A SEARCH FOR DEBRIS DISKS WITH A DUAL CHANNEL ADAPTIVE OPTICS IMAGING POLARIMETER

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ASTRONOMY

May 2003

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To Dad
Acknowledgements

I received support in many forms and from a number of sources during all phases of my thesis. The motivation to incorporate a dual channel polarimeter into an AO system came from a suggestion by Gordon Walker in 1998 at the ESO/OSA Topical Meeting on Astronomy with Adaptive Optics held in Sonthofen, Germany. I thank Buzz Graves and Malcolm Northcott for creating the Hokupa’a AO system, and for guidance in the optical design and incorporation of the polarimeter. I am also indebted to Laird Close for introducing me to the “field” of high-contrast imaging and for supporting my efforts as a scientist. Thanks also to Jeff Kuhn and the SAC Peak Solar Observatory which loaned a high quality Wollaston prism used in this experiment. The Hokupa’a adaptive optics instrument is supported by NSF grant AST-9618852.

I would like to acknowledge the psychological help afforded by my fellow graduate students who created the healthy office environment in “Cold and Calculating”, namely Bob Thornton, Scott Sheppard, Dale Kocevski, Michael C. Cushing, and Henry Heish (a.k.a. “Triple H”). In particular, Michael C. Cushing deserves a special thanks for taking the time to proofread papers and thesis chapters, while being the brunt of almost a constant barrage of practical jokes, verbal assaults, and having to endure a three year “heavy bombardment” era characterized by a high influx of projectiles into his office cubicle. M.C. introduced me to the magical sounds of Kenny G, an inspiration that helped me accomplish this work. I thank Sean Andrews for his support in writing and processing the HST data in section 4.2.

I thank Dave Jewitt, Jeff Kuhn, Eduardo Martín, Don Mickey, John Tonry, Nick Kaiser, and Alan Tokunaga for helpful advice while writing my thesis.
My wife Vanessa provided immeasurable support throughout my time spent as a graduate student, and had the most to do with my survival through the doctorate program. I cannot imagine completing this work without her. Thanks Hun.

Financially, I have been supported by a NASA fellowship through the Graduate Student Research Program (GSRP).
Abstract

A Wollaston prism based dual channel polarimeter was designed and successfully incorporated into the Hokupa'a adaptive optics system mounted on the Gemini North telescope to enhance sensitivity to detecting the light scattered by circumstellar material. The technique suppressed the noise introduced by non-repeatable variations of the point spread function which limit the sensitivity of non-simultaneous adaptive optics imaging. Polarimetric images of easily observed classical T-Tauri star environments around GG Tauri Aab, TW Hydrae, LkCa 15, LkHα 242, GM Aurigae, and SR24 N/S were observed to establish the instrument’s sensitivity.

A survey of nearby \((d < 25 \text{ pc})\), young \((age < 1 \text{ Gyr})\), solar analog (spectral type K0V-G0V) stars was undertaken with the polarimeter to search for the presence of collisionally active debris disks analogous to our solar system during the late heavy bombardment era. Of the 24 stars sampled, none were found to have obvious scattered light signatures. Isotropic and Mie scattering model images of the scattered light appearance of debris disks are used to convert a given debris disk’s physical properties into observable quantities. The residual polarized surface brightness profiles of the survey stars are compared to those produced by the models to conclude that no more than \(M_{\text{dust}} \sim 10^{-2} M_{\text{Moon}}\) of \(1 - 10 \mu m\) sized dust is contained between 5-50 AU from the sample stars.

The cross-sections and scattering parameters produced from Mie theory are used to estimate particle lifetimes under the influence of the Poynting Robertson Drag and radiation pressure as a function of the spectral type of the central star. Through an investigation of other particle removal mechanisms, and it is found that the corpuscular drag from the
stellar winds shorten the dust lifetimes by an amount that is inversely proportional to the stellar wind mass-loss rate. Considering the recently estimated stellar wind mass-loss rates around young solar analog stars, the dust lifetimes should be 100-1000 times shorter than dust lifetimes in the present day solar system. This effect can significantly reduce the near-IR detectability of the debris disks which may exist around these chromospherically active stars.

The polarimetric survey for debris disks was also sensitive to the detection of faint, low-mass companions. Out of the stars surveyed, one binary brown dwarf system was found as a companion to the star HD 130948 (HIP 72567), as confirmed by proper motion and near-IR spectra, as well as a low-mass stellar companion around HD 72760. Orbital motion between the two brown dwarfs was measured, but the 14 month time baseline is inadequate to accurately measure the system’s dynamical mass. Upcoming observations will measure lithium absorption in the brown dwarf’s optical spectra and will provide a more accurate age estimate of the system. The eventual dynamical mass determination coupled with the age determination will provide a valuable check of brown dwarf evolutionary models.
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Chapter 1

Introduction

Circumstellar disks are a natural consequence of angular momentum conservation in the star formation process. They play a vital role in removing the angular momentum of infalling material, allowing it to accumulate onto a central star. During the star formation process, or soon after, planets are thought to form within circumstellar disks. We also know that at least one planet harbors life. Although these general statements can be made with some certainty, our understanding of the details of the star and planet formation process are still uncertain. With only one example of a planet with life, our understanding of the formation of life is based on unchecked educated guesses. At this point, we are not able to accurately predict or observe even the nearest stars with enough sensitivity to see if they resemble our present day solar system. We do not know enough about formation mechanisms and circumstellar disk evolution to predict if young, nearby stars will eventually evolve into something like our solar system.

However, progress is being made on both the technical and theoretical fronts to further our understanding of solar system evolution. With the planned space missions such as the *Space Infrared Telescope Facility (SIRTF, Werner 2002)*, the *Next Generation Space Telescope* (NGST, Mather & Stockman 2000), the Kepler Mission, (Koch et al. 1998), a number of space interferometers (Fridlund 2000) such as the *Space Interferometry Mission (SIM)*, the *Terrestrial Planet Finder (TPF)*, and the DARWIN space interferometer, as well as advances in ground based high resolution near-IR imaging on large telescopes,
and interferometric millimeter arrays (SAO and ALMA), our future ability to address the question of the commonality of exo-solar systems around at least our stellar neighbors looks promising over the next 20 years.

In this dissertation, an observational technique is developed which enhances the sensitivity of ground based AO systems towards detecting circumstellar dust. This technique is applied to a sample of young, nearby, solar-type stars to check for the presence of dust at levels associated with our solar system during the period of the late heavy bombardment.

1.1 Circumstellar Disk Evolution

Because circumstellar disk evolution is closely tied to star formation, it is useful to review what is known of the star formation process. The now popular classification sequence of star formation for $M_* < 2.0M_\odot$ has been developed by Lada & Wilking (1984), and Andre et al. (1990) based on an analysis of spectral energy distributions of sources in the Rho-Ophiuchi star forming region. Stars in their earliest stages, class 0 and class I sources, are completely obscured from their surrounding molecular gas, and are not visible in optical and near-IR wavelengths ($\lambda < 10\mu m$). In these early stages, the stellar core is thought to be accumulating a significant fraction of its final mass through an accretion disk. Young stars do not become visible to optical wavelengths until the envelope of source material is dispersed. This is thought to mark the transition from class I sources to class II sources. For class II systems, commonly referred to as classical T-Tauri stars (CTTS), the circumstellar material is dominated by an optically thick circumstellar disk, rather than a circumstellar envelope, as inferred from IR excess and Hα emission. Typically, CTTS disks mass range from $0.03 < M_{\text{disk}} < 0.3M_\odot$. The class III sources, or weak-line T-Tauri stars (WTTS), are like CTTS with the exception of a lack of strong Hα emission (Martin et al. 1998) and near-IR excess. However, some WTTSs have longer wavelength IR excess similar to CTTSs (Brandner et al. 2000), so they presumably have circumstellar material, but for some reason, this material does not accrete as readily onto the central star creating the Hα emission. Therefore it is still a matter of debate whether or not the
WTTSs are always the evolutionary product of CTTSs, since they have similar age ranges as estimated through model comparisons of their positions on the HR-diagram and their spatial distribution within star formation regions generally overlap. Regardless, for both WTTS and CTTS, it appears that within $\sim 10^7$ yrs, the T-Tauri star optically thick disk disperses (Haisch & Lada 2001; Brandner et al. 2000; Beckwith et al. 1990). However, the process responsible for removal of the accretion disk remains unknown. There are a number of proposed mechanisms, such as planet formation (Kenyon 2002), angular momentum loss via disk viscosity, photoevaporation (Matsuyama et al. 2003), close stellar encounters (Larson 2002), and stellar winds.

After the replenishing source of accretion disk material has run out and the optically thick circumstellar disk is depleted, the remaining material slowly erodes during the main-sequence lifetime of the central star (Kenyon 2002). The optically thin remnants of the once more massive optically thick accretion disks are referred to as *debris disks*. As will be outlined in the following chapter, stellar winds and radiation limit the lifetime of dust smaller than $100\mu m$ to less than $10^7$ yrs. Collisions break apart large bodies into smaller pieces and dust which are then more efficiently removed from the disk. This process exponentially depletes the mass of the debris disk throughout the main-sequence lifetime of the star.

The amount of debris material in large bodies remaining after the optically thick disk is dispersed is determined both by dust grain growth processes within the optically thick disk as well as the dispersal mechanism. With uncertainty in both these processes, the amount of material expected to be present at the beginning of the initial debris disk phase is largely unknown. In the case of our solar system, this “leftover” material set the initial conditions for evolution of the solar system through its main-sequence solar lifetime. With the majority of this mass in the larger bodies with a relatively low emitting or scattering cross section it is relatively difficult to detect compared to optically thick CTTS disks. Optically thin disks can have vastly different masses depending on the size distribution of the total mass.

Because of the observational difficulty in detecting exo-solar debris disks, the most studied debris disk is our own. The history of the solar system is recorded in the cratering
pattern on the Moon’s surface. The ages of the large impacts were measured from rock samples retrieved from the Apollo space missions (Tera et al. 1974). These ages indicate that the rate of impact on the Moon was much greater, by a factor of about 100-1000, when the Sun was less than 1 Gyr old. With dust produced from collisions, if the dust lifetimes are unchanged, it is likely that the solar system would have been on the order of 100-1000 times more dusty than it is now. This would make the disk more easily detectable in near-IR wavelengths. The detection of this dust would be a tell-tale sign of a population of larger bodies creating the dust.

1.2 Observing Debris Disks

Space-based mid-infrared observations have shown that other main-sequence stars harbor significant populations of dust. In the calibration of the IRAS satellite, the nearby A0V star, Vega ($\alpha$ Lyr), was found to have an excess of infrared emission above what is expected to arise from the stellar photosphere (Aumann et al. 1984). A more thorough analysis of the IRAS database revealed that a significant fraction of nearby main-sequence stars had infrared excesses (Aumann 1985). This discovery prompted a number of more sensitive surveys which have found mid-IR excesses around 15-20% of the A to K type stars (e.g. Fajardo-Acosta et al. 1999; Habing et al. 2001).

The first optically resolved images of a debris disk around another star were taken of the nearly edge-on disk around $\beta$ Pictoris (Smith & Terrile 1984). Despite extensive searches of over 100 nearby stars using coronographs in optical wavelengths, until recently only one other debris disk candidate was reported around BD +31 643 (Kalas & Jewitt 1997). Since then, the use of the Hubble Space Telescope, and ground based infrared and adaptive optics systems, a few additional debris disks, such as HR 4796A and HD 141596 A, have been resolved through their scattered light and thermal IR emission (for review see Lagrange & Artymowicz 2000). Also, the millimeter wavelength dust continuum emission from the
nearby, relatively massive, debris disks, Vega, Fomalhaut, \( \beta \) Pictoris, and \( \epsilon \) Eridani have been resolved (e.g. Greaves et al. 1998; Wilner et al. 2002; Holland et al. 2003).

Resolved optical and near-IR observations of debris disks around other stars are difficult, as the PSF halo overwhelms the signal from the disk. Even so, a handful of such disks have been resolved from their thermal signature, and from their scattered near-IR radiation. These examples seem to be the “tip of the iceberg” so to speak, based on the vast number of IR excess stars.

Adaptive optics (AO) imaging can markedly improve the dynamic range detection limits for both faint surface brightness and point sources in close proximity to the central PSF (Close et al. 1998). Even so, speckle noise from the atmosphere and from the fixed optical imperfections of the telescope severely limit the detection limits within \( \sim 3^\prime\!0 \) from the PSF center. However, if there is an aspect of the coherent light that has a sharp contrast, dual channel imaging subtraction techniques can be utilized in conjunction with AO to alleviate this speckle noise problem (Racine et al. 1999). Once this is successfully accomplished, the sensitivity may approach the photon noise limit, and could conceivably make improvements by two orders of magnitude.

To alleviate the speckle noise problem for faint companion detection, Racine et al. (1999) proposed simultaneously imaging the speckle pattern in two wavelengths to create a contrast between the companion and the bright star. The method takes advantage of the contrast between the continuum and the methane absorption characteristic of cool brown dwarfs. When the two images are differenced, the speckle halo of the bright star subtracts out, except where a methane dwarf creates an enhanced contrast.

This dissertation presents the results from an experiment using the Racine et al. (1999) principle applied to polarimetry observations. Instead of a sensitivity to detecting low-mass methane dwarfs, the instrument has improved sensitivity for detecting polarized circumstellar nebulosity, using the polarization signature as the contrast between the simultaneous images. This technique has been used before to increase sensitivity to detect circumstellar disks (Gledhill et al. 1991; Wolstencroft et al. 1995; Mauron & Dole 1998;
Kuhn et al. 2001), however without the improved resolution and dynamic range offered by AO, and never on an 8-meter class telescope. The application of the dual imaging technique in conjunction with AO fully exploits the improved image quality for the purpose of detecting faint surface brightnesses next to bright stars, by eliminating the primary problem in conventional high contrast AO work, namely the time variable PSF.

1.3 Thesis Objectives

This thesis has three main objectives.

1. The first component is instrumental: a dual channel polarimeter was successfully incorporated into the Hokupa’a adaptive optics system which was mounted on the Gemini North 8 meter telescope. An accompanying data analysis package was developed to reduce the data for the purpose of high contrast detection of polarized surface brightnesses around relatively bright point sources.

2. I present the results of an observational survey for debris disks around a sample of young solar-analog stars using the dual channel polarimeter. These observations significantly constrain the amount of micron sized dust particles around the sampled stars. This survey was also sensitive to the detection of low-mass companions to these young solar analog stars.

3. Lastly, theoretical models of optically thin debris disks using Mie scattering theory produce model images, providing a means to translate a given debris disk’s physical properties into observable quantities. The cross sections calculated in the Mie scattering models are used to estimate dust particle lifetimes under the influence of radiation pressure, Poynting-Robertson (P-R) drag from radiation and the solar wind, collisions, and sublimation. These particle lifetime calculations are considered as a function of the physical properties of the central star over the range of the main-sequence stars and in conjunction with other dust destruction/removal processes.
General statements are made regarding the expected lifetimes of dust as a function of the composition, size, density, and stellar spectral type. This investigation finds that the stellar wind may play a significant and overlooked role in the removal of dust from debris disk around young stars with strong stellar winds.

In addition to these three components, I discuss a few interesting Classical T-Tauri stars (TW Hydrae, GG Tau, LkCa 15, and SR24 N/S) which were observed to test the performance of the polarimeter.
References


Fridlund, C. V. 2000, Proc. SPIE, 4006, 762


Smith, B. A. & Terrile, R. J. 1984, Sci, 226, 1421


Chapter 2

Noise Analysis and Data Reduction Techniques for an Adaptive Optics Dual Imaging Polarimeter

In order to reveal faint nebulosity that is close to a bright star, the point spread function (PSF) of the unresolved light from the target star must be subtracted to an accuracy better than the ratio of the disk brightness to the PSF halo brightness. Traditional techniques use a reference PSF, a nearby star with similar brightness and spectral type, to scale and subtract from the target star’s PSF to reveal any excess surface brightness. However, the atmosphere distorts the single plane wave diffraction limited PSF in a largely non-repeatable fashion, making it difficult to obtain an accurate reference PSF. This is the main reason why most high-contrast imaging of circumstellar disks has been achieved from space with the Hubble Space Telescope (HST). Without the atmosphere, the much smaller temporal variations of the telescope optics create smaller uncertainty in the reference PSF (Silber et al. 2000; Krist et al. 2002).

Although ground based AO systems offer significant improvements in image quality and act to stabilize the PSF, the atmosphere introduces aberrations to the incoming stellar wavefront that are beyond their corrective capabilities. These aberrations primarily manifest themselves in the image plane as a number of diffraction limited "speckles" that are spatially displaced from the center of the star. These spatially displaced speckles accumulate with exposure time and are the primary constituent in the extended halo of the PSF above
the diffraction limited profile. Also, there are other wavefront aberrations introduced by imperfections in the optics that are time dependent. In short, even with adaptive optics, the PSF halo changes significantly over a broad range of timescales. Because the PSF variability is the result of a number of discrete diffraction limited images, rather than a random distribution of photons, the noise that describes this halo follows a shot noise function which is proportional not to the number of photons counted in each bin, but to the number of speckles and the number of photons in each speckle. This speckle noise typically is a factor of 10-100 times the noise that would result from pure photon noise (Racine et al. 1999, hereafter R99).

R99 offered a solution to the speckle noise problem by using a subtractive, dual imaging technique. By creating two simultaneously exposed images using a beamsplitter, the speckle pattern should be nearly identical in each image. The two images are passed through different filters chosen to maximize a contrast between, for example, a bright main-sequence star and an ultra-cool methane dwarf. When the two images are differenced, the speckle halo of the bright star subtracts out, except where a methane dwarf creates an enhanced contrast. This method has been refined in Marois et al. (2000) to accommodate the wavelength dependence of the speckle pattern.

In this experiment, I use the same principle of speckle noise suppression presented by R99. However, instead of using methane absorption which provides a contrast for the detection of methane dwarfs, I use the intrinsic polarization of light scattered from dust around stars to infer the presence of circumstellar material. Polarimetry is well suited for this purpose because the Q and U Stokes parameters are formed from a subtraction of two images, and because birefringent materials are natural polarization beamsplitters. The technique has been used extensively in telescopes without high-order adaptive optics (e.g. Gledhill et al. 1991; Wolstencroft et al. 1995; Mauron & Dole 1998; Kuhn et al. 2001). Here I present the first experiment to use the polarimetric technique with AO corrected images. With the high resolution near-IR images (FWHM ~ 0.07) provided by Hokupa’a on the
Figure 2.1 A simplified schematic illustrates the implementation of the polarimeter into the AO system. The positions of the Wollaston and the HWP were less than ideal, but were adequate for the experiment. The field stop was placed at the first telescope focus from the Gemini North Telescope, with the HWP retarder immediately following. After the AO system, the Wollaston prism splits the corrected beam into two, with a 1.5° divergence angle. The optics encountered by the two beams in the QUIRC camera are not the same.

Gemini North 8 m telescope, the system has imaged a number of previously unresolved circumstellar disks (Potter 2001; Potter et al. 2001).

In Section 2 of this chapter I overview the design of the polarimeter. Section 3 presents a data reduction method which subtracts the polarized and unpolarized components of the sky and PSF, but leaves the polarization signal from scattering of circumstellar material intact. Section 4 investigates the sources of noise which limit the high contrast sensitivity, and shows the measured system performance based on observations of the nearby classical T-Tauri star TW Hydrae. Section 5 discusses unresolved issues of the data reduction as well as possible future improvements to the system while Section 6 summarizes the main points of the chapter.

2.1 The Dual Imaging Polarimeter

The polarimeter was incorporated into Hokupa’a, a 36 element curvature sensing AO system (Graves et al. 2000) which used the QUIRC near-IR camera (Hodapp et al. 1996). At the time the polarimeter was incorporated into Hokupa’a (June 2000) it was a visitor instrument on the Gemini North telescope. The design of the implementation was constrained as the existing Hokupa’a optics could not be changed. Fortunately, there were acceptable places where the polarimetry components (Figures 2.1 & 2.2) could be added to the system. The field stop was necessary to prevent the two fields created by the Wollaston prism from
Hokupa'a on Gemini

Field stop

Birefringent optical element

Ideas figure by Jeff Douglas

Figure 2.2
overlapping on the QUIRC camera. It consisted of two blades mounted such that the edges were parallel, separated by 4.5" and placed at the first telescope focus before the incoming light encounters any optics on the Hokupa’a optical bench. The quartz half-wave plate (HWP) used in this experiment was already a component in the Hokupa’a AO system, previously used in conjunction with the wire grid analyzer in QUIRC (Close et al. 1997; Potter et al. 2000). This was the first optical element encountered by the beam on the AO bench. The HWP was optimized for use in the H band and rested in a rotating mount on a motorized stage that could be inserted into the beam remotely. The Wollaston prism was the last optical element on the optical bench before the AO corrected light entered QUIRC. The Wollaston has a 1.5° divergence angle between the orthogonal polarization components. It was placed in a warm, rotating filter wheel used to house neutral density filters at, unfortunately, a converging beam. Before the elements were incorporated into the system, a ZEMAX model of the telescope/AO/polarimeter system was constructed to investigate the differential image degradation that would result from placing the Wollaston prism in this position. When the image quality and chromatic effects were investigated, it was found that for both H-band images produced by the polarimeter, the geometric spots were within the first airy rings of the diffraction limited images. The polarimetry components were incorporated into the Hokupa’a AO system while the system was mounted on the Gemini North Telescope in late June 2000. The polarimeter was used up until the last observing run for Hokupa’a (36) on Gemini in April 2002, and was used for a total of about 15 nights on the telescope.

