text{m} \)) and was thus was earmarked as an excellent candidate for follow-up observations. In 1995 Skinner et al. presented imaging of SAO 26804 that presumably showed a nearly edge-on disk at 10 \( \mu \text{m} \). Their 10 \( \mu \text{m} \) (N-band) image was consistent with the dust being confined to a disk at PA = 20° with FWHM = 1.5” and an inclination angle of < 30° (Skinner et al. 1995). The mid-IR imaging was obtained as part of an extensive suite of observations made by the group from the near-IR to the millimeter regime. In the paper that presented the mid-IR imaging they also published near-IR photometry, a mid-IR spectra, and an upper limit for the flux of the source at 1100 \( \mu \text{m} \) (Skinner et al. 1995). All of their observations, except the 1100 \( \mu \text{m} \) upper limit were obtained on the 3.6 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea under good observing conditions using the Berkeley/Livermore mid-IR camera.
(Berkcam). Since our OSCIR results are at odds with the observations of Skinner et al. (1995) we list a few of the most relevant characteristics of Berkcam here. Berkcam contains a 10 x 64 array of which a 10 x 16 section was used to image the source. The pixel size of Berkcam is 0.4” per pixel (Skinner et al. 1995; Keto et al. 1991). The Skinner et al. (1995) observations were made using the standard “chop-nod” technique of mid-IR observing (see Appendix A). A nearby standard star (β Gem) was used as a photometric standard and as a PSF star for their observations. It is interesting to note is that the SIMBAD service calculates that β Gem is 26° from SAO 26804. Our experience has shown that this is a rather large distance between a program object and PSF star. For our Vega-like survey all of the PSF stars were within 10° of the target to minimize systematic errors like telescope flexure.

The broad band N image of SAO 26804 presented in Skinner et al. (1995) has FWHM = 1.1 ± 0.1” in right ascension, and FWHM = 1.5 ± 0.1” in declination. Their image showed a position angle for the extended emission of 20°. Photometry of the source gave a flux density of F_N = 0.43 Jy, consistent with the IRAS 12 μm point and our N-band flux estimate of 0.44 Jy. The Skinner et al. (1995) paper also discussed the possible grain populations that would exist in such a disk. In a later section we show how our modeling of the global grain properties agree with theirs. However, due to the new size limits we place on the source, we believe that their discussion of spatial structure in the disk and how that may change the interpretation of their models must be treated with the utmost of caution.
New Keck Imaging with OSCIR

We obtained near diffraction-limited images of SAO 26804 using OSCIR on Keck II in 1999 May. Observations were made in the 10.8 μm (N-Band) and 18.2 μm (IHW18) bands on 01, 02, and 04 May 1999 under good observing conditions. Our observations show SAO 26804 to be an unresolved point source with FWHM of 0.31" at 10.8 μm and FWHM of 0.41" at 18.2 μm. Our observational strategy used for the SAO 26804 observations was similar to those used for the Vega-like survey. The sequence of observations made on each night was: observations of a nearby PSF star at 10.8 and 18.2 μm, deep integrations on SAO 26804 at 10.8 and 18.2 μm, another set of PSF star observations, and finally observations of an IR standard star for photometric calibration. The PSF star used for all SAO 26804 observations was PPM 50530 (K5V), which is at a distance of 9.8° from the source. The IR standard stars, α Lyr, α CrB, and α Boo were used for absolute flux calibration (see Table 2-2 for standard star flux densities). The Keck autoguider system was used for all of the observations. Our experience with the autoguider system shows that there is a 1 pixel ‘jitter’ associated with the guiding corrections, which corresponds to 0.06” on Keck. Close inspection of the data shows that the seeing was mostly stable on the nights of the observations and that the primary limit to the resolution of the data is diffraction.

All of the OSCIR observations were made using the standard “chop/nod” technique. The chopper throw was 10” in declination at a frequency of 3 Hz. The telescope was nodded every 30 seconds. All of these parameters are well within the specifications of the system and there were no problems evident during the observations. OSCIR uses a 128×128-pixel detector and the entire field of view was used for the SAO
26804 observations. On Keck OSCIR has a plate scale of 0.06” per pixel, a factor of 6.7 times finer than that of Berkcam on UKIRT. The *chopped* integration time of each of our SAO 26804 observations was 20 minutes (i.e. 10 minutes on-source). Our experience at Keck has shown that the PSF does exhibit some variation throughout a single night (see Figure 2-1), but we believe that this observational sequence minimizes the effects of that variation by pairing observations of the PSF star with SAO 26804 observations that are taken very closely in time.

We present our imaging data in two ways, first as contour plots, then as scans through the source. Experience with a large set of data looking for extension around bright sources has shown that the combination of these two visualizations are an excellent way to determine if there is extended emission present. Looking at both the contour plots and the scans is necessary since we often obtained data in diffraction limited or near diffraction limited conditions. Under these conditions we often imaged the first, and in some cases third, diffraction rings for unresolved sources. More commonly we saw broken, or partial diffraction rings in our data. Because of this, we use the combination of the contour plots, FWHM measurements, and the radial scan plots to look for extension around science sources. In Figure 6-1 we present contour plots of SAO 26804. We observe SAO 26804 to be unresolved at both 10.8 and 18.2 μm. Our images place limits on the size of the source of $FWHM = 0.31"$ at 10.8 μm, and $FWHM = 0.41"$ at 18.2 μm.

The lowest contour in the SAO 26804 observations is at a level of approximately 4 times the smoothed noise in the image. Due to the relatively high brightness of the source and the fact that the source is unresolved, we see the effects of diffraction in Figure 6-1. These effects are apparent as the broad lowest level contour in each panel.
Figure 6-1: Contour plots of SAO 26804 and a nearby PSF star at 10.8 and 18.2 μm. North is up and East is left. A 2-pixel Gaussian smooth (FWHM = 0.12") has been applied to all images. The lowest contour in the SAO 26804 panels is approximately 4 times the smoothed noise in the image. (a) N-band image of SAO 26804. Contours spaced linearly at (mJy arcsec^2): 43, 328, 615, 902, 1189, 1476, 1763, 2050 (b) N-band image of PSF star (PPM 50530). Contours placed at same relative brightness levels as in panel (a). (c) IHW18 image of SAO 26804. Contours spaced linearly at (mJy arcsec^2): 305, 1290, 2275, 3260, 4245, 5230, 6215, 7200 (d) IHW18 image of PSF star. Contours placed at same relative brightness levels as in panel (c).

of Figure 6-1. The asymmetry seen in the low level contours of the 18.2 μm images is due to the fact that the observed diffraction ring was ‘broken’, that is not azimuthally symmetric. The asymmetry is more subtle in the 10.8 μm images but is still present as the ‘bump’ visible on the SW quarter of the second contour of both panels.

In Figure 6-2 we show north-south scans of SAO 26804 and a nearby point-spread-function (PSF) star at 10.8 μm and 18.2 μm which show that there is no
Figure 6-2: Normalized North-south scans through SAO 26804 and a nearby PSF star (PPM 50530). (top) Scans at 10.8 μm. (bottom) Scans at 18.2 μm. These scans are approximately along the position axis of the disk reported by Skinner et al. (1995) and show SAO 26804 to be unresolved at a high level of confidence. No smoothing has been applied to the data.

appreciable difference between the radial profile of SAO 26804 and the PSF star. The small difference in widths of the scans seen at low levels at 10.8 μm is most likely due to the fact we observed SAO 26804 for much longer than the PSF star, and the accumulated effect of seeing on the science object slightly broadened its profile. It is very
informative to compare Figure 6-2 with Figures 4-2, and 5-3 in this dissertation. Such a comparison shows the differences between scans through an unresolved source like SAO 26804, and sources that are sources that are resolved (HD 141569, HD 169142). The bottom panel of Figure 6-2 shows that the profiles of SAO 26804 and the PSF star are almost identical at 18.2 μm.

First-Ascent Giant or Main-Sequence Dwarf?

