

CANDIDACY PROPOSAL - C. SLESNICK
THE EFFECTS OF EVOLUTION AND ENVIRONMENTAL FACTORS ON
YOUNG BROWN DWARFS

1 Introduction

Recent photometric and spectroscopic surveys have led to discovery of an abundance of isolated substellar objects over a wide mass range, from just below the hydrogen burning limit ($\sim 0.08 M_{\odot}$) down to the planetary mass regime ($< 0.02 M_{\odot} = 20 M_{Jup}$). Of particular interest are the *young* brown dwarfs associated with regions of recent star formation, which can provide insight into the poorly understood formation process for substellar objects. Observational evidence on the spatial distribution (Briceño et al. 2002) and on the inner disk frequency (e.g., Liu, Najita & Tokunaga 2003; Jayawardhana et al. 2003) of young brown dwarfs, both comparable to stellar counterparts in the same clusters, indicates that brown dwarf formation may follow the standard stellar formation model similar to their higher mass stellar counterparts. In this model (cf., Shu, Adams & Lizano 1987), objects are formed from cloud-core collapse and subsequent accretion of material. However, recent theoretical work by Reipurth & Clarke (2001), Bate, Bonnell & Bromm (2003) and Kroupa & Bouvier (2003) argues that brown dwarf formation may deviate from this sequence. Instead, they suggest an ‘embryo ejection hypothesis’ which puts forth that brown dwarfs may be unfinished stellar embryos, or failed stars, which are ejected from dynamically unstable multiple-star-forming systems. Among other implications, this theory leads to loss of the protostellar envelope and truncation of the circumstellar disk on relatively short timescales, resulting in a lower disk frequency and systematically smaller disks around substellar objects. This hypothesis is inconsistent with the high disk frequencies ($> 50\%$ – 80%) and measured accretion (e.g. White & Basri 2003; Muzerolle et al. 2003) onto proto-brown dwarf photospheres.

Although brown dwarfs may form in a manner analogous to stars, the evolution of material around such extremely low mass objects will not necessarily follow the same path as for their higher mass stellar counterparts. In particular, young circum-brown dwarf disks may be remarkably different than the disks surrounding young stars. Disks are heated via a combination of irradiation and accretion. The much lower temperatures and masses of pre-main sequence brown dwarfs compared to stars may cause differences in the evolution of accretion, disk composition and grain size. The eventual dispersal of disks around low mass young stars remains an unsolved question and active area of current research. The standard photoevaporative model (cf., Hollenbach, Johnstone, Lizano & Shu 1994) of high mass disk destruction requires a high flux of EUV Lyman continuum photons from a hot central object to ionize and heat the disk surface. In the absence of an outside source of ionizing radiation, the photoevaporative disk destruction rate decreases with decreasing stellar mass due to much lower levels of EUV photons produced, possibly leading to longer disk lifetimes with corresponding effects on the potential of brown dwarfs to form planetary systems.

Observational surveys of young stellar clusters, while possibly pointing to a common formation mechanism for individual objects both above and below the hydrogen-burning limit, do reveal some key differences between the formation of brown dwarfs and higher mass stars as ensemble populations. Recent studies of young clusters still embedded in molecular clouds suggest that primordial mass segregation may play a role in cluster formation with the lowest mass members forming over a wider spatial area than the massive stars (cf., Hillenbrand & Hartmann 1998; Carpenter et al. 1997). There is also evidence that the distribution of brown dwarf masses formed within a cluster is not simply an extension of the stellar mass function applied to substellar objects. Instead, studies of rich clusters such as the Orion Nebula Cluster (ONC) and IC 348 (cf., Luhman et al. 2000; Muench et al. 2002; Luhman et al. 2003; Slesnick et al. 2004) give evidence for a

turnover in the initial mass function (IMF) near the substellar limit ($\sim 0.1\text{--}0.2 M_{\odot}$). Comparison of these results to those for the more sparsely populated region of Taurus indicates that the substellar IMF may not be universal, but instead may depend directly on star formation environment (cf., Slesnick et al. 2004; Luhman et al. 2003b).