2.2 Data Reduction Technique

The reduction of dual imaging polarimetry data has been discussed by a number of authors (Gledhill et al. 1991; Wolstencroft et al. 1995; Kuhn et al. 2001). All take advantage of the simultaneous creation of the extraordinary and ordinary images (e and o) to form Stokes parameters that are insensitive to atmospheric image degradation. The reduction
procedures include a redundant set of polarimetry data created by extra retarder positions to reduce systematic errors. The following method uses both of these principles, but includes steps similar to Kuhn et al. (2001) to specifically isolate the polarization signal of extended sources which overlap a relatively bright PSF halo and the sky background.

The Wollaston prism polarimeter described above simultaneously creates two images which are orthogonally polarized relative to each other (see Figure 2.3). Between sets of exposures, the HWP rotates the effective polarization angle of the two images in the same direction. One complete data set is formed after four 22.5° rotations of the HWP denoted by the subscript $\alpha$, with $\alpha=1$ representing the 0° position, $\alpha=2$ for 22.5°, $\alpha=3$ for 45°, and $\alpha=4$ for 67.5°. Each 22.5° rotation of the HWP rotates the effective polarization angle by 45°. Although only two rotations are required to obtain the full Stokes parameters for linear polarization, the extra retarder rotations create a redundant set of both the Q and U Stokes images. This allows for all components to be measured through both optical paths downward of the Wollaston prism. This practice allows for a data reduction method which reduces the residuals from a number of calibration steps such as the sky subtraction, and the residuals from a fixed component of the instrumental polarization. The systematic optical variations between the two channels were significant in this experiment, and this redundant data set proved to be crucial in obtaining photon noise limited subtraction residuals.

In describing this data reduction method, I first define the sources contributing to the measured pixel values on the detector. It is necessary to distinguish the two simultaneous images independently, so the subscripts $e$ and $o$ are chosen to represent the extraordinary and ordinary images created by the Wollaston prism which do not change position relative to the detector with HWP position. Three sources are considered here, the sky, the PSF halo, and the scattered light from circumstellar material, denoted by $F_S$, $F_P$, and $F_D$. It is assumed that the polarization amplitude of all sources, $P_P$, $P_D$, and $P_S$ does not change significantly in the course of the exposures. The dark current, $D$, is also included even though it is negligible compared to the other sources. A full list of the parameters is given.
in Table 1. The unreduced measured pixel values for both the $e$ and $o$ frames taken with HWP position $\alpha$, $I_{ae}$ and $I_{ao}$, are expressed as,

\[
I_{ae} = D_e + f_e \left[ \frac{F_S(t_\alpha)}{2} (1 + P_S \cos 2\theta_S) + \frac{F_P(t_\alpha)}{2} (1 + P_P \cos 2\theta_P) + \frac{F_D(t_\alpha)}{2} (1 + P_D \cos 2\theta_D) \right],
\]

(2.1)

\[
I_{ao} = D_o + f_o \left[ \frac{F_S(t_\alpha)}{2} (1 - P_S \cos 2\theta_S) + \frac{F_P(t_\alpha)}{2} (1 - P_P \cos 2\theta_P) + \frac{F_D(t_\alpha)}{2} (1 - P_D \cos 2\theta_D) \right].
\]

(2.2)

The first reduction step in each 1024 x 1024 frame is the subtraction of a dark frame followed by a division of the calibration flat field. Next, the two subframes, one for $e$ and one for $o$, are created, each centered on one of the two images in the full frame. The sky level is calculated from sky dominated regions on each subframe and subtracted independently for the two subframes to remove the sky even if it is partially polarized. These steps applied to Equations 2.1 and 2.2 result in the following expressions,

\[
I'_{ae} = R_D + R_Q + \eta_e \left[ \frac{F_P(t_\alpha)}{2} (1 + P_P \cos 2\theta_P) + \frac{F_D(t_\alpha)}{2} (1 + P_D \cos 2\theta_D) \right],
\]

(2.3)

\[
I'_{ao} = R_D + R_Q + \eta_o \left[ \frac{F_P(t_\alpha)}{2} (1 - P_P \cos 2\theta_P) + \frac{F_D(t_\alpha)}{2} (1 - P_D \cos 2\theta_D) \right],
\]

(2.4)

where $R_{D,e,o}$ and $R_{Q,e,o}$ are the subtraction residuals from the dark and sky subtraction respectively. The light from the stellar PSF (both polarized and unpolarized) can then be removed as it will have a field independent, constant polarization. This is accomplished by finding the alignment and scaling values which minimize the subtraction of PSF$_e$ with PSF$_o$ with the scaling parameter $C_{ae,o} = \frac{< I_{ae} >_r}{< I_{ao} >_r}$. This works under the
assumption that $F_P \gg F_D$. The scaling becomes less certain with saturated images as PSF information is lost. However, sufficient scaling and alignment can be achieved by choosing identical unsaturated regions in each of the two fields for the comparison, with the reference point in each of the fields being the stellar centroids. The resulting $C_{eo}$ scaled subtraction results in an individual $Q$ or $U$ Stokes image with both the sky and stellar PSF subtracted. If $\alpha = 1$, $Q = I_{1e}' - C_{1eo}I_{1o}'$ or from Equations 2.3 and 2.4,

$$Q_1 = (R_{D\epsilon} - C_{1eo}R_{D\epsilon}) + (R_{S\epsilon} - C_{1eo}R_{S\epsilon}) + R_{P_1} + \frac{F_D(t_1)}{2} (\eta_e - C_{1eo}\eta_0) + \frac{F_D(t_1)}{2} P_D \cos 2\theta_D (\eta_e + C_{1eo}\eta_0)$$ (2.5)

Then the same procedure is carried out for the frames that have the polarization components swapped compared to the above set (e.g. retarder position 3 vs. 1). The only difference is that the image chosen to be scaled is opposite from the previous complementary HWP image so the absolute intensities are the same for both. This produces a $-Q$ Stokes image, $-Q = C_{3oe}I_{3e}' - I_{3o}'$, or,

$$-Q_3 = (C_{3eo}R_{D\epsilon} - R_{D\epsilon}) + (C_{3eo}R_{S\epsilon} - R_{S\epsilon}) + R_{P_3} + \frac{F_D(t_3)}{2} (\eta_e - C_{3oe}\eta_0) - \frac{F_D(t_3)}{2} P_D \cos 2\theta_D (\eta_0 + C_{3oe}\eta_0)$$ (2.6)

To reduce errors introduced by the non-common optics, $Q_1$ and $-Q_3$ are then subtracted from each other to result in a final $2Q$ image, $2Q = Q_1 - (-Q_3)$. The same procedure is carried out for the 2 and 4 retarder positions to produce a $2U$ image. With a negligible instrument polarization, $C = C_{1eo} = C_{3oe}$, and assuming $F_D(t_1) = F_D(t_3)$, the final residuals for the $2Q$ image are,

$$2Q = \delta R_{D_{1,3}} + \delta R_{S_{1,3}} + \delta R_{P_{1,3}} + 2Q_{FD}$$ (2.7)

with,

$$2Q_{FD} = \frac{F_D}{2} (\eta_e - \eta_0)(1 - C) + \frac{F_D}{2} P_D \cos 2\theta_D (\eta_0 + \eta_e)(1 + C)$$. (2.8)
Figure 2.3 The four images produced from two exposures (6 seconds each) of the classical T-Tauri star, TW Hydrae are used to illustrate the data reduction technique. The left plot shows the four subframes of two exposures which are used to create one $2Q$ image. In the unreduced subframe images on the left, the top two are for HWP position 1, $0^\circ$ (images $1e, 1o$) and the bottom two are for HWP position $3=45^\circ$ (images $3e, 3o$). Note that the peak regions of the PSF saturate the detector. Shown in the right box of scaled and subtracted images, $Q_1$ is formed from images $1_e$ and $1_o$ with the reduction steps mentioned in the text and expressed in Eq. 2.5. Likewise for $-Q_3$. The final $2Q$ image is expressed through Eqs. 2.7 and 2.8. It is apparent in the subtracted images that there is high frequency component that does not subtract away. This noise is attributed to optical differences between the two channels after the Wollaston prism. Fortunately, these variations are not strong on larger spatial scales ($\sim 0''25$) and can be taken care of with a low-pass filter as seen in Figure 2.4.

For $C = \eta_e = \eta_o = 1$, Equation 2.8 reduces to the familiar Stokes parameter form, $Q = P_D F_D \cos 2\theta_D$. A detection occurs when the errors associated with the residuals in Equation 7 are smaller than $2Q_{FD}$. $2U$ is equal to the same expression as Equation 8, except $\theta_D$ is replaced with $\theta_D + \pi/4$. The rest of the linear polarization parameters are obtained using the following equations:

$$I_Q = (I_{1e} + C_{1eo} I_{1o} + C_{3oe} I_{3e} + I_{3o})/4 \quad (2.9)$$

$$I_U = (I_{2e} + C_{2eo} I_{2o} + C_{4oe} I_{4e} + I_{4o})/4 \quad (2.10)$$
\[
\theta = \frac{1}{2} \tan^{-1}(U/Q) + \theta_{\text{calibration}} \tag{2.11}
\]

\[
PI = \left( \frac{Q^2 + U^2}{2} \right)^{1/2} \tag{2.12}
\]

\[
P = \left( \frac{(Q/I_Q)^2 + (U/I_U)^2}{2} \right)^{1/2} \tag{2.13}
\]

The order in which one combines the above quantities needs to be evaluated in order to minimize noise and will be discussed further in chapter 5. In making this decision, it is important to realize that the dual imaging technique produces speckle suppressed \( Q \) and \( U \) images of the non-PSF component, not \( I \) images. With the flat-field error becoming a dominant noise source for large numbers of counts, as will be discussed in the following section, it seems beneficial to normalize \( Q \) and \( U \) using \( I_Q \) and \( I_U \) to eliminate the flat field noise. It has been pointed out by Clarke et al. (1983) that this practice introduces a bias. Also, because \( I \) has a non-repeatable, time varying structure, the measurement of the absolute polarization amplitude of the extended, non-PSF halo light depends on the traditional methods of non-simultaneous PSF subtraction. However, the polarization angle, \( \theta_D \), is based on a division between \( U \) and \( Q \), so is not affected by the flat-field noise. The quantities which maximizes the signal-to-noise ratio for centrosymmetric scattering sources will be discussed in Chapter 5.

### 2.2.1 Conditions for Frame Selection

Depending on the orientation of the retarder, each frame produced by the polarimeter produces either a \( Q \) or \( U \) Stokes parameter image that is insensitive to PSF variability. However, it should be noted that they are each produced from different exposures, so \( Q \) and \( U \) are formed from non-common PSF conditions. When constructing the final polarization image, this non-simultaneous aspect may introduce error into the final polarization intensity.
Figure 2.4 With a full set of exposures for one dither position, in this example 5 exposures per HWP position \((total = 5 \times 4 \times 6\text{sec})\), the final polarization images can be constructed using the average of the \(2Q\) and \(2U\) images (in this case 5 of them). To reduce the high frequency noise, each frame is convolved with a \(FWHM = 0^\circ 2\) gaussian before the subtractions. The polarization angle \((\theta)\), polarized intensity \((PI)\), and polarization amplitude \((P)\) images are then obtained through Eqs. 11, 12, and 13 respectively. Here, the centrosymmetric polarization signature of single scattered light from a central point source is displayed by the disk around TW Hydrae. Because the normalized polarization amplitude, \(P\), is formed from a division of the intensity, the flat-field noise is not a factor in this quantity. However, as apparent in the \(P\) image, the PSF intensity radial profile, and field dependent structure make it difficult to infer if there is circumstellar scattering, and the problem of PSF variability is re-introduced.
image which should be on the order of the square root of the amplitude of the PSF variability (not the total variability).

For this investigation, I assume that the polarimeter suppresses the speckle noise well enough so the primary source of noise in individual exposures is the photon noise. The signal is the polarization signal from a circumstellar disk. To simplify matters, I assume that this is an unchanging resolved surface brightness, \( F_D \). The signal-to-noise for one pixel in one exposure is, \( S/N = F_D/F_P^{1/2} \). Considering a number \( n \) of frames taken with the same exposure time, we get \( S/N = nF_D/(n<F_P>)^{1/2} \), with \(<F_P>\) equal to the average of the counts in the pixel from the \( n \) exposures. The magnitude of a particular PSF variation that results in a decrease in the total signal-to-noise ratio in a series of exposures is found by setting up an inequality between the signal-to-noise ratio expression given above and the signal-to-noise ratio expression after an exposure with a PSF halo intensity, \( F_P' \), is combined to the final image. The simplified inequality is,

\[
F_P' > \frac{2n+1}{n} <F_P> .
\]  

(2.14)

So in order to warrant the exclusion of a frame in a data set, the relative number of counts between the PSF halo and the disk in an individual frame must be a factor of between 2 to 3 times greater than the mean value over all frames. Non-photometric conditions do not change this relation, and as long as the other sources of noise do not dominate, all exposures in non-photometric conditions can be used in the final average. For large numbers of frames the limit is 2 times the average pixel value. For the Hokupa'a AO system, the magnitude of PSF halo variation rarely occurs in regions > 0.2 from the PSF center.

2.3 System Performance

With the noise from PSF variability suppressed, it is worthwhile to investigate other noise sources to determine which ones dominate the dynamic range sensitivity, and to see if the observations agree with the expected noise characteristics. An extensive body of
Figure 2.5 The plots show how the flat field and photon noise components vary with the total accumulated exposure time. The relative scaling was chosen to approximate the observed noise characteristics from the experiment. The plot shows that for small exposure times, the photon noise dominates, but after a certain number of counts are measured, flat field calibration errors dominate. Because the calibration errors and the disk signal have the same proportionality relative to $t_{\text{exp}} n_{\text{exp}}$, for a fixed number of dithers and/or field rotations there is a hard signal-to-noise limit which cannot be improved upon by longer exposure times. Because the detector calibration error is of the same order of magnitude as the $P1$ disk/PSF contrast, the ability to calibrate the detector and the non-common systematic optical variations from the two channels sets the limit for the minimum detectable disk signal. One solution in breaking this signal-to-noise barrier is to use photon counting devices.

Work discussing the noise analysis of polarimetry data already exists (e.g. Leyshon 1998, Ramaprakash et al. 1998, and Simmons & Stewart 1985). Here I do not go into a detailed statistical analysis, saving this for another paper. Instead, I identify the primary noise sources which determine the dynamic range sensitivity and discuss their correlation/lack thereof to the operations of taking successive exposures, dithering, and rotating the field with the Gemini cassegrain instrument rotator.

2.3.1 Analysis of Noise Sources
The residual terms in Equation 7, except $2QF_D$, ideally have a mean value of zero and obey gaussian statistics. Unfortunately this is not the case for all the noise sources. The error associated with the dark current subtraction residual, $\delta R_{D_{1,3}}$, is very small compared to the other sources of noise, unless the temperature of the array varies greatly from one exposure to the next which usually is not the case. The error introduced by $\delta R_{S_{1,3}}$ is primarily photon noise. With virtually all observations in the H band, the variable OH line emission introduces some time variable structure relative to the flat field, but this error is only occasionally a factor only when working far from the PSF. Most important is the error associated with the photon noise, and the miscalibration of the flat field and the differential optical aberrations in $\delta R_{F_{1,3}}$. These errors determine the high-contrast sensitivity of the system for the detection of scattered light from circumstellar material.

Each source of noise will have different correlation properties, so they should be expressed independently. Four sources of noise in each measuring bin are considered: the shot noise of the photons ($N_{\text{photon}}$), the noise introduced from a miscalibration of the flat field ($N_{ff}$), the noise introduced from the miscalibration of the differential optical aberrations ($N_{doa}$), and the read noise ($N_r$). I decompose the total number of exposures as, $n_{tot} = n_{\text{exp}}(n_{\text{dth}} + n_{\text{cr}})$, with $n_{\text{exp}}$ equal to the total number of exposures taken at each dither position ($n_{\text{dth}}$) or at each change of cassegrain rotator position ($n_{\text{cr}}$, $n_{\text{cr}} = 0$ for first data set). This relation is true as long as, after one set of exposures is taken, only a dither or field rotation occurs, not both. This exposure decomposition is necessary in the noise analysis because the relative scaling of the different noise components correlates differently with different observation actions. For example, the differential optical aberrations stay fixed relative to the field with field dithering, but change with field rotations brought about from a rotation of Gemini's cassegrain instrument rotator. I have not included the errors introduced from imperfect alignment and scaling in the data reduction. The noise components are given by,

$$
N_{\text{photon}} = \sqrt{F_{\text{tot}}t_{\text{exp}}n_{\text{exp}}(n_{\text{dth}} + n_{\text{cr}})},
$$

(2.15)
with \( F_{\text{tot}} = F_D + F_S + F_P \). The sought after signal is the polarized brightness of the circumstellar material. The signal per bin \((S)\) is then given by,

\[
N_{ff} = \sigma_{ff} F_{\text{tot}} t_{\exp} n_{\exp} \sqrt{n_{cr} + n_{dth}},
\]

\[
N_{\text{doa}} = \sigma_{\text{doa}} F_{\text{tot}} t_{\exp} n_{\exp} \sqrt{n_{cr} + n_{dth}^2},
\]

\[
N_r = \sigma_r \sqrt{n_{\exp}}
\]

with \( F_{\text{tot}} = F_D + F_S + F_P \). The sought after signal is the polarized brightness of the circumstellar material. The signal per bin \((S)\) is then given by,

\[
S = P_D F_D t_{\exp} n_{\exp} n_{\text{tot}}.
\]

Because \( N_{\text{photon}} \) is uncorrelated from exposure to exposure, as is the primary component of \( N_r \) (although there is usually a correlated component of the read noise), the effective signal-to-noise ratio when these components dominate increases as \( \sqrt{n_{\text{tot}}} \). However, the \( N_{ff} \) of exposures taken with the same dither or cassegrain rotator position is correlated, but is assumed to be uncorrelated with sets of exposures taken at different dither positions and so with a limited number of dithers the effective signal-to-noise ratio does not change with accumulated exposure time. Like \( N_{ff} \), \( N_{\text{doa}} \) is correlated with exposures taken without dithering or rotating the field. However, \( N_{\text{doa}} \) seems to be isolated at high spatial frequencies as apparent in Figure 2.3, and can be reduced to a level below \( N_{ff} \) by convolving the images with a \( FWHM \sim 0''2 \) gaussian. It is worthwhile to note that this term is reduced by a factor of \( \sim 10 \) through the double subtraction technique. If there were not a retarder to allow sampling \( Q \) and \( U \) through both optical paths, the calibration would depend on obtaining a reference residual PSF taken of another star. The calibration flat fields were obtained to an accuracy of \( \sigma_{ff} \sim 5 \times 10^{-4} \) over a \( 0''2 \) bin. The read noise \( (\sigma_r \sim 5 \ e^-) \) is such that for the exposure times dealt with in this experiment, the read noise is never a dominant
noise source, even far from the PSF. However, for fast read-out cameras, regions far from the PSF can easily be read noise dominated.

From the plot shown in Figure 2.6, noise becomes dominated by $N_{ff}$ once $\sim 1/(\sigma_{ff})^2$ photons are accumulated in each dither set. With $\sigma_{ff} \sim 5 \times 10^{-4}$, the flat-field errors dominate once $\sim 4 \times 10^6$ photons are accumulated in a bin.

### 2.3.2 Observed System Performance and Comparisons with HST/NICMOS

The polarimeter was used on the Gemini North telescope for about 15 nights between July 2000 and April 2002. The measured noise follows the expected noise characteristics, except in a few isolated regions where the detector read noise was large around the quadrant edges on QUIRC. Data were taken so that the flat-field noise limit was almost reached before either dithering or rotating the field. The convolved exposures are photon noise limited outside a radius of $\sim 0\prime.7$ from the PSF center after about 10 minutes of exposure on an $H=10$ point source (Figure 2.5).

In a survey of over 100 young, nearby stars, a number of the target stars exhibit scattered light from circumstellar material. Some stars, like LkHα 262, and LkCa 15, were previously undetected in scattered light. Papers are in preparation to report results of circumstellar material found around stars in the MBM-12 Association, the TW Hydrea association, the Rho-Ophiuchi star forming region, and the Taurus-Aurigae star forming region, as well as for a few other samples of debris disk candidate stars.

It is noteworthy to point out that the presented sensitivity for detecting circumstellar disks is a great leap forward compared to traditional ground-based techniques, albeit this leap applies just to the narrow scope of detecting polarized surface brightnesses with centrosymmetric signatures. With this easy to implement technique, simultaneous imaging polarimetry can allow 8 m class telescopes to complement the scattered light circumstellar disk detections of HST/NICMOS. Some target disks with high polarization were detected with the polarimeter that HST failed to detect, such as the disk around LkCa 15 (chapter 4).
However there are conceivable target disks that would not have a high intrinsic polarization, such as disks primarily made of large \((R > 1\text{cm})\) components, or gas. These disks would be more easily imaged with HST/NICMOS as their detection does not depend on the intrinsic polarization of the disk. In either case (strongly and weakly polarized disks) both ground-based and spaced based instruments are required to accurately infer disk properties.

2.4 Discussion

The data reduction method presented above is tailored to a specific instrument configuration, and for the specific purpose of detecting the scattered light of circumstellar material. Future instruments will undoubtedly need to alter the reduction method according to the specific instrument and goal of the observation. A number of dual imaging polarimetry systems are currently being developed. One method being implemented uses an additional piece of birefringent material to create four simultaneous images so both \(Q\) and \(U\) can be created simultaneously. In this arrangement, only one retarder position is required to create one full set of linear Stokes parameters. However, a retarder would still be necessary to reduce the differential optical aberrations. Instead of one set of double subtraction Stokes parameters formed from four rotations, four sets are produced from four rotations. Because both \(Q\) and \(U\) are produced simultaneously, a small error is eliminated. Also, the flat field errors should be slightly reduced by a factor of \(\sim \sqrt{2}\) as the same data is taken over twice as many pixels. It is unclear if the errors from differential optical aberrations will increase or decrease with four beams instead of two.

