THE DIVERSITY AND KINEMATIC EVOLUTION OF CIRCUMSTELLAR DISKS

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1 Introduction

The planar geometry of the solar system and the evidence for accretion in young stars motivated some theoretical models for star formation (Lynden-Bell & Pringle 1974). The rotation of star forming cores stimulated theoretical models incorporating rotation into collapse calculations (e.g. uniform clouds Ulrich 1976; isothermal clouds Terebey, Shu & Cassen 1984). These calculation naturally led to predictions of disks around all forming stars (Shu, Adams, & Lizano 1987 and references therein). Observational evidence for the existence of disks around young stars began mounting with the proposal that the polarization of scattered light could be explained by disks (Elasser & Staude 1978) and the analyses of forbidden line profiles (Appenzeller, Oestreicher & Jankovics 1984). Disks around main sequence stars were suggested by observations from the Infrared Astronomical Satellite (IRAS) (Aumann et al. 1984). These discoveries sparked three independent modes of research: 1) flux measurements from the infrared to the millimeter, 2) the spectroscopy of the cool disk gas, and 3) the resolving of images of nearby disks.

First, flux measurements at different wavelengths allow modeling of the excess emission (i.e. emission in excess of that expected from the stellar photosphere). Modeling of the spectral energy distribution (SED) in the infrared provides estimates of the temperature of the emitting material (e.g. Adams, Shu & Lada 1988). Disks are suggested to explain the SEDs because the excess infrared emission cannot come from the photosphere and the emitting material is consistent with blackbody emission from a range of temperatures. The modeling of SEDs has allowed a classification scheme to be created which is based on the infrared SED. Class 0 objects are considered to be the youngest and have the bulk of their emission in the submillimeter. Class I, II, and III sources indicate less infrared excess as a function of time. This is an indication of a rough evolutionary trend (Lada & Wilking 1984, Ward-Thompson 1993, Andre & Montmerle 1994). The (sub)millimeter flux must be in a flattened configuration to allow the central source to be visible but still include the measured amount of mass. Flux in the sub(millimeter) also allows the measurement of the disk mass (e.g. Beckwith et al. 1990).

Second, spectroscopy has provided insight into the physical conditions, content and dynamics of disks. Infrared spectroscopy can determine the content of disks and the physical conditions giving rise to the emission in the inner disk (for state-of-the-art spectroscopy, see the review by van Dishoeck 2004) and (sub)millimeter spectroscopy gives insight into the abundances and temperatures in the outer disk. Also, the detection and kinematic resolution of emission lines probes the gas dynamics of the system (see Walter et al. 2003 for UV H_2 studies, Najita, Carr & Mathieu 2003 for infrared measurements and Dutrey et al. 1998 or Mannings, Koerner & Sargent 1997 for millimeter data).

Third, the search for resolved emission provides insight into the structure of disks. Resolving dust emission in optical/near-infrared light is difficult unless there is some way to block the central emission (i.e. there is a contrast problem). Alleviating this problem requires using coronagraphs (see Smith & Terrile 1984 or Kalas, Liu & Matthews 2004), the disk itself (see Burrows, Stapelfeldt & Watson 1996), near-infrared interferometry (see Eisner et al. 2003 and Millan-Gabet, Schloerb & Traub 2001) or a background source to illuminate the disk so the disk is seen in extinction (O'Dell, Wen & Hu 1993). Mid- and far-infrared emission can be resolved without these methods given the reduced stellar contribution at these wavelengths (Koerner et al. 1998; Jayawardhana et al. 1998; Weinberger, Beckline & Zuckerman 2003). At (sub)millimeter wavelengths the dust emission dominates and resolving the emission does not depend on the central source (e.g. Dutrey et al. 1998; Corder, Eisner & Sargent 2004).