It is important to explore young brown dwarfs both as individual objects and as a population if we are to understand the fundamental similarities and differences between formation and early evolution processes of extremely low mass objects in comparison to higher mass stars and to each other. This understanding requires large samples of objects spanning a wide range in both age and star formation environment. I have chosen to focus my thesis on the substellar populations of three young clusters: Taurus, the ONC and Upper Sco. Specific clusters were chosen to span a factor of five age range and provide distinct star-forming environments: Taurus (~ 1 Myr) is sparsely populated and does not contain any massive stars while the equivalently-young ONC is still partially embedded and includes OB stars which provide external sources of ionizing radiation that may influence lower mass object evolution. The more evolved (~ 5 Myr) OB association Upper Sco is more extended than the ONC and has already dispersed its parental molecular cloud.

The first part of my thesis explores the substellar objects within each cluster as a population. Here I will concentrate on the underlying mass and spatial distributions of low mass objects by investigating the brown dwarf formation histories as well as the spatial distributions of objects as a function of mass and age within each cluster (Section 2). In the second part of my thesis I use optical and mid-infrared observations to explore properties of individual brown dwarfs. My focus for these studies will be on characterizing activity (both chromospheric and accretion) and disk properties. For these projects I will narrow my investigations to include only the Upper Sco and Taurus clusters. The extreme nebulosity of the ONC along with its large distance (480 pc) limits observations in that region (Section 3).

For all aspects of my thesis I will focus on comparison of results for the two (or three) clusters. The project as outlined below will be able to help answer the following questions about brown dwarf formation and early evolution: Is the substellar formation history within a cluster dependent on environmental conditions? Is it a function of spatial distribution? Are disk geometry and dust properties different for brown dwarfs in dense environments compared to brown dwarfs in more isolated regions? How have circum-brown dwarf disks and accretion processes evolved as an object ages from 1–5 Myr?

2 Young Brown Dwarfs as an Ensemble Population

Observational studies of young clusters provide evidence that brown dwarf formation history (eg., mass and spatial distributions) may differ from star formation history within a cluster. By examining clusters with different properties, some authors have argued that the substellar IMF and the presence of mass segregation may depend on external conditions. In the following subsections I outline how my thesis will help address these issues.

2.1 The Brown Dwarf IMF

The stellar mass and age distributions in young star clusters can help answer some of the fundamental questions of cluster formation theory: Do all cluster members form in a single burst or is star formation a lengthy process? Is the distribution of stellar masses formed during a single epoch within a cluster universal or does it vary with either star formation environment or time? While the stellar mass function has long been studied (e.g., Salpeter 1955), we are only recently beginning to explore the very low mass end of the distribution into the substellar regime. To this end, numer-

ous diagnostic studies have been carried out within the past decade to characterize the low mass stellar and substellar mass functions of young clusters in various environments. Because of the intrinsic faintness of these objects, most surveys are photometric. Authors then use a combination of theoretical models and statistical analysis to transform a cluster’s color-magnitude diagram or luminosity function into an IMF. However, details of the brown dwarf formation process remain sufficiently poorly understood that knowledge of magnitudes and colors alone is not enough to accurately predict an individual star’s age, extinction and infrared excess (arising from the possible presence of a circumstellar disk) for young low mass objects. Magnitudes alone also cannot distinguish between cluster members and nonmembers, and field star contamination must be modeled rather than accounted for directly. Thus, spectroscopy is needed to study a cluster’s IMF in more than a statistical sense.

