

Candidacy Proposal: Dust and gas dissipation in protoplanetary disks

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1 Introduction

Circumstellar disks around pre-main sequence stars are known to be the birthsites of planets. Within 10 Myrs, these systems evolve from dust enshrouded protostellar cores to main sequence stars, potentially with planetary systems. However, the formation processes remain unclear due to observational difficulties caused by obscuring dust and small spatial scales. Direct observation of young planets seems unlikely at this time. Thus, properties of more easily observable circumstellar disks must be studied to determine the protoplanetary environment and constrain formation scenarios of planets.

Determination of the physical conditions and structure of the envelopes and disks is crucial to understanding the processes at work. A wide range of conditions exist in circumstellar disks with both strong radial and vertical gradients. Radially, gas and dust near to the star is hotter than material at greater distances. Thus, spatially unresolved observations across the range of wavelengths at which the disks emits can still yield constraints on the physical properties of the disk. To study inner disk conditions, for example, it is possible to observe the dust in the near-infrared and to detect molecular transitions of appropriate energy, such as the CO ($v=1-0$) rovibrational band at $4.7 \mu\text{m}$. To observe the cold, outer portions of the disk and envelope, it is necessary to study the dust via its (sub)millimeter emission and the gas in lower-energy pure rotational transitions, such as CO($J=1-0$) at 3 mm.

In addition, for so-called passive disks, in which the energy liberated by accretion is small compared to that of the central stellar luminosity, the vertical structure is stratified with a temperature gradient from the hotter surface layers to the colder midplane. The midplane is shielded from stellar and interstellar radiation by the surface layers. The upper layers are exposed to both the stellar and the ambient interstellar radiation fields which stimulate an active gas-phase chemistry. Dust grains can gravitationally settle towards the midplane making conditions even more diverse. Heating by stellar light in the near-surface layers evaporates the volatile ices in the disk and excites gas phase molecules. Far-ultraviolet photons can drive an ice chemistry and can excite small dust grains (PAH molecules) as well. In hydrostatic equilibrium the disks have a flared geometry with increasing radius, exposing a greater fraction of the disk to the radiation, than in the flat disk case. Thus, it is essential to understand the properties of the central star because the star drives the evolution of the entire system. The radiation field from the star influences both the physical and chemical properties of the disk, creating very different environments around high and low mass pre-main sequence (PMS) stars.

In order to further our understanding of planet formation, all these different pieces must be explored and reconciled, for knowledge of the process and timescales of dust and gas dissipation is crucial to understanding disk evolution and planet formation. Jovian planets must obviously form while gas and dust are still present. The most common theory of planet formation is the core-accretion scenario, where large planetesimals accrete the surrounding gas and create gaps in the disk (e.g. Pollack et al. 1996). However, timescale estimates for this process range over a few-10 Myrs (e.g. Bodenheimer, Hubickyj & Lissauer 2000), while loss of gas from the disk proceeds on

timescales of $\sim 3\text{-}5$ Myr (IR - Strom et al. 1989, mm - Beckwith et al. 1990). Transitional disks, where dust clearing has begun, provide a unique opportunity to directly observe disk dissipation and its effects on planet formation. Classical T Tauri star disks, which preserve a large amount of dust and gas, are too optically thick to detect the protoplanets in their midst. At the other extreme, systems cleared of their dust and gas contain already formed planets and it is too late to study the nascent phase. Transitional disks, where dust clearing has begun, are systems which balance the requirements of observability and youth; but few are known at present. The method of dust dissipation (e.g. dust dissipation at equal rates throughout the disk vs. acceleration in the inner disk region) has implications for viable scenarios of planet formation in different disk regions. It is easier to trace dust dissipation through SED fitting than gas dissipation where different species and temperatures must be observed in many different spectral lines. However, the dust is not the main component of the disk and it is not clear how tightly the gas and dust distribution is coupled. Thus, gas dissipation must be considered as a separate, although closely related, problem of equal importance to dust dissipation.