Combining these modes of research provides great insight into the nature of disks found around young stars. Spatially and kinematically resolved spectroscopy in the millimeter has provided definitive evidence of Keplerian rotation for several disks. SED modeling with resolved images has revealed two different types of disks. Disks around class I and II objects (hereinafter circumstellar disks or CSDs) are massive ($\sim 0.01 M_{\odot}$) and gas rich ($M_{gas} >\sim 10 M_{dust}$). Disks around class III and main sequence objects (hereinafter debris disks or DDs) are typically gas deficient ($M_{gas} < 10 M_{dust}$), less massive and contain second generation material (i.e. large bodies have formed in these disks and small dust is formed via collision or destruction of larger grains, see Dutrey, des Etangs & Augereau 2004). CSDs likely evolve into DDs but few examples of transition disks have been found. (NB The term “disk” will be used as a generic term in what follows, standing for either CSDs or DDs.)

The general drive to understand disk structures is fueled by the desire to understand the formation, evolution and uniqueness of the solar system. These disks are likely to be precursors to fully developed, stable planetary systems. Only through the exploration of proto-solar systems at differing points in their evolutionary cycle can there be hope of understanding our own solar system. Each of three modes of study listed above is poised to make great advances in the next decade with the resolution of dust and gas emission playing a key role.

SED modeling will benefit from improved sensitivity or extended spectral coverage with Spizter Space Telescope (SST), the Millimeter Telescope (MMT), the Thirty Meter Telescope (TMT), and the Green Bank Telescope (GBT). Spectroscopic studies will be enhanced by SST as well as new interferometers like the Submillimeter Array (SMA), the Combined Array for Millimeter Astronomy (CARMA), and, eventually, the Extended Very Large Array (EVLA) and the Atacama Large Millimeter Array (ALMA). Resolving disks in the (sub)millimeter will become easier with SMA, CARMA, EVLA and ALMA and improvements to infrared adaptive optics at Gemini and the VLT will provide further advantages. Benefits from extending the wavelength coverage of SED fitting and improving the sensitivity of flux measurements will increase the quality of SED models and searches for diversity can begin both in individual SEDs and the SED distribution of large populations of similar stars. New and/or more sensitive spectroscopic studies will allow the temperature to be explored over the entire disk (by combining IR and submillimeter spectra). Also, adaptive optics may allow kinematic mapping of inner disks.

Resolving disks is especially important. Resolved continuum emission allows the structure of the disk to be probed directly. The disk size, inclination, temperature structure and density structure are all quantities that can be determined from resolved images with few degeneracies. Additionally, these resolved images can reveal substructure in the disks that may indicate the presence of planets. Spatially and kinematically resolved spectroscopy allows the kinematics of disks to be mapped and diversity of kinematic signatures to be probed. Models combining these upcoming improvements will allow a number of vital components to be addressed. Resolving the dust emission at different wavelengths can give information on dust grain sizes and their location (Duchene, McCabe & Ghez 2004). Mapping the kinematics in the millimeter and mid-infrared allows the dynamics of the disk to be explored from the outer regions where material may still be accreting onto the disk to the terrestrial region where Earth-like planets may be forming. These, coupled with spectroscopic observations which determine chemistry, can complete the picture of the evolution and diversity of protoplanetary systems.

The focus of this thesis will be to address the kinematic evolution and diversity of disks by spatially resolving the dust and/or gas emission. The thesis will consist of four parts:

- Preliminary: A small sample of CSDs has been observed in the 1mm continuum band and the carbon monoxide (CO) J=2-1 molecular line transition (CO(2-1)) using the Owens Valley Radio Observatory Millimeter Array (OVRO). From this data models of the line and continuum emission will be constructed.