Prior to our recent work (Slesnick et al. 2004; see below), the substellar populations of two young star-forming clusters had been studied spectroscopically. Luhman (2000), Briceño et al. (2002) and Luhman et al. (2003a) surveyed the sparsely-populated Taurus star-forming region, and Luhman et al. (2003b) studied the rich cluster IC 348. These clusters have similar ages (1 and 2 Myr). Therefore, if the IMF is universal, similar mass distributions should be observed for both. Contrary to this hypothesis, Luhman et al. (2003b) discuss the very different shapes of the substellar mass distributions in Taurus and IC 348. The IMF for Taurus peaks around $\sim 0.8 M_{\odot}$ and then declines steadily to lower masses through the brown dwarf regime. The IC 348 mass function rises to a peak around $0.15 M_{\odot}$ and then falls off sharply and levels out for substellar objects.

2.1.1 The Spectroscopically Derived Substellar Mass Function of the Orion Nebula Cluster

In Slesnick et al. (2004) we present a spectroscopic study of candidate brown dwarf members of the Orion Nebula Cluster (ONC). We obtained new J - and/or K -band spectra of ~ 100 objects within the ONC which are expected to be substellar based on their K , $(H - K)$ magnitudes and colors. From our derived spectral types and existing near-infrared photometry we constructed an HR diagram for the cluster. Masses were inferred for each object and used to derive the brown dwarf fraction and assess the mass function for the inner 5.1×5.1 of the ONC, down to $\sim 0.02 M_{\odot}$. We find that our mass function (Figure 1) for the ONC bears remarkable resemblance to that presented for IC 348 in Luhman et al. (2003b) (see for comparison Figure 12 in Luhman et al. 2003b). Both IMFs peak at ~ 0.15 – $0.2 M_{\odot}$ and fall off rather abruptly at the substellar boundary. The fact the IMFs derived for these two dense, young clusters bear such close resemblance to each other while exhibiting distinguishable differences from the IMF determined for the much more sparsely-populated Taurus cluster gives strong support to the argument put forth by authors such as Luhman et al. (2003b) that the substellar IMF is not universal, but may instead depend on star formation environment.

2.1.2 The substellar Mass distributions of Upper Sco and the Outer Taurus Clusters

In addition to the spectroscopic study of the ONC, I am also involved in a long-term U, B, R, I monitoring program (using the QUEST-2 camera at Palomar) to identify young and intermediate-age pre-main sequence stars and brown dwarfs in Taurus and Upper Sco through photometric variability. Specific survey areas were selected to extend well beyond the main parts of the known young stellar population, thereby encompassing stars and brown dwarfs that formed over a wider spatial area, as well as objects that may have formed in the central regions of the clusters and

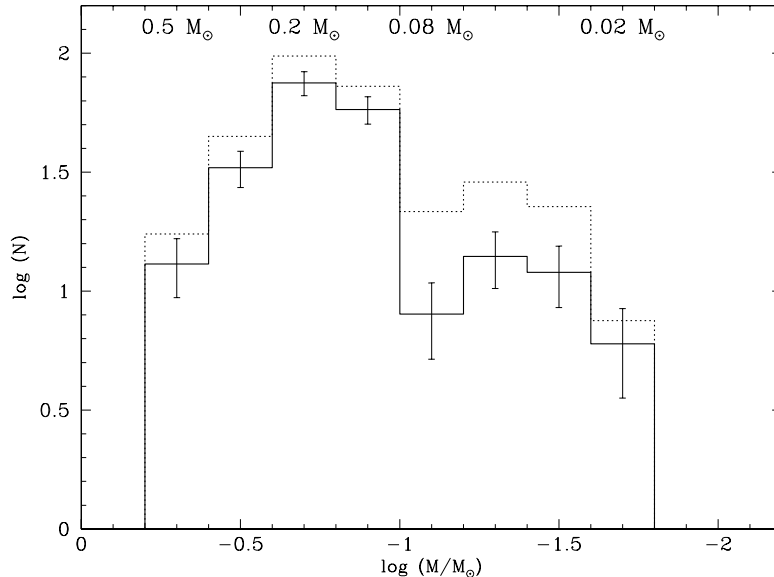


Figure 1: Mass function for all stars within the inner 5.1×5.1 of the ONC that have spectral types presented in Slesnick et al. (2004) or the literature later than M0. Thick-lined open histogram shown with \sqrt{N} errorbars indicates all stars; the dotted open histogram represents the same sample corrected for incomplete magnitude bins (see Figure 12 of Slesnick et al. (2004)).

subsequently drifted outside. This survey is targeted at identifying previously unknown young pre-main sequence stars and brown dwarfs, and is sensitive to hard to find intermediate-age ($\approx 3\text{--}100$ Myr) low mass objects, if present (see Section 3).