In order to understand the formation and dispersal of low-mass circumstellar disks, my thesis will be comprised of the following projects:

- 1.) Spitzer study of disks with potential dust clearing
- 2.) High resolution studies of the CO(1-0) fundamental rovibrational transition
- 3.) Multi-wavelength observations of Perseus star forming region
 - a.) Spitzer IRS disk source follow-up
 - b.) Chandra ACIS-I X-ray observations of new sources in Perseus
 - c.) K-band high resolution studies aimed at determining spectral types and stellar properties
 - d.) CSO SHARCII determination of cold dust properties
 - e.) OVRO/CARMA observations of cold gas and dust

2 Summary

Although each of the projects described below is self-contained, these projects tie together to give different information about the systems and answer different questions. Finding transitional disks in which active planetesimal growth is occurring has been dramatically enhanced by Spitzer, especially *c2d* (§3). The Keck NIRSPEC data (§4) provides information about the gas content of the inner disk region and complements the dust information given by Spitzer. As many of the Spitzer sources are newly-discovered/poorly-studied, follow-up at different wavelengths is necessary to characterize the systems. Given Caltech's observational resources, a focus on the northern hemisphere constellation of Perseus seems natural. Obtaining such information for Perseus will be a component of this thesis and work is in the preliminary/future stage (§5). Although Spitzer photometry can provide candidate transitional disks, mid-infrared spectroscopy is necessary to determine the dust structure (§5.1). To get quantitative estimates for the fraction of PMS stars, X-ray observations are needed as IR signatures disappear as dust dissipates but high X-ray luminosity continues until the star reaches the main sequence (§5.2). This method could provide target transitional disks which have recently dissipated their dust. The central star is the driver of the entire evolutionary process so characterization is vital. K-band spectroscopy can provide the necessary information of spectral type, temperature and surface gravity (§5.3). CSO SHARCII provides a quick method of examining the cold dust and determining the Rayleigh-Jeans slope of the thermal dust blackbody (§5.4). CARMA will be used to search for grain growth, measure disk sizes and inclination angles (§5.5).

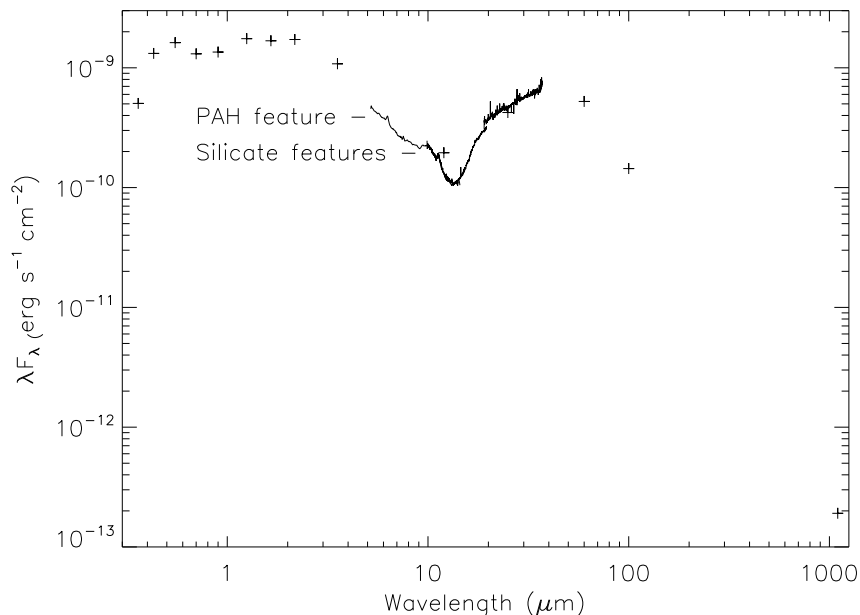


Figure 1: SED of LkH α 330. LkH α 330 is a potential transitional disk in Perseus identified by Spitzer.

3 Spitzer mid-infrared spectroscopy, esp. transitional disks:

Spitzer provides valuable access to the mid-infrared wavelengths, which are inaccessible from the ground due to the atmosphere. These wavelengths are particularly vital for examination of circumstellar disks as the thermal dust continuum peaks here. Important spectral features in this region include amorphous and crystalline silicates, PAHs, molecular hydrogen and a variety of different ices including H₂O and CO₂. I have been working as part of the “From Molecular Cores to Planet-Forming Disks (C2D)” Legacy Team, which will collect spectra of at least 170 young stars (Evans et al., 2003). Data collection is currently $\sim 50\%$ complete.