- Preliminary: In collaboration with Melissa Enoch, I am conducting a 1mm flux limited survey of targets in ρOphiuchi (ρOph) with OVRO using 3mm continuum and the HCO+ and HCN molecular line transitions. From this survey, I will identify targets for the principal components of my thesis and determine the population statistics of the region.
- Principal: I will conduct a 1mm survey for CO(2-1) and continuum emission for a sample of stars in the Taurus and ρOph star forming regions with CARMA. With the models developed as part of component 1, I will determine the kinematic evolution of CSDs and determine CSD parameters for a large range of sources in different star forming regions. I also hope to compare evolutionary trends in two different regions. I will determine light profiles for resolved CSDs using the profile to determine density and dust properties and address the diversity of profiles and kinematic structures.
- Principal: In collaboration with John Carpenter and other members of the FEPS SST Legacy team, I will observe SST targets from the FEPS program that show excess emission at 24μm and 5-8μm with LWS and NIRSPEC at Keck. We hope to resolve the thermal emission from DDs at 24μm and detect CO gas emission from the terrestrial region. With these observations we hope to determine the minimum size of dust grains in DDs, measure the size of DDs, and break degeneracies in the modeling of DD SEDs. We will also place limits on time scales for building giant planets and constrain the evolution of small dust grains which in turn effects the time scales for building of rocky cores.

2 Preliminary OVRO Survey and Models

Despite the increasing number of known CSDs, few have been resolved spatially. Resolving the continuum emission from CSDs in the millimeter would be extremely useful but existing facilities must strain their capabilities to do so and programs to resolve even a modest sample of CSDs are not feasible. Only a few CSDs have been resolved in the (sub)millimeter (e.g. GGTau, GMAur, ABAur, CQTau, LkCa15) and these are not well resolved (i.e. the number of beams across the source is only a fraction larger than one). The number of CSDs resolved and modeled in molecular line emission is somewhat larger (e.g. GMAur, TWHya, BPTau, MWC480, LkCa15, DLTau, CYTau, GGTau, UZTau). These molecular CSD have smooth, systematic velocity gradients and have been well fit by Keplerian disks. This is certainly a selection effect as a large diversity velocity patterns have been seen in low resolution surveys (Mannings & Sargent 1997, 2000 for HAes; Koerner & Sargent 2003 for TTs). Figure 1 shows a sample of velocity patterns.

As part of the final season of observations on the valley floor at OVRO, I initiated a small program to observe six sources, spanning a range in ages, chosen specifically because of existing low resolution OVRO data. Included in the sample were three intermediate mass stars with CSDs (CQTau, ABAur, and MWC758, called Herbig Ae or HAe stars, Corder, Eisner & Sargent in prep.), two classical TTs (DRTau and DOTau) and a class (0/I) source SVS13. Each source was observed in high resolution configurations in the CO(2-1) line (with the exception of ABAur which was observed in OVROs ultra-high resolution in the CO(1-0) line). The resulting beams were of order 0.75-1 arcsec giving spatial resolutions of ~120 AU at the distances of these sources. A map of ABAur is shown in figure 2. The moment map strongly exhibits the signature of a rotating disk, seen as velocity gradient parallel to the major axis. The preliminary signatures seen in DOTau (not shown) are much more complicated, showing evidence of outflow, rotation, possible cloud contamination and other signatures that may be revealed by detailed kinematic modeling.

Detailed models of continuum and molecular line emission can provide information on the

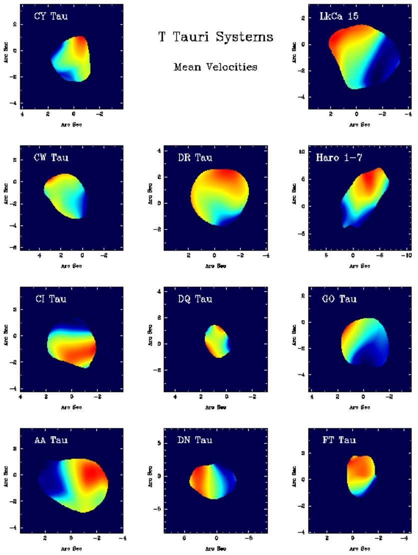

Figure 1: This is a subsample of the 12CO(2-1) survey of Koerner & Sargent. These maps display the flux averaged velocity of different portions of the map (i.e. first moment maps). Green represents material moving at the systemic velocity of the source. Sources like LkCa15 (top right) have been mapped and modeled in detail. More complex velocity patterns (like the others shown here) have not been explored. Such observational bias must be removed before a reasonable conclusions about kinematic evolution can be made.