As we touched on in the introduction the overall classification and therefore the evolutionary status of SAO 26804 is very much in question. There is no question that the source exhibits a strong IR excess in the mid and far IR. There is also little question that the cause of this excess is due to IR-emitting circumstellar dust. Most of the mystery surrounding the source deals with whether it is a classical Vega-like star, or if it belongs to a class of giant stars with circumstellar dust around them. Considerable work has been done investigating this mystery. In particular, two groups made observations of SAO 26804 trying to definitively place it in one class or the other. Most of the previous observations were either optical photometry (e.g. Miroshnichenko et al. 1996) or high-resolution optical spectra (e.g. Fekel et al. 1996). As we will see, these observations help each camp make strong claims to the classification of the source. Additionally, these observations have refined the fundamental parameters of the central star which are shown in Table 6-1. In the following sections we detail the characteristics that place it, incongruously, in both luminosity class V and luminosity class III, and we speculate on the nature of the source after presenting a new piece of evidence that may help the classification question.
**Figure 6-3:** SED of SAO 26804. This optical to mm SED is comprised of the photometry of Skinner et al. (1995). The SED shows the IR excess of the source for $\lambda > 10$ µm. SAO 26804 exhibits no near-IR excess, which is different than the source HD 169142. This lack of near-IR excess emission may be a way to help place SAO 26804 in the correct luminosity class.

**Luminosity Class V: A Main-Sequence Dwarf**

For this work, the story of SAO 26804 starts with the inclusion of the source of the list of Vega-like sources presented by Walker and Wolstencroft in 1988. Using IRAS data as a diagnostic, WW placed SAO 26804 on their primary (‘A’) list of disk candidates. The WW list is comprised of sources that have similar characteristics as the archetypal Vega-like sources. Those sources in the “A” section of the WW list were singled out as most resembling the archetypes and therefore likely to have resolved disks.

The first set of follow-up observations that relate directly to our study of SAO 26804 were those of Sylvester et al. (1996) when they published an extensive set of
photometric observations of the source in the optical (U, B, V, R, I) and the near-IR (J, H, K, L, M). They also observed SAO 26804 in the mm regime and obtained an upper limit to the flux of the source. Used in conjunction with the previously published IRAS data, an accurate SED of the source was constructed which is shown in Figure 6-3.

Qualitatively the SED of SAO 26804 looks very similar to the SED of a Vega-like source. The IR excess of the source is seen for all wavelengths longer than approximately 10 \( \mu \)m, and the excess peaks around 40 \( \mu \)m. Both of these characteristics are similar to a number of sources on the WW list, including the archetypes. Working with color corrected IRAS flux densities WW found that a single temperature blackbody with \( T = 105 \) K fit the excess well.

To try to fit SAO 26804 into the broader class of Vega-like sources we can compare its SED to other members of the class. It is informative to compare Figure 6-1 with Figure 4-1, the SED of HD 169142. As we discussed, we believe that HD 169142 is a transition object between a Herbig Ae/Be star and a Vega-like source. We therefore believe that it is moving down across the main-sequence toward the ZAMS. If SAO 26804 were in the same stage of its evolution, we could reasonably expect it, and its SED, to have similar characteristics. A careful comparison of Figure 4-1 and Figure 6-1 shows that there is a major difference in the SEDs of the two sources. While HD 169142 exhibits strong near-IR excess, the excess of SAO 26804 does not begin until around 10 \( \mu \)m. This lack of near-IR excess emission is a strong piece of evidence against the source being pre-main-sequence, rather it seems to imply that SAO 26804 is more evolved.
Lithium Abundance

One of the reasons that SAO 26804 is so difficult to classify is that it exhibits a very strong Li line at 6707 Å (Fekel et al. 1996). The equivalent width of the line is 580 mÅ which yields a lithium abundance of $\epsilon(\text{Li}) \sim 3.3$ using the conversions of Soderblom et al. (1993) and Carlsson et al. (1994). This level of Li is equal to that found in young Population I stars whose lithium has not been significantly mixed or destroyed by nuclear processes (Carlsson et al. 1994). This very strong lithium emission are consistent with SAO 26804 being a young K dwarf, however, if it is a young source then there should also be strong chromospheric emission seen in its spectrum as predicted by Skinner et al (1995). To look for signatures of such activity Fekel et al. (1996) present two spectra of SAO 26804 the first spanning the Ca II H & K lines, and the second the Hα region. Fekel et al. (1996) finds that there is calcium emission present in the SAO 26804 spectrum, but unlike other K dwarfs such as HD 82558 (Fekel et al. 1986) and HD 181943 (Strassmeier et al. 1990) the emission feature of SAO 26804 is very weak and comes no where near the level of the relative continuum. The equivalent widths of the H & K lines are 0.07 Å and 0.14 Å respectively. These values are very low for a K dwarf, but are well within the range of values those found for active giants that rotate rapidly (Strassmeier et al. 1990).

With regards to the second Fekel et al. (1996) spectrum, spectroscopic studies of T Tauri stars have shown that they exhibit a wide range of Hα profiles, from absorption to strong emission (Walter et al. 1988). However, even the deepest Hα absorption line of the PMS K-stars studied by Walter et al. (1988) has a low equivalent width, indicating that it is significantly filled with emission. This is relevant to SAO 26804 since the spectrum of Fekel et al. (1996) clearly shows that the Hα profile of the source is not
significantly filled. Direct comparison with profiles of other sources shows that the profile most resembles that of a giant or supergiant. Line ratio analysis by Fekel et al. (1996) discounts the hypothesis that SAO 26804 is a supergiant, which allows us to reasonably interpret the Hα profile in the context of a luminosity class III giant undergoing some mass loss.

Up to this point, we have shown that from an emission feature standpoint it is likely that SAO 26804 is a luminosity class III star, but we have yet to answer the question of its high lithium abundance, which is normally associated with very young objects of this mass. To explain this we turn to the model of de la Reza et al. (1996). An important aspect of this model is that invokes a circumstellar dust shell to explain the presence of the infrared excess associated with the source. The main characteristics of the model scenario are summarized in de la Reza et al. (1997) and are shown here:

1. Normal K giants with mass between 1.0 and 2.5 M⊙ become Li rich during a short time in their red giant phase. This stage lasts $\leq 10^5$ yr compared to the red giant phase $5 \times 10^7$ yr.
2. An abrupt deep mixing mechanism, in which the deep convective currents reach the core of the star, produces a rapid injection of fresh $^7$Be to the surface regions of the source. This $^7$Be is rapidly transformed to $^7$Li, which explains the high lithium abundance in these stars. This process also induces the creation of a circumstellar gas and dust shell.
3. When this sudden mass loss (in the form of the circumstellar gas and dust) stops, this material detaches and is ejected into the surrounding region. The best values for the circumstellar shell (see de la Reza et al. 1996) give an expansion velocity of $< 2$ km/sec and a mass loss rate of $2$ to $5 \times 10^{-8}$ M⊙/yr, which is 100 times the mass loss of an ordinary K giant.
4. The new $^7$Li that has not been ejected into the surrounding region stays in the photosphere. This lithium is depleted on a timescale that is less than the circumstellar dust and gas ejection episode that may explain the presence of K giants without high Li as observed by Fekel et al. (1996).
The observed characteristics of SAO 26804 are well explained in the context of this model. In fact, de la Reza et al. (1997) use SAO 26804 as an example of a success story for their model. Using our observations in conjunction with this model we can place a tighter constraint on the expansion velocity the ejected circumstellar material. Fekel et al. (1996) report that the ejected shell for SAO 26804 is ~1000 years old. If the source is at a distance of ~600 pc as proposed by Fekel et al. (1996), our new images place a limit of ~ 60 AU on the source size in the mid-IR. This means that the expansion velocity of the material must be < 0.3 km/sec or we would have resolved the dust shell detected extended emission in our observations. This expansion velocity is consistent with the de la Reza model summarized above adding weight to the hypothesis that their model is valid.