My component of this project has focused on SED modeling of potential transitional disks. These sources show falling emission until 13 μm and then rise steeply with a large cold disk/envelope (see Figure 1 for an example). Five such sources have already been identified in the *c2d* sample and spectra obtained. Several more candidates have been identified through the *c2d* mapping and photometry efforts. These disks could show evidence for dust clearing in the inner disk regions and, thus, be the key to understanding gas and dust dissipation in planetary systems. Spitzer spectroscopy is essential in measuring the shape of the continuum and identifying gaps due to dust clearing.

As part of my work on these rising spectra sources (particularly LkH α 330 in Perseus), I have been using Kees Dullemond’s 2 dimensional, passive disk, radiative transfer code (Dullemond 2001). This code is a gray opacity disk model. The model has been customized to allow insertion of a gap in the disk to try to account for the steep spectral shapes. I plan to further customize the model to incorporate the UV flux that appears to be essential to account for the near-IR excess in LkH α 330.

4 M-band high resolution spectroscopy of CO emission:

The Spitzer data and SED modeling described above provides an overall estimate of the dust/disk structure and evolutionary state. If the core-accretion model is indeed correct, gas must still be present in these transitional disk systems. What is needed to make progress, then, is a means of examining the $R < \text{few AU}$ region of circumstellar disks. One such approach is high resolution infrared spectroscopy of abundant molecules such as CO.

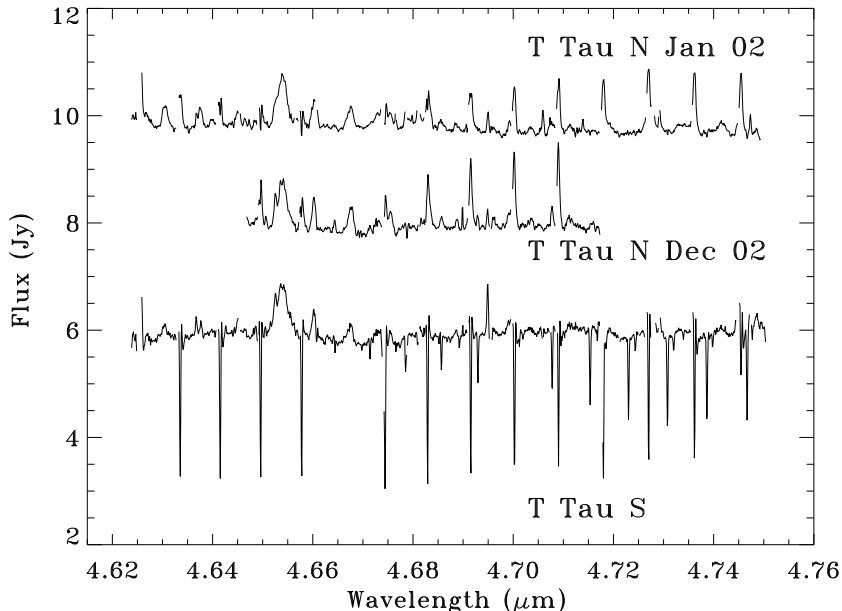


Figure 2: Keck NIRSPEC M-band spectrum of the T Tau system. T Tau N displays emission features while T Tau S is seen in absorption. Variability of the T Tau N lines was considered so the two observational dates were analyzed separately before being combined. The T Tau N lines are resolved and the T Tau S lines are unresolved.

Little IR work on pre-main sequence star disks has been done in the M band around $5 \mu\text{m}$ due to the high thermal background and atmospheric lines in this wavelength region. NIRSPEC, mounted on Keck 2 atop Mauna Kea, provides high-resolution wide-coverage spectra ($R=25,000$, $\Delta v=12 \text{ km s}^{-1}$). The Blake group has undertaken an M-band survey of approximately 100 pre-main sequence stars over the past three years (Boogert, Brown & Blake, in prep). The spectra show a range of characteristics often tied to the inclination. Edge-on disks have a prominent ice band at $4.7 \mu\text{m}$, while face-on disks often show bright CO emission. Within the sample, many intermediate types of spectra are seen. Of course, the exact nature of the spectra is due to more than simply the inclination. CO emission from the $\nu=1-0$ ro-vibrational band near $4.7 \mu\text{m}$ reflects the temperature and velocity structure and UV and X-ray radiation field illuminating the disk. These CO lines can be excited by collisional excitation close to the star or by radiative excitation from the star's UV field farther out in the disk. I am developing on a computer program to model the CO emission spectra seen in the M band survey based on the models by Kees Dullemond. By fitting the distribution of molecules in the different rotational levels and the line shapes, a variety of disk parameters, including the hydrogen column, temperature structure and the size of the disk, can be determined.