We were awarded six nights in the 2003B season on QUEST-2 to begin our variability survey of a $40 \times 4 \text{ deg}^2$ strip in the southern Taurus-Auriga region. We have four more nights scheduled for the end of 2004A to observe a similar area in Upper Sco. The goal of this survey is to first identify candidate pre-main sequence objects by looking for variability (see Section 3) and by requiring an object have R , $(R - I)$ magnitudes and colors consistent with those of young substellar objects at the distance of either Taurus or Upper Sco (140 and 145 pc). Since variability itself is not a unique indicator of youth, we will follow-up candidate pre-main sequence brown dwarfs using the Double Spectrograph on P200 to obtain optical spectra with sufficient resolution to determine spectral types (thereby confirming the objects are substellar) and search for Li I absorption signatures. For stars and brown dwarfs with convective envelopes lithium is depleted in the stellar atmosphere once core temperatures reach $\approx 2 \times 10^6$ K. Therefore lithium absorption, if still abundant in the photosphere, is a standard indicator that a low mass object is young. Magazzú et al. (1997) have found intermediate-mass F–K pre-main sequence stars located up to tens of degrees away from the Taurus cluster by measuring Li I $\lambda 6708 \text{ \AA}$ equivalent widths of X-ray selected stars, and comparing them to older nearby Pleiades objects of the same spectral type. Our QUEST-2 data combined with optical spectra will allow us to identify lower mass brown dwarf equivalents. For the lowest mass objects ($M < 63 M_{Jup}$; Burrows et al. 2001) whose core temperatures are never sufficient to deplete lithium, youth will be assessed through surface gravity sensitive features in the spectra.

Though we have only very recently begun receiving data from the QUEST team, based on preliminary analysis of a small data subset we anticipate finding > 100 objects within the Taurus

region alone which show signatures of variability and have magnitudes/colors consistent with those of young low mass objects. While the majority of these candidate pre-main sequence objects will be stellar rather than substellar, the brown dwarfs will be easily identified from spectral types. From our P200 spectra we will be able to measure radial velocities for targets with reasonable precision ($\pm 1-2$ km/s). This information combined with positive signatures of youth from Li absorption measurements or surface gravity analysis will allow us to establish cluster membership (and therefore distance) of pre-main sequence brown dwarfs. We will use derived spectral types combined with QUEST-2 photometry to construct an HR diagram for new cluster members from which we will infer a mass and age for each object. Age distributions will be analyzed, though depending on the observed spread results may be inconclusive particularly for Upper Sco due to the closeness of theoretical isochrones at intermediate-ages (10–100 Myr). More definitively, from this information we will be able to construct mass distributions for Upper Sco and previously unstudied outer regions of Taurus, similar to our studies in the ONC. Thus, with my thesis we will expand the number of clusters with spectroscopically derived substellar IMFs, thereby allowing us to draw more definitive and statistically robust conclusions about how external environment (ie., density, massive star content) influences the formation history of substellar objects within a cluster.