Position in the H-R Diagram

Another diagnostic we can use to try to answer the classification is the H-R diagram. In Figure 6-4 we show the H-R diagram constructed from the latest version of the Hipparcos data with two possible positions of SAO 26804 marked. Assuming that SAO 26804 is a luminosity class V dwarf, and using the correct set of parameter from Table 6-1, we place SAO 26804 at the position of the filled circle in the diagram. This position in the diagram is very reasonable for a late-type K dwarf, particularly if the dwarf is still moving onto the main sequence along its designated Hayashi track. The second possible position for SAO 26804 in the diagram is shown as the filled square. This position was determined assuming SAO 26804 is a class III giant and using the parameters on the right side of Table 6-1. Note that this position for SAO 26804 falls in a heavily populated part of the giant branch, while the position of the source near the main
Table 6-1: Characteristics of SAO 26804 as luminosity class V and class III.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Luminosity Class V</th>
<th>Luminosity Class III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Type</td>
<td>K5 to K7(^{\dagger})</td>
<td>K2(^{\ddagger})</td>
</tr>
<tr>
<td>(B − V)</td>
<td>1.20(^{\dagger})</td>
<td>1.20(^{\dagger})</td>
</tr>
<tr>
<td>Distance</td>
<td>&lt; 40 pc(^{\dagger})</td>
<td>(\approx 600) pc(^{\ddagger})</td>
</tr>
<tr>
<td>(T_{\text{eff}})</td>
<td>4170 K(^{\dagger})</td>
<td>4420 K(^{\ddagger})</td>
</tr>
<tr>
<td>(L/L_\odot)</td>
<td>0.28(^{\dagger})</td>
<td>79.1(^{\ddagger})</td>
</tr>
<tr>
<td>(M/M_\odot)</td>
<td>0.73(^{\dagger})</td>
<td>1.15(^{\ddagger})</td>
</tr>
<tr>
<td>(R/R_\odot)</td>
<td>0.66(^{\ddagger})</td>
<td>20(^{\ddagger})</td>
</tr>
</tbody>
</table>

\(^{\dagger}\) Miroshnichenko et al. (1996); \(^{\ddagger}\) Fekel et al. (1996); \(^{\ddagger}\) Allen (2000)

sequence is sparsely populated at best. Recall that SAO 26804 exhibits no measurable near-IR excess. Photometry in the J, H, and K bands is entirely consistent with photospheric emission only (Skinner et al. 1995). By analogy with our proposed evolutionary sequence for Vega-like sources presented in Chapter 3, this lack of near-IR excess makes it unlikely that the source is at a evolutionary state where it is still moving onto the main sequence. Granted, in this case we can not distinguish between the source moving onto and off of the main sequence. However, if the source is luminosity class V, and has already spent much of its life moving across the main sequence from the left to right, there would be no reasonable explanation for its very high lithium abundance.

Perhaps the most significant feature of Figure 6-4 is the gray box plotted near the giant branch of the main sequence. This box denotes a region in the H-R diagram where 31 other lithium rich giants are found to reside by Jasiewicz et al. (1999). Using high resolution optical spectrometry in conjunction with Hipparcos data, Jasiewicz et al.
Figure 6-4: Possible positions of SAO 26804 in the H-R diagram. The circle marks the position that SAO 26804 would occupy assuming the star is Luminosity class V with a distance of ~40 pc as suggested by Miroshnichenko et al. (1996). The square denotes where the star would lie assuming a distance of 600 pc in accordance with Fekel et al. (1996). The gray box outlines a region that contains 31 lithium rich giant stars from the list of Jasniewicz et al. (1999). The (B-V) = 1.20 value from Miroshnichenko et al. (1996). Hipparcos H-R diagram from Perryman et al. (1995).

(1999) determined accurate fundamental parameters for lithium rich giants from the list of Zuckerman et al. (1995). Using these refined parameters new intrinsic luminosities for the sources were calculated and they were plotted on the H-R diagram. It is clear that SAO 26804 resides well within the region of the other 31 sources. We believe that the proximity of these other sources to the position of SAO 26804 is strong evidence that the
model of de la Reza (1996) does describe this source, and that it is most likely not Vega-like, but is a luminosity class III giant.

Summary and Conclusions

We have presented new 10.8 and 18.2 μm images of SAO 26804 made with OSCIR on Keck II. Using our new observations in conjunction with previous data we make the following conclusions about SAO 26804:

1. Our main conclusion is that SAO 26804 is unresolved in the mid-IR at the highest resolution currently possible at these wavelengths. We measure the source to have a FWHM less than 0.45" at both 10.8 μm, and 18.2 μm. The 10.8 μm size is inconsistent with previous observations that showed what appeared to be a highly inclined disk with FWHM = 1.5". The fact that there is no disk-like structure seen around the source weakens the theory that SAO 26804 is a member of the Vega-like class of objects and strengthens the idea that the source has Luminosity Class III.

2. We believe the fact that SAO 26804 is unresolved in the mid-IR is strong circumstantial evidence that the star is not a classical Vega-like source. Coupled with evidence presented in other works (e.g. Fekel et al. (1996) and de la Reza et al. (1996)) our new mid-IR images support the classification of SAO 26804 as a luminosity class III giant. We also present evidence supporting this classification in the form of the H-R diagram. To definitively place the source in one luminosity class or the other more diagnostic observations are needed. In particular, a robust distance measurement would answer the question of where SAO 26804 is in its evolution.
CHAPTER 7
INSTRUMENTATION ACTIVITIES: THE OSCIR SYSTEM

Another aspect of the research done for this dissertation is centered on the commissioning, use, and support of the OSCIR camera system. OSCIR is a mid-infrared (5 to 25 μm) camera slit spectrometer system built by the University of Florida Infrared Astrophysics Group (IAG). OSCIR is built around a 128 x 128 Si:As HF-16 blocked-impurity-band (BIB) array from Boeing. This detector technology is currently the most advanced available for this wavelength regime. As is common with this generation instrument OSCIR is cooled through the use of liquid nitrogen and helium to cryogenic temperatures. A common dewar design was modified to incorporate an uplooking entrance into the surface of the vacuum shield. This design allows easy access to the inner levels of the dewar, and makes it relatively easy to handle and setup the dewar in laboratory conditions. The uplooking design also has the advantage of easy interfacing to classical cassegrain mounting positions on various telescopes. OSCIR is a compact system and can be easily handled by two people. The dewar and assembled mounting assembly for Gemini North stand ~1 m tall and are approximately 50 cm in diameter. The dewar weighs ~ 45 kg when fully prepared for observing. This includes the weight of the attached components and the cryogens.

Originally planned for exclusive use on the NASA IRTF, OSCIR has evolved into a self-contained, traveling system that has been adapted for use on other telescopes. Since commissioning in late 1995, OSCIR has been used productively at four major observatories; the IRTF, the CTIO 4m, Keck II, and Gemini North. Table 7-1

140
summarizes the 18 observing runs that OSCIR has been used on. As a basic measure of the system productivity we determined the number of ‘useable’ nights on each observing run where a useable night is defined as a night in which any data was obtained. Clearly, this is not an accurate measure of a nights quality, or the quality of the data obtained on that night. However, it does illustrate the fact that when all the external requirements were met (i.e. weather, telescope operation), OSCIR was ready to observe. Of the 140 official nights that have been awarded to OSCIR data was obtained on 102 of them. Approximately 14 of the remaining 38 nights were lost to OSCIR related problems, and of those 14 nights, 8 were lost on the pre-commissioning run. These numbers show that OSCIR has been a very reliable and robust system for its entire existence. Table 7-1 also hints at the tenacity of the OSCIR observers as there were certainly data obtained on “useable” nights that were not really useable at all. We start the chapter with a detailed description of the system itself and its operation.