In particular, I have been working on analyzing the M-band spectra of the T Tau system (see Figure 2). The spatial resolution of the spectra are enough to separate the $0.7''$ binary. T Tau N is seen in emission as would be expected from its face-on orientation while T Tau S is seen in absorption as expected from its edge-on orientation. The T Tau N lines are resolved at the NIRSPEC resolution of 12 km s^{-1} and average 44 km s^{-1} for full-width, half-maximum. T Tau South is known to be deeply enshrouded in dust unlike the more visibly bright northern star. In agreement with this observation, our data shows deep CO gas absorption lines indicating a large column in front of an illuminating source. However, there is no CO ice band indicating that all the CO is in the gas phase and the temperature of the material is thus above 50K. The curve of growth indicates a doppler broadening parameter of 1.7 km s^{-1} , a CO column of $1.2 \times 10^{19} \text{ cm}^{-2}$ and a temperature of 90 K. This doppler parameter is consistent with small scale turbulence in the disk

above the level of thermal broadening. The populations of the J levels appears to be in thermal equilibrium and follow the Boltzmann distribution. The CO column gives a hydrogen column of between 9.35×10^{21} and $1.87 \times 10^{22} \text{ cm}^{-2}$. Koresko et al. (1997) derived a significantly higher value of 35 magnitudes of extinction from their models of T Tau S, which translates to a hydrogen column of $6.55 \times 10^{22} \text{ cm}^{-2}$. The column derived from the CO gas is larger than all estimates based on the dust, possibly indicating dust grain growth.

5 Perseus

I have recently begun putting together a multi-wavelength campaign to examine star formation, particularly the class II phase, in Perseus. The Perseus cloud is a particularly interesting star formation environment in that the stellar characteristics and cloud structure are intermediate between that of Taurus and Orion (Ladd, Lada & Myers 1992). The region does not produce very high mass stars like Orion but neither does it predominantly form low mass stars like Taurus. The amount of cloud structure is intermediate with dense clumps joined by more diffuse clouds. The Perseus cloud is believed to be one of the more distant local star forming regions at 320 pc (de Zeeuw et al. 1999). Distance estimates for the cloud vary and it has been proposed that it is composed of two structures with a nearer component at 200 pc and one more distant at 300 pc (Cernicharo et al. 1985). The Perseus star forming cloud has been previously undersampled due to its distance and large extent, with observations focused on the densest clusters, particularly IC 348 and NGC 1333. There have been relatively few studies of the less dense regions, which should on average contain more evolved young stellar objects. Many of the ground based studies of Perseus focus on deeply embedded protostars at millimeter wavelengths (e.g. Motte & Andre 2001) and on clusters of young stars in the near-infrared (e.g. Haisch, Lada & Lada 2001). It is important to examine the larger, less dense regions for an unbiased view of star formation in this cloud.

5.1 Spitzer Perseus follow-up:

I recently submitted (February '05) a Spitzer GO proposal to examine star+disk candidates in Perseus. We proposed a low resolution IRS survey of newly-discovered young stars in Perseus that possess infrared excesses suggestive of protoplanetary disks. This sample of stars was identified in the Cores to Disks Legacy Project (*c2d*) IRAC and MIPS mapping program which covers the Perseus ridge (Evans et al. 2003). This region was chosen to be complete for $A_v \geq 2$ although areas overlapping with GTO maps of the dense clusters IC 348 and NGC 1333 are currently embargoed. Objects for this proposal were identified as young stars with protoplanetary disks from fits to optical through $24 \mu\text{m}$ SEDs. The majority (26/35) of these stars have no SIMBAD entries and even the identified ones are poorly studied with generally only 1-2 references and none have published infrared spectroscopy (see Figure 3). This sample would almost double the number of Spitzer IRS observations in Perseus according to the ROC (≈ 50). Over half of the reserved targets are within IC 348 and NGC 1333. The proposed sample of Perseus sources is complete down to an $8 \mu\text{m}$ flux of 5 mJy and a $24 \mu\text{m}$ flux of 15 mJy, values selected as a compromise between a desire to characterize objects near or below the hydrogen burning limit and the need to limit contamination of the sample by extragalactic sources. These limiting fluxes also permit the detailed (high SNR) examination of a wide variety of sources within this region in reasonable integration times.