One item not addressed quantitatively here is the spatial power spectrum of the noise. As mentioned above, the differential optical aberrations for this system seem to be mostly in high frequencies \((\sim 0\text{'0.05})\) and can be reduced through a spatial filter. The flat-field variations seem to occupy a broader range of spatial scales. How the signal-to-noise ratio varies with different binning/convolution schemes as well as a more complete statistical analysis of these polarimetry data will be investigated in a future paper.
From the analysis in Section 2.3, it is clear that the noise from the calibration error of the flat field needs to be reduced in order to detect an evolved circumstellar debris disks like the one around the sun around the nearby stars. Although the exact polarized surface brightness to PSF ratio of a solar system like debris disk is model dependent, roughly a contrast ratio of $\sim 10^{-6} - 10^{-5}$ needs to be accomplished before such disks are detected through their scattered light. With the current detection level set by the flat-field calibration of $\sim 10^{-4}$, assuming that the flat-field error is not correlated between dither positions, it would take $\sim 10^2 - 10^4$ dithers to reduce the noise to an acceptable level. This was not feasible with the current system. A potential method to alleviate this problem by using zero-read-noise photon counting detectors is under development.

2.5 Summary

1. A dual imaging polarimeter was successfully incorporated into the Hokupa'a AO system. The experimental system was effective in suppressing speckle noise and other detrimental effects that PSF variability has on high contrast imaging.

2. A data reduction technique was presented which is tailored to the detection of circumstellar disks.

3. The system produced photon noise limited polarized surface brightness sensitivity up to a limit when calibration errors begin to dominate. For this system, polarimetry can be performed to an accuracy of $\sim 5 \times 10^{-4}$ across $0''2$ bins, before calibration errors prevent improved detection.
Figure 2.6 The top plot shows the polarized surface brightness detection limits for the dual imaging system on Gemini North after a total of 8 min exposure on TW Hydrae (dashed line). These detection limits are close to the photon noise limit (bold grey line) beyond $R>0''7$. Shown in the lower plot, the sensitivity is a factor of $\sim 20-40$ improvement over the traditional method using a non-simultaneous reference PSF (thin grey line) from disk with a polarization amplitude of 30 percent. These data are binned over 0.1 $\text{arcsec}^2$ cells. For a rough comparison, the 20 min exposure HST/NICMOS detection limits (lower plot dash-dot line) are estimated from the errors published in Weinberger et al. (2001). The measured H-Band polarized surface brightness (top) and surface brightness (bottom) profiles of TW Hydrae are plotted as a black lines.
Table 2.1 Parameters for Noise Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{#a(e)}$</td>
<td>total counts measured in pixel $(e)$ on subframe, $a$ taken through retarder position, $#$</td>
</tr>
<tr>
<td>$F_P$</td>
<td>intrinsic flux from PSF halo</td>
</tr>
<tr>
<td>$F_D$</td>
<td>intrinsic flux from light scattered from circumstellar material</td>
</tr>
<tr>
<td>$F_S$</td>
<td>intrinsic flux from sky</td>
</tr>
<tr>
<td>$P_P$</td>
<td>polarization from PSF halo</td>
</tr>
<tr>
<td>$P_D$</td>
<td>polarization amplitude of light scattered from circumstellar material</td>
</tr>
<tr>
<td>$P_S$</td>
<td>polarization of the sky</td>
</tr>
<tr>
<td>$f_{(e)}$</td>
<td>actual gain of pixel $(e)$ in subframe $a$</td>
</tr>
<tr>
<td>$f'_{(o)}$</td>
<td>measured gain of pixel $(o)$ in subframe $b$</td>
</tr>
<tr>
<td>$D_{(e)}$</td>
<td>actual dark current for pixel $(e)$</td>
</tr>
<tr>
<td>$D'_{(e)}$</td>
<td>calibration dark current for pixel $(e)$</td>
</tr>
<tr>
<td>$C_{#ab}$</td>
<td>scaling factor to subtract partially polarized PSF</td>
</tr>
<tr>
<td>$R_D$</td>
<td>final residual from dark subtraction</td>
</tr>
<tr>
<td>$R_S$</td>
<td>final residual from sky subtraction</td>
</tr>
<tr>
<td>$R_P$</td>
<td>final residual from PSF subtraction</td>
</tr>
</tbody>
</table>
References


Potter, D. 2001, BAAS, 199, 102.09

Potter, D., Baudoz, P., Guyon, O., Brandner, W., Close, L., Graves, J. E., & Northcott, M. 2001, BAAS, 198, 18.02


Chapter 3

Modeling Optically Thin Debris Disks

Scattered light models of debris disks provide a means to translate their physical properties into observable quantities. In this chapter, models of debris disks are created to establish this link. Also, the forces acting on debris disk dust are investigated as a function of the central star’s mass, temperature, luminosity, and stellar wind to gain insight into the possible dust populations which would exist around a given star. These models are used to interpret the observational data presented in Chapter 5, and to direct future observational searches.

3.1 Scattered Light Models

A goal of this thesis is to check for the presence of debris disk material around a sample of young solar analog stars. In the case of a detection, it is of interest to explore what range of dust populations could result in the given observations. In the case of non-detections, it is useful to know what dust populations would have been detected if they had been present around the sample stars. In either case, scattered light models are needed to link observables to the material parameters of debris disks.

The appearance of optically thin debris disks is relatively simple to calculate compared to the multiple scattering environment of optically thick circumstellar disks found around classical T-Tauri stars. Calculating the expected surface brightness resulting from a given disk, around a given star requires a knowledge of the scattering properties of the dust. Unlike
thermal radiation, the power per solid angle of scattered radiation from dust depends on
the scattering angle, and is generally non-isotropic. In some conditions, particularly when
the size of the scattering particle is larger than the wavelength of the scattered light, this
anisotropy grows, and the intensity scattered in the forward direction (small \( \theta \)) can be 100­
1000 times the intensity in the backward scattering direction. There is an exact solution
describing the scattering behavior of homogeneous spheres, referred to as Mie theory, which
is utilized in section 3.1.3. To start simply, an isotropic scattering model is presented using
the decided forms of the dust populations.

3.1.1 Debris Disk Dust Populations

As mentioned in the introductory chapter, and as will be presented in more detail later
in this chapter, the lifetime of dust orbiting around the Sun is orders of magnitudes less
than the age of the solar system due to drag forces associated with the Poynting-Robertson
drag, the analogous Solar wind drag, sublimation, collisions, and gravitational interactions
with planets. Without a replenishing source, particles of size \( a < 100\mu m \) could not exist
around any main-sequence star as their lifetimes are small compared to the main-sequence
lifetime. In our solar system, it is thought that dust is produced from collisions between
larger bodies and sublimation from comets on highly elliptical orbits which pass close to
the Sun. Both sources produce steep power law size distributions of the form,

\[
dN(a) = n_0 a^{-p} da
\]  

with \( dN(a) \) equal to the number of dust particles with size between \( a \) and \( a + da \) with
\( p \sim 3.5 \) (Dohnanyi 1969). The surface density of the rocky/metal component of the solar
system fits a shallow power law of the form,

\[
\Sigma(r) = \Sigma_0 r^{-\gamma}
\]
with $\gamma$ equal to $\sim 1 - 2$. These analytical forms for the size, and radial distribution of the dust are used in the following development of scattered light models.

The out-of-plane dimension of debris disks, or the flaring profile, is not considered as this will not greatly effect the order of magnitude surface brightness values that we are after, except in the case of near edge-on disks.

With the assumed forms of the size distribution and number surface density of the dust as outlined above, the coefficients $n_o$ and $\Sigma_o$ can be put in terms of the total mass of the dust ($M_{dust}$), the density of the dust ($\rho_{dust}$), and the power law indices, $p$ and $\gamma$, and the upper and lower size limits of the dust ($a_{max}, a_{min}$).

The constant $n_o$ in the size distribution can be found by integrating dust masses over the size distribution. This yields a value of,

$$n_o = \frac{3(4 - p)M_{dust}}{4\pi\rho_{dust}(a_{max}^{(4-p)} - a_{min}^{(4-p)})}.$$ \hspace{1cm} (3.3)

as long as $p \neq 4$. The result is a natural log function for $p = 4$. The total number of particles in the size range is then,

$$N_{tot} = n_o(a_{max}^{(1-p)} - a_{min}^{(1-p)}) \quad \frac{1}{1-p}$$ \hspace{1cm} (3.4)

with $p \neq 1$ or else it is again a natural log function as the case for the mass normalization.

The constant for the surface number density, $\Sigma_o$ is then found by equating $N_{tot}$ to the integral of the surface density over the total area of the disk between a radius of $r_{min}$ and $r_{max}$.

$$\Sigma_o = \frac{N_{tot}(2 - \gamma)}{2\pi(r_{max}^{(2-\gamma)} - r_{min}^{(2-\gamma)})}$$ \hspace{1cm} (3.5)

### 3.1.2 Geometrical Optics, Isotropic Scattering

Here we start with simple assumptions using geometric cross-sections and isotropic scattering to calculate the scattered light appearance of an ensemble of dust grains
distributed around a star of luminosity $L_*$. In the realm of geometric optics, the total power available for scattering or absorption from an incident flux of radiation on a given particle is the particle’s geometrical cross-section ($C_{\text{ext}} = \pi a^2$), times the incident flux at a distance $R$ from the star ($F_* = L_*/4\pi R^2$). It is assumed that this available power can only be scattered or absorbed, so the sum of the scattered and absorbed fractions equal unity. The fraction of this incident flux that is scattered, as opposed to absorbed by the particle, is defined as the single scattering albedo,

$$A = \frac{Q_{\text{sca}}}{Q_{\text{sca}} + Q_{\text{abs}}}$$  \hspace{1cm} (3.6)

with $\pi a^2 Q_{\text{sca}} = C_{\text{sca}}$, $\pi a^2 Q_{\text{abs}} = C_{\text{abs}}$ and $C_{\text{sca}} + C_{\text{abs}} = C_{\text{ext}}$ in this pseudo-geometric optics assumption.

The total power scattering from a dust particle of radius $a$ at a distance $r$ from a star of luminosity $L_*$ over $4\pi$ radians is then,

$$L_{\text{dust}}(r) = \frac{L_* A a^2}{4 r^2}$$  \hspace{1cm} (3.7)

To translate this into the observed flux over a given frequency band $F_\nu$, the spectral energy distribution of the star must be considered. The relationship between the total power scattered by a dust particle and the measured specific flux is given by,

$$F_\nu(r) = \frac{L_{\text{dust}}(r) f_\nu(\Delta\nu)}{4\pi d^2 \Delta\nu}$$  \hspace{1cm} (3.8)

with $d$ the distance between the observer and the dust grain. $f_\nu$ is the fraction of the total luminosity that is emitted through the frequency bandpass, so the spectral energy distribution of the source must be known. For the sun, $f_\nu$ is about 0.05 assuming a $T_{\text{eff}} \sim 5700K$ blackbody using the frequency limits set by the H band.

Observationally, the scattering component of a circumstellar disk results from the combined scattering from an ensemble of particles. Of interest here is modeling the
observational case where there is sufficient spatial resolution to resolve the circumstellar disk from the unresolved stellar light into a surface brightness. In this resolved case, the observed surface brightness profile of the disk would just be the observed flux integrated over all dust particles in a given solid angle, \( S_\nu(R) = F_\nu(R, d) \Sigma(R, d) \), with \( R = r(\text{AU})/d(\text{pc}) \) the angular distance from the central star in units of arcseconds.

The average geometrical cross-section over the distribution is \( \langle a^2 \rangle \) with,

\[
\langle a^2 \rangle = \frac{\int_{a_{\text{min}}}^{a_{\text{max}}} a^{(2-p)} da}{\int_{a_{\text{min}}}^{a_{\text{max}}} a^{-p} da}
\]

(3.9)

\[
\langle a^2 \rangle = \frac{(1-p)(a_{\text{max}}^{(3-p)} - a_{\text{min}}^{(3-p)})}{(3-p)(a_{\text{max}}^{(1-p)} - a_{\text{min}}^{(1-p)})}
\]

(3.10)

with \( p \neq 3 \) or else it is again a natural log function.

The total measured surface brightness as a function of radius from a given star, \( S_\nu(R) \), is then obtained by using the average geometrical cross-section in the equation for \( F_\nu(R) \) where \( F_\nu(\langle a^2 \rangle, R) \equiv \langle F_\nu(R) \rangle \).

\[
S_\nu(R) = \langle F_\nu(R) \rangle \Sigma(R)
\]

(3.11)

This works for a face on disk where the inclination angle of the disk is \( i = 0^\circ \). To accommodate effects of disk inclination, the radial surface density relation changes, and becomes a function of the position angle, \( \theta \), and scales using the relation,

\[
R(\theta) = \left( \frac{\cos \theta^2}{R_{\theta o}^2} + \frac{\sin \theta^2}{R_{\theta o} \cos i} \right)^{-1/2}
\]

(3.12)

To first order, for a finite thickness disk with a small flaring angle, the effective surface density increases by a factor of \( 1/\cos i \). So the surface brightness assigned to a given sky coordinate centered on the star \((R, \theta)\) is

\[
S_\nu(R, \theta) = \frac{\langle F_\nu(R, \theta) \rangle \Sigma(R, \theta)}{\cos i}
\]

(3.13)
This approximation is only appropriate for disks that are less than the flaring angle away from being edge on.

Now the framework is in place to make simple, but quantifiable, calculations regarding the expected radial profiles of the surface brightness around a disk of given viewing angle and dust population around a given star.

The slope of the dust size distribution determines what size particles have the most influence in the total scattering. From equation 3.7 it is apparent that for $p > 3$ the geometric cross-section is dominated by the small particles. The majority of the total mass of the distribution is contained in the larger particles for $p < 4$, after which most of the mass is contained in the smaller particles. In a collisional environment, $p \sim 3.5$ from theoretical estimations Stern (1995). Although not measured for dust sized particles, this steep power law fits the measured size distribution of Kuiper Belt objects with sizes between 50 and 1000 km (Trujillo et al. 2001). Therefore, the scattering cross-section should be dominated by smaller particles. However, for the condition $3.0 < p < 4.0$, while the scattering cross-section is dominated by the smaller particles, the total mass of the distribution is dominated by the larger bodies. However, a distribution which continuously describes both dust and larger bodies where $p > 4$ would not last long in a steady state equilibrium considering the very short lifetime of the small sized dust, and that this dust is produced from the larger masses, so the mass must be contained in the larger bodies or $p < 4$. This produces a situation where similar scattered light signatures can be produced by a large range of total masses, or in other words, scattered light models are not necessarily sensitive to directly measuring the total disk mass. In comparing different scattered light models on the basis of total mass, it is important to note the size ranges and the slope of the power law index or models can easily be misunderstood (Trilling et al. 2000).

The optical depth is a more relevant parameter for measuring the expected surface brightness of a given dust population. The expression for the optical depth resulting from a surface density between $R_{\text{min}}$ and $R_{\text{max}}$ is given by,
\[
\tau_{sca} = N_{tot} < a^2 Q_{sca} > \frac{(b-2)}{4b} \frac{(R_{max}^{-b} - R_{min}^{-b})}{(R_{max}^{(2-b)} - R_{min}^{(2-b)})} 
\]

With \( N_{tot} \propto M_{dust} \), it is apparent through Equation 3.11 that for a fixed model, \( \tau_{sca} \propto M_{dust} \).

To illustrate the relationship between disk mass, geometrical optical depth, and size ranges, the \( \tau_{sca} \) from the inferred surface density of the measured Kuiper belt objects between the size range of \( 50 \text{km} < a < 1150 \text{km} \) (\( M_{KB} \sim 4 \times 10^{-2} M_{\odot} \)) is on the order of \( \tau_{sca} \sim 10^{-12} \). However, if the same mass is distributed between sizes \( 1 \mu m < a < 1 m \) then \( \tau_{sca} \sim 10^{-4} \). Further, if the mass is all in \( a \sim 1 \mu m \) sized particles then, \( \tau_{sca} \sim 0.1 \). As will be discussed in Section 3.2, the actual mass of \( a \sim 1 \mu m \) dust in the Kuiper belt as estimated from the dust impact detections of Voyager (Gurnett et al. 1997) is \( M_{dust} \sim 2 \times 10^{-8} M_{\odot} \) which gives \( \tau_{sca} \sim 10^{-7} \) for the Kuiper belt dust population.

Figure 3.1 shows the radial surface brightness profiles resulting from the isotropic scattering model, using solar values for the luminosity and temperature of the central star for a specified dust population.

### 3.1.3 Mie Scattering

In reality, dust and even larger debris disk material does not scatter light isotropically, and geometric cross-sections are only relevant when diffraction effects are negligible, principally when the particle size is much larger than the wavelength of the incident radiation \( (a >> \lambda) \). Particles much smaller than the incident wavelength, \( (a << \lambda) \) are not efficient scatters, and the effective cross-section for scattering and absorbing incident radiation becomes smaller for smaller values of \( a \) (not necessarily linearly). Mie scattering theory offers an exact solution predicting the scattering behavior of spherical particles. Given the index of refraction of the particle and surrounding medium, the size of the particle, and the wavelength and polarization state of incident light, one can exactly predict the measured intensity as a function of scattering angle, as well as the absorption of light by the particle. This is
accomplished by using Maxwell's equations to solve the boundary value problem of a plane wave electric field incident on a sphere with homogeneous dielectric properties. The solution depends on the orientation of the incident plane wave relative to the scattering plane, or its polarization state. Because any polarization state can be described by the superposition of two orthogonal components of the electric field parallel and perpendicular to the scattering plane, two separate solutions are needed to solve the boundary problem for an incident wave of arbitrary polarization. The solution can be expressed in the form of a 2 × 2 matrix,

\[
\begin{pmatrix}
E_{||} \\
E_{\perp}
\end{pmatrix} = \frac{e^{ik(r-z)}}{-i kr} \begin{pmatrix}
S_2 & S_3 \\
S_4 & S_1
\end{pmatrix} \begin{pmatrix}
E_{||i} \\
E_{\perp i}
\end{pmatrix}
\]

(3.15)

With the matrix values \((S_1, S_2, S_3, S_4)\) dependent on the scattering angle, and the ratio of the particle size to the incident wavelength defined as, \(X = 2\pi a/\lambda\). The details of the solution to the problem, are given in Bohren & Huffman (1983, hereafter BH). Mie calculations find deviations from geometric scattering and absorption cross-sections.

We do not observe the electric field directly, but rather the amplitude of the electric field in the form of electromagnetic radiation. The observable quantities which fully describe the complete state of radiation including polarization states, can be expressed by the Stokes parameters. The Stokes parameters are, in terms of the parallel and perpendicular electric field given by:

\[
I = E_{||} E_{||}^* + E_{\perp} E_{\perp}^*
\]

(3.16)

\[
Q = E_{||} E_{\perp}^* - E_{\perp} E_{||}^*
\]

(3.17)

\[
U = E_{||} E_{\perp}^* + E_{\perp} E_{||}^*
\]

(3.18)

\[
V = i(E_{||} E_{\perp}^* - E_{\perp} E_{||}^*)
\]

(3.19)

A relationship between the incident and scattered Stokes parameters can be written down in the form of a 4 × 4 matrix,


\[
\begin{pmatrix}
I_s \\
Q_s \\
U_s \\
V_s
\end{pmatrix} = \frac{1}{k^2 r^2} \begin{pmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{pmatrix} \begin{pmatrix}
I_i \\
Q_i \\
U_i \\
V_i
\end{pmatrix}
\]

(3.20)

with relationships between the amplitude scattering matrix elements and the stoke parameter matrix elements given in BH.

Although there is an exact analytical solution to the problem, numerical methods make the theory practical to various physical applications. There are a number of readily available and tested programs which calculate the full Stokes parameters given the polarization of incident light of a specified wavelength, the index of refraction, \( m = n + ik \), and the radius of the particle. Here I use the FORTRAN based BHMIE routine from BH. Before being utilized in this dissertation, it was tested as suggested by BH to make sure the numerical methods converged to physically realistic values.

The components to the amplitude scattering matrix are formed based upon the index of refraction, and the ratio of the wavelength to the particle size. For the application of scattering in debris disks, the more physically correct assumptions of calculating the scattering and absorption cross-sections allow one to tie in observations with the possible physical circumstances within the debris disks.

Here we investigate the relationships between a given dust population and its optical depth to produce quantifiable surface brightness and polarized surface brightness model disks. The Mie calculations will also be used to calculate the Poynting - Robertson drag forces associated with the radiation pressure felt by the dust to offer a hypothesis on the role the central star plays in shaping the associated debris disk dust population.

### 3.1.4 Dust Composition Selection

It is rather easy to see the importance of dust composition by considering the different appearance of a debris disk composed of shiny metallic particles compared to the same
disks with the metal particles replaced with black obsidian. Fortunately, we have a good idea of the dust composition in the solar system's "debris disk" to offer a starting point. Laboratory experiments simulating the formation of dust in space through a variety of techniques finds the dust to have complicated, non-spherical morphologies Rotundi et al. (2002). The scattering characteristics have been examined for the zodiacal light (Hahn et al. 2002), and for newly created cometary dust (Farnham 1996). A composite grain mixture has been developed by Mathis & Whiffen (1989) to model the composition of interstellar grains (table 1) and is close to the expected composition of zodiacal light. It is found that the steep power law size distribution of these grains produces similar angular dependent scattering characteristics compared to those measured for cometary dust (Farnham 1996) and zodiacal dust (Hahn et al. 2002). With the goal to just produce an order-of-magnitude model which translates changes in physical properties of debris disk dust into changes of observable quantities, the Mathis-type grain composition is adequate.