density structure, kinematics, inclination, mass of the central object and physical conditions in the CSD. Such models will be developed as part of this thesis to address the data obtained in this preliminary program. The basic modeling program is still under development but figure 3 shows a reasonable fit to ABAur (shown in figure 2). The determined CSD structure aids our understanding of disks in general. Also, if complex kinematic patterns are pervasive, the impact of these velocity patterns on planetary formation must be considered. Tracing evolutionary trends with such a sample is unreasonable, but the detailed modeling program will aid in future studies (see section 4) which should reveal such evolutionary trends.

3 Preliminary: Survey of ρOph

Due to the location of the large millimeter inferometers, the rich, young (10^6 yr) star forming cluster ρOph has not been studied at high resolution except for a few sources (specifically IRAS16293 and VLA1623). The region has been studied at low resolution with large single dish observations in the millimeter and submillimeter (e.g. Andre & Montmerle 1994; Motte et al. 1998; Johnstone et al. 2000). The continuum fluxes and therefore masses of possible CSDs in ρOph are uncertain because of problems in removing background cloud emission. (The fluxes from Andre & Montmerle (1994) and Motte et al. (1998) disagree by as much as factors of 7 because of differences in background subtraction). An interferometric survey would provide the benefit of spatial filtering (i.e. extended cloud emission along the line of sight is removed). The CSD masses could be more directly compared to those in other star forming regions and environmental differences can be addressed. The ability of interferometers to do line spectroscopy would provide yet another benefit, allowing infall to be measured in very young sources, and, at minimum, allows the detection of a

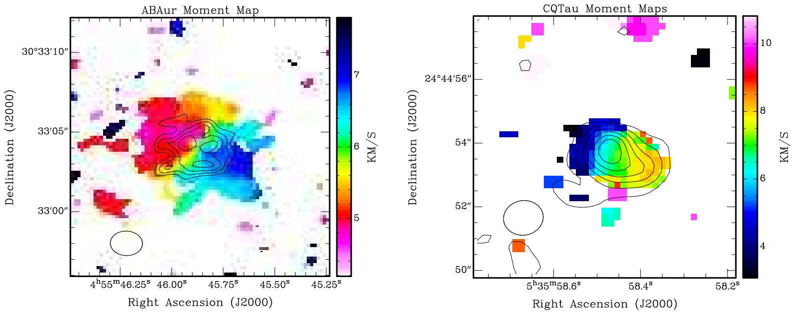

Figure 2: First moment map of the HAe stars ABAur and CQTau. The contours represent integrated gas emission (i.e. the zeroth moment). The double peak structure along the major axis of the image is expected for a rotating disk. The fact that the velocity gradient is in the same direction as the major axis also points to rotation. Modeling of source structure is done with individual channel maps (i.e. not these integrated images). Emission is clipped at 2.5σ in the first moment map and the smallest contours are at least 3σ in both maps. The CSD is well resolved with four beams filling the CQTau emission and at least nine beams filling the ABAur emission. Beam sizes are shown as the black ellipses in the lower left corner of the field.

massive gas CSDs around older stars. Identification of massive gas disks provides opportunities to follow up with more sensitive and high resolution observations with stronger transitions in hopes of determining disk parameters and mapping kinematics.

In collaboration with Melissa Enoch, I am undertaking a 3mm continuum survey (limited by 1mm single dish flux) of objects in ρOph. In addition, we are observing in the molecular transitions of HCO+ and HCN. We have obtained observations of over 30 targets in multiple array configurations. Detailed data reduction has yet to occur but there are several promising detections. My focus in this survey is in the mass distribution and gas presence in class II (TTs) and transition (from class I to II) objects. The detection of HCO+ emission indicates the likely presence of CO gas. Some of the sources detected will be observed with greater sensitive and higher resolution CO, 1mm observations in the future. Particularly strong emission may lend itself to modeling without additional observations. Certainly, with the presence of HCO+ and HCN, and later observed CO, the disk structure can be explored for ionization fraction, abundance ratios and different kinematic tracers.