**System Overview**

The OSCIR instrument is composed of three primary sub-systems; the dewar, the electronics crate, and the control computer. Each of these sub-systems is absolutely critical to the operation of OSCIR since the signal from an astronomical source has to pass successfully through each before the observer even sees an image or spectra of the source. The first of the sub-systems the signal passes through is the dewar. The dewar contains the optics, the detector, and the analog circuitry needed to produce a signal that is used in the high speed electronics crate. The electronics crate is the second sub-system of the OSCIR instrument. It is a system of electronics boards housed in a conventional
Table 7-1: OSCIR Observing Runs

<table>
<thead>
<tr>
<th>Date</th>
<th>Facility</th>
<th>Useable/Total nights</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995 July</td>
<td>IRTF</td>
<td>1/9</td>
<td>Pre-Commissioning Observing run</td>
</tr>
<tr>
<td>1995 December</td>
<td>IRTF</td>
<td>5/5</td>
<td>Commissioning run</td>
</tr>
<tr>
<td>1996 May</td>
<td>IRTF</td>
<td>7/7</td>
<td>Daytime observations of Comet Hyakutake</td>
</tr>
<tr>
<td>1996 December</td>
<td>IRTF</td>
<td>7/10</td>
<td></td>
</tr>
<tr>
<td>1997 March</td>
<td>CTIO</td>
<td>3/4</td>
<td>Commissioning run on CTIO 4 meter</td>
</tr>
<tr>
<td>1997 September</td>
<td>IRTF</td>
<td>9/10</td>
<td></td>
</tr>
<tr>
<td>1997 December</td>
<td>CTIO</td>
<td>3/8</td>
<td></td>
</tr>
<tr>
<td>1998 March</td>
<td>CTIO</td>
<td>3/6</td>
<td>First visitor use – HR 4796 discovery</td>
</tr>
<tr>
<td>1998 May</td>
<td>Keck II</td>
<td>8/8</td>
<td>Commissioning run on Keck – HD 141569 discovery</td>
</tr>
<tr>
<td>1998 July</td>
<td>CTIO</td>
<td>6/6</td>
<td></td>
</tr>
<tr>
<td>1998 September</td>
<td>CTIO</td>
<td>4/5</td>
<td></td>
</tr>
<tr>
<td>1998 November</td>
<td>CTIO</td>
<td>6/7</td>
<td></td>
</tr>
<tr>
<td>1999 February</td>
<td>CTIO</td>
<td>3/4</td>
<td></td>
</tr>
<tr>
<td>1999 April</td>
<td>Keck II</td>
<td>7/8</td>
<td>HD 169142 discovery</td>
</tr>
<tr>
<td>1999 June</td>
<td>CTIO</td>
<td>10/14</td>
<td></td>
</tr>
<tr>
<td>1999 September</td>
<td>CTIO</td>
<td>4/9</td>
<td>Last visitor use at CTIO</td>
</tr>
<tr>
<td>1999 November</td>
<td>IRTF/Keck II</td>
<td>10/10</td>
<td></td>
</tr>
<tr>
<td>2000 June</td>
<td>Gemini North</td>
<td>6/10</td>
<td>Commissioning run on Gemini North</td>
</tr>
</tbody>
</table>

Total = 102/140

a A useable night is defined to be a night in which any data was obtained.

VME chassis. The output signal from the dewar is sent here to be buffered and processed at the most fundamental level. This processing is done entirely within the VME crate with no user interaction. Both the dewar and the VME crate reside on the telescope. The third and final sub-system of the instrument is the control computer. This is a high-end PC which contains a special frame-grabber card that interacts with the electronics. The current version of the control computer is a Pentium III 450 with 40 GB storage and 384 MB RAM. It currently uses a single 21” monitor that will be shortly upgraded to
include a second monitor. The control computer resides in the control room of the telescope and is connected to the VME crate by a single fiber optic cable. At Gemini North there is approximately 300 meters of fiber between the VME crate and the control computer. Figure 7-1 shows a high-level block diagram of the instrument sub-systems. Major components of each sub-system are also shown schematically. Figure 7-1 only gives the highest level overview of each of the sub-systems. In the next part of this chapter we deal with each of the sub-systems individually. Important components of each are discussed and the overall operation of the instrument is touched on.
The Dewar

The dewar is the sub-system of the instrument that is most often identified as "the camera". It is a large aluminum cylinder that contains the optics and detector as well as the cryogenic fluids used to cool them. The dewar (and the VME crate) resides on the telescope. At Gemini North, the IRTF and CTIO the dewar is mounted on the telescope at classical cassegrain focus, at Keck II it was used at a 'bent' cassegrain focus. Since OSCIR was designed to be uplooking, an IR Labs dewar case was modified to have the entrance window on the top surface instead of out the side of the cylinder. The dewar case is anodized aluminum with heli-coiled holes and mounting brackets around its outermost surface. The handling brace for moving OSCIR manually and the braces for mounting the dewar to the telescope attach to this case. This case also acts as an electrical ground for the circuitry inside it.

The dewar case also serves as a vacuum jacket. Since the detector and optics of OSCIR are cooled by cryogens, the cryogenic fluids must be stored within the dewar case. In fact, a large amount of the volume of the dewar itself is taken up by the two cryostats inside the case. Figure 7-2 shows a cutaway view of the OSCIR dewar and the major components in it, including these cryostats. The only way to achieve reasonable hold times for the cryogens is if the dewar is kept under a deep vacuum. Roughing and turbo pumps are used to evacuate the dewar down to $10^{-3}$ mTorr. The pumps are normally left on the dewar for approximately 12 hours. Once the dewar is evacuated to this level the cryogens are added. OSCIR uses liquid nitrogen (LN$_2$) and liquid helium (LHe) to cool the detector and optics to acceptable temperatures. The two storage vessels inside the dewar each hold five liters of liquid. The nominal temperature of liquid nitrogen is 77
Figure 7-2: 3-D view of the OSCIR dewar. The vacuum jacket is the outermost layer, and surrounds all of the optical components of the system as well as the vessels for the LN$_2$ and LHe. The beam path through the system is shown in dark gray. All of the optical components are labeled. “F” designates a flat mirror, “P” is a powered component. There are 11 folds in the OSCIR beam after it enters the vacuum jacket. Also shown are the three internal components that are moved via the external stepper motors (filter wheel, slit wheel, grating/mirror turret).
K, the helium temperature is 4 K. Under non-operational conditions a single charge of liquid helium has a hold time of about 36 hours. During an observing run, where the detector heater is used to hold the chip at a stable temperature, the dewar must be filled with LHe once per night. The LN2, which acts as an insulator for the LHe, is topped-up with each helium fill. There is also active shielding inside the dewar to help keep the interior components cold. A foil-wrapped aluminum shield is heat-sunk to the helium vessel inside the dewar case. This reduces the radiative load on the LHe vessel, but more importantly the heat-sinking of this shield to the helium vessel greatly reduces the conduction between the nitrogen temperature surfaces and the helium temperature material. Even the evaporated helium gas is used as a cooling agent as it escapes the dewar through a long metal coil heat-sunk to the optical bench.

Approximately 20 kg of material (mostly metal) is cooled to nitrogen temperature (77 K) or cooler. Of this approximately 11 kg is taken down to helium temperature (4 K). It takes 15 liters of LHe and 20 liters of LN2 to cool OSCIR to its nominal operating temperature range of 7 to 9 K. Normally it takes about 12 hours for the detector to reach equilibrium with the LHe at ~5 K. Once the detector is cold if we need to bring the system back to room temperature, it is warmed up slowly over a period of 24 hours or so. This prevents damage from thermal expansion to the detector and other susceptible components as the system warms. Under extreme circumstances the dewar has been “cold-cycled” (i.e. gone from cryogenic temperatures to room temperature and back to cryogenic temperature) in around 15 hours. OSCIR and its peers will most likely be the last mid-IR instruments to use liquid cryogens. Because of the trouble and expense of transporting these substances to the remote observing sites the later generations of
Instruments will be equipped with closed-cycle coolers. These are mechanical coolers that can cool large amounts of material to helium temperatures without any liquid cryogens. The closed-cycle cooler that will be used with T-ReCS, a first generation instrument for Gemini South can cool 42 kg of metal to 20 K in ~23 hours. These mechanical coolers are also very robust. A requirement for T-ReCS is that the entire dewar must be able to stay cold and ready to observe for at least six months with no removal from the telescope.