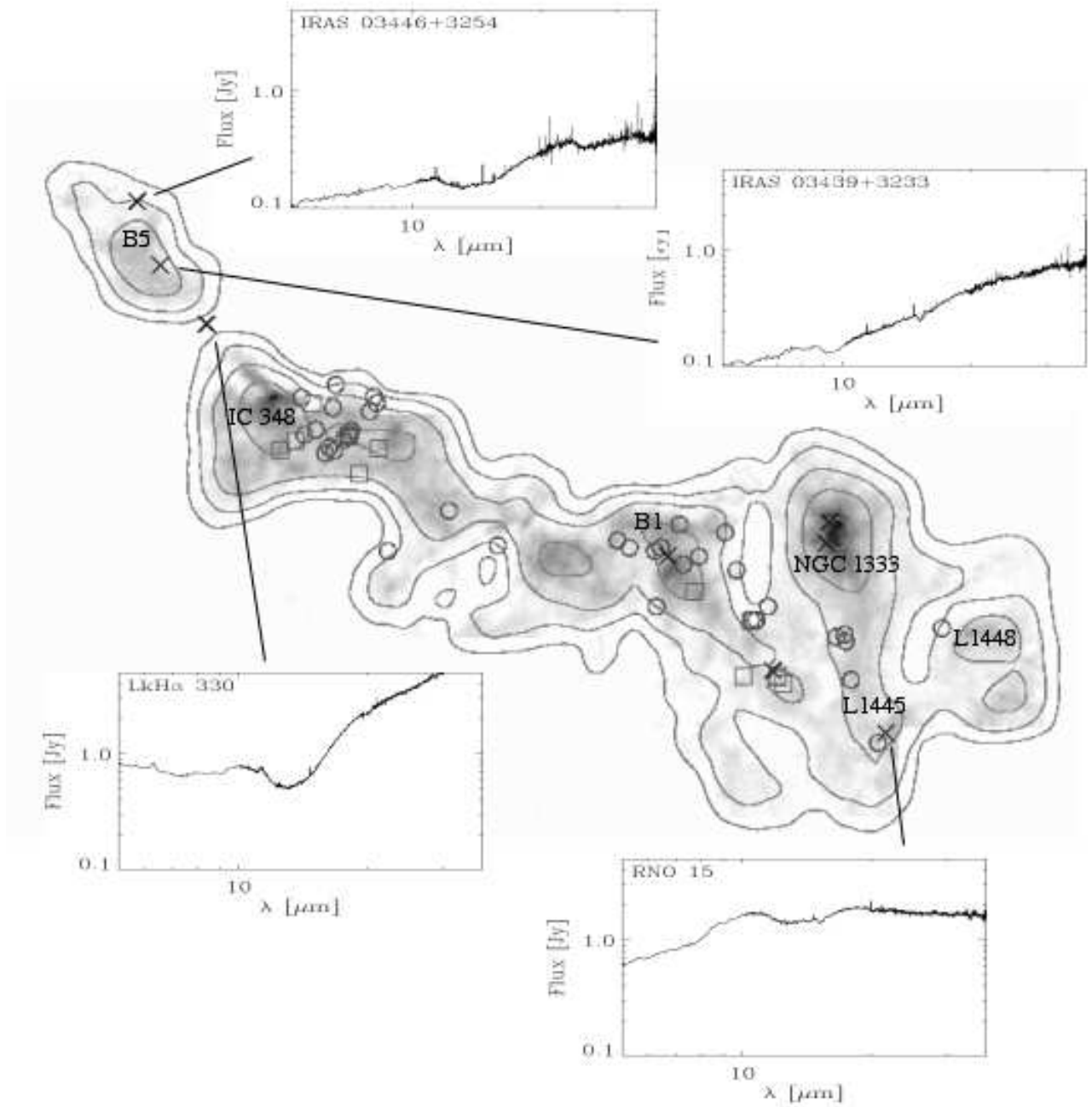


Figure 3: Distribution of sources in Perseus. The circles and squares represent the sources in this proposal; circles are newly-discovered sources (no SIMBAD entry), squares are previously known sources, and crosses denote IRS targets from the *c2d* program. The sources are overplotted on a ^{13}CO map (Padoan et al. 1999) in both grayscale and contours that are spaced evenly on a logarithmic scale at 0.8, 2.25, 4.88, 9.60, 18.1, 33.5 K. The proposed sources are spread throughout the cloud and cover a range of gas densities. The IRS spectra indicate clearly the range of SED shapes and spectral features in the Perseus cloud. A larger, more diverse sample is essential to understand the trends of star formation in Perseus