4 Principal: High Resolution CARMA Evolution Program

The benefits of high resolution imaging and spectroscopy in the millimeter have been described above. However, it is important to recognize that the bulk of circumstellar disks are ~200 to less than 100 AU in size. With the present OVRO array, continuum disks may be well resolved using the ultra high resolution configuration at 1mm (0.6x0.4 arcsec beams implying 70 AU spatial resolution). Some molecular disks have been resolved (e.g. CQTau and ABAur in figure 2) using high resolution configuration at 1mm or ultra high resolution configuration at 3mm (beams 1.1x0.8 acrsec implying 140 AU spatial resolution). The improved CARMA site allows more extended configurations, resulting in beams as small as 0.15 arcsec. At Taurus and ρOph distance, this

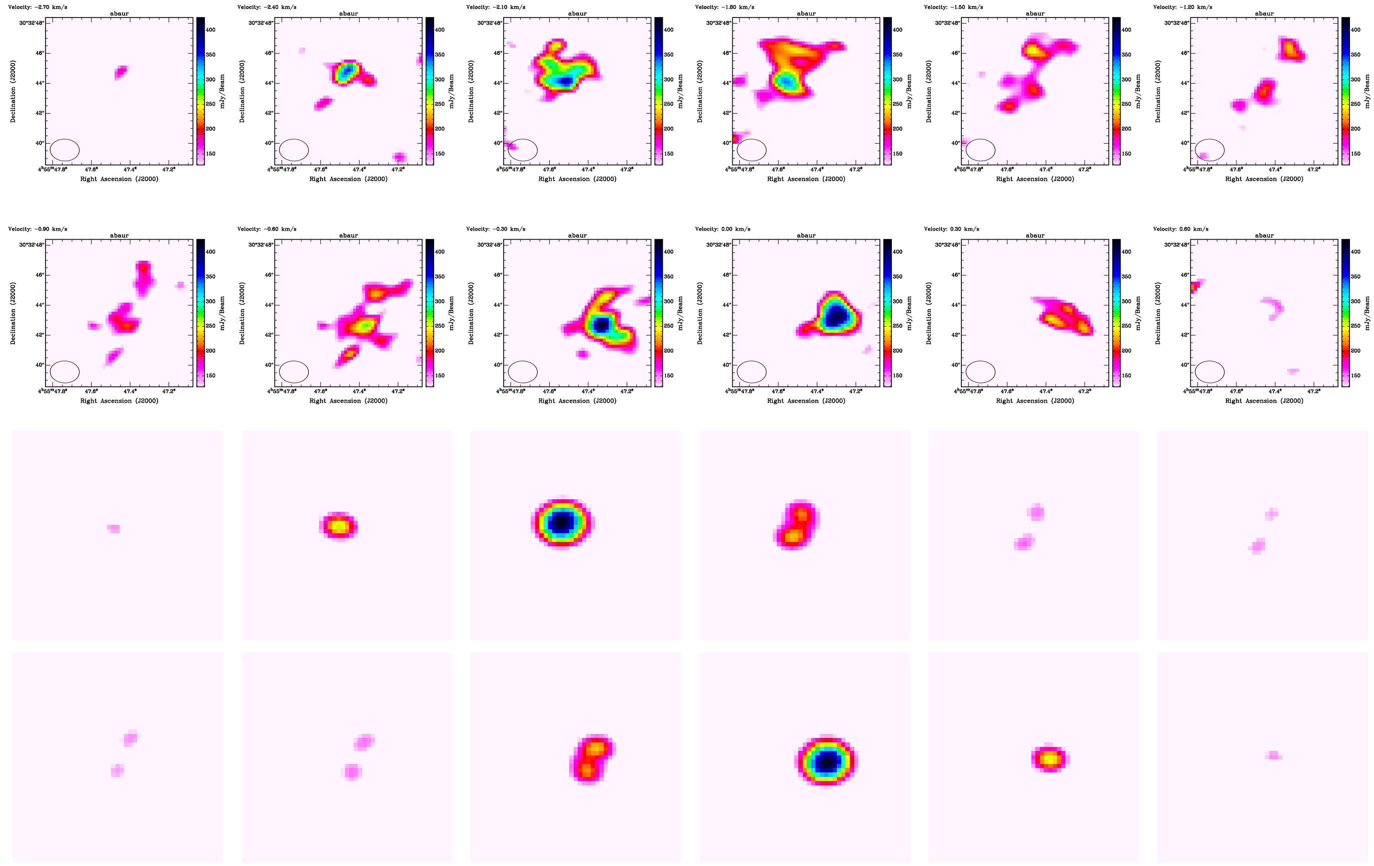

Figure 3: The top two rows represent the actual channel maps of ABAur. The coordinates and velocities are listed and the beam is shown in the bottom left corner. The model (bottom two rows) is shown over the same coordinates and velocity channels. The general shape and of the profile is consistent with a relatively face on disk (inclination 20 degrees) with large extent (2000 AU). The inclination is contrary to values from the literature but consistent with near-infrared interferometry measurements.

corresponds to 22 AU resolution, more than sufficient to resolve disk structure in detail. The modeling program mentioned in the OVRO high resolution study section will be applied to this sample. I emphasize that the improved resolution of CARMA allows well resolved continuum and molecular emission to be mapped. Additionally, the larger sample size (in ρOph and Taurus, see below) allows evolutionary trends to be traced.

The Taurus region is ideal for kinematic evolution and diversity studies with CARMA. There is less cloud emission to contaminate molecular signals, it is at a preferable declination for study with northern-hemisphere interferometers, and there have been a number of studies that allow target selection to be made more straight forward. An unpublished survey of 1mm emission in continuum and CO(2-1) (P.I.s D. Koerner and A. Sargent) provides a measure of CO flux for a variety of targets. In addition, a number of individual objects (e.g. HLTau, GMAur, GGTau) have been studied in