**Optics**

The optics are one of the, if not the, most important component of any instrument. The surface of the optics is the only place inside the dewar that the mid-IR photons of the source and background truly interact with the system. The very photons that the instrument is herding toward the detector must be directed, and re-directed through the complex path through the dewar shown in Figure 7-2. There are 11 folds in the beam between the dewar entrance window and the detector. The folding of the beam allows for the compact dewar design and the implementation of the spectrometer within the system. As Figure 7-2 shows, other than the entrance window and the filters, OSCIR is a completely reflective system. There are two primary advantages of an all reflective system in the mid-IR. First, with a reflective system, one does not have wavelength dependent chromatic effects to content with. Secondly the mirrors are easy to use in a cryogenic environment, and are robust enough to handle the repeated temperature cycling that a system like OSCIR is subject to. The mirrors in OSCIR are fabricated out of high-grade aluminum and diamond turned to the correct shape. The optical surfaces are then
Figure 7-3: Keck artificial and observed PSF. Each image is 4” x 4”. Both images have been normalized to one at their peak. (a) Azimuthally symmetric model PSF for Keck II at a wavelength of 18.2 μm. (b) Observed PSF at Keck II in 1999 May. This IHW18 image of the standard star γ Aquila was taken under good observing conditions using the Keck auto guiding system. Note the overall hexagonal shape to the Airy ring and the 6-sided spider pattern in the image. The asymmetry of the first ring is most likely due to a small amount of coma induced into the image by slight misalignment of entrance beam with respect to the dewar.

coated with a thin surface of pure gold. The advantage of gold is that it has a very high reflectivity in the infrared (> 99% per surface). Even with the gold coating we lose a minimum of ~ 11% of the light entering the dewar \((0.99)^{11}=0.895\). The optics currently in OSCIR have been there since the commissioning of the dewar and will be used for the remainder of OSCIR’s scientific and engineering use.

The optical performance of OSCIR is excellent. OSCIR has demonstrated diffraction-limited performance at both 10 and 18 μm at the IRTF, CTIO and Keck. Figure 7-3 shows an example of the performance on Keck II. Since the wavelengths that OSCIR observes in are relatively long as compared to the visual, the effects of diffraction are correspondingly easier to see in OSCIR data. Subtle mirror form problems that are
impossible to see when observing in the visible are often easily discernable in OSCIR images. We have in the past used asymmetries and distortions in OSCIR data to predict and diagnose problems with telescope systems. It is safe to say that at each telescope OSCIR has been used at this form of “image” engineering has helped with the overall operation of the facility.

To achieve the best focus of the system we focus using the K filter. In this regime OSCIR is normally not diffraction limited and fine adjustments to the focus can be made. Experience with OSCIR under observing conditions has shown that the telescope can be well out of focus before there is any noticeable difference in a 10 μm stellar image. However being out of focus does has a detrimental effect on the observations. When the telescope is slightly out of focus power from the core is pumped into the wings of the pattern. A significant amount of power can be pumped into the first airy ring before there is any noticeable degradation of the image visually. Due to diffraction, the apparent size (e.g. full width at half-maximum intensity) of a stellar image is not a good measure of the quality of focus. The peak intensity (or Strehl ratio, when normalized by the theoretical peak) or the encircled energy in the core is a far more sensitive measure. The OSCIR interface includes a utility to measure the Strehl ratio of a stellar image while we are changing the focus. Visual inspection of the stellar image and monitoring of this ratio is the best way to assure the system is in focus throughout an observing night. Figure 2-1 shows how the FWHM of stellar images can change within a night. At Keck, where the data from Figure 2-1 was obtained, typical changes in the FWHM of a stellar image for a night are around 0.1 to 0.2 arcseconds.
**Entrance Window and Filters**

Not all of the optical components in OSCIR are reflective. Both the dewar entrance window and the filter complement are made of infrared transmitting materials. Since normal glasses become opaque in the near and mid-IR they are inappropriate for use in a mid-IR system like OSCIR. For the mid-IR a variety of crystalline substances are used instead. Natural crystals like cesium iodide (CsI) and barium fluoride (BaF₂) are commonly used as well as man made substances like KRS5. Each of these materials has a unique set of advantages and disadvantages. The major disadvantage of natural crystals is that they tend to be very soft, and therefore are easy to scratch or gouge. The natural crystals, which are actually salts, are also hydroscopic. This makes them difficult to work with when one of the crystal surfaces would be exposed to water or high humidity. The main advantage of natural crystals like CsI and BaF₂ is that they transmit IR radiation very well. For example the transmission of CsI is well over 95% throughout the mid-IR regime. This is compared to a transmission of ~70% for a similar sized piece of KRS5. Man made materials like KRS5 and others also have the disadvantage of being toxic and therefore dangerous to work with. On the other hand, the man made materials are extremely strong and are mostly impervious to water. For most of OSCIR’s scientific use the advantage of overall durability outweighed the gain in throughput and a KRS5 entrance window was used. In Figure 7-2 the KRS5 window is shown. This window has been removed from the dewar and replaced with a custom window assembly for use of OSCIR at Gemini North.

The custom entrance window assembly currently installed on OSCIR is comprised of two CsI lenses which have been anti-reflection (AR) coated and have a waterproof coating applied on top of the AR coating to protect the crystal surface. This
assembly is also unusual in the sense that the lenses can be moved both independently of each other and in unison to achieve a precise focus of the telescope entrance beam. This is needed since the Gemini telescope produces a f/16 beam while OSCIR is designed to accept a f/35 beam. No special assembly was required to use OSCIR on the IRTF, CTIO and Keck since the focal ratios of those telescopes are: f/35, f/30, and f/40 respectively. The dewar is exactly matched to the beam of the IRTF, the CTIO beam was slightly vignetted by the Lyot stop in the dewar, and the entrance beam of Keck was slightly undersized for optimal use with OSCIR. Since the beam produced by Gemini is so much faster than the other three the special entrance window assembly is essential to the operation of OSCIR at this telescope. The dewar window assembly was successfully used on the commissioning run of OSCIR on Gemini North in 2000 June.

The complement of filters in OSCIR is the only other place in the optical train where transmissive materials are used. All of the fourteen filters in OSCIR are multi-layer interference filters. These filters are designed to pass only a certain range of wavelengths. All other wavelengths are excluded partly by the interference properties of the filters themselves, but also by the overall transmission properties of the coatings and the filter substrate materials. The transmission of an interference filter within the passband is normally between 80 to 90% and the filters in OSCIR bear this out. Figure 7-4 shows the passbands of the OSCIR broadband N and IHW18 (International Halley Watch) filters. These are the two filters that have so far been the filters used the most by both team members and visiting scientists. These are also the filters used for all of the observations in this dissertation. Figure 7-5 shows a similar plot for the narrowband silicate filters installed in OSCIR. The seven filters are called the ‘silicate’ filters since
Figure 7-4: OSCIR broadband N and IHW18 filter transmission plots. These transmission plots were made when the filters were at room temperature. The passband of each shifts approximately 2% to shorter wavelengths when the filters are at operating temperature (77 K).

Their passbands span the 8 to 14 μm atmospheric window where there is a prominent silicate feature seen in some astronomical objects. Along with the N and IHW18 filters, the silicate filters have been the main ones used in OSCIR since its commissioning. All of the filters in OSCIR are in excellent condition. Except for a slight ‘ghost’ in the N-band filter when observing extremely bright stars there are no stray light problems with the system. There is a significant image shift when using the 10.3 μm silicate filter though. In this filter the image is shifted 27 pixels along the horizontal detector axis and 28 pixels in the vertical detector axis. We believe this shift is due to a slight wedge shape to the filter. This known effect is compensated for while observing.
Figure 7-5: OSCIR silicate filter transmission plots. These transmission plots were made when the filters were at room temperature. The passband of each shifts approximately 2% to shorter wavelengths when the filters are at operating temperature (77 K).