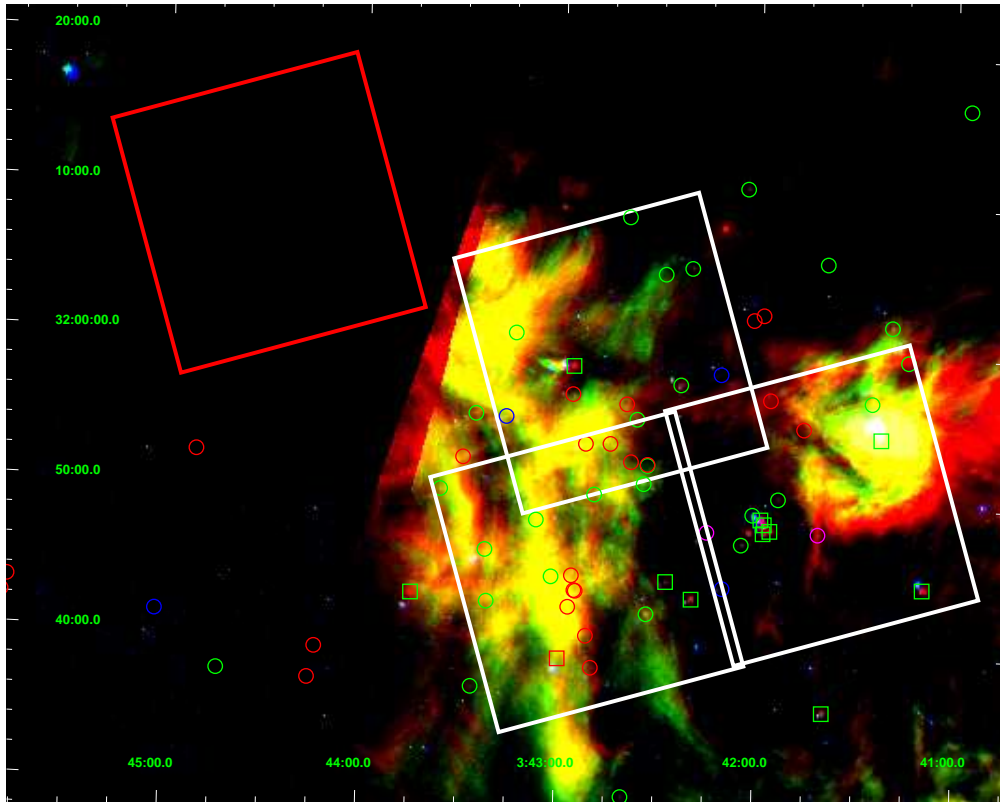


Figure 4: Overlay of ACIS-I fields on a three color Spitzer IRAC/MIPS map of the region (blue = IRAC2 ($4 \mu\text{m}$), green = IRAC4 ($8 \mu\text{m}$), red = MIPS1 ($24 \mu\text{m}$)). The proposed fields are shown as white 17 arcmin boxes, while the existing IC348 field (still under *Spitzer* embargo) is the red box to the upper left. The roll angle of the fields is 105° , which is the allowed orientation for this sky position. The S2 and S3 detectors will lie to the left (SE) or right (NW) increasing the area covered. Bright sources within this field have been classified according to their SEDs by the *c2d* team. Symbols are as follows **background stars** ($A_V > 5$, $F_{8\mu\text{m}} > 15\text{mJy}$) - blue circles; **rising spectra** - magenta (squares $F_{8\mu\text{m}} > 50\text{mJy}$, circles $F_{8\mu\text{m}} > 2\text{mJy}$); **stars with circumstellar disks** - green (squares $F_{8\mu\text{m}} > 50\text{mJy}$, circles $F_{8\mu\text{m}} > 3\text{mJy}$); **embedded stars** - red (squares $F_{8\mu\text{m}} > 50\text{mJy}$, circles $F_{8\mu\text{m}} > 2\text{mJy}$). Many more sources, which are not infrared bright, will be visible in the X-ray.