this region. I will select a sample of 10-20 stars to observe in B configuration (effective baselines 81.6 to 942.6 m) with CARMA. The required amount of time will depend on the actual sensitivity of the array and the fraction of time available at high resolution as well as the final sample size. The sample will be selected from the literature and from the survey of Koerner & Sargent and will be limited by CO flux. The sample will include targets which are borderline class I/II objects and class II objects. Some of these may also be transition class II/III objects. This selection will certainly bias the sample but sufficient signal MUST be present to observe these objects at high resolution. Known binary systems will be excluded from the sample to limit the number of variables. As an additional selection criterion, targets with existing CO 5μm spectroscopy will be favored provided the CO(2-1) flux is sufficient to guarantee signal in the millimeter. Existence of mid-infrared spectroscopy may allow velocity structures to be probed into the terrestrial region (Blake & Boogert 2004, Blake & Boogert in prep).

The literature from which to select targets in ρOph is surprisingly small and only a few sources have millimeter line emission maps (e.g. Elias 29 Boogert, Blake & Tielens 2002). The survey of ρOph objects for HCO+/HCN emission (see section 3) has provided several promising candidates for further study. Using configurations A and D (effective baselines from 4.5 to 1692.3 m) with CARMA, a beam of 0.32 x 0.15 arcsec can be produced. Given the requirement of more extended and multiple configurations, the sample of stars in ρOph will be necessarily small (especially given that a larger sample in Taurus will make conclusions of evolution more robust). Sensitivities for similar integration time will be reduced from the Taurus sample by roughly a factor of two. The main goal of the ρOph sample is to compare trends to the Taurus sample and discover if the environment strongly effects the evolution of the sample. Additionally, this study may provide motivation for study of this southern cluster at a later date with upcoming southern hemisphere interferometers (ALMA). If the amount of time available in A configuration is prohibitively small this subsample can be eliminated without extreme impact to the significance of this thesis.