2.2 Spatial Distributions of Substellar Objects in Clusters

Evidence has been found for primordial mass segregation both in rich clusters (eg., ONC; Hillenbrand & Hartmann 1998) and more sparsely populated regions (eg., η Cha; Lyo et al. 2004). However, in Taurus Briceño et al. (2002) find no evidence for differences in the spatial distributions of low and intermediate mass objects. More detailed studies of the inner and outer regions of clusters are needed before we can draw conclusions about the cause of primordial mass segregation and whether it extends to the lowest mass objects. Our spectroscopic studies will allow us to analyze the spatial distributions as a function of mass and age for low mass stars and brown dwarfs within all three clusters. We will also be able to look at the radial velocity distributions of brown dwarfs in the outer parts of Taurus and Upper Sco. Two predictions of the ‘embryo ejection hypothesis’ of brown dwarf formation are that clusters should have a halo of brown dwarfs in their outer regions and that the velocity distribution for brown dwarfs within a cluster should extend to a high velocity tail. A study such as ours which will measure both the spatial and radial velocity distributions of brown dwarfs in outer cluster regions will provide crucial discriminating evidence between formation scenerios.

3 Young Brown Dwarfs as Individual Objects

We expect differences in accretion and disk properties of brown dwarfs compared to those of stars due to their lower mass and cooler nature. My thesis will explore optical and UV activity signatures (both accretion and chromospheric in origin), and mid-IR disk signatures of substellar objects within Taurus and Upper Sco. Of particular interest is how activity and disk properties have evolved from 1 Myr (Taurus) to 5 Myr (Upper Sco).

3.1 Activity in Low Mass Objects

Activity in young, low mass stars and brown dwarfs occurs through a number of processes, the two most prominent being related to accretion of material from the circumstellar disks onto the photosphere thereby producing hot spots (youngest stars, < 3 Myr) and chromospheric activity which causes modulation of the photometry due to the presence of large, cool spots produced by

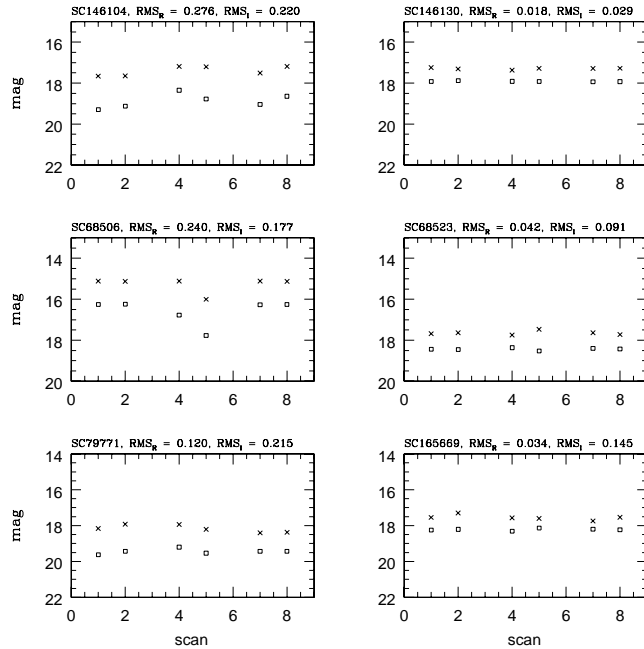


Figure 2: Left panels show light curves of 3 candidate variable stars. Corresponding right panels illustrate light curves for the closest (spatially) non-variable object with the same number of detections. Boxes and X's represent R - and I -band data, respectively. Scans were taken on 4 consecutive nights, two per night. Scans 3 and 6 were determined to be highly non-photometric and have been left out of our preliminary analysis. In all cases photometric errorbars are smaller than the plotted symbol and thus are not shown.

magnetic fields (young, as well as older stars up to at least the 120 Myr age of the Pleiades). The QUEST-2 variability survey (see above) will identify and monitor young stars and brown dwarfs which show signs of photometric variability, both periodic (which may indicate chromospheric activity) and irregular (likely due to hot spots from accretion). Figure 2 shows light curves in R and I magnitudes for three isolated objects in our survey which meet all criteria described in Section 2 for consideration as a candidate pre-main sequence object (left side panels). The right-side panel next to each target light curve shows the light curve for the closest ($<60''$) object with a similar number of detections, to demonstrate the quality of the photometry.