For large values of $X$ with $X = 2\pi a/\lambda$, Mie scattering theory predicts that forward scattering becomes more efficient than to back scattering by a factor of $> 1000$. However, one expects the Mie scattering model to become inaccurate for these large dust sizes, because the wavelength of the radiation becomes small enough to resolve the non-spherical grain shape, and irregularities within the composition of the particle. The value of $X$ where Mie theory becomes inaccurate depends on the degree of inhomogeneity of the particle's composition, and on the degree of morphological deviation from spherical shape. Empirical tests show that the front-to-back scattering ratio is overcalculated by Mie theory for large particles, with more energy being scattered into other directions. Fortunately, the average cross-section of the size distribution favors the lower sized particles, and a disproportionately smaller contribution to the scattered light appearance of the disk is from the larger particles. However, for debris disks where the scattering cross-section is dominated by particles much larger than the predominant illumination wavelength, Mie scattering models may need to be modified to accommodate the overestimated forward scattering efficiency, with a slightly more isotropic scattering model a more realistic model (Farnham 1996).
Table 3.1 Index of Refraction for Interstellar Grains (Mathis & Whiffen 1989)

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>n</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500.</td>
<td>1.819</td>
<td>0.024</td>
</tr>
<tr>
<td>1000.</td>
<td>1.830</td>
<td>0.038</td>
</tr>
<tr>
<td>300.</td>
<td>1.886</td>
<td>0.124</td>
</tr>
<tr>
<td>200.</td>
<td>1.885</td>
<td>0.137</td>
</tr>
<tr>
<td>150.</td>
<td>1.880</td>
<td>0.161</td>
</tr>
<tr>
<td>100.</td>
<td>1.745</td>
<td>0.144</td>
</tr>
<tr>
<td>60.0</td>
<td>1.720</td>
<td>0.172</td>
</tr>
<tr>
<td>50.0</td>
<td>1.706</td>
<td>0.184</td>
</tr>
<tr>
<td>35.0</td>
<td>1.657</td>
<td>0.208</td>
</tr>
<tr>
<td>25.0</td>
<td>1.600</td>
<td>0.233</td>
</tr>
<tr>
<td>20.0</td>
<td>1.533</td>
<td>0.244</td>
</tr>
<tr>
<td>18.0</td>
<td>1.484</td>
<td>0.220</td>
</tr>
<tr>
<td>12.0</td>
<td>1.526</td>
<td>0.207</td>
</tr>
<tr>
<td>9.7</td>
<td>1.381</td>
<td>0.253</td>
</tr>
<tr>
<td>9.0</td>
<td>1.318</td>
<td>0.184</td>
</tr>
<tr>
<td>7.0</td>
<td>1.385</td>
<td>0.066</td>
</tr>
<tr>
<td>5.0</td>
<td>1.407</td>
<td>0.062</td>
</tr>
<tr>
<td>3.40</td>
<td>1.408</td>
<td>0.064</td>
</tr>
<tr>
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</tr>
<tr>
<td>1.65</td>
<td>1.394</td>
<td>0.067</td>
</tr>
<tr>
<td>1.25</td>
<td>1.392</td>
<td>0.078</td>
</tr>
<tr>
<td>0.70</td>
<td>1.389</td>
<td>0.095</td>
</tr>
<tr>
<td>0.55</td>
<td>1.390</td>
<td>0.100</td>
</tr>
<tr>
<td>0.434</td>
<td>1.395</td>
<td>0.103</td>
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<tr>
<td>0.40</td>
<td>1.399</td>
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<td>0.28</td>
<td>1.400</td>
<td>0.110</td>
</tr>
<tr>
<td>0.26</td>
<td>1.395</td>
<td>0.117</td>
</tr>
<tr>
<td>0.24</td>
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<td>0.133</td>
</tr>
<tr>
<td>0.2175</td>
<td>1.337</td>
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</tr>
<tr>
<td>0.20</td>
<td>1.315</td>
<td>0.125</td>
</tr>
<tr>
<td>0.19</td>
<td>1.317</td>
<td>0.112</td>
</tr>
<tr>
<td>0.17</td>
<td>1.334</td>
<td>0.105</td>
</tr>
<tr>
<td>0.16</td>
<td>1.351</td>
<td>0.111</td>
</tr>
<tr>
<td>0.15</td>
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<td>0.142</td>
</tr>
<tr>
<td>0.14</td>
<td>1.347</td>
<td>0.167</td>
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<tr>
<td>0.13</td>
<td>1.353</td>
<td>0.175</td>
</tr>
<tr>
<td>0.12</td>
<td>1.357</td>
<td>0.199</td>
</tr>
</tbody>
</table>

43
The value of the size distribution power law index chosen in the models is somewhat arbitrary within the range 3.5-4.0 range expected from a collisional environment. As will be seen in a following section, smaller particles in an optically thin disk have lifetimes which are proportional to their size, an effect which becomes dominant only for small sizes. Therefore, the shallower range of 3.5 is chosen. The power law distribution smooths out the resonances and structure common in Mie calculations of specific sizes, and to first order, the slope of the size distribution just changes the representative size of the dust population \(< a \rangle\), as defined by,

\[
< a > = \frac{\int a^{1-p}da}{\int a^{-p}da}
\]  

(3.21)

### 3.1.5 Appearance of Mie-Scattering Disks

The same equations used to create the isotropic scattering disks apply in the creation of Mie-scattering disks, except now a there is the addition of non-geometric values of scattering cross-sections, and the scattering angle will be a factor in assigning the value of the surface brightness versus position angle around the disk. For a given dust grain, the BHMIE program produces the amplitude scattering matrix for all scattering angles, as well as the scattering and absorption cross-sections. The effective scattering angle needs to be known as a function of position angle for the star. These scattering properties must be computed as weighted averages over the size distribution.

Because the flaring profile of the disk is not taken into consideration, the calculation is simplified, and for a given disk inclination (\(\theta_i\)), the scattering angle (\(\theta_{sca}\)) applicable for a given on the sky position angle (\(\theta_{PA}\)) is given by,

\[
\theta_{sca} = \arctan (\cot \theta_i \csc \theta_{PA})
\]  

(3.22)
The scattering phase function, or scattering diagram, \( p(\theta_{\text{sca}}) \), is a function that represents the relative scattering versus scattering angle, which here is normalized to a value of 1 over \( 4\pi \) radians,

\[
1 = \int P(\theta_{\text{sca}})d\Omega
\]  

(3.23)

In the case of isotropic scattering, under this normalization definition \( P(\theta) \) is a constant \( P(\theta) = 1/4\pi \). A comparison between the isotropic phase function and the phase function produced from a model of solar system dust is shown in Figure 3.2.

Another helpful parameter commonly used in describing scattering properties is the asymmetry parameter, \( g \), which is defined by,

\[
g = \int P(\theta_{\text{sca}})\cos(\theta_{\text{sca}})d\Omega.
\]  

(3.24)

For the adopted composition, the variation in \( g \) as a function of particle size is shown in Figure 3.3.

To simplify the calculation of the scattering from the size distribution of dust, the average cross-section efficiencies, \( Q_{\text{sca}} \), \( Q_{\text{abs}} \), and \( Q_{\text{ext}} \) (Figure 3.4), as well as the scattering phase function \( P(\theta) \), (Figure 3.5) and the corresponding polarized intensity and polarization amplitude dependence on scattering angle (Figures 3.6 and 3.7 respectively) are calculated over the size distribution as,

\[
< P(\theta) > = \frac{\int P(\theta, a)a^{-\rho}da}{\int a^{-\rho}da}
\]  

(3.25)

\[
< Q > = \frac{\int Q(a)a^{-\rho}da}{\int a^{-\rho}da}
\]  

(3.26)

So the first deviation from the simplistic model from Section 3.1.1 is that the average scattering cross-section, \( < Q_{\text{sca}} > \) is used in equation 3.2 instead of the value of \( A \).
The second difference, the surface brightness dependence on the scattering angle, is represented by a multiplicative factor of $4\pi < P(\theta) >$ to Equation 3.11

$$S_\nu(R, \theta) = \frac{< F_\nu(R, \theta) > \Sigma(R, \theta) 4\pi < P(\theta) >}{\cos i}$$ (3.28)

These two changes transform the isotropic scattering models into Mie-scattering models. Now the scattered light appearance of different dust populations can be explored.

### 3.2 Scattered Light Models of our Current Solar System

A model of the external appearance of our solar system’s debris disk serves as an appropriate baseline to use in model comparisons with observational searches for debris disks around nearby solar analog stars. For scattered light searches in the near-IR, the dust with sizes $a \sim 1\mu m$ will dominate the scattering cross-section, and so it is worthwhile to investigate this size of dust in our solar system to determine its scattered light appearance.

Dust in our own solar system can be seen with the naked eye in dark skies. As mentioned in the introductory chapter and further explained below, the lifetime of this dust is on the order of $t_{dust} < 10^6$ yrs so in order for dust to be present in the solar system, it must be continually produced. The dust in the inner solar system is referred to as the Zodiacal dust, and is the result of dust production from collisions in the asteroid belt, and from comets on highly elliptical orbits which pass close to the Sun (Hahn et al. 2002). Mass estimates are in the range of $M_{zodi} \sim 2 \times 10^{18} g$, with a typical size of $a > 0.5 \mu m$. The bulk density of the dust is estimated to be $\rho_{dust} \sim 2.5 g/cm^3$ from compositional studies of meteorites.

After dust is produced in the solar system, it migrates inward toward the Sun via drag forces if it is of a sufficient size and density to avoid removal by radiation pressure. The gravitational influence of the giant planets efficiently removes any dust crossing their orbits.
This situation creates a relative void of dust in the region outward of the asteroid belt, and inward of Neptune’s orbit.

The dust in the outer solar system beyond the orbit of Neptune is not as well studied as the inner solar system dust, as it is much fainter and more physically isolated. Collision rates estimated by Davis & Farinella (1997); Stern (1995) suggest that Kuiper belt objects should be a source of dust. An extrapolation of a $p = 4$ Kuiper belt power law size distribution measured for the brighter objects between radii ranging from 50 and 1000 km, Trujillo et al. (2001) down to dust sizes ($a \sim 1\mu m$) gives an unrealistically large total dust mass. With $p = 4$ the mass relation indicates that there should be an equal mass over equal decade ranges of particle sizes, so the extrapolation results in a total mass of $M_{Kuiper} \sim 0.1 M_\oplus$ over the size range of $a_{min} = 1\mu m$ and $a_{max} = 25\mu m$. This much mass in relatively small, efficient scattering particles would make a bright, easily observable surface brightness (Figure 3.1). However, despite ground based and space based observational efforts in a variety of wavelengths (for review see Backman & Paresce 1993; Jewitt & Luu 2000) dust in the Kuiper Belt has yet to be detected by non-in-situ observations, suggesting that the size distribution power law becomes shallower for smaller sizes as suggested by Kenyon (2002).

Fortunately, as Voyager passed through the Kuiper Belt, it was sensitive to detecting dust with sizes $a > 1.4\mu m$. A number density of $2 \times 10^{-8} m^{-3}$ was detected in the region from $R \sim 30-40AU$ from the sun (Gurnett et al. 1997), which translates into a total dust mass of $M_{Kuiper} \sim 10^{-8} M_\oplus$ for particles larger than $1.4 \mu m$.

The resulting surface brightness profiles and disk images produced using these dust parameters in the Mie scattering models are shown in Figures 3.8-3.12. It is apparent that the forward scattering efficiency helps the prospects for detection of more edge-on disks by markedly increasing the surface brightness, and to a lesser degree, the polarized surface brightness in at least a small portion of the disk.
3.3 What Stars are most likely to Reveal their Disks? Dust Destruction Versus Dust Production

As seen in Figure 3.6, dust scatters light most efficiently if the dust size is on the order of the wavelength of scattered light. With this established, the representative size of a given dust population compared to the peak wavelength of the illuminating source determines their relative brightnesses, and thus how detectable they are. If the stellar environment prohibits the existence of dust with sizes comparable to the wavelength of the incident radiation, detection would likely require a much greater amount of material for which there may not be a source. With this in mind, it is worthwhile to investigate the sources of debris disk dust, as well as the destructive processes which diminish debris disk dust populations. An estimate of which stars are more likely to reveal their debris disks from scattered light observations can be made by considering the variation in the sources and sinks as a function of the central star. Here, we consider a range of main sequence stars and young solar-type stars.

3.3.1 Dust Production Processes

Dust can be produced in a variety of ways in the circumstellar environment. Collisions between larger bodies have been widely considered as the primary replenishing source of debris disk dust, followed by comet outgassing. Here the primary dust production mechanisms are reviewed, with a brief consideration of dust condensation in the atmospheres of cool stars of spectral type later than M5V.

Collisions

Collisions between debris disk material redistribute $dN(a)$. If the typical collision velocity is small enough, collisions will bring together many small particles as they stick together to form larger ones. In very young, optically thick environments, this process can provide seeds which lead to the growth of planets Safronov (1972). If the relative velocity is large,
collisions will break up larger bodies into more numerous smaller ones. Without a high density of gas to dampen the velocity dispersion in the disk, collisions in debris disks are dominated by higher velocity collisions. These high velocity collisions are producing dust in today’s evolving solar system.

However, collisions also can remove dust in that the resulting particles have a distribution of velocities, some of which result in hyperbolic orbits (Backman & Paresce 1993). However, the net result is a production of smaller sized dust particles. The role that collisions have in removing debris disk dust is discussed in more detail in section 3.3.2.

With the dust production dependent on the velocity dispersion of the orbiting bodies, perturbing forces can inflate the effective velocity dispersion of the debris disk and increase the collision rate. Consequently, these perturbing forces can greatly influence dust production. Perturbations can be internal to the disk in the form of gravitational interaction with planets (Levison et al. 2001). Externally, close encounters with a passing star could also inflate the velocity distribution, causing more path crossing and increasing the collision rate Larwood (1997); Kalas et al. (2000). With these perturbations largely unpredictable, the dust production rates in debris disks are correspondingly uncertain.

Comet Outgassing

A significant fraction of the zodiacal dust is associated with the sublimation from comets passing close to the sun. About 30% of the zodiacal cloud is thought to be produced from comets (Hahn et al. 2002) and can be distinguished by a more spherical distribution out of the ecliptic plane of the solar system compared to the collisionally produced dust. Fortunately, the size distribution of dust produced from comets can be described by a steep power law distribution as is produced from collisions (Farnham 1996). Because this dust production is dependent on heating from the Sun, the production rate rises dramatically with decreasing separation from the Sun. Therefore, it is expected that comet outgassing would not significantly contribute to the dust population in the outer regions of stars, and to a lesser extent around lower luminosity stars.
Condensation in Atmospheres of Cool Stars

In giant stars, dust is produced in the extended, cool atmosphere. The dust grains are then blown out by radiation pressure in a continuum driven wind. This process is thought to be the primary source of dust in the interstellar medium. Around main sequence stars with spectral types earlier than M5V, temperatures are typically much too high where there is enough density for grain condensation to occur. However, it is thought that dust may be produced in the atmospheres of brown dwarfs complicating their spectral signature (Burrows et al. 2001). One would not expect this to be a significant source of circumstellar dust through a continuum driven wind as found around giant/supergiant stars, as the radiation pressure from a brown dwarf would be very small (see below). However, with dust condensation occurring at the level of the photosphere for late M spectral type stars, and slightly below the photosphere for brown dwarfs, it is possible that stellar flaring activity or other stellar activity could transport this dust away from the photosphere into the circumstellar environment. High energy processes are correlated with some brown dwarfs as indicated by X-ray observations (Rutledge et al. 2000), and radio observations (Berger et al. 2001). With many unresolved, and under realized issues regarding low-mass stars and brown dwarfs, especially the high energy processes associated with stellar wind phenomena, the possibility of such a process creating an observable infrared excess cannot be ruled out. These processes may alter the spectral energy distribution in such a way as to confuse observable quantities now associated with circumstellar disks (Liu et al. 2002; Muench et al. 2001).

3.3.2 Dust Removal Processes

Radiation Pressure and Poynting-Robertson Drag

The Mie calculations used to compute the expected scattering and absorption by dust around a given star can also be used to make a refined estimate of forces acting on the dust. The force on a particle imposed by an incident photon is the result of a time rate
of momentum being removed by the particle from incident radiation. To treat the case of a dust particle in orbit around a star, it is convenient to use spherical coordinates, with the origin centered on the star. If the particle has no tangential velocity, normal to the propagation direction of the incoming radiation, the net force is only in the radial direction ($r$). However, if the dust grain has a tangential velocity ($\dot{\theta} \neq 0$), then the dust grain will absorb more momentum in its direction of movement. Because the net momentum transfer will always be in an opposite direction of the dust particle's motion, it is a drag force, commonly referred to as the Poynting-Robertson drag (Poynting 1903; Robertson 1937).

The radial force, or the radiation pressure force, $F_R$, felt by a spherical dust particle of radius $a$ at a distance $r$ from a star of luminosity $L_*$ is given by,

$$F_R = \frac{L_* Q_{PR}a^2}{4cR^2}$$

(3.29)

Where $c$ is the speed of light and $Q_{PR}$ is the Pointing-Robertson absorption coefficients (Burns, Lamy, & Soter 1979) related to the absorption ($Q_a$) and scattering ($Q_s$) cross-section efficiencies by $Q_{PR} = Q_a + Q_s(1 - g)$ where $g$ is the scattering asymmetry parameter from Equation 3.22. The ratio of outward radial force on the dust particles $F_r$, to the radially inward gravitational force $F_g$ is commonly referred to as $\beta$ and is given by,

$$\beta = \frac{F_R}{F_g} = \frac{3L_*Q_{PR}}{16\pi G M_* c a \rho}$$

(3.30)

$\beta$ is an important parameter used to estimate what sized particles can exist around a given star, and also in calculations of the spiral-in lifetimes of dust via the P-R drag ($T_{PR}$). Particles with values of $\beta$ greater than 1 are obviously short lived and susceptible to being blown away from the star and incorporated into the interstellar medium. This is by no means a hard lower limit for a criterion of ejection, as one must consider the circumstances of the dust production. If dust originates from a larger body with a circular orbit, it is found that the post-production orbit will on average be hyperbolic (escaping) for $\beta > 1/2$,
and that $\beta$ values required for escape are lower for cases where the parent body is in a non-circular orbit, $\beta > (1 - e)/2$ (Burns et al. 1979).

The tangential force of the Poynting - Robertson drag is equivalent to the rate of angular momentum ($T$) loss, and is given by the relation,

$$ \left( \frac{dT}{dt} \right)_{\text{rad}} = \frac{L_y Q_{PR} a^2 \dot{\theta}}{4c^2} \quad (3.31) $$

or in another form,

$$ \frac{dT}{T} = \frac{L_y Q_{PR} a^2}{4R^2 c^2 m_{\text{dust}}} dt \quad (3.32) $$

From Equation 2.23, the orbital decay timescale is on the same order as the time it takes for the particle to encounter a radiation equivalent of its mass.

In reviews of debris disks and the Kuiper Belt, (Backman & Paresce 1993; Jewitt & Luu 2000), the radiation pressure and P-R drag are treated in terms of geometrical optics ($Q_{PR} = 1$, without consideration of the wavelength dependence of $Q_{PR}$). In the geometrical limit,

$$ \beta = 0.57 \frac{L_y}{L_\odot} \left( \frac{\rho}{g/\text{cm}^3} \right)^{-1} \left( \frac{a}{\mu m} \right)^{-1} \quad (3.33) $$

The corresponding timescale for orbital decay for circular orbits ($e = 0$) is given by (Burns, Lamy, & Soter, 1979),

$$ T_{PR} = \frac{400}{\beta} \left( \frac{R}{\text{au}} \right)^2 \text{yr s} \quad (3.34) $$

However, $Q_{PR}$ is a function of both the wavelength of the incident radiation, and the particle size ($Q_{PR}(\lambda, a)$). So $< Q_{PR} >$, must be calculated by integrating $Q_{PR}(\lambda, a)$ over, and normalizing to, the source star's spectrum.

$$ < Q_{PR} > = \frac{\int Q_{PR} B_\nu d\nu}{\int B_\nu d\nu} \quad (3.35) $$
The values of $\beta$ calculated with Mie scattering coefficients for particle sizes smaller than the wavelength where the bulk of the energy is emitted ($a < 0.1\mu m$ for most stars) are most significantly different from those calculated using geometric optics assumptions as shown in Figure 3.13. As opposed to the geometrical approximation of $\beta \sim a^{-1}$ across all size ranges, the Mie values show constant $\beta$ values for small particles up to sizes where $\beta$ rises to a maximum $a_{\text{max}} \beta \sim \lambda_{\star}/2\pi$ where $\lambda_{\star}$ is the Wein's wavelength of peak emission from the star. Figure 3.14 shows a family of $\beta$ values as a function of particle size for a number of stars. For $a \sim 0.1\mu m$ particles around main-sequence stars, the miscalculation of $\beta$ is overestimated by a factor between 10-50 depending on the star. For brown dwarf environments, this over estimation moves up to a factor of $\sim 100$.