5 Principal: Keck Observations of Debris Disks

The SST Legacy program FEPS will observe ∼330 solar mass stars spanning ages between 3 Myr (class II/III objects) and 3 Gyr (well onto the main sequence), obtaining spectra and photometry from 3 to 160 μm. This program will establish the frequency and temporal evolution of DDs around solar mass stars. It will quantify the dissipation time scales for dust and gas from the primordial accretion disks thereby constraining the formation time scales for planetary systems. Finally, FEPS will infer the spatial structure in DDs and the locations of any orbiting planets. The bulk of the information to be gleaned from these systems will be by way of SED fitting and low resolution spectroscopy. The resolution of these observations is insufficient to probe structure directly. Observations with large ground based facilities provide the necessary resolution and sensitivity to

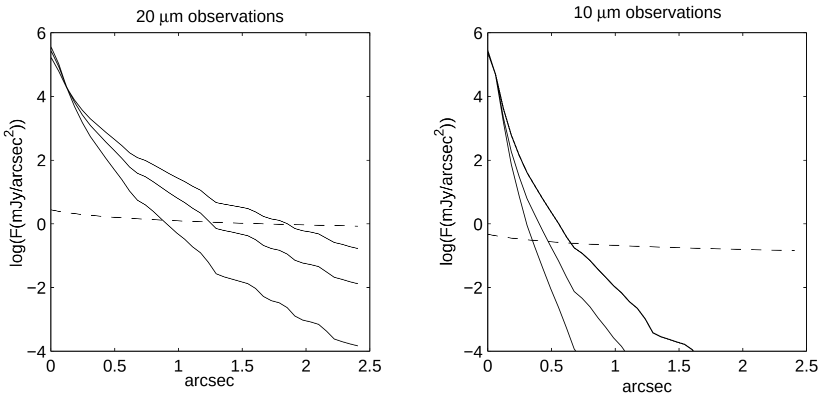

Figure 4: Model disk light profiles (solid curves) at two different observed wavelengths. Dashed line shows the 3σ isophotal sensitivity limits for 30 minutes of on source time with LWS. The disk models assume a fixed 24μm infrared excess and power law density profiles (with disk dust masses ranging from 10^{-7} to 10^{-6} solar masses). The distance is assumed to be 40 pc, the outer radius is 100 AU, the inclination is 20 degrees and the grain size distribution is $n(a) \propto (a/a_{min})^{-\alpha}(a > a_{min}, whereaisthegrainsize)$. The lines give surface brightness for three different values of a_{min} (0.1 μm, μm, and 10μm for the top, middle and bottom lines respectively). By resolving the emission, we can directly establish the size of the disk, place constraints on grain sizes and possibly observe structure in the disks.

detect these DDs and possibly resolve them. The resolution of the light profiles of these disks is vital to breaking degeneracies between density profile and dust properties. For example, dust emission at 24μm may originate from dust at 3 AU (for grains $\gg$24 μm) or 150 AU (for $<$1μm sized grains). The angular resolution provided by Keck with LWS provides access to spatial scales beyond 10 AU for the majority of the stars in the FEPS sample. Resolving the DDs provides three critical pieces of information for modeling SEDs, (i) the size of the disk, (ii) the light profile and possibly (iii) the detailed structural properties (e.g. gaps, asymmetries; see for example: HR4796 Koerner et al. 1998, Jayawardhana et al. 1998; ABAur Chen & Jura 2003; βPic Weinberger et al. 2003). The light profile allows the minimum size of dust grains to be determined (see figure 4) and the degeneracy is reduced. The minimum size of grains has important consequences on the time scale for collision of large bodies (current understanding is that small grains in the terrestrial region are lost into the star via the Poynting Robertson (PR) effect or radiation pressure effects on short time scales). If there are not small grains present it would indicate that there are no large bodies colliding on short time scales, setting limits on the time for formation/destruction of planetesimals.