The optical wavelength regime is of extreme interest for young low mass objects and brown dwarfs because it contains a host of activity-sensitive spectral features. In particular, we expect such objects to exhibit $H\alpha$ emission, produced either via chromospheric activity or accretion. The $H\alpha$ line profile shape has been traditionally used as a robust discriminator between activity processes (cf., Muzerolle et al. 2003). Broad, asymmetric profiles produced from infalling accretion will be easily distinguished in our P200 spectra from the more narrow and symmetric profiles produced from chromospheric activity. In addition, our spectra will contain the Ca II triplet as well as several permitted ($\text{He I } \lambda 6678 \text{ \AA}$) and forbidden ($[\text{O I}] \lambda 6300$, $[\text{Si II}] \lambda 6716$, $\lambda 6731 \text{ \AA}$) lines, which, if seen in emission at stronger than typical dwarf/non-accreting T Tauri star levels, are indicative of active accretion and/or accretion-induced outflows.

Activity in young stars is also observable via UV excess emission. This emission has been

seen in classical T Tauri stars to arise both from accretion shocks and from magnetically-driven chromospheric activity (Johns-Krull et al. 2000), and flux measurements must be combined with stellar temperature estimates (eg., from spectral types) to decouple their origins. Due to sensitivity restrictions, UV emission has not yet been explored for substellar objects. We have proposed for GALEX observations (18 orbits) of regions within Taurus and Upper Sco, placing emphasis on regions of overlap with our QUEST-2 fields. These observations are not targeted at specific objects but instead will provide $\lambda 1516 \text{ \AA}$ and $\lambda 2267 \text{ \AA}$ emission measurements for all objects within our fields. We will measure UV fluxes for known QUEST-2 pre-main sequence objects as well as new young cluster candidates. The high sensitivity of GALEX beyond previous instruments will allow us an unprecedented opportunity to explore UV excess properties of young brown dwarfs.

We will analyze activity signatures in the optical spectra and UV GALEX data for brown dwarfs of different ages found in both regions. Our observations will explore a much larger sample of objects than has previously been investigated in this manner (cf., Muzerolle 2003). In the case of Upper Sco these objects will be located both in the inner regions and much further from the hot ionizing stars which may disrupt circumstellar disk material leading to decreased accretion.

3.2 A mid-IR study of Disks around Brown Dwarfs

As discussed in Section 1, most observational evidence points us to the conclusion that disks around young brown dwarfs are common. However, lower characteristic masses, temperatures and accretion rates for circum-brown dwarf disks compared to circumstellar disks will lead to differences in composition as well as dispersal mechanisms and timescales. The existence of a near-IR excess has commonly been used to infer the presence of disks around stars. This technique is less effective when we investigate cool objects for which emission at 1-3 μm is largely dominated by the stellar photosphere. Disks around the lowest mass objects as well as those with moderate ($>3 R_*$) inner truncation radii will be detectable only in the mid- and far-infrared. Smaller irradiating flux from cooler photospheres means that the temperature range probed by mid-infrared observations is closer to the source (inner few tenths of an AU in the disk; see Figure 3), allowing us to infer inner disk structure in finer detail around young brown dwarfs than is possible for hotter stellar objects.

Natta et al. (2002) analyzed a sample of 9 known brown dwarfs in the 1 Myr ρ Ophiuchi star-forming region which were detected by ISOCAM at both 6.7 and 14.3 μm (Bontemps et al. 2001). For all objects they find excesses at mid-IR wavelengths consistent with optically thick disks, and place some (self-admittedly weak) constraints on individual disk geometries and accretion. *Spitzer* has $>10\text{-}1000\times$ the sensitivity of any previous mid- to far-infrared instrument. Therefore, it allows for the first time a more detailed and precise study of disks around young brown dwarfs.

We have proposed for 30 hr of *Spitzer* time using combined IRAC, MIPS and IRS observations of a sample of 20 spectroscopically confirmed young substellar objects: 10 in the Taurus dark cloud and 10 in the Upper Scorpius OB association. Photometry (*RI, JHK*) as well as low-