Stellar Wind Pressure and Drag

In the paragraphs above it was found that the radiation pressure force felt by a particle in a radiation field is proportional to the momentum flux (momentum / area / time) of the radiation field. If the particle is moving, the angular momentum loss rate is proportional to the the mass loss of the radiation field (Energy / $c^2$ / area / time). The same holds true for the solar wind particles, but instead of the mass equivalent of the radiation used in the calculation, it is just the mass. The angular momentum loss from a solar wind of mass loss, $\dot{M}_a$, is given by Misconi (1976),

$$\frac{dY_{sw}}{dt} = \frac{\dot{M}_a a^2 \dot{\theta}}{4} \quad (3.36)$$

and the outward radial force given by,

$$F_{sw} = \frac{\dot{M}_a V_{sw} a^2}{4R^2} \quad (3.37)$$

The energy flux from the solar wind is a very small fraction of the radiative flux ($L_{sw}/L_\odot \sim 10^{-6}$). The radiation pressure term does not depends on the energy flux. This means that the solar wind equivalent of the radiation pressure force is correspondingly as
small. This ratio has been the basis for dismissing the solar wind drag from consideration. However, as shown here, a more important quantity for dust lifetime calculations is the rate of angular momentum loss caused by the solar wind which from Equation 2.34 is a function of the mass loss rate, or the outward mass flux of the solar wind.

So for particles in our solar system with \( Q_{pr} \sim 1 \), i.e., large particles, the ratio of the angular momentum loss due to the solar wind, compared to that of the radiation P-R drag is \( \sim 0.3 \) using the solar mass loss rate (Feldman et al. 1977) of \( 2 \times 10^{-14} M_\odot yr^{-1} \), \( L_{sw} = 7.6 \times 10^{35} p^{+} s^{-1} \). So the mass flux is given by, \( L_{sw}/4\pi R_\odot^2 \sim 2 \times 10^{5} p^{+} cm^{-2} s^{-1} \). Although the solar wind energy flux is orders of magnitude smaller than the solar radiation flux, the effects on angular momentum loss are of the same order-of-magnitude. Considering the drop off in \( Q_{pr} \) for smaller sized dust, the solar wind drag becomes more dominant compared to the radiation P-R drag for these size ranges. With the solar wind mass loss rate when the Sun was just 100 Myr old thought to be up to \( \sim 1000 \) times the present mass loss rate, the solar wind would dominate the radiative P-R drag and \( \beta \) for all size ranges. The implications regarding debris disk detectability are discussed below.

**Collisions**

The collision rate depends on the cross-section of the colliding bodies, the ellipticity distribution of the objects, the orbital velocity, and the number density of objects. An estimated mutual collision timescale is given by Backman & Paresce (1993),

\[
t_{coll} = \frac{t_{orb}}{8\sigma(r)} \sim \frac{r_{AU}^{3/2}}{8\sigma(r)} \left( \frac{M_\odot}{M_*} \right)^{1/2} \text{yr}
\]

(3.38)

Using this equation, the dust removal time scales are estimated around \( \beta \) Pic, Vega, and Fomalhaut, and it is found that for the \( \tau \sim 10^{-2} - 10^{-3} \) environment of \( \beta \) Pic, collisions are more important than the P-R drag in removing dust for the inner regions of these debris disks. However, collisions were less important for the lower density environments suspected
around Vega and Fomalhaut. For debris disks with dust densities less than 1000 times those found in our current solar system, P-R drag is the dominant dust removing mechanism.

Sublimation

Sublimation affects volatile materials which comprise a significant fraction of the debris disk material in our solar system (Hahn et al. 2002). Because sublimation is a strong function of temperature \( t_{\text{sub}} \propto T_{\text{ice}}^{-5.5} \) for water ice, (Isobe 1970; Backman & Paresce 1993), its importance is limited to within a critical distance of the star, and is more of an issue in more luminous stars. Because of the variation in volatile properties of debris disk material, sublimation is expected to cause compositional variances with stellar separation in the sense that closer to the star, the dust will be composed of silicates and less volatile materials compared with the more ice-rich outer regions.

For solar-type stars, sublimation acts as a catalyst for dust destruction working with the P-R drag. The inward dust migration resulting from P-R drag places the dust in regions where sublimation can effect it, and dust is destroyed at a larger radius from the star. With lifetimes short in the regions where sublimation is important, sublimation is not significant in globally effecting the balance between dust production and destruction.

3.3.3 Expected Dust Populations as a Function of Central Star

For observational searches, it is worthwhile to compare how the dust production and destruction mechanisms depend on the central star to see which stars may have more detectable debris disks. Wyatt & Whipple (1950) first pointed out that the P-R lifetimes should be much shorter for higher luminosity stars (they estimated by a factor of \( \times 100,000 \) for O-type stars) and longer for lower luminosity stars (\( \times 100 \)) simply because the fundamental relationship between stellar mass to luminosity \( (L \sim M^{2.3}) \) skews the balance towards the radiation pressure for higher mass stars. Divari & Reznova (1970) performed more detailed calculations, similar to those presented in Figures 3.14 and 3.15.
Although the dust lifetimes are shorter, these have to be compared with the dust production mechanisms to estimate steady state dust contents.

Under the assumption that dust production ($\eta_+$) is collisionally dominated, $\eta_+$ is proportional to the typical orbital velocity which, for a given radius, scales as $V_{\text{orbit}} \propto M_*^{1/2}$ or $\eta_+ \propto M_*^{1/2}$. If the dust removal processes are radiation P-R drag dominated, the removal rate, $\eta_-$, is proportional to the stellar luminosity. With $L_* \propto M_*^{2-3}$, $\eta_- \propto M_*^{2-3}$. This gives the stellar mass dependence on the ratio of dust production to destruction as $\eta_+ \propto \eta_- \propto M_*^{-1.5-2.5}$, or dust production is favored for lower mass stars.

The solar wind drag has the same effect on dust orbits, and so in terms of calculating dust lifetimes, it can be treated as an additive term to the value of $\beta$ used in Equation 2.13. However, one should keep in mind that the actual outward counter-balancing force to gravity is only increased by the ratio of the energy flux, which for the case of the Sun is dominated by radiation by a factor of $\sim 10^6$.

From Figures 3.14 and 3.15, stars with spectral types later than M3 do not have sufficient luminosity to efficiently remove of the dust via radiation pressure and/or radiation P-R drag. Thus, if there are no other mechanisms to remove this dust, and the sizes correspond with efficient scattering regimes ($a \sim \lambda_{\text{star}}$), these stars would potentially reveal their disks more easily in terms of contrast. However, stellar winds may remove this dust.

The stellar winds around other main-sequence stars are difficult to detect. Because the stellar wind consists of charged particles, the distribution of stellar winds depends on the magnetic field strength and structure of the circumstellar environment. This is largely unknown, although it is most likely not a simple function of the spectral type of the star, or linear with the radiative luminosity. Recently however, HST observations have been able to measure the H I Ly$\alpha$ emission from the stellar winds of stars interacting with their surrounding interstellar medium (Wood et al. 2002). Although this work is not fully developed and based on just $\sim 5$ examples, there appears to be a correlation for G and K type stars between their X-ray flux and their inferred solar wind mass-loss rate. A considerable amount of work has established a relationship between stellar rotation and age
(Skumanich 1972; Soderblom et al. 1993) and X-ray flux and stellar rotation (e.g. Pallavicini et al. 1981; Fleming et al. 1989; Stauffer et al. 1994). These relations suggest that the Sun at an age of 100 Myr had a solar wind mass-loss rate that was about 1000 times higher than the present day value of $2 \times 10^{-14} M_\odot yr^{-1}$.

Computing the dust lifetimes with a larger wind velocity would accelerate the dust removal processes by roughly the same factor as the wind production rate. Therefore, although the era of heavy bombardment is considered to be a time of a marked increase in dust production, the dust removal processes are conceivably just as elevated.

3.4 Summary and Conclusion

1. Dust scattering models are created based on isotropic scattering and Mie scattering theory.

2. Calculations of the radiation pressure and the Poynting Robertson drag forces are made based on Mie scattering cross-sections and considering a variety of main-sequence stars. It is found that radiation pressure is not sufficient to remove any size of interstellar-like dust for main-sequence stars with spectral types later than ~M5V.

3. Based on radiation forces alone, the debris disks around lower-mass stars are expected to be more detectable, in that given the same dust production rates, more of the dust mass will be in sizes that correspond with the size of the emitted radiation for lower mass main-sequence stars compared to higher mass main-sequence stars, and this dust will last longer around lower-mass stars.

4. Stellar winds may play a significant role in diminishing circumstellar dust populations. Although stellar winds around main-sequence stars are not well understood, Wood et al. (2002) show that young K-G type stars have stronger stellar winds. It is thought that the stellar wind from the young (age ~ 100 Myr) Sun could have a mass-loss
rate about 1000 times than mass-lose rate from the present day solar wind. This would have a profound effect on the dust population physically allowed around the early solar system, severely reducing the effective scattering cross-section (near-IR detectability).

5. The near-IR polarimetric observations are most sensitive to the presence of dust in the size range of $0.1\mu m < a < 10\mu m$. In the expected size distribution of the debris disk mass, this size range most likely does not contain the majority of the mass of the debris disk. As a result, near-IR observations alone are not direct indicators of total disk mass.
Figure 3.1 H-Band radial surface brightness profiles are shown for decade increments of the optical depth as calculated for an isotropic scattering model with $b = 1.5, p = 3.5, a_{\text{min}} = 0.5\mu m, a_{\text{max}} = 2.5\mu m$. It is found that $\tau = 10^{-9}$ corresponds to a total dust mass of $M_{\text{dust}} = 4.25 \times 10^{15} g$ with a density of $\rho_{\text{dust}} = 1.5 g/cm^3$ distributed between $0.5 < R < 50 AU$ from the central star with a linear relationship between $\tau$ and $M_{\text{dust}}$. The isotropic scattering resulting from the total dust mass in the Zodiacal dust cloud as estimated from Clementine observations (Hahn et al. 2002) to be $M_{\text{zodi}} \sim 2.3 \times 10^{18} g$ distributed between $0.5 < R < 4.5 AU$ is shown as a dashed line. The scattering from dust in the Kuiper Belt is plotted using an alternating dash-dot line. The Kuiper belt dust mass is estimated to be $M_{\text{Kuip}} \sim 10^{20} g$ from the Voyager plasma wave detector (Gurnett et al. 1997) distributed between $30 < R < 45 AU$. An albedo of $A = 0.1$ is used for all calculations in this plot.
Figure 3.2 The scattering phase function of the Mathis-type interstellar composite grains from a power law distribution with $p = 3.5$ and $a_{min} = 0.5\mu m$, $a_{max} = 2.5\mu m$ is similar to that compared to the phase function measured in the Zodiacal cloud. Although the model dust is spherical, the composite grains are appropriate for modeling debris disks to first order. The isotropic scattering phase function is plotted for comparison.
The Asymmetry parameter versus particle size for $\lambda = 1.6\mu m$

Figure 3.3 The scattering asymmetry parameter as a function of the ratio of the particle size to the scattering wavelength is plotted for Mathis-type dust with properties listed in Table 1. For isotropic scattering, $g = 0$. It is shown that $g$ rapidly departs from isotropic scattering when $2\pi a \sim \lambda_{\text{scatter}}$, or $X \sim 1$. 
Figure 3.4 Scattering, Absorption and P-R cross-section efficiencies are plotted as a function of the ratio of the particle size to the scattering wavelength. The cross-sectional efficiencies become larger when $X \sim 1$ as in the case of $g$ (Figure 3.3). The resonating structure of $Q_{sca}$ is averaged out over the particle distribution.
Phase functions for $\lambda = 1.65\mu m$

Figure 3.5 The scattering phase function of the Mathis-type interstellar composite grains from three different size ranges of the power law size distribution with $p = 3.5$. The Rayleigh scattering sizes produce near isotropic scattering, while the larger grains have markedly stronger forward scattering asymmetry.
Phase functions for $\lambda = 1.65 \mu m$

Figure 3.6 The polarized intensity versus scattering angle is plotted for three different size distributions as in Figure 3.8. For the scattering angles near $0^\circ$ and $180^\circ$, the polarized intensity drops to zero, as the polarization amplitude drops to zero here as well (Figure 3.7).
Phase functions for $\lambda = 1.65\mu m$

Figure 3.7 The polarized amplitude versus scattering angle is plotted for three different size distributions as in Figure 3.8. The polarization amplitude peaks for $90^\circ$ scattering angles in the Rayleigh limit of small particles. For larger particles, this peak shifts towards a slight backscattering angle. For the scattering angles near $0^\circ$ and $180^\circ$, the polarized amplitude drops to zero.
Zodiacal light and Kuiper Belt Dust

Figure 3.9 The polarized surface brightness radial profile in the forward scattering direction for solar system dust is plotted for the three different viewing inclination angles shown in Figure 3.8 (15°, 50°, 75°). The radial scale represents the solar system as it would appear from a distance of \( d = 10pc \).
Zodiacal light and Kuiper Belt Dust

Figure 3.10 The radial profile polarized surface brightness in the backward scattering direction for solar system dust.

Zodiacal light and Kuiper Belt Dust

Figure 3.11 The radial profile in the forward scattering direction for solar system dust.
Zodiacal light and Kuiper Belt Dust

Figure 3.12 The radial profile in the backward scattering direction for solar system dust.
Beta for Mie and geometric cross-sections

Figure 3.13 Calculation of Beta using geometric cross-sections overestimates Beta for small particles and bel.
Figure 3.14 The dust lifetimes due to P-R drag for different sized Mathis-type particles are compared for different spectral class main sequence stars. The sun is plotted with a solid line. The dust with values of $\beta > 0.5$ will be 'blown out' on hyperbolic orbits after being released from a parent body with a circular orbit, and these regions are marked in the plot with a dark grey color. The critical value of $\beta$ which results in a hyperbolic orbit is lower in the case where the parent body is in an elliptical orbit where $\beta_{\text{crit}} > (1 - e)/2$. The lighter grey area marks regions where particles will only escape if they originate bodies in in more elliptical $e \sim 0.8$ orbits. For stars of later spectral type than $\sim$ M5V, the radiation pressure alone does not “blow out” any size particle, contrary to results using geometrical cross-sections to calculate $\beta$. 

$\beta$ and the P-R lifetimes
Figure 3.15 The dust lifetimes at a distance of 1AU from the central star due to P-R drag are compared for different spectral class main-sequence stars of later type than our sun where radiation pressure does not blow out all dust sizes. Just considering the radiation drag, dust lasts more than 10 times longer around low-mass stars is compared with lifetimes computed for our Sun. Considering the mass dependence of the dust production mechanisms, given a similar starting mass, it is expected that lower-mass stars should have more of their mass in smaller sized \((a \sim 1\mu m)\) grains corresponding with wavelengths where most of the stellar luminosity is radiated. This means that one would expect to more easily detect the same mass of material around low mass stars.
References


Davis, D. R. & Farinella, P. 1997, Icarus, 125, 50

Divari, N. B. & Reznova, L. V. 1970, Soviet Ast., 14, 133


Isobe, S. 1970, PASJ


Liu, M. C., Najita, J., & Tokunaga, A. T. 2002, /baas, 201, 25.03


Chapter 4
First Results from Previously known Circumstellar Disks

A few objects with known, relatively bright, circumstellar disks were observed to confirm the performance of the system. To illustrate the power of this technique, I present the first results on an object with a previously measured resolved polarization signature, the circumbinary disk around GG Tauri Aa and Ab, as well as the CTTS binary pair SR24 N/S.

4.1 The Circumbinary Ring around GG Tau AB

The circumbinary disk around GG Tau AB was resolved in millimeter wavelength interferometric observations (Dutrey et al. 1994; Guilloteau et al. 1999) which found it to extend between 180 AU and 800 AU (assuming a 140pc distance to the Taurus star-forming region). Most (90%) of the material was found to be concentrated in a torus, or ring, of material extending between radii $180AU < R < 260AU$ from the central binary. It is the first circumbinary disk detected from its scattered light signature (Roddier et al. 1996, hereafter R96). R96 found that the orbit of the central binary is almost certainly elliptical and currently near periastron. They found evidence for filamentary structure between the ring and the central stars, but admitted that these structures could be deconvolution artifacts. Modeling of these observations (Close et al. 1998; Wood et al. 1999) suggests that the dust scattering is largely due to grains $<1\mu m$ in radius (Rayleigh scattering). This
was confirmed by the more recent *Hubble Space Telescope (HST)* polarimetric observations of Silber et al. (2000, hereafter S00) who also marginally detected material in regions that correlated with the filaments of R96. Most recently, Menard & Stapelfeldt (2001), and Krist et al. (2002) claim that the filamentary structures seen in the AO images are artifacts as they are not seen in WFPC2 *HST* images.

### 4.1.1 Observations

The polarimetric observations were obtained on four separate nights (October 2, 2000, December 21, 2000, February 24, 2001, and February 03, 2002) using the polarimeter described in Chapter 2 incorporated into the 36 element curvature wavefront sensing adaptive optics instrument, Hokupa’a, mounted on the 8 meter Gemini North Telescope (Graves et al. 2000).

For stars with adequate visible light for wavefront sensing such as GG Tau (V=12), the Hokupa’a AO system consistently delivers $FWHM \sim 75$ mas H-band images when the natural seeing is $<0'.7$. The QUIRC IR camera with the Wollaston prism is background limited after a $\sim 3$ second exposure in the H-band. All exposures used in the images shown in Figures 4.1 and 4.2 are at least 6.3 seconds, thus background limited. Each polarization data set consists of 20 frames with 5 frames taken in each of the 4 half-waveplate angles. Although the polarimeter detects the bright ring in an individual double subtraction of 2x6.3 second exposures, a total of 240x6.3 second exposures were taken (12 sets) between the four separate nights, with four different field rotation positions, and three different dither position. By comparing the polarization data sets taken with different field rotation angles, it was found that the measured polarized intensity in some regions in the field stayed fixed relative to the PSF (artifacts) while others rotated with the field as one would expect for real physical features of the GG Tau system. These fixed artifact regions were cover a small fraction of the total field, are isolated by using the four different field rotation angles, and eliminated in the final images.
Both polarization standard stars (Whittet et al. 1992), as well as photometric calibration standards from the UKIRT faint standard star catalog (Hawarden et al. 2001) were taken on the nights GG Tau Aa-Ba was observed. Only the night of February 3, 2002 was photometric, so the flux calibration of the polarized intensity is based solely on the observations from this night. The polarization standard star HD147283 was observed on this night as well as the faint near IR standard star FS137. As pointed out in Chapter 2, the main source of noise lies in the flat-field calibration, as also found by Kuhn et al. (2001). Therefore care was taken to accumulate as many detector counts in our flat field as in each polarization data set (30000x20 counts). Also, flat field exposures of the QUIRC detector were obtained in incremental exposure times, to check the linearity of the response of each pixel to H-band light. The counts in the regions of interest reported here were kept well within the linear response of the detector ($\lesssim$30000 counts). A bad pixel mask was created using the pixels deviating from the mean linear response. The reduction technique outlined in Chapter 2 were used to produce the final polarization images (Figures 4.1 and 4.2).

Although systematic errors prevent a determination of the signal-to-noise ratio by standard deviation measurements within a data set, a quantity representing the signal-to-noise ratio in the final polarization map can be determined by a standard deviation of the polarized intensity over unique data sets that have either been dithered or field rotated. An image of the polarization angle was used to distinguish regions of high signal-to-noise ratio. A mask was created where the angle was within 15 degrees of what expected from centrosymmetric scattering from the photocenter of the binary. The multiplication of this mask to the polarization intensity image is shown in Figure 4.2. Figure 4.2 shows the centrosymmetric vectors that are at radii outwards of the previously defined ring (260 AU). This material has been detected in the submillimeter wavelengths, (Guilloteau et al. 1999) but has not previously been detected in the near-IR. There is also material detected inward of the previously detected scattered light ring Krist et al. (2002).
4.1.2 Analysis and Discussion

A number of features are apparent in the image presented in Figures 4.1 and 4.2. First to note is an obvious gap at position angle PA=270° first seen in the images of R96. The polarization intensity contours have local minima and maxima that are departures from a homogeneous torus model of the ring. Scattered light was also detected interior to the inner ring boundary which correlates to the speculative structure noted by R96 and S00.

4.1.3 The Position Angle Gap

Figures 4.1 and 4.2 clearly shows the position angle gap first seen in the images of R96, and also noted by S00 and Krist et al. (2002), but because it overlapped with the HST diffraction spikes, the existence of the gap was uncertain. These observations confirm that this region shows a sharp disjunction from the polarized intensity of the surrounding ring. Such a position angle gap could be the result of shadowing between the stars and the disk as suggested by S00, or from the disk to the telescope. It could also indicate a lack of material, possibly from a solid body in an orbit with a radius similar to the ring. If this gap is a stable entity, the clearing of material by an orbiting body would have to keep up with shearing effects caused by the different orbital periods of the inner and outer ring. A self gravitational collapse within the ring is not physical. The differential gravitational force between the inner and outer ring by the central stars is greater than the attraction between the inner and outer portion of the ring by about two orders of magnitude, using the measured radii of the inner and outer edges of the ring, and the density and mass of the central stars reported in (Guilloteau et al. 1999).

Hydrodynamic simulations show that circumbinary disks typically break into two spiral arms (e.g. Artymowicz & Lubow 1996; Bate 2000) over the course of their evolution, with transient features in the density profile that resemble the observed gap. However, because the disk is seen in scattered light, and the ring is optically thick, seeing a gap due to a lack of material would require too efficient of an evacuation of material to result in a decreased measured polarized intensity. Therefore, this gap is most probably the result of a shadowing
effect. Higher resolution sub-millimeter observations that trace the density should reveal
the cause of this gap.