The proposed objects sample a wide variety of different conditions within the Perseus cloud. The foreground and circumstellar A_V ranges from 5 to 25, as determined from fitting from the optical through $24 \mu\text{m}$ SEDs. The proposed targets are also a mixture of clustered and isolated stars which will allow a direct comparison of different star forming conditions. The individual objects proposed for IRS study span a range of SED characteristics, with varying degrees of disk excess emission (see Figure 3). Some sources have large near-infrared excesses with excess flux in the IRAC $5.8 \mu\text{m}$ band, while others appear photospheric until the MIPS $24 \mu\text{m}$ band. These redder disks are particularly exciting as they may be transitional objects where dust clearing or coagulation has begun in the inner disk (e.g. CoKu Tau 4, Forrest et al. 2004).

5.2 Chandra ACIS-I

I have also recently proposed (March '05) for Chandra ACIS-I spectral imaging to complement the Spitzer observations. Pre-main sequence (PMS) stars are prominent X-ray sources at all stages of their evolution from deeply-embedded protostars to the point when accretion has ceased and

circumstellar disks have dissipated. High energy phenomena, such as X-ray and radio emission and magnetic flaring, play a major role in the evolution of young PMS stars and protoplanetary disks (Feigelson & Montmerle 1999). From the youngest protostellar stages, strong high-temperature X-ray emission is seen (Koyama et al., 1996), implying a central role for magnetic fields in controlling the physical processes close to the star and determining the interaction between the star and its circumstellar disk. The angular momentum balance between the star and the accretion disk is mediated by the magnetic field (e.g. Shu et al., 1994). Strong X-ray emission continues throughout the PMS evolution at much higher luminosities than seen for typical main sequence stars. Stellar X-ray and UV emission significantly impacts the disk thermal and dynamical structure as well as its chemistry. High energy photons and particles produced during flares can physically alter solids within a protoplanetary disk through spallation, with signatures that are clearly seen in the remnant material from the formation of our own solar system (see e.g. Goswami & Vanhala, 2000).

The three fields cover one of the densest regions of the cloud to the southwest of IC 348. The fields contain 47 sources bright enough for IRS follow-up and several times that should appear in the x-ray. The ACIS-I X-ray observations will provide the spatial distribution of all sources, including those which are infrared faint, the X-ray luminosity, hardness ratio and crude coronal temperature of several hundred PMS sources, an independent measurement of N_H and the variability of the sources. Correlation with the infrared data will place these objects into the context of their circumstellar environment.

5.3 K-band spectral typing:

Determining the spectral types of young stars is a historically difficult problem. Traditionally, the stellar properties of young stars have been determined photometrically through fitting the optical spectral energy distribution (SED). However, younger, more embedded stars are often obscured at optical wavelengths and longer wavelengths are dominated by dust emission from the surrounding regions. Diagnostics of the central star can be directly observed in the near-IR where the stellar photosphere is bright and the continuum dust veiling is low (Merill & Ridgway 1979). Longward of $2 \mu\text{m}$ the excess infrared emission from the dust dominates and shortward the emission from accretion dominates. K-band spectroscopy has thus become a standard method to observe the central stellar photosphere since the improvements in IR detectors in the 1980s. Within the $2 \mu\text{m}$ atmospheric window several characteristic lines allow one to distinguish between stars of different spectral types. Much work of this nature has been done in the K-band, particularly in ρ Ophiuchi and Taurus (Casali & Matthews 1992, Greene & Meyer 1995, Greene & Lada 1996). The K-band observations are fairly quick and can be easily combined with the M-band CO measurements using Keck NIRSPEC.

In order to determine spectral type, the spectra will be cross correlated with spectra of known standard stars, both from spectral standards taken with the observations and literature catalogs. Several catalogs of stellar MK standards at medium resolution exist in the K band (e.g. Meyer et al. 1998, Wallace & Hinkle 1997, Kleinmann & Hall 1986). In the K band, early-type stars show HI Br γ and later types show Na I, Ca I and CO $v=2-0$ lines. For the class II flat-spectrum sources, we expect lines to be visible in both the H and K bands. For the class I rising spectrum sources, we hope to see lines in the K band where the system is intrinsically brighter. However, this extra brightness comes from the dust and could produce extreme veiling in the lines. Some objects may show CO emission, probing the inner disk and providing an interesting comparison with the CO $v=1-0$ lines in the M band data should they be present.