OSCIR also contains two short wavelength and a suite of newly installed long wavelength filters. The K (2.2 \mu m) and M (4.8 \mu m) filters are normally used for engineering and setup purposes like focusing. There have also been a few science observations made through these filters but the low system sensitivity limits them to very bright objects. Observing in the 1 to 5 \mu m region with OSCIR is also not recommended because there is no background radiation to help fill the wells of the detector and the observations become read-noise limited. Even frametimes as long as 80 to 100 ms do not get the well depth above 10%. In the thermal IR the wells fill to \sim 60\% in 20 ms in the broadband N filter.
The long wavelength filters were installed in preparation for the commissioning run on Gemini North. All of the four new long wavelength filters have a central wavelength longer than that of the IHW18 filter. With the addition of these filters OSCIR will be the only camera in full operation on Mauna Kea with filters that have passbands in the 25 μm range. Since the atmospheric window in this regime is riddled with H2O and CO2 absorption bands the use of these filters will be heavily dependent on the quality of the atmosphere. In particular, the Qwide filter, which is the long wavelength equivalent of the N band with a bandwidth of 5.2 μm, will only be able to be used on extremely good nights. If there is any significant water in the atmosphere, the background is too high to use this filter since we cannot read out the detector fast enough to prevent saturation. We are particularly eager to observe with the new H25 filter which has the longest central wavelength at 24.1 μm. This filter will be extremely useful in extending of the research presented here. Table 7-2 lists some relevant filter characteristics.

**Detector**

The recent evolution of the detector technology is arguably the single most important development in the area of infrared astronomy in the last 10 years. Instruments have rapidly moved from being single element detectors, to small bolometer arrays, to the detector arrays that are now common in all front-line instrumentation. While it has been common for visible light CCD cameras to have in excess of one million pixels for the last decade, the size of the biggest mid-IR arrays now in common use have around 16,000 pixels. The reason for this large discrepancy in the size of the arrays lies in the fact that the mid-IR observing regime requires totally different detector technology from the
Table 7-2: Characteristics of the OSCIR filter set.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Central Wavelength (μm)</th>
<th>Bandwidth (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K (2.2)</td>
<td>2.20</td>
<td>0.42&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>M (4.8)</td>
<td>4.80</td>
<td>0.60&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>7.9</td>
<td>7.94</td>
<td>0.76</td>
</tr>
<tr>
<td>8.8</td>
<td>8.79</td>
<td>0.87</td>
</tr>
<tr>
<td>9.8</td>
<td>9.83</td>
<td>0.95</td>
</tr>
<tr>
<td>10.3</td>
<td>10.28</td>
<td>1.10</td>
</tr>
<tr>
<td>11.7</td>
<td>11.65</td>
<td>1.11</td>
</tr>
<tr>
<td>12.5</td>
<td>12.45</td>
<td>1.16</td>
</tr>
<tr>
<td>N (10.8)</td>
<td>10.38</td>
<td>5.23</td>
</tr>
<tr>
<td>IHW18 (18.2)</td>
<td>18.08</td>
<td>1.65</td>
</tr>
<tr>
<td>Qwide (17-24)</td>
<td>19.67</td>
<td>5.25&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Q3 (21)</td>
<td>20.75</td>
<td>1.65</td>
</tr>
<tr>
<td>LPF (20-29)</td>
<td>21.73</td>
<td>7.40&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>H 25</td>
<td>24.13</td>
<td>3.60&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
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<sup>a</sup> Approximate bandwidths. Accurate to ± 0.2 μm.

visible. In particular, the silicon based detectors for the visible are normally used for relatively long exposures, and can use conventional shift-counter readout technologies.

This is not possible for mid-IR detectors since the detectors need to be read out at much higher rates to combat the high backgrounds and avoid saturation.

OSCIR uses a Rockwell/Boeing 128 x 128 HF–16 blocked Impurity band (BIB) detector. The detector in OSCIR (serial number: HF02) has been fully characterized by the OSCIR team, and much effort has been put into optimizing its performance for use in ground-based astronomy. The blocked impurity band technology was born from the Star Wars Defense program of the 1980s. It is an ‘extrinsic’ semiconductor, as opposed to a CCD which is an ‘intrinsic’ semiconductor. An intrinsic semiconductor is made from a
pure semiconducting material that can interact with higher energy photons. The silicon in a CCD array interacts with an optical photon causing electrons in the semiconductor’s valence band to be excited to the conduction band. The electrons in the conduction band are then free to conduct electricity, and this charge can be read out. However, silicon by itself does not effectively interact with photons of lower energy, such as mid-infrared photons. Instead extrinsic semiconducting materials are created such as silicon or germanium that have atoms in their crystalline structure deliberately replaced with other atoms, a process referred to as ‘doping’. These ‘impurities’, or ‘dopants’, are atoms that can be excited by longer wavelength photons, hence providing electrons for the conduction band. The problem with doped photoconductors is that their quantum efficiency is dependent upon the concentration of dopant. However, too much dopant causes ‘tunneling’ or ‘hopping’ across the valence band, and this can lead to large dark currents. The only other choice is to make the photoconducting material lightly doped but very thick, which leads to many operational problems. A way of overcoming this is to use a ‘blocking band’. By placing a layer of pure silicon between the doped material and the read-out contact, electrons cannot hop across the material and out the contact, thus reducing the dark current. In this way, the infrared reactive material can be heavily doped to increase quantum efficiency, and the read out through the contact will only be from

<table>
<thead>
<tr>
<th>Table 7-3: OSCIR Detector characteristics</th>
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<tbody>
<tr>
<td>Array size:</td>
</tr>
<tr>
<td>Pixel Size:</td>
</tr>
<tr>
<td>Full-well capacity:</td>
</tr>
<tr>
<td>MUX readnoise:</td>
</tr>
<tr>
<td>Dark Current:</td>
</tr>
</tbody>
</table>
electrons that were excited into the conduction band by interaction with a mid-infrared photon. The detector used in OSCIR has excellent cosmetic quality. Figure 7-6 shows an image of the detector under uniform illumination. There are only ~10 dead pixels distributed across the array. Although there is a small amount of vignetting in the lower right corner of the array, the response of the array is in general very flat and the flat-field
varies by ±5%. The structure seen on the array is “fixed” and is removed during the chop-nod process.

**VME Crate**

The purpose of OSCIR is to propagate a source signal from the focal plane of the telescope to the screen and hard drive of the control computer. To do this the system must synchronize many different electrical signals with nanosecond precision. Most of these signals are generated in the VME crate and sent to the dewar then onto the detector. However, because of the way that observations are made in the thermal IR the instrument is very much integrated into the telescope itself. Several aspects of the instrument operation must be in precise synchronization with telescope systems or the observation will fail. In particular the secondary control system and the telescope pointing systems have to accept signals from OSCIR and must also provide the instrument with status information. The dewar responds to these signals with a stream of data that returns to the VME crate through 16 output channels from the detector. The 128 x 128 pixel detector in OSCIR has 16 readout channels meaning the 16 pixels can be read out simultaneously.

Having 16 outputs dramatically increases the speed at which the detector can be readout, but at the same time it increases the amount of data that the system has to deal with simultaneously. A more detailed view of the VME crate and its components are shown in Figure 7-7. Propagating the signals through the system is no trivial matter. Due to the high backgrounds encountered in the mid-IR, to effectively observe any astronomical source the electronics have to readout the detector every 20 ms. The data handling processes of the VME crate are complex. Many of the most complex signals,
Figure 7-7: Detail of VME crate and communication links.

including clocking patterns for the detector, are sent from the VME crate to the dewar. The dewar sends output signals as well as the data stream back to the crate. Under normal observing conditions the data stream moving from the dewar into the VME crate is approximately 3 MB/sec. We give a high-level overview of the data path through this sub-system here. The signals from the dewar arrive along 16 analog lines which come directly from the pre-amplifier on the dewar. These signals enter the VME crate into four analog-to-digital (ADC) converter boards. Each of the four ADC boards handles four channels from the detector. The ADC boards are responsible for converting the analog signals from the dewar into digital signals the rest of the system can work with. This conversion is done is sixteen ADC units on the four boards, one for each channel. The
data is digitized at a resolution of 16-bits using a 2 MHz sample rate. Once a signal is
digitized the result is stored in on-board RAM until the proper number of frame co-adds
is completed. Once the co-adds are finished the final stack of data is transferred across
the VME backplane to the upper fiber communication board. The data is transferred from
the upper fiber board through a 45 MB/sec optical fiber cable to the lower fiber board
which is located in the control room close to the control computer. The data is stored in
RAM in the lower fiber board until the control computer is ready to accept it into the
RAPTOR frame grabber card resident in the control computer. Once the data is
transferred to the RAPTOR card it is accessible to the control computer and can be
brought into the OSCIR software interface, which is written in IDL. The IDL software
environment is the last step of the data path. From here the data is written to disk in a
standard, albeit a 6-dimensional, FITS file and displayed to the observers in a graphical
user interface written using IDL widgets.