4.1.4 Ring Structure

Besides the obvious PA gap mentioned above, Figures 4.1 and 4.2 show polarized intensity
variations with localized minima and maxima that are not expected based on a smooth,
homogeneous torus of material that is evenly illuminated. This is either the result of an
uneven illumination of the material, a density/composition inhomogeneity of the disk, or a
combination of both. The inhomogeneous light source scenario is supported by the fact that
some of these non-homogeneous regions vary on timescales shorter than the orbital timescale
of the material as discussed below. However, there are forces in the system that will perturb
the circumbinary ring, considering the central binary has an elliptical orbit. Because of the
ambiguous cause of the measured structure in the ring, future high-resolution observations
from the upcoming submilimeter arrays that can trace the density of the material will help
to determine the cause of the polarized intensity spatial variations.

4.1.5 Material Inward of the Ring

The filamentary streamers

Figure 4.2 shows the detection of scattered light from material inward of the ring defined by
the ellipse from Figures 1b and 1d of S00. The observed distribution of material corresponds
with the features first reported by R96, and also with the “cavity material” speculated by
S00. Confidence that this is scattered light from material inward of the ring is boosted by the
fact that the polarization angle measured in this region is roughly centrosymmetric with the
expected light source. Because this centrosymmetric vector measurement depends on four
images, and since the structures have been observed by the polarimeter on four occasions,
it is very unlikely that the structures inward of the ring in Figure 4.2 are the result of “AO
artifacts” as speculated in Krist et al. (2002). The simultaneous imaging method largely
eliminates the possibility that artifacts can be introduced by the varying PSF inherent
in all AO systems. Although the Q and U Stokes parameter images are obtained non-simultaneously, they are both constructed from simultaneous imaging techniques, and the only variations are of second order that follow as the square root of the variations from the number of photons measured in each pixel.

Using the WFPC2 mode of HST, Krist et al. (2002) imaged the ring, and the "gap" in position angle as well as the bright "arc" on the northern (forward scattering) side of the binary. However, they failed to image material inward of the ring that is presented in Figure 4.2. The object that was used as the PSF in their effort was LkCa15, which is known to have a disk through millimeter observations (Duvert et al. 2000), and in the near-IR (Figure 4.3). The degree to which this excess would confuse the Krist et al. (2002) reduction is unclear, as the polarization fraction for the disk around LkCa 15 is not well constrained and the optical properties of the disk remain uncertain. The fact that the polarimeter clearly resolves the disk around LkCa15 and both NICMOS and WFPC2 do not detect it, suggests the power of AO imaging on a large aperture telescope for high contrast imaging using the dual imaging technique.

**Bright Inner Region**

First discovered by Potter et al. (2000a), and noted by Krist et al. (2002), a polarized surface brightness in close proximity to the central stars is detected. Further evidence that this is real scattered light is that the polarization vectors on the Northern portion of the ring are consistent with a scattering source that is North of GG Tau Ab, indicating secondary scattering from material in this region. The Southern region around GG Tau Aa also shows a polarized intensity excess, but is at a low signal-to-noise ratio.

Although a number of explanations are possible, this material is most likely not part of the circumprimary disk around GGTau Ab as the tidal forces from GG Tau Aa would shortly disrupt this material. This material may be part of a transient tidal arm that extends into the ring of material as seen in models of circumbinary disk evolution (e.g. Bate 2000). The orientation of this bright region agrees with the models in that it is in line with
the binary pair. It could also be the result of scattering from material that is out of the orbital plane of the circumstellar and circumbinary disks.

4.1.6 Time Variability of the Scattering Profile

With full polarization datasets obtained on four different nights, changes in the polarization intensity image which may trace the changes in the disk illumination source caused either by moving accretion hot spots or by optically thick shadowing material in close proximity to the light source (Wood et al. 2000). Figure 4.4 shows the four polarized intensity images taken on the four different nights. The first and last nights are separated by over a year. Because only February 3, 2002 was photometric, each polarized intensity image was normalized to a combination of ten high signal-to-noise ratio regions around the ring so an accurate relative comparisons can be made.

The polarized intensity varied between the dates GGTau was observed. In particular, the eastern portion of the ring changes between the December 21, 2000 and February 24, 2001 with fluctuations of about 25%±5% based on the standard deviation of the polarized intensity in each of the individual nights' data sets. The time sampling is not sufficient to trace a continuous motion of polarized intensity variation in PA around the disk. The polarized intensity within 0".2 from the central binary varies as well, however these variations are at the 1-2 σ level of significance considering the larger photon noise in this region, and a greater sensitivity to the image alignment and calibration errors.

4.1.7 Dust Scattering Constraints

The polarized intensity was extracted as a function of the scattering angle from the data to compare to Mie scattering models. The scattering angle was obtained by assuming the geometry of the ring using the relation between the scattering angle (θ_{scat}) and the position angle (θ_{PA}) for a flat disk of inclination θ_{incl}.

\[ \theta_{scat} = \tan^{-1}(\cot(\theta_{incl}) \csc(\theta_{PA})) \]
The Mie scattering model uses the numerical method from Bohren & Huffman (1983) to calculate the amplitude scattering matrix for given values of the index of refraction, size of scattering particles and wavelength. For this effort, the total scattering from the disk is produced by integrating the dust size over a given power law size distribution \( dN(R) \propto R^{-(p+1)} \) with upper and lower dust size cut-offs \( R_{\text{max}} \) and \( R_{\text{min}} \). The dust index of refraction from Mathis & Whiffen (1989) was used. A least squared method was then used to find the maximum and minimum dust sizes, as well as the power law index for their size distribution, by minimizing the difference between the measured and observed polarization amplitude profiles (Figure 4.5). As in Potter et al. (2000b), the assumption is made that the observed scattering is primarily single scattering off the thin shell of the optically thick ring. This assumption is based on the results of Wood et al. (1999) who found the average number of scatters before exit to be 1.2. The ring geometry was taken into account by limiting the polarized intensity measurements used in the comparisons to a narrow ellipse resulting from an inclination of \( i = 37^\circ \). Models using steep power law indices \( (p \sim 4.5-5.0) \) and maximum grain sizes no larger than 1 \( \mu \text{m} \) resulted in the best fits. The worst fits to the data occurred with low values of the power law index \( (\sim 2) \), and with high values of the maximum dust size \( (R_{\text{max}} > 2 \mu \text{m}) \) which cause the forward side of the disk to be much brighter than the back side. The value of the minimum dust size is an insensitive parameter in fitting the data, as long as this size is significantly lower than the H-band wavelength. Although there are a large number of parameters that can create the measured profiles within the degree of uncertainty in the illuminating source and density, the least-squared minimization exercise supports the conclusion from previous work (Close et al. 1998; Wood et al. 1999; Krist et al. 2002) that the disk as seen in the near-IR is dominated by smaller particles with a steep power law size distribution with \( R_{\text{max}} < 1 \mu \text{m} \).
4.2 SR24N/S: Possible evidence for disruption

Recent simulations of a star-forming, collapsing, molecular cloud (Bate et al. 2002; Bonnell 1999) illustrate the significant role that dynamical interactions play in the star formation process. The gravitational perturbations of passing stars can both induce more star formation by creating circumstellar density enhancements and halt the accretion process by stripping young stars of their mass reservoirs. The disruptions of circumstellar disks will increase the rate of mass accretion onto the central star, feeding the mechanisms which generate outflows (Reipurth & Bally 2001). In turn, these dynamically triggered outflows can provoke further perturbations on the circumstellar environment (Reipurth et al. 1996; Raga & Canto 1996). With most, if not all, stars forming in rather crowded cluster environments, the interactions between young stars and/or multiples must be considered to build a complete picture of the formation and evolution of stars, brown dwarfs, and planets.

The observational evidence supporting the hypothesis that dynamical interactions influence circumstellar disks is based on studies of anomalies in a few individual cases, including β Pic (Kalas et al. 2000, 2001) and the silhouetted disks in Orion (McCaughrean 1996). A non-negligible fraction of observed circumstellar disks shows signatures of warping that can be explained by a close encounter with a passing star (McCaughrean 1996). The 7° tilt of the Solar System relative to the orbital plane of the Sun and the high eccentricities of the outer Kuiper Belt objects may be results of such a close encounter (Ida et al. 2000). Despite a large body of theoretical work predicting the effects that perturbing gravitational sources might have on the formation of stars and circumstellar disk evolution, there are no reported observational examples of the interaction process where young stars are caught in the act of such a close encounter (Barsony et al. 2002).

The triple star system SR 24 (RoxR1-35, Haro 1-3) has been reported to have a number of characteristics typical of classical T Tauri stars with active accretion disks, including: Hα emission and Li absorption (Martín et al. 1998); the presence of cool dust (Reipurth et al. 1993; Greene et al. 1994; Nuernberger et al. 1998); and L-band excess (Chelli et al.
1995). Nuernberger et al. (1998) measure excess mm emission from SR 24 S consistent with a $0.035M_\odot$ circumstellar disk, and place a $0.003M_\odot$ upper limit on the mass of any disk around SR 24 N(ab). Both stars are noted to have similar 10 $\mu$m excesses, indicating the presence of dust within a few AU of their photospheres.

In this section, the high resolution images of SR 24 N(ab)/S and their circumstellar environments are presented from both ground-based Gemini Telescope adaptive optics (AO) polarimetric imaging and archival Hubble Space Telescope (HST) optical images. Possible dynamical mechanisms which could generate the observed circumstellar morphology are also presented.

### 4.3 Observations and Data Reduction

The polarimetric data were obtained in 2001 June using the polarimeter. The optical light from SR 24 S ($V \sim 15$) was used for AO wavefront correction, producing FWHM $\sim 0^\prime 085$ $H$-band images with a Strehl ratio of 10% in the FWHM $\sim 0^\prime 7$ natural seeing conditions encountered during the observations. As pointed out in Chapter 2, the accuracy of the flat-field calibration can determine the polarimetric precision, requiring our flat-field images to have $\sim 10^7$ photons/pixel. Incrementally increasing exposure times were used to calibrate the pixel response linearity and ensure that our data remained unsaturated. The UKIRT faint standard star FS137 was observed to calibrate the polarized surface brightnesses in the images.

Two H-band polarization datasets were obtained, with each set consisting of $5 \times 20$ s exposures taken at each of the 4 half-waveplate positions ($0^\circ$, $22.5^\circ$, $45^\circ$, $67.5^\circ$), for a total exposure time of 800 s. Although only 2 half-waveplate positions are needed to construct the linear Stokes parameters, 4 rotations were obtained to accommodate the double-subtraction data reduction technique.

To accurately measure the polarization of any circumstellar material, the non-zero polarization of the unresolved stellar light must be removed. Two polarized intensity ($PI$)
images were created by properly subtracting the polarization signal of the unresolved light from SR 24 N(ab) ($PI_N$), and similarly for SR 24 S ($PI_S$). The final $PI$ image, shown in Figure 4.7, was weighted to represent the scattered light from the circumstellar material and not the unresolved polarized star light as follows:

$$PI = \frac{\left(PI_N \frac{d^2}{d_N^2} + \Psi PI_S \frac{d^2}{d_S^2}\right)}{\left(\frac{1}{d_N^2} + \frac{\Psi}{d_S^2}\right)}$$ (4.1)

with $d_N$ and $d_S$ the radial distances from SR 24 N(ab) and S, respectively, and $\Psi$ ($\approx 1.8$) the intensity ratio between the sources.

The $HST$ WFPC2 images of SR 24 N(ab)/S were obtained in 1999 May as part of the Cycle 7 Program #7387. Three images in the wide-$V$ filter (F606W) were weighted by exposure time and combined with a median filter to minimize residual cosmic rays. The SR 24 system falls entirely within the PC chip, which has a resolution of $0''045$ per pixel.

4.3.1 Analysis and Discussion

The collection of images in Figure 4.7 displays the intriguing morphology of SR 24 N(ab)/S, characterized by a number of filamentary features extending from both components. A bridge of material between SR 24 N(ab) and S is detected in both the Hokupa'a $H$-band $PI$ and the $HST$ optical images, shown on the right and the left of Figure 6, respectively. This bridge extends from SR 24 N(ab) at a position angle (PA) of $\sim 80^\circ$, approximately the position angle of the resolved companion (Simon et al. 1995), at a separation of $0''1$. However, within $3''$, the bridge turns toward SR 24 S and, at $\sim 1''$ south of SR 24 N(ab), expands and bifurcates into two filamentary structures. The bridge material approaches SR 24 S at an offset from the stellar photo-center, marked by the shorter exposure stellar image superimposed on the masked saturated region. From the centrosymmetry signatures seen in the polarization angle map in Figure 6, it is apparent that the bridge material closest to
the northern component is illuminated by SR 24 N(ab) and, likewise, the bridge material closest to the southern component is illuminated by SR 24 S. Therefore, this bridge is not a chance alignment of isolated components, but rather material which physically spans the space between SR 24 N(ab) and S. To the north of SR 24 N(ab), the $PI$ image shows an extension of scattered light at $PA \sim 354^{\circ}$ stretching $3''$ to the north. This feature is not collimated and cannot be attributed specifically to either SR 24 Na or b.

The scattered light morphology around SR 24 S exhibits elliptical $PI$ isophotes centered on the star with a 2:3 axis ratio and major axis at $PA = 160 - 340^{\circ}$. The western side of this region reveals a $PI$ minimum and deviations from the centrosymmetric polarization angles. This signature is consistent with optically thick scattering from a relatively high inclination angle ($i \sim 60^{\circ}$) circumstellar disk. The mm excess of SR 24 S quoted by Nuernberger et al. (1998) can account for such a near-IR thick-disk density. A likely scenario is that the elliptical shaped isophotes trace the $\tau = 1$ surface of the "top" of an optically thick disk along the line of sight. A diffuse lobe of light-scattering material extends from SR 24 S at $PA \sim 70^{\circ}$, which is coincident with a collimated feature in the $HST$ image, described below in §3.1. Less prominent, smaller radial extensions from SR 24 S are seen at PAs of $125^{\circ}$ and $210^{\circ}$. About $15^{\circ}$ south of the $210^{\circ}$ extension is another radial arm which seems to connect with the material seen in the larger field of view $HST$ image. This arm extends almost due south of SR 24 S for $\sim 4''$ and fans out into a fainter, yet structured, morphology. This extension breaks into three distinct filaments on top of a diffuse background about $5''$ south of SR 24 S.

Scenario 1: Complex Outflow Environment

Curved structures similar to those around both SR 24 N(ab) and S have been identified around other classical T Tauri stars (Grady et al. 2001), and are particularly common around FU Orionis objects (Goodrich 1987). A firm explanation for such structures has yet to be presented in the literature. These morphologies are not necessarily the result of
accretion-driven outflows, but are likely indicators of some form of mass-loss from winds and/or jets.

In Figure 4.8 the difference between the HST image shown in Figure 4.7 and the same image convolved with a gaussian of width 20 pixels (0.9) is shown. The resulting image enhances high spatial frequency features. It exhibits a collimated feature emanating from SR 24 S at PA ~ 70°. This feature is not coincident with any diffraction spikes and is not associated with any known HST PSF anomalies. The Hokupa’a PI image in Figure 4.7 shows a similar feature at the same PA, yet fainter and at a greater radial distance (as discussed in the previous section). If this is the same feature seen at different times, the velocity of the feature would be about 200 km s\(^{-1}\). Based on this morphology, the inferred velocity, the orientation of the feature relative to the elliptical isophotes (roughly perpendicular), and the presence of a number of bow shocks in the vicinity (Gomez et al. 1998), I interpret this feature as a Herbig-Haro (HH) jet driven by SR 24 S, perhaps confirming the suggestion of Reipurth et al. (1993).

At the same time, however, the orientation of this jet feature detracts from the possibility that the observed circumstellar morphology is caused by a destructive outflow. Rather, any outflow activity is more likely a consequence of whatever physical mechanism is responsible for generating the appearance of the environment. In fact, Reipurth & Bally (2001) and others suggest that HH objects are the products of bursts of outflow activity resulting from increased mass accretion caused by circumstellar disk disruption from a dynamical interaction.

Scenario 2: Very Young, Semi-Bound Triple System

One such dynamical situation is that the SR 24 N(ab)/S system is in the formation process, where the northern binary pair has coalesced from the spiral density wave enhancement in the circumstellar disk around SR 24 S, as described by Bonnell (1999). However, this scenario requires a large mass reservoir to continually feed the spiral arms, which is implausible given the relatively low optical extinction. Even so, the system is seen in
the foreground of the dark cloud L1688 and may have recently been ejected from it. In this case, SR 24 N(ab) would have formed after SR 24 S. Although the ages of the stars are not well-constrained, published spectral types and luminosity estimates (Greene et al. 1994; Martín et al. 1998; Luhman & Rieke 1999) can be used in conjunction with theoretical pre-main sequence evolution models (Siess et al. 2000) to infer an age range for SR 24 S ($L \sim 2.4L_\odot$, K7-G7) of $7 \times 10^5 - 7 \times 10^6$ yrs and for SR 24 N(ab) ($L \sim 2.3L_\odot$, M2-K5) of $6 \times 10^4 - 1.2 \times 10^6$ yrs. Although the errors are consistent with the two components having the same age, all models compute a younger relative age for SR 24 N(ab), which is compatible with the formation of a multiple system.

Scenario 3: Unbound Close Gravitational Encounter

The observed circumstellar morphology of SR 24 N(ab)/S is also similar to those produced in simulations of unbound, close dynamical encounters between young stars with circumstellar disks (Bate et al. 2002; Larwood 1997). In particular, the symmetric, curved extensions on the western side of SR 24 N(ab), the bridge between the two stars, and the tail of material extending to the south of SR 24 S are strikingly consistent with the signatures produced in such simulations.

Circumstellar disks should be influenced to some degree by stellar encounters during the two-body relaxation of the star-forming cluster (Scally & Clarke 2001; Larson 2002). In the rough limit of dynamical interactions between $N$ equal-mass point sources, the relaxation timescale of a cluster,

$$t_{relax} \sim (2 \times 10^6) R_{pc}^{3/2} \frac{N^{1/2}}{\ln N} \text{ yrs}$$

(4.2)

is of the same order of magnitude as the inferred lifetimes of optically thick circumstellar disks ($t_{disk} \sim 10^6 - 10^7$ yrs) (Brandner et al. 2000) for clusters with typical parameters (e.g. $R \lesssim 3$ pc and $N \lesssim 10^3$). The significant stellar velocity gradients induced by close gravitational encounters over this timescale will undoubtedly perturb any existing circumstellar disks (Clarke & Pringle 1991; Larwood 1997; Larson 2002; Bate et al. 2002).
Possible effects on these disks range from truncation, tilting, and warping to partial dissipation through short-lived tidal tails similar to those seen in merging galaxies. Models accounting for evolution in clustered environments predict that such interactions will produce density perturbations within the disks, triggering the formation and subsequent ejection of brown dwarf embryos (Bate et al. 2002). Additionally, the tidal disruption incurred on the disks will increase the mass accretion rate for a brief period as angular momentum is exchanged between the two disks (Larwood 1997; Larson 2002). This increased accretion would, in turn, explain the strong Hα emission, quoted as W(Hα)=73Å by Martín et al. (1998), and the collimated structure we interpret as a jet in §3.1. We have compiled published astrometric measurements of SR 24 N(ab)/S from 1958 Palomar Sky Survey data (Wilking et al. 1987) up through the 2001 Hokupa’a data to determine if proper motions can distinguish between bound and unbound scenarios. Unfortunately, the errors associated with the oldest measurements prevent us from making any conclusive statements on the matter. Martín et al. (1998) do not report any notable relative radial velocity difference between SR 24 N(ab) and S at the estimated ~10 km s⁻¹ maximum sensitivity to such measurements.

4.4 Summary

1. The observations of GG Tau and SR 24 N/S demonstrate that the dual imaging polarimetry technique successfully suppresses speckle noise and PSF variability which is the primary problem in high dynamic range imaging for the detection of polarized, scattered light from circumstellar disks.

2. We imaged the circumbinary disk of GG Tauri Aab at a much improved signal-to-noise ratio than previous measurements. These observations, undeniably confirm the PA gap in the circumbinary ring previously speculated to exist from HST observations, a “clumpy” ring structure with a non-elliptical inner ring edge, and material seen at angular heliocentric radii inward from the ring defined by millimeter observations.
3. A comparison of the polarized intensity images taken over a year baseline reveal statistically significant changes between observing nights. These changes are too fast to be associated with the orbital motion of the material, and are likely due to changes in the illumination source caused by shadowing from faster moving material in close proximity to the central stars.

4. The first resolved near-IR observations the circumstellar disk around the CTTS, LkCa 15, were presented in Figure 4.3.

5. High-resolution polarimetric $H$-band and optical images of the circumstellar environment around the triple classical T Tauri star SR 24 N(ab)/S reveal a complicated morphology which may be indicative of the mutual gravitational disruptions of circumstellar disks caused by either bound or unbound dynamical interactions.