In addition to spectral type, the lines in the K band spectra can be used to determine more quantitative parameters. The amount of dust extinction can be measured once the spectral type is known by comparing with a standard MK non-veiled star. The lines can then be corrected for dust veiling, allowing further stellar parameters to be constrained. The surface gravity can be determined directly from the equivalent widths of the CO 2-0 band head or the NaI line and the temperature can be determined from the line ratios. Luminosity and mass estimates can then be derived from these parameters. For very strong lines, it might also be possible to determine the stellar rotation velocity.

5.4 CSO SHARCII:

The IRS wavelength range extends to 40 μm where many of these sources still have rising emission. In order to characterize the dust emission at larger radii, it is essential to measure the SED at longer wavelengths. SHARCII provides a quick means of doing this as the sources are still bright at 350 μm but are also definitely on the Rayleigh-Jeans side of the Planck function. Sources detected at 350 μm would then be observed at 450 μm allowing determination of the SED slope. Our survey focuses mainly on potential transition disks detected through the *c2d* project. Around 10 such objects have already been identified with an estimated 30 more still to be identified. The TAC granted time for this project in April and June 2005, which will allow observation of sources in both Perseus and Ophiucus.

5.5 OVRO/CARMA:

OVRO/CARMA data are important to determine the nature of the cold regions of disks and envelopes. We have already taken observations of 5 sources in the *c2d* Perseus sample in order to determine disk masses. Millimeter wavelengths contain extensive information about the conditions in the cold, outer regions of protoplanetary disks. By examining a variety of different molecules the physical parameters can be determined as well as constraining the chemical composition. The continuum and CO (1-0) emission provide tracers of the dust and gas mass respectively. ^{13}CO and C^{18}O provide optically thin lines of sight in the disk probing towards the denser disk midplane. HCO^+ traces the ionization fraction particularly in the upper layers of the disk and allows insight into the ion-molecule chemistry. HCN, CN and HNC constrain the nitrogen chemistry occurring in the disk. In particular the CN/HCN ratio, which is driven by the UV flux, shows the strength of the UV field illuminating the outer portions of the disk. All these observations combine to characterise the physical and chemical properties of the outer regions of the disk.

CARMA, the combination of the OVRO 10m and the BIMA 6m millimeter antennas, is due for first light within the coming year. I will be involved in the start-up operations and a component of my thesis will involve CARMA data. Until the array is functional and the new capabilities determined (improvements are expected to be ongoing over the next several years), the feasibility of any of these CARMA projects remains undecided. High resolution millimeter observations of transitional disks would contain a wealth of information. In Fall 2003, I was PI of an OVRO program to observe the transition disk source HD 141569. However, the object was not detected due to its intrinsic faintness and poor weather conditions. CARMA's improved sensitivity would make detection of transitional disks more viable. Follow-up of sources from the Perseus data also seems a likely CARMA project. The high angular resolution of CARMA should permit resolution of the disks in order to determine velocity structure and a direct measurement of stellar mass.

6 References

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7 Timeline:

- Spring 2005: Continue work on LkH α 330 and other Spitzer transitional disks, finish T Tau paper, CSO and Keck observing
Summer 2005: Finish LkH α 330 paper; CSO and Keck data analysis
Fall 2005: CARMA start-up; prepare for Spitzer and Chandra observations (hopefully)
Spring 2006: CARMA start-up/early data collection; hopefully analyze Spitzer and Chandra data
Summer 2006: Write papers based on CARMA, Spitzer, Keck and Chandra data
Fall 2006: Apply for jobs, finish papers
Spring 2007: Finish up, write and defend thesis

Papers:

In prep:

A survey of CN, HCN, CO, and HCO⁺ emission from T Tauri and Herbig Ae disks w/ J. Kessler-Silacci

CO gas in the T Tau system

LkH α 330: Dust clearing in a protoplanetary disk?

Potential:

Spitzer rising spectra sources

CO emission in T Tauri disks

Young stars with disks in Perseus

X-ray and infrared correlations of PMS stars in Perseus