The CPU in the VME crate is a 68020 Motorola chip. It is responsible for
coordinating all of the activities in the VME crate. In particular the CPU is responsible
for making sure that the correct clocking patterns and settings are loaded into the Xilinx
programmable gate array. The various clocking patterns are stored in static memory
(PROMs) on the CPU board in the crate. The pattern generator board contains a Xilinx
programmable gate array (PGA) microprocessor. It is in the Xilinx chip that the clocking
signals are generated. This chip also obtains various detector settings (i.e. bias
information) from the command computer to translate and send the detector. Since there
are different modes of operation that are used with OSCIR (i.e. chop only, nod only,
stare, and chop/nod) there are different sets of commands and setting that need to be sent
to and from the CPU the detector and the Xilinx chip. Each of the approximately 25
different “cycle types” that can be used in the PGA correspond to one of the ways that the
detector is clocked.

A second crate mounted near the dewar on the telescope houses the temperature
controller and the controllers for the three stepper motors used with OSCIR. We have
found that excess noise can be introduced into an observation if the temperature varies by
more than ~0.005 K during the observation. We therefore use a Lake Shore model 330
temperature controller with a PID feedback loop to hold the temperature constant. The
temperature of the detector is held between 8 to 9 K during normal operations.
Calculations shows that approximately 1.6 mW of power must be input into the detector
through a carbon resistor to hold the temperature at ~8.5 K. One consequence of having
to keep the detector at a constant temperature is that the observer must wait for the
temperature to stabilize any time that the background flux level on the detector is
changed. For example, when changing from the broadband N filter to a narrow band
silicate filter. In this extreme case (high background flux at N, low background at 9.8
\(\mu m\)) it takes approximately 45 to 60 seconds for the temperature to stabilize.

The optical fiber cable between the upper and lower fiber boards is the only
physical connection for OSCIR between the control room and the dewar and VME crate
on the telescope. Configuration commands from the control computer are sent through
this fiber to the dewar and crate. Once in the crate they are translated and sent as serial
signals between upper fiber board and the various controllers through RJ-11 cables.
Clock signals and bias settings are sent to the dewar from the VME crate through 40 pin
and 25 pin ribbon cables respectively. Communication between the VME crate and the
telescope control systems is handled through connection with BNC cables. The control computer communicates with the telescope systems are through a TCP/IP socket connection.

The final component of the VME crate are linear power supplies that produce clean power for the bias board and the pre-amps at 15 V. Normal 60 Hz 110 V power is used to power the VME crate itself, the temperature controller, the motor controllers, and the power supplies themselves. At Gemini North the 110 V power provided is UPS power which is free of line noise. The entire dewar is electrically isolated form the telescope itself using G-10 inserts between the dewar and the mounting hardware to prevent electrical “pick-up”.

**Control Computer**

The control computer is the final sub-system of the OSCIR instrument. The data is transferred from the VME crate to the computer through the optical fiber and the upper and lower fiber boards. The current incarnation of the control computer is a 450 MHz Pentium III PC with 384 MB RAM and 30 GB storage space. It uses a 21” monitor to display the OSCIR software interface. The only non-standard piece of hardware in the control computer is the previously mentioned RAPTOR frame-grabber card. This card ‘grabs’ the frames that are output from the lower fiber board and stores them in on-board memory until the OSCIR software interface needs to assess the data frames to store them to disk and present them visually to the observer. A second control computer is kept on-site with the OCIR system and can be used in case of failure of the primary computer. For most of OSCIR’s use the control computer was used to backup the data at the end of each observing night. The data was transferred to optical disks at the telescope for eventual
burning onto CD-ROM. To date there are 132 CD-ROMs that make up the OSCIR data archive which hold approximately 81 GB of data.

A part of the OSCIR system that most likely deserves its own section is the OSCIR software interface. The software interface is as critical to the operation of the system as any piece of hardware, and it is arguably the most complex component of the entire instrument. It is comprised of approximately 250 individual programs which control most aspects of the system status. We give a broad overview of it here since it resides on the control computer and is such an integral part of the system as a whole. Dr. Robert Piña wrote the entire interface including the dynamic link libraries needed to access various pieces of hardware (e.g. RAPTOR card). The majority of the interface is written in the IDL software environment. The graphical user interface (GUI) of the software uses IDL widgets to present the observer with an easy and efficient way to communicate with the system as a whole. All communication between the observer and the dewar pass through the various windows that make up the GUI and the observer can access the data in almost real-time through the same windows. This near real-time data access is made possible with a suite of “quicklook” data analysis tools that are built into the GUI. These tools allow the observer to display the data that was just obtained by the system and perform basic analysis on the data very quickly. This is extremely useful in assessing the quality of an observation and gives the users immediate feedback on the overall status of the observational program. These tools were used extensively in the data reduction and analysis of the observation presented in this dissertation.
Summary of Activities

The experience gained through the instrumentation work with OSCIR while carrying out the observations for this dissertation is extremely valuable. We consider this to be an important and relatively unique aspect of this research. The opportunity to be involved with the final steps of fabrication, commissioning, characterization and use of a front-line instrument like OSCIR is the best way to learn about instrumentation issues and observing in general. Similarly, the observing experience gained from taking part in every one of the OSCIR observing runs gives one the opportunity to learn how to observe in the mid-IR, and support other observers as well. We look forward to observing with OSCIR at Gemini North and the next generation of instruments that are now being fabricated in labs around the globe.
Poor atmospheric transmission, highly variable sky conditions, and incredibly high background levels have made it impossible to work in this regime until relatively recently. The first major obstacle for the mid-infrared light from a source to hurdle is getting through the earth’s atmosphere. There are two useful ‘windows’ in the atmosphere between the wavelengths of 5 to 25 μm. The first is a relatively high transmission window between 7 and 14 μm, which contains an absorption feature at 9.6 μm due to ozone. Between 14 and 16 μm, transmission drops to nil due to CO2. However, after 16 μm is the second window, which continues until about 30 μm. This window is riddled with water vapor absorption features, but enough mid-infrared radiation can penetrate through the atmosphere at these wavelengths to be useful (Figure 1-A). After 40 μm, the atmosphere is opaque to radiation until wavelengths reach the submillimeter regime, where once again it is possible to conduct ground-based astronomy. Within these mid-infrared windows, there can be rapid variations in transmission due to atmospheric turbulence and water vapor.

Once the radiation from the source penetrates the atmosphere, it is then collected by the telescope. However, the telescope optics do not just send the photons from the source to the camera. They also send many photons of their own due to the fact that they are sources of thermal radiation as well. The same is true for the entrance window to the
Atmospheric Transmission, Mauna Kea
(altitude=4200m, airmass=1.0, pwv=1.2mm, R=3000)

Figure A-1: ATRAN model of atmospheric transmission for Mauna Kea. The 8-14 μm window can be seen clearly as well as the shorter wavelength near-IR windows. The absorption feature at 9.8 μm is due to atmospheric ozone, the opaque band at 15 μm is from CO₂. Longer wavelength filters take advantage of the 16-30 μm window, which has many absorption features.

camera. These sources of ‘background radiation’ can be removed, as will be discussed in the next section.

Once the mid-infrared radiation from the astronomical source passes through the entrance window in to the camera system of OSCIR (Figure 7-2), it undergoes very little attenuation before hitting the detector. This is because except for the filters and the camera entrance window, OSCIR is an entirely reflective system. All of the mirrors in the optical path of OSCIR are gold-coated, to take advantage of the low emissivity gold has in the mid-infrared. Furthermore, the entrance window is the only component in the camera that is not cryogenically cooled. By cooling the optical components in this way,
they do not contribute any thermal background. The detector is also cooled to cryogenic temperatures to suppress the thermally generated dark current. Infrared cameras like OSCIR have optics that reimage the field onto the detector with a system of mirrors for two reasons. The first is to achieve the desired plate scale at the detector, and second is to create pupils within the cryostat. There are two reasons for wanting internal pupils. One reason is that the filters, which need to be placed at the pupil, can be cryogenically cooled. The second reason is that at the pupil can be placed a Lyot stop. This is done because a large background problem comes from stray light entering the camera system. In order to cut down this stray light, a circular aperture or ‘stop’ is placed near the pupil image of the secondary mirror where it can reject stray light from outside the beam. This stop is located internally where it can be cryogenically cooled (called a ‘cold’ stop) so as too not contribute any thermal emission of its own.

The filters used in the survey are highly transmissive and have fairly broad wavelength coverage. As can be seen in Figure A-3, the N filter takes advantage of the whole 7-14 μm atmospheric window. Once the source radiation has passed through the filters and optical path, it finally ends it journey at the detector. More will be said about the detector later.

**Extracting the Source Signal**

As was mentioned, the detector not only receives the mid-infrared radiation from the astronomical source, but also the highly variable radiation from the sky (i.e. sky background), and the relatively static radiation from telescope optics and camera entrance window (i.e. radiative offset). In fact this background radiation dominates observations
in the mid-infrared. For example, typical bright infrared standard stars used for flux calibration are frequently an order of magnitude fainter than the background emission. For scientifically interesting astronomical objects, which are typically much fainter than the standard stars, we may be receiving 1 source photon for every 100,000 background photons.

One consequence of such high background levels is that the detector fills its wells very quickly. For example, using OSCIR at the IRTF it was found that the background emission at N is typically $\sim 4 \times 10^{13}$ photons cm$^{-2}$ s$^{-1}$. Given the high quantum efficiency of the detector, and a well depth of $22 \times 10^6$ electrons, the wells of the detector fill to $\sim 60\%$ in 20 ms. Obviously, these short frame integration times requires fast electronics to handle these high data rates.

More importantly to the observer is that this extremely low ratio of source photon rate to background photon rate requires extremely precise background flux subtraction to extract the signal of interest.

**The Standard Chop-Nod Technique**

The requirement of precise background subtraction dictates the method by which images are acquired at a telescope. Background subtraction is effected in real time using the standard infrared astronomical “chop/nod” technique. In this technique, the telescope is pointed at an object of interest (the “program object”) and the camera acquires a set of images. An image consists of signal from the program object superposed on the much larger signal from the background. The secondary mirror of the telescope is then moved slightly away from the nominal position so that the program object moves
Figure A-2: Schematic of ‘chop/nod’ observing. The top four images are the raw, coadded data transferred from the VME crate to the control computer at ~1 Hz. The middle level shows the “dif” frames that are constructed from the difference of the two frames above it. Here the pattern of radiative offset is clearly visible. The bottom image is the sum of the “difs”. Finally we see the astronomical source. In this case the nucleus of the starburst galaxy NGC 253. Data taken at the IRTF.

out of the field of view of the camera. Another set of images is acquired by the camera. This procedure, called a “chop” cycle, is repeated many times at typically a 5-10 Hz rate moving back and forth between “on-source” and “off-source” positions. A “chop-differenced” signal is formed by taking the difference between the on-source and off-source images.

While this rapid movement of the secondary mirror allows subtraction of a spatially uniform background that is varying in time at frequencies below the chop
frequency, it usually generates a spurious signal which may still be significantly larger than the source signal. This spurious signal, termed the “radiative offset,” results from the fact that the emission pattern of the telescope, as seen by the camera, depends on the optical configuration of the telescope. Movement of the secondary mirror changes this configuration, resulting in two different emission patterns. The difference in these emission patterns shows up in the chop-differenced signal.

In order to remove the radiative offset, the entire telescope is moved after a short period of time (typically on the order of tens of seconds) so that the source now appears in what was previously the off-source position of the secondary mirror. This movement of the telescope is termed a “beam switch” or “nod”. Chop-differenced frames are then formed with this new on-source and off-source configuration. A little thought shows that in this new configuration, the radiative offset will have changed sign and will cancel identically when the new chop-differenced data is added to the old chop-differenced data (provided the telescope emission has not changed in the time between beam switching).

Figure A-4 demonstrates the acquisition of data in the standard “chop/nod” mode. The images shown here were obtained with OSCIR at the IRTF. The top row of four images shows the raw data frames from the two secondary mirror positions at each of the two nod positions (called “Nod Position A” and “Nod Position B”) of the telescope. These images are dominated by fixed-pattern off-sets due to pixel-to-pixel variations and offsets between the 16 channels of the acquisition electronics. The background counts in these raw images correspond to $7.4 \times 10^8$ e-/s. Each raw image consists of ~5 minutes of total integration time (i.e. 15,000 frames coadded using a 20 ms frame integration time and the N-band filter) obtained in the chop/nod sequence as described above. The second
row of two images shows the “chop-differenced” data derived from the subtraction of the on-source and off-source data in the two nod positions of the telescope. Note that the dominant pattern (principally a gradient along the diagonal connecting the lower-left to upper-right corners of the images) has changed sign between the two chop-differenced frames. However, since the subtraction is always done as “on-source minus off-source”, the source signal remains positive in both chop-differenced frames. The signal levels in these differenced frames range ±3.2×10^6 e-/s, which is ~0.4% of the raw background signal. Finally, the bottom row shows the net signal obtained by adding together the two chop-differenced frames shown in the middle row (note that no other processing has been done to the data other than the additions and subtractions as described above). The detected source is the nuclear region of the starburst galaxy NGC 253. The net signal is the result of a total exposure of ~20 minutes in which half that time is actually spent imaging the off-source “reference” position. The signal level at the “tail” of this source near the middle of the frame is ~6.4×10^4 e-/s. This is about four orders of magnitude below the background level shown in the raw frame. In fact, the signal-to-noise ratio at this level in each pixel is about seven, so that the effective background sub-traction is more nearly five orders of magnitude below the background.
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BIOGRAPHICAL SKETCH

I was raised in the town of Mapleton Depot, Pennsylvania until age 10. After middle school in PA, I moved to Florida and finished high school in Leesburg. I spent three semesters at a community college there and earned an AA degree. I then was awarded a Congress-Bundestag Youth Exchange Fellowship, 1 of 50 nationwide, and spent a year in Germany as an exchange student. My scientific work started there as an intern at the Gesellschaft fuer Schwerionenforshung, a particle accelerator where I worked on my first instrument project, a high energy photon detector. I returned to Florida and started my undergraduate work at the University of Florida. I double majored in physics and astronomy and graduated in 1993. I was accepted to graduate school at the University of Florida and continued with instrumentation related activities at Rosemary Hill Observatory. I was involved with the total refurbishment of the 18” telescope there and spent many nights observing in shorts with the 30”.

Charlie Telesco interviewed me in January 1995, and as soon as that meeting was over, I knew things were about to change in a big way. I spent 12 months working on ISO data with Charlie and he, Robert, and I setup the lab for the IAG. We then fleshed out the idea for this disk project, and the rest is history. A year or so of OSCIR development, 22 observing runs, 14 GB of data, 9 refereed publications, and 188 pages later … here we are.
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Charles M. Telesco, Chairman
Professor of Astronomy

Robert K. Piña
Assistant Professor of Astronomy

Stanley F. Dermott
Professor and Chair of Astronomy

Richard J. Elston
Professor of Astronomy
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Roger F. Knacke
Director, School of Science, Penn State Erie

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Paul Avery
Professor of Physics

This dissertation was submitted to the Graduate Faculty of the Department of Astronomy in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Dean, Graduate School