6. A high spatial frequency, collimated feature is found extending from SR 24 S, which is interpreted as a jet.

7. Follow-up high resolution spectroscopy is recommended to measure any relative radial velocity difference between SR 24 N(ab) and S which may differentiate between the stars being in a bound or unbound configuration to confirm or disprove the notion that the objects are undergoing a one-time close encounter. Additionally, narrowband imaging of shocked emission lines (e.g. H$\alpha$ or [S II]) could serve to confirm the suggested presence of an HH jet from SR 24 S, as well as the possibility of shock-heated gas from a dynamical interaction.
Figure 3.8 The H-band surface brightness, polarized surface brightness, and polarization amplitude images of the known dust populations in our solar system are shown as calculated from Mie scattering Mathis-type grains. To illustrate the effects of the anisotropic scattering resulting from Mie theory, images are shown for three different viewing inclination angles (15°, 50°, 75°). The radial profiles from these model images are shown in Figures 3.9 through 3.12.
Figure 4.1 The final combination of the entire data set shows the circumbinary disk with the gap at position angle 270° (referenced to GG Tau Aa). Note the large number of centrosymmetric vectors measured interior of the well defined ring. The lines normal to the polarization vectors on the north side of the disk converge to a point just North of the GG Tau Ab, a possible multiple scattering effect from the material found between the ring and GG Tau Ab. The same converging point for the vectors on the south side of the disk is consistent with GG Tau Aa as the scattering light source.
Figure 4.2 The same as Figure 4.1 except with the $3\sigma$ signal-to-noise ratio mask applied to the image. Note that there are regions interior to the ring that survive the mask. In particular, the bright structure to the North of GG Tau Ab and the surrounding, fainter filamentary structures are significant detections with measured polarization vector angles that are centrosymmetric about the binary illumination source.
Figure 4.3 The disk around LkCa 15 is clearly seen in individual sets of 20x15sec exposures of polarimetry data. This image is the result of a combination of 3 complete sets of 20x15sec exposures, each taken with different field rotation angles. The orientation of the major axis of the disk (PA=60°) corresponds to that found in the submillimeter (Duvert et al. 2000). A full analysis of the polarimetric data will be discussed in an upcoming paper.
Figure 4.4 The polarized intensity images from each of the four nights GG Tau was observed are compared to reveal any possible time variable phenomena in the scattering profile. The amplitude varies as much as 25%±5% between the different nights the observations were taken. This rapid variation is most likely the result of a varying illumination source caused by material orbiting inbetween the stars and the ring, as the orbital motion of the ring is far too long to account for the variations.
Figure 4.5 The measured polarized intensity (intensity x linear polarization amplitude) as a function of scattering angle is plotted (solid line and diamonds) with the best least-squares fit from the Mie scattering model. The best fits resulted from steep power laws (3.7 - 5.5) with maximum particle sizes limited to grains less than ~ 1 \( \mu \)m in size. The presence of a larger number of grains > 1 \( \mu \)m produces a greater contrast of the polarized intensity between the front and the back of the disk than measured.
Figure 4.6 The first resolved detection of a disk around GG Tau Ba is shown. The disk radius measured from the semi-major axis is $0\farcs6$ on the Northwest side and $0\farcs9$ on the Southwest side. The apparent structure that seemingly bridges GG Tau Ba and GG Tau Bb is at the 1-2 $\sigma$ signal-to-noise ratio level, and like the disk, needs to be confirmed with more sensitive observations.
Figure 4.7 The high resolution (FWHM ~ 0.075) HST WFPC2 image of SR 24 N(ab)/S in the F606W filter is shown on the left, with a surface brightness scale in mag arcsec$^{-2}$. The H-band PI image (FWHM ~ 0.085) is shown on the right, with a similar surface brightness scale. The regions within 0.2 of the stellar photocenters were saturated in this data. Intensity images showing SR 24 N(ab) as a 0.1 binary and SR 24 S as a single star have been overlayed on these masked-out saturated regions. The overlaid polarization vectors are the results of binning by 0.2.
Figure 4.8
An apparent HH jet from SR 24 S is revealed by using a high-pass spatial frequency to the HST image. This collimated feature extends 2" from SR 24 S at PA~70° and is clearly offset from any HST diffraction spikes. The feature has a knotty morphology with non-uniform surface brightness.
References


Potter, D., Baudoz, P., Brandner, W., Close, L., Graves, B., Guyon, O., & Northcott, M. 2000a, BAAS, 197, 91.05


Reipurth, B. & Bally, J. 2001, ARA&A


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In this chapter, the adaptive optics dual channel polarimeter's high contrast imaging capabilities are used to search for debris disks around solar analog stars. Although the sensitivity to detecting scattered light from circumstellar material is impressive, a comparison between the detection limits in Chapter 2 with the models of solar system dust in Chapter 3 shows that the sensitivities are insufficient to check even the nearest stars to see if they harbor dusty debris disks with surface densities found in our current solar system.

However, the early solar system was most likely much dustier than it is today. The cratering rates measured on the Moon’s surface imply that about 400-800 Myr after the moon formed, or about 4.1-3.7 Gyr ago, the Moon’s impact rate was as much as 1000 times higher than today (Tera et al. 1974), marking an era referred to as the late heavy bombardment (LHB). Analysis of the cratered surfaces of other satellites and planets in the solar system further suggest that the the LHB era was a phenomena not confined to the vicinity of the Earth’s orbit, but was widespread throughout the solar system (Strom 1987).

There have been many efforts investigating the impact that the LHB would have on the development of life, considering that the end of the LHB corresponds to the time for the first evidence of life on Earth. A massive influx of volatiles from infalling comets during the LBH could have significantly altered the composition of the Earth’s atmosphere, possibly
providing the organic material which led to the formation of life after the violence of the LBH subsided (Fegley et al. 1986; Melosh & Vickery 1989; Chyba 1990).

Regardless of the influence the LBH may have had on our existence, such an event in a young solar analog star may make them easier to detect. As pointed out in chapter 3, dust production is a function of the collision rate, so it is expected that the LHB would result in a considerable increase of dust production ($\eta_+$) in the stellar environment. If the destruction mechanisms ($\eta_-$) stay the same, the amount of dust would correspondingly rise, along with the total scattering cross section $\tau_{sca}$. Depending on the severity of the rise in collision rates, the potential is there for the debris disk surface brightness to become orders of magnitudes brighter than the present, making them detectable with the dual imaging polarimeter.

So, based on the evidence from of our solar system at an earlier age, one would consider it possible that solar analog stars less than 1 billion years old would be statistically dustier, and easier to detect compared with older solar-type stars. A comparison with the solar system debris disk models from chapter 3, to the polarized intensity detection limits measured from chapter 2, shows that a dust density increase by just a factor of $\sim 100 - 300$ would make debris disks around solar analog stars within $D < 25pc$ detectable using the dual imaging technique. With the expected LHB duration $\sim 10 - 100Myr$, compared with the accuracy with which we can distinguish a young solar type star, $< 1Gyr$, a survey of 10-100 stars has a favorable probability of detecting at least one star undergoing an era analogous to the LHB in our solar system.

IRAS measurements of a sample of young solar analog stars Gaidos (1999) were sensitive to the $a \sim 10 - 100\mu m$ dust to a level $> 1000$ times the surface density found in our inner solar system. One star, HD 128400, was found to have infrared excess corresponding to levels of $\sim 7000$ times that of our solar system. Unfortunately, this star is too far south to observe from Mauna Kea to confirm with the polarimeter. The other stars in the sample did not have infrared excesses detected by IRAS.
Although the sample stars do not have IRAS detected infrared excess, this does not mean they do not have debris disks that would be detected by the Hokupa'a-Gemini dual imaging polarimeter. Small dust grains \( (a < 10\mu m) \) cooler than 300K do not efficiently radiate thermally. However, they do efficiently scatter near-IR light. So detecting dust via scattered light is more effective when the dust sizes are smaller than the wavelength of light characteristic of the temperature to which the star can heat the dust. Therefore, the dual imaging polarimeter is more sensitive (by about an order-of-magnitude) than detecting debris disks that have dust populations similar to the solar system model from Chapter 3. Moreover, because detection is based on scattered light, the polarimeter is sensitive to dust detection at larger radii than the temperature dependent Mid-IR observations. Thus, it is worthwhile to carry out a survey of these young solar analog stars with the polarimeter to search for the scattered light signature of debris disks.

### 5.1 Survey Sample

The age of main sequence stars is difficult to determine with any accuracy, but a number of indicators are thought to be associated with stars with ages less than 1 billion years old. These younger stars are thought to have faster rotation rates, increased X-Ray luminosity, distinct space motions associated with young clusters, Calcium H-K emission, and photospheric Lithium as determined from optical spectra. A sample of solar type stars with spectral types between K1V-G0V exhibiting these characteristics are compiled in Gaidos (1998), and further studied in a series of papers (Gaidos 1999; Gaidos et al. 2000; Gaidos & Gonzalez 2002). These stars are selected to be single stars within 25 pc as measured from the Hipparcos satellite (Perryman et al. 1997) so they are ideal candidates for high resolution studies. The list of Gaidos sample stars observed with the polarimeter is shown in table 1 with their physical properties.
Table 5.1 Survey Sample of Young Solar Analog Stars

<table>
<thead>
<tr>
<th>Star</th>
<th>Spec. Type</th>
<th>$T_{\text{eff}}$</th>
<th>Distance (pc)</th>
<th>Observation Date</th>
<th>$M_{\text{dust}}$ 1 - 10$\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 1835</td>
<td>G3V</td>
<td>5675(60)</td>
<td>20.38</td>
<td>Dec 10, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 7590</td>
<td>G0V</td>
<td>5940(75)</td>
<td>23.64</td>
<td>Dec 10, 2001</td>
<td>$2 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 10008</td>
<td>G5V</td>
<td>5415(50)</td>
<td>23.61</td>
<td>Dec 10, 2001</td>
<td>$3 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 10780</td>
<td>K0V</td>
<td>5295(40)</td>
<td>9.98</td>
<td>Oct 2, 2000</td>
<td>$4 \times 10^{-2}$</td>
</tr>
<tr>
<td>HD 11131</td>
<td>G0V</td>
<td>5700(60)</td>
<td>23.00</td>
<td>Oct 2, 2000</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 37394</td>
<td>K1V</td>
<td>5295(47)</td>
<td>12.24</td>
<td>Dec 10, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 41593</td>
<td>K0V</td>
<td>5296(66)</td>
<td>15.45</td>
<td>Dec 10, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 63433</td>
<td>G5IV</td>
<td>5763(74)</td>
<td>21.82</td>
<td>Feb 20, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 72760</td>
<td>G5V</td>
<td>5332(53)</td>
<td>21.76</td>
<td>Feb 24, 2001</td>
<td>$2 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 72905</td>
<td>G1.5VB</td>
<td>5850(70)</td>
<td>14.27</td>
<td>Feb 24, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 73350</td>
<td>G0V</td>
<td>5743(43)</td>
<td>23.63</td>
<td>Dec 10, 2001</td>
<td>$2 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 82443</td>
<td>K0V</td>
<td>5250(est)</td>
<td>17.75</td>
<td>Dec 17, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 109011</td>
<td>K2V</td>
<td>5207(72)</td>
<td>23.74</td>
<td>Dec 17, 2001</td>
<td>$2 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 113449</td>
<td>GV5</td>
<td>5287(78)</td>
<td>22.12</td>
<td>April 28, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 116956</td>
<td>G9IV-V</td>
<td>5380(52)</td>
<td>21.85</td>
<td>Feb 24, 2001</td>
<td>$2 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 128987</td>
<td>G6V</td>
<td>5539(51)</td>
<td>23.57</td>
<td>Jun 22, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 130948</td>
<td>G1V</td>
<td>5832(50)</td>
<td>17.94</td>
<td>Feb 24, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 135599</td>
<td>K0V</td>
<td>5300(48)</td>
<td>15.58</td>
<td>Feb 03, 2002</td>
<td>$6 \times 10^{-2}$</td>
</tr>
<tr>
<td>HD 152391</td>
<td>G8V</td>
<td>5418(51)</td>
<td>16.94</td>
<td>April 19, 2001</td>
<td>$5 \times 10^{-2}$</td>
</tr>
<tr>
<td>HD 165185</td>
<td>G5V</td>
<td>5681(77)</td>
<td>17.37</td>
<td>April 19, 2001</td>
<td>$8 \times 10^{-2}$</td>
</tr>
<tr>
<td>HD 180161</td>
<td>G8V</td>
<td>5464(58)</td>
<td>20.00</td>
<td>July 27, 2000</td>
<td>$2 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 206860</td>
<td>GOV</td>
<td>5900(103)</td>
<td>18.39</td>
<td>Sept 19, 2001</td>
<td>$1 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 217813</td>
<td>G5V</td>
<td>5825(50)</td>
<td>24.28</td>
<td>July 9, 2000</td>
<td>$2 \times 10^{-1}$</td>
</tr>
<tr>
<td>HD 220182</td>
<td>K1V</td>
<td>5279(69)</td>
<td>21.92</td>
<td>Dec 10, 2001</td>
<td>$2 \times 10^{-1}$</td>
</tr>
</tbody>
</table>
5.2 Observations and Data Reduction

The observations were obtained at the Gemini North Telescope using the dual imaging polarimeter described in chapter 2 over a range of nights between July 2000 and February 2002. The total exposure time for each object listed in table 1 was greater than ~ 5 minutes. The data reduction procedures outlined in chapter 3 were followed. However the data were binned in order to increase signal to noise at the expense of spatial resolution.

The systematic errors associated with the flat field calibration and the differential optical aberrations determine the sensitivity for the detection of polarized surface brightness in high contrast. The component of the systematic errors with smaller scale sizes can be minimized by binning the Stokes parameter data, increasing the signal to noise for detection. A selection of bins that are not centrosymmetric, and/or too big could decrease the polarization signal. To avoid this signal degradation, a total of 20 radial regions centered on the stellar photocenter were defined with widths of $0''2$ between radial separations $0''2$ and $2''$. Each of these radial regions were further analyzed over 120 evenly distributed, but overlapping, position angle bins each 10 degrees wide. A binned image is created with new pixel values equal to the average of the Stokes parameter images of the bin centered on the pixel. To calculate the radial profile of the polarized surface brightness, $Q$ and $U$ were averaged over the pixels contained in the given bin before forming the polarized intensity, or,

$$PI_{avg} = \frac{\left(\sum Q_i^2 + \sum U_i^2\right)^{1/2}}{N_{tot}} \quad (5.1)$$

The average using the sum of the polarized intensity values calculated for each pixel, or

$$PI_{avg} = \frac{\sum \left((Q_i)^2 + (U_i)^2\right)^{1/2}}{N_{tot}} \quad (5.2)$$

essentially fixes the errors at the level for single exposure times and for single pixels.
As outlined in chapter 3, the cassegrain rotator was used to rotate the field relative to the polarimeter calibration axis in order to reduce the systematic errors associated with the flat field errors and the differential optical aberrations. After the field rotation, the $Q$ and $U$ Stokes parameters are then transformed back to the normal field orientation through the transformation,

$$
\begin{pmatrix}
    I' \\
    Q' \\
    U' \\
    V'
\end{pmatrix} = \frac{1}{k^2r^2}
\begin{pmatrix}
    1 & 0 & 0 & 0 \\
    0 & \cos 2\phi & \sin 2\phi & 0 \\
    0 & -\sin 2\phi & \cos 2\phi & 0 \\
    0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
    I \\
    Q \\
    U \\
    V
\end{pmatrix}
\tag{5.3}
$$

With Stoke’s parameter values representing the same calibration angle, data sets taken with different field rotations can be averaged according to equation 1 to further reduce systematic errors associated with fixed positions relative to the PSF.

### 5.3 Survey Sensitivity

Searches for circumstellar disks around bright stars using non-polarimetric techniques are faced with the problem of distinguishing the variable PSF halo from the real signal of a circumstellar disk. Because the radial profile of the PSF surface brightness falls off in a similar fashion as that expected from a circumstellar disk, it is not surprising that there have been a number of disks mistaken to be real, when in fact they are PSF artifacts (e.g. 55 CNC and Iota Hor). Polarimetry offers a robust method for confirming the presence of a disk because of the unique, position angle dependent (as opposed to the radial profile) signature produced from a single scattering dominated disk.

After the Stokes $Q$ and $U$ images are formed by properly averaging the data sets, the final images and radial surface brightness profiles can be examined for signal. The non-gaussian noise characteristics of the data make the determination of significant detections more difficult to define. Because of the multiplicative nature of the systematic errors due to
the flat field and differential optical aberrations, it is desirable to identify useful quantities from the polarimetry data based on a division between two parameters which would be insensitive to these errors. Both the polarization amplitude and the polarization angle ($\theta$) are based on division between Stokes quantities. The polarization amplitude is corrupted by the overwhelming and non-uniform light from the PSF making it a confusing parameter to use. Fortunately, $\theta$ is formed from PSF subtracted $Q$ and $U$ parameters, and, there is a distinct signature of the image of the measured polarization angle values resulting from single scattering environment illuminated by a central source. The calibration of $\theta$ was first obtained in the standard way by observing polarization standard stars. Using this angle calibration measurement, observations of the CTTS TW Hydrae revealed that the polarization map was almost perfectly what would result from a nebulosity illuminated by a single central source. These sources have polarization angles which are normal to the illuminating source and referred to as a “centrosymmetric” scattering pattern. Under the assumption of centrosymmetric scattering, the angle calibration can be found to a higher accuracy by using all $\theta$ values around the illuminating source rather than just one angle.

Once the polarization angle was calibrated, each source can be checked for continuous regions of centrosymmetric scattering. Examples of easily detected, high signal-to-noise CTTS disks are shown in figures 1-3. The analysis procedure is carried out on a star that is likely not to have any measurable excess polarized intensity, a distant star used as an unpolarized standard. This check for a centrosymmetric pattern and a measurement of the residual polarized surface brightness is carried out for the sample of stars listed in Table 1. The results are presented in Figures 4-28. Although a couple stars in the sample exhibit signs of centrosymmetric scattering, there are not statistically different than the other stars in the sample based on the standard deviation of the bin amplitudes.

5.3.1 Model Comparisons

At the time the survey was conducted, the polarimeter operating with Hokukpa’a/Gemini was arguably the most sensitive instrument for the detection of dust through scattered
light observations, rivaling the sensitivity of the Hubble Space Telescope. However unlike conditions in space, atmospheric seeing and photometric conditions varied over the course of the 10 nights. Some observations were taken in non-photometric conditions; for others the natural seeing was poor and significantly affected the image quality after the AO system. Also, given that each star in the sample is at a different distance and that there is a range of intrinsic luminosities, the sensitivity for dust detection must be calculated separately for each object.

Through a comparison between the observed residual radial polarized surface brightness profiles and those produced by the models, constraints on the dust population can be made. As shown in chapter 3, the isotropic scattering model is a conservative approximation of the polarized surface brightness profile relative to Mie scattering models as long as the dust sizes used in the models are small compared to the observed wavelength. From fitting the models to the residual polarized surface brightness profiles, it is found that the $1 - 10\mu m$ dust content around these stars can be constrained to be less than $M_{dust} < 10^{-2}M_{Moon}$. While this appears to be a very small amount of dust, these levels are on the order of 100-300 times that found in our present day solar system. These results also confirm that the survey is sensitive to dust densities expected during heavy bombardment eras.

To develop confidence in the model comparisons, model disks were inserted into each frame of the data set and taken through the entire data reduction procedure. It was found that a noticeable increase in the polarization signature can be significantly measured for disks with surface densities around 100-300 times that found in the present day solar system for the entire sample.

5.4 Discussion

It is worth emphasizing that the constraints on the dust are not constraints on the total mass of the debris disks. As pointed out in chapter 3, the lifetime of dust which scatters light efficiently is small. If the dust production mechanism produced a steep power law such
than most of the mass was in smaller grains, this disk would have a disk lifetime on the order of the small grains, which is small. If most the mass of the debris disk was contained in these small grains, then the disk would be short lived.

Debris disks around these stars may have eluded detection because of relatively large mass loss rates from their stellar winds. As mentioned in Chapter 3, recent measurements of Ly α emission from the interaction of stellar winds with the interstellar medium indicate a correlation between X-ray luminosity and stellar wind mass loss rates (Wood et al. 2002). Because all the stars in the sample were selected to be young, partially based on having increased X-ray luminosity, these stars likely have stronger stellar winds with 100-1000 times the mass loss rates of the sun. This increased mass loss rate, would drastically shorten the dust lifetimes through the corpuscular version of the PR drag outlined in section 3. This effect would counterbalance the increased dust production caused by a LHB episode. With a preferential removal of smaller dust particles, the solar wind may reduce $\tau_{\text{sc}}$ in these young debris disks by more than an order of magnitude.