Similarly, the low resolution spectra of SST will under-resolve the spectral lines by a factor of $\sim$100 and separating line from continuum may be difficult. In addition, the sample of stars with spectra will be small compared to the entire FEPS sample. Observations with large ground based telescopes with high resolution infrared spectrographs can detect CO gas at 5 μm (see Najita, Carr & Mathieu 2003; Blake & Boogert 2004). While detection of CO gas in debris disks has proven difficult, one reason for that dearth is the lack of a systematic way to select reasonable targets for observation. FEPS provides this possibility. At the spectral resolution provided by NIRSPEC we can not only hope to detect lines but we may kinematically resolve them. The detection of CO gas in this region has very important consequences. The existence of gas sets constraints on the time scale for formation of massive gaseous planets in the terrestrial region. Also, the presence of gas will effect the aforementioned PR effect. Standard calculations of the time scale for PR drag assume no hydrodynamic influence. The presence of gas and small grains therefore does not allow the conclusion that large bodies are colliding (or they are doing so on longer time scales).

While SST will have unparalleled sensitivity in the mid- and far-infrared, it has rather poor resolution. As a complement to the FEPS observations, I will observe (in collaboration with J. Carpenter here at Caltech and several other members of the FEPS team) FEPS sources that have 24μm excesses as seen by SST with LWS at Keck. We have been allocated three nights scheduled for this June and have requested an additional two nights to observe winter targets. In addition to the LWS observations, J. Carpenter and I have requested two nights to observe FEPS targets that show SED excesses in the 5-8μm band with NIRSPEC. By virtue of excess emission at these wavelengths there is (likely) dust in the terrestrial region of these sources and they may contain gas as well.

6 Future: High Resolution Follow-up of the CARMA Program

While some diversity may be visible in the aforementioned programs, higher resolution, other line transitions and other wavelengths of resolved continuum emission will provide greater opportunity for revealing substructures which may in turn indicate the presence of planets or companions. Additionally, the mapping in multiple line transitions provides the ability to probe the vertical structure of the disk, giving evidence of the location of angular momentum transporting turbulence and other density and velocity structures (see Dartois, Dutrey & Guilloteau 2003). If the line transitions occur at sufficiently different temperatures, radial structure in the velocity profile can be determined (e.g. CO fundamental emission, see Blake & Boogert 2004; Najita, Carr & Mathieu 2003). Resolving emission at multiple wavelengths in continuum reveals the dust disk structure and differences in dust grain size (Duchene, McCabe & Ghez 2004). This information can be obtained from further observations with CARMA, SMA, NIRSPEC, HST STIS, Gemini, (E)VLA, or ALMA.

7 Summary & Timeline

In this thesis I plan to obtain an evolutionary picture of the velocity structure of circumstellar disks and explore the evolution of different velocity components. In addition, I will address the structure and diversity of disks from young gas rich CSDs to older DDs. Finally if a number of transition objects (from class II to class III) are identified an evolutionary connection between CSDs and DDs may be firmly established. (NB The time line for operation of CARMA in B (or A) configuration is unknown and will strongly influence the timeline.)

- May/June 2004: Complete basic modeling program and apply to results from OVRO HAe 1mm survey. Write up results.
- June 2004: Attend NRAO Interferometry Summer School. Conduct LWS observations.
- July-November 2004: Analyze LWS data and complete modeling program. Write up results of ρOph survey and initial LWS results.
- November 2004 to March 2005: Assist with CARMA start-up. Conduct further LWS/Keck observations if granted.
- December 2004-2005: Conduct CARMA evolution program. Complete detailed modeling effort for quick analysis of CARMA data. Apply for necessary SMA, Keck, VLA or HST time.
- December 2005-June 2006: Write up CARMA evolution program, conduct higher resolution CARMA follow-up.
- July 2006-December 2006: Apply for jobs, write up CARMA follow-up and supplementary programs.

- January 2007-May 2007: Write thesis.

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