5.5 Conclusion

23 young, nearby solar analog stars were observed using a high dynamic range polarimetric technique. While the observations did not definitively detect any circumstellar material around these stars, the survey excludes the possibility of the presence of dust at the level of 100-300 times that found in our current solar system in the range of 1 – 10µm.
Figure 5.1 The polarization diagnostics for the nearest CTTS, TW Hydrae is a near perfect example of a centrosymmetric scattering pattern from a circumstellar disk, with a 45 degree position angle shift between Q and U images in the upper panel. The rightmost pannel is a greyscale display of the deviation between the measured polarization angle and that produced from perfect centrosymmetric scattering. The plot on the left shows the radial profile of the polarized surface brightness. The right plot is a histogram of the number of bins at a given deviation angle from the centrosymmetric pattern. The verticle axis shows the fraction of total bins in the deviation range noted by the horizontal axis.
Figure 5.2 The polarization diagnostics for the CTTS, GG Tau shows a centrosymmetric pattern even within the more obvious ring of material as discussed in Chapter 4.
Figure 5.3 The polarization diagnostics for the CTTS, GM Aur shows another example of a centrosymmetric pattern.
HD 1835

Figure 5.4 Same as 5.1, but for young solar analog star HD 1835.
Figure 5.5 Same as 5.1, but for young solar analog star HD 7590.
Figure 5.6 Same as 5.1, but for young solar analog star HD 10008.
Figure 5.7 Same as 5.1, but for young solar analog star HD 10780.
Figure 5.8 Same as 5.1, but for young solar analog star HD 11131.
Figure 5.9 Same as 5.1, but for young solar analog star HD 37394.
Figure 5.10 Same as 5.1, but for young solar analog star HD 41593.
Figure 5.11 Same as 5.1, but for young solar analog star HD 63433.
Figure 5.12 Same as 5.1, but for young solar analog star HD 72760.
Figure 5.13 Same as 5.1, but for young solar analog star HD 72905.
Figure 5.14 Same as 5.1, but for young solar analog star HD 73350.
Figure 5.15 Same as 5.1, but for young solar analog star HD 82443.
Figure 5.16 Same as 5.1, but for young solar analog star HD 109011.
Figure 5.17 Same as 5.1, but for young solar analog star HD 113449.
Figure 5.18 Same as 5.1, but for young solar analog star HD 116956.
Figure 5.19 Same as 5.1, but for young solar analog star HD 128987.
Figure 5.20 Same as 5.1, but for young solar analog star HD130948.
Figure 5.21 Same as 5.1, but for young solar analog star HD 135599.
Figure 5.22 Same as 5.1, but for young solar analog star HD 152391.
HD 165185

Figure 5.23 Same as 5.1, but for young solar analog star HD 165185.
HD 180161

Figure 5.24 Same as 5.1, but for young solar analog star HD 180161.
Figure 5.25 Same as 5.1, but for young solar analog star HD 206860.
Figure 5.26 Same as 5.1, but for young solar analog star HD 217813.
Figure 5.27 Same as 5.1, but for young solar analog star HD 220182.
References


Strom, R. G. 1987, Icarus, 70, 517


Chapter 6
Companion Search around Young Solar Analog Stars

6.1 Introduction

The near-IR sky surveys and technological advances in high dynamic range imaging in the past decade have resulted in the discovery of a large number (~100) of very low-mass (VLM), ultracool objects. This has brought about spectral classification schemes (Burgasser et al. 2002; Geballe et al. 2002; Kirkpatrick et al. 1999, 2000; Martín et al. 1997, 1999b) attempting to organize and understand them in the same way as we understand main-sequence stars through the MK spectral classification scheme. However, the interpretation of physical parameters from the classification schemes is a more complicated exercise with ultracool objects as the lack of a sustained hydrogen burning core creates a degeneracy between mass and age as the luminosity fades in time. Also, the spectra of these objects are significantly affected by photospheric dust (Allard et al. 2001; Basri et al. 2000; Schweitzer et al. 2001) possibly introducing a weather-like time variable phenomenon (Bailer-Jones & Mundt 2001; Martín et al. 2001; Nakajima et al. 2000). The evolutionary models of VLM objects need to be mass calibrated in the same way stellar evolution theory was calibrated using the dynamical mass estimates of binary stars.

In recent years, there have been surveys using the high-resolution capabilities of HST (Martín et al. 1999a, 2000a; Reid et al. 2001) and of large ground-based telescopes (Close
et al. 2002; Koerner et al. 1999; Martín et al. 2000b) to look for companions to the known VLM objects. One goal of these searches is to build a sample of VLM binary systems for which accurate dynamical masses can be obtained. A handful of brown dwarf binaries are known, but only Gl 569B (Lane et al. 2001; Kenworthy et al. 2001), 2MASSW J0746425+200032 (Reid et al. 2001), and 2MASSJ 1426316+155701 (Close et al. 2002) have periods $\lesssim$10 years to accommodate a timely dynamical mass determination.

In this paper we add to the growing list of VLM ultracool binary systems. In a companion search around nearby, young (less than 1 Gyr), solar-type stars selected from the sample of Gaidos (1998), we found two brown dwarf companions next to the star HD 130948, and a low mass stellar object in close proximity to the star HD 72760. Section 6.2 outlines the observations, section 6.3 presents the photometric, astrometric, and spectroscopic results which confirm that the brown dwarf companions are truly associated with the primary star. Section 6.4 discusses the placement of the objects on an HR-diagram compared with theoretical evolutionary models and presents estimations of the age and mass of the brown dwarf companions.

6.2 Observations and Data Reduction

The two companions of HD 130948 were discovered using the same data used in the debris disk survey (Chapter 5) with the Hokupa’a/Gemini (Graves et al. 2000) on the night of 2001 February 24 (UT). The Hokupa’a AO system consistently delivers near diffraction limited images (Strehl $\sim$ 0.2) in the H Band. Before the photometric and astrometric analysis, all images were flat-fielded with the bad pixels filtered from the images. The field of view in the Wollaston prism mode is a rectangle that is 4"x20". Three sets (20 exposures/set) of 20 second exposures were obtained to give a total exposure time of 1200 seconds. Each set of exposures was taken with different field orientations separated by 90° using Gemini’s instrument rotator.
The point source detection limit as a function of radius from the central star was obtained by inserting fainter versions of the AO PSF at random position angles but at fixed radii from the central star and finding the faintest artificial companion which could be consistently recovered by eye (Figure 6.1). Figure 6.2 displays the discovery image of the companion system which is separated by 2\".64±0\".01 and is 8 magnitudes fainter in the H-band relative to the primary star.

To check for a common proper motion between the primary star and the new companions, and for possible orbital motion between the VLM binary pair, the objects were observed on four different occasions over a time baseline of 14 months between 2001 February 24 (UT) and 2002 April 23 (UT). The proper motion of HD 130948 is well known (Perryman et al. 1997) to be 148 mas/year, which equates to 4.3 pixels of relative movement between background stars and common proper motion objects on the Hokupa'a/QUIRC detector. We find there is no significant differential motion between the binary pair (B and C) and the primary star (A) within our astrometric accuracy of ~5 mas. Therefore, the two objects are most likely a gravitationally bound pair at the same distance as the primary star (17.9 pc). The average astrometric result is a separation between HD 130948 B and C equal to \( \rho = 0\".134±0\".005 \) and a position angle equal to \( PA = 317^\circ±1^\circ \).

Relative astrometry between HD 130948 B and C was carried out to check for possible orbital motion. Over the 14 month time baseline a relative position change of 25 mas was measured with a 5\( \sigma \) confidence level (Figure 6.3). Although this is insufficient to make a dynamical mass measurement, and astrometric observations must be carried out in forthcoming years to construct the orbit and obtain a dynamical mass, it does offer promise that a dynamical mass will be obtained eventually.

The J, H, K photometry was obtained using the MKO near-IR photometric system based on the UKIRT faint standard star list (Hawarden et al. 2001). The photometry was obtained on 2001 April 19 (UT). The halo of the bright primary star presented an obstacle in obtaining accurate photometry of the companions. In order to subtract the profile of the halo, each image was differenced with a version of itself, rotated about the photocenter of...
Table 6.1 Photometry of HD 130948B and C

<table>
<thead>
<tr>
<th>Component</th>
<th>$M_J$</th>
<th>$M_H$</th>
<th>$M_K_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>12.6 ±0.2</td>
<td>11.9 ± 0.1</td>
<td>11.0 ± 0.1</td>
</tr>
<tr>
<td>C</td>
<td>12.9 ± 0.2</td>
<td>12.3 ± 0.1</td>
<td>11.3 ± 0.1</td>
</tr>
</tbody>
</table>

the primary by 180°. After the subtraction, the background immediately surrounding the companions was relatively flat which allowed the use of curve of growth aperture photometry on the combined light of both companions. The brightness ratio of the two companions was then estimated to be $B/C=4/3$ based on the profiles of the stars. The same parameters for the curve of growth method were used for the UKIRT faint standard, FS137. The absolute magnitudes based on a 17.9 pc distance and their errors are provided in Table 1. The measured colors of both objects are consistent with those of field L dwarfs (Leggett et al. 2001).

Medium-resolution spectra (R=1500) from 1.15-1.35 μm of each component of the binary were obtained on the Keck II 10-meter telescope using NIRSPEC (McLean et al. 2000) with AO on 2001 June 30 (UT). The AO correction was made using HD 130948 as the wavefront sensor guide star. The system delivered images with FWHM=0'06 (3.4 pixels) in the $J$-band. HD 130948 B and C were clearly resolved, and the NIRSPEC 3 pixel wide slit was placed along the axis joining both objects. Three exposures of 300 s were obtained. An A0 V standard star, HD 131951, was observed immediately after to correct for telluric absorption features.

Data reduction was performed using IRAF tasks. The reduction procedure included sky subtraction, flat field division, aperture tracing, extraction of the one dimensional spectrum, wavelength calibration using a lamp spectrum, division by the normalized spectrum of the A0 star (after removing the $P_\beta$ absorption feature at 1.28 μm), and multiplication by a black body function for a temperature of 9500 K. Figure 6.4 displays the final NIRSPEC spectra of HD 130948B and C. We compared these NIRSPEC spectra with SpcX data of VLM dwarfs with spectral types in the range M8 to L5 (Cushing et al. 2003). The SpcX
Table 6.2 Spectroscopic measurements

<table>
<thead>
<tr>
<th>Name</th>
<th>SpT</th>
<th>EW(KI) (Å)</th>
<th>EW(KI) (Å)</th>
<th>EW(FeH) (Å)</th>
<th>EW(H₂O) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δλ (nm)</td>
<td>1.1655-1.1715</td>
<td>1.1750-1.1810</td>
<td>1.1930-1.2080</td>
<td>1.3420-1.3600</td>
</tr>
<tr>
<td></td>
<td>Pseudo-Continuum (nm)</td>
<td>1.1710-1.1750</td>
<td>1.1710-1.1750</td>
<td>1.1830-1.1930</td>
<td>1.2880-1.3020</td>
</tr>
<tr>
<td>VB10</td>
<td>dM8</td>
<td>3.9</td>
<td>7.2</td>
<td>8.3</td>
<td>31.6</td>
</tr>
<tr>
<td>DENIS-P J104814-395606</td>
<td>dM9</td>
<td>5.6</td>
<td>8.1</td>
<td>10.7</td>
<td>38.7</td>
</tr>
<tr>
<td>2MASSW J1439284+192915</td>
<td>dL1</td>
<td>6.7</td>
<td>9.3</td>
<td>12.8</td>
<td>47.2</td>
</tr>
<tr>
<td>Kelu 1</td>
<td>bdL2</td>
<td>6.0</td>
<td>8.2</td>
<td>14.1</td>
<td>44.4</td>
</tr>
<tr>
<td>2MASSW J1146345+223053</td>
<td>bdL3</td>
<td>5.9</td>
<td>9.2</td>
<td>14.7</td>
<td>40.4</td>
</tr>
<tr>
<td>2MASSW J1507476-162738</td>
<td>dL5</td>
<td>7.7</td>
<td>9.5</td>
<td>13.1</td>
<td>56.6</td>
</tr>
<tr>
<td>HD 130948B</td>
<td></td>
<td>6.4</td>
<td>8.1</td>
<td>13.7</td>
<td>43.0</td>
</tr>
</tbody>
</table>

Data have a resolution (R=2000) similar to the NIRSPEC data. We measured the strength of the absorption features indicated in Figure 6.4. Spectroscopic measurements are given in Table 2. Integration limits and equivalent widths (EW) for objects with spectral types in the range M7 to L5 are provided. The spectrum of HD 130948C is indistinguishable from that of HD 130948B, and thus we only give the EW values of the brighter component of the pair.

On the basis of the measurements shown in Table 2, and the visual comparison with standard spectra, we estimated that both HD 130948B and C are cooler than M9 and warmer than L5. However, the relatively narrow spectral region covered with NIRSPEC does not allow us to distinguish between spectral subclasses in the range L0 to L4. Thus, we adopt a spectral type of L2 with an uncertainty of 2 spectral subclasses for both HD 130948B and C.

6.3 Discussion

HD 130948 is a chromospherically active single G2V star with high lithium abundance, and fast rotation (P=7.8 days). All these properties are indicative of youth (age<0.8 Gyr; Gaidos et al. 2000). The space motions of HD 130948 suggest that it could be related to the Ursa Major stream (Fuhrmann 2002, in preparation), which has an age of about 300 Myr.
The two new companions of HD 130948 are probably contracting brown dwarfs because of the young age of the primary star. With the aim of estimating their ages and masses, we placed HD 130948 B and C on an H-R diagram with theoretical evolutionary tracks shown in Figure 6.5. We used the evolutionary models of Chabrier et al. (2000) that include dust in the equation of state and the opacity because those are appropriate for L dwarfs (Allard et al. 2001). Basri et al. (2000) and Schweitzer et al. (2001) have estimated the effective temperatures (\(T_{\text{eff}}\)) of L dwarfs using the dusty models of Allard et al. (2001). Leggett et al. (2001) have used the same atmosphere models plus structural models for objects of known distance. We adopt \(T_{\text{eff}}=1950\pm250\) K for HD 130948B and C, which includes the whole range of \(T_{\text{eff}}\) estimates for L0–L4 dwarfs in the literature. Our NIRSPEC data alone are not sufficient to tell whether HD 130948B and C have different L spectral type because the region that we observed does not contain features that are sensitive to changes in subclass in the range L0 to L4. We note, however, that if we force HD 130948B and C to lie on the same isochrone, their spectral types should differ by about 2 subclasses. Further spectroscopic observations, particularly at optical wavelengths, can test the agreement between the position of these objects in the H-R diagram and the model predictions.

For an age younger than 1 Gyr (consistent with youth of HD 130948A), the Chabrier et al. (2000) dusty models give a mass less than 0.075 M\(_{\odot}\) for HD 130948B, and less than 0.065 M\(_{\odot}\) for HD 130948C. It is very likely that both objects are young contracting brown dwarfs. For a total mass of the binary system of about 0.013 M\(_{\odot}\), and a semimajor axis of 2.4 AU, the orbital period should be \(\sim10\) years. Follow-up observations of this binary system over the next few years will yield dynamical masses for these two L dwarfs, which will extend the mass-luminosity-spectral type relation to cooler temperatures, and will provide two well constrained calibration points for the theoretical models describing low-mass, ultracool objects.

Although there are a handful of brown dwarfs known as companions to main-sequence stars, HD130948 B-C is the first brown dwarf binary system imaged around a G-type star. This advance has been rendered possible by the high dynamic range provided by the
Hokupa’a AO system on the Gemini-North telescope. At the time of writing this paper, 31 G-type stars less than 1Gyr old have been observed with Hokupa’a/Gemini in our ongoing survey for VLM companions to the stars in the Gaidos (1998) sample and other nearby, young G-type stars. The survey observations are sensitive to objects 2 magnitudes fainter than the HD130948B-C objects at radii inbetween 10 AU and 100 AU from the stars. The detection of this new binary brown dwarf system in our survey gives a 3.2% ±3.2% frequency of brown dwarfs in the radius region we are sensitive to. This number is likely a lower limit because we are not sensitive to low mass brown dwarfs. Gizis et al. (2001) have reported a frequency of brown dwarf companions to G-type stars of 18% ± 14% for separations larger than 1000 AU. Liu et al. (2002) have found an L-type companion at 14 AU of a G-type star using adaptive optics. Combining our result with that of Gizis et al. and Liu et al., we suggest that brown dwarf companions to G-type dwarfs with separations larger than 10 AU may be common. The brown dwarf desert may be restricted to separations less than 10 AU. This supports the theoretical models of Armitage & Bonnell (2002) that explain a lack of brown dwarfs within 10 AU of solar type stars as a consequence of orbital migration in circumstellar disks.
Figure 6.1 Point source detection limits versus radius from the PSF center. The horizontal dotted line indicates the approximate contrast required to detect a substellar mass object around a 0.5 Gyr old solar-type star based on Burrows et al. (2001). The vertical dotted lines mark the radial range where the survey is sensitive to detecting the brightest brown dwarfs (a polarimetry field stop cuts the field off at 3.0'). This equates to radii between 10-60 AU with the stars at a distance of ~ 25 pc. The low-mass companions found in the survey around HD 72760 and HD 130948 are labeled with arrows.
Figure 6.2 The discovery image (Potter et al. 2002) clearly resolves the companion to HD 130948 as a binary with a 135 mas separation. The companion is ~8 magnitudes fainter than the primary star in the H band at a separation of 2".64.
Figure 6.3 The relative astrometry between the two brown dwarf companions to HD 130948A plotted over a 14 month baseline shows a movement of \( \sim 25 \) mas. This motion is a confirmation that the two brown dwarfs are gravitationally bound, but at present, there is not enough orbital information known to make an accurate mass estimate. Follow-up observations are needed to accurately measure the mass of the brown dwarfs.
Figure 6.4 Keck/NIRSPEC spectra of HD130948 B and C compared with IRTF/Spex spectra of known VLM objects. The M9 dwarf is DENIS-P J104814-395606 (Delfosse et al. 2001), and the L2 dwarf is Kelu 1 (Ruiz et al. 1997).
Figure 6.5 The positions of the companions to HD130948 on the H-R diagram are compared to the dusty models of Chabrier et al. (2000). The 0.12, 0.5, 1.0, and 5.0 Gyr isochrones are distinguished by different line styles and are labeled. The masses corresponding to the isochrones are plotted as bold squares and triangles connected with bold lines for 0.08 M\(_{\odot}\) and 0.06 M\(_{\odot}\) respectively. The shaded boxes labeled B and C mark the range of temperature (x-axis) and photometric (y-axis) error values. The range of T\(_{\text{eff}}\) corresponds to our measured range of spectral types (L2±2).
References


Martín, E. L., Brandner, W., & Basri, G. 1999a, Sci, 283, 1718


Chapter 7

Summary

7.1 High-Contrast Polarimetric Imaging Technique

A Wollaston prism-based dual-channel polarimeter was incorporated into the Hokupa’a curvature sensing adaptive optics instrument mounted on the Gemini North 8 m telescope. It was installed with a motivation to improve sensitivity for detecting the faint scattered light signature of circumstellar disks relative to the central star’s PSF halo. Observations of the circumstellar environments around CTTS demonstrated that the dual imaging polarimetry technique improves dynamic-range sensitivity compared to non-simultaneous imaging. These improvements were over an order-of-magnitude in terms of high-contrast detection within the inner 1” of the PSF. The success has prompted the development of other polarimeters now in operation at the Lick observatory (Perrin et al. 2002) and at the Multiple Mirror Telescope.

7.2 New and Improved Images of CTTS disks

We imaged the circumbinary disk around GG Tau Aab at a much improved signal-to-noise ratio compared to previous observations using the Hubble Space Telescope, revealing an apparent structure in the polarized intensity profile. Our observations detect scattered light interior of the well defined ring. A comparison of the polarized intensity images taken over a year baseline reveal statistically significant changes between observing nights. These
changes are too fast to be associated with the orbital motion of the material, and are likely due to changes in the illumination source caused by shadowing from faster moving material in close proximity to the central stars. The first resolved near-IR observations the circumstellar disk around the CTTS, LkCa 15, were presented, as well as the first resolved near-IR linear polarimetry of the circumstellar disks around GM Aurigae, and TW Hydrae.

High-resolution polarimetric H-band and optical images of the circumstellar environment around the triple classical T Tauri star SR 24 N(ab)/S reveal a complicated morphology which may be indicative of the mutual gravitational disruptions of circumstellar disks caused by either bound or unbound dynamical interactions. An apparent jet is found extending from SR 24 S. Coupled with the published measurement of strong Hα emission, this is strong evidence for active mass accretion, perhaps caused by tidal perturbations.

7.3 Model Images of Debris Disk

Theoretical model images of optically thin debris disks were created using both isotropic scattering assumptions and Mie scattering theory. These models provide a means to translate a given debris disk's physical properties into observable quantities to make comparisons with observations. The cross-sections calculated in the Mie scattering models are used to estimate dust particle lifetimes under the influence of radiation pressure and Poynting-Robertson drag from radiation. It is found that radiation pressure is unable to efficiently "blow away" particles of interstellar composition around stars of spectral-type later than M5V. The Poynting-Robertson drag lifetimes are compared with the lifetimes calculated from the destructive effects of the solar wind, collisions, and sublimation. The particle lifetime calculations are considered as a function of the central star over the range of main-sequence spectral-types. Although key elements of the environments of main-sequence stars are not known, such as the initial debris disk mass and size distribution, as well destructive mechanisms such as stellar winds, the models favor lower-mass stars to be more detectable from their near-IR scattered light appearance.
The investigation of the forces acting on debris disk dust from a stellar wind were put into the context of the recent measurements of stellar winds around X-Ray luminous K-G type stars. These measurements indicate that the Sun when it was less than ~100 Myr could have had a stellar wind mass-loss rate as much as 1000 times the present mass-loss rate. Because the lifetimes of the dust are inversely proportional to the mass-loss rate, this increase would make the dust lifetimes to solar wind drag around young solar analog stars up to 1000 times shorter than today. Thus, it is realized that the corpuscular version of the radiative Poynting-Robertson drag may play a significant role in determining the dust populations around young solar analog stars.

7.4 Dust Constraints around Young Solar Analog Stars

Using the sensitivity afforded by the dual-imaging polarimeter, a sample of young solar analog stars were observed to check their environments for the presence of dust. Out of 24 stars observed, none of them were found to have dusty debris disks. These observations significantly constrain the amount of micron sized dust particles around the sampled stars to be on the order of less than 100-300 times the current surface densities in our present day solar system. Debris disks with 300 times the dust content as found in today’s solar system would have been easily detected in all 24 sample stars using conservative isotropic scattering models.

7.5 Companion Search around Young Solar Analog Stars

This debris disk survey was also sensitive to the detection of low-mass companions to the sample of young solar analog stars. Around the 24 stars surveyed, previously unknown companions were found around two stars, HD 72760 and HD 130948, with the companion around HD 130948 consisting of a binary. Follow-up spectroscopy of the binary companion found that they are most likely substellar objects with spectral types of L2 ± 2. The other companion found around HD 72760 is most likely a mid-late M spectral-type star.
based on the H-band magnitude alone. Using the results from this survey, coupled with a survey of other solar type stars, a statement concerning the commonality of brown dwarfs around solar type stars is made which indicates that there is not a brown dwarf desert for separations between 10-50 AU.
References

Perrin, M., Lloyd, J., Kalas, P., & Graham, J. R. 2002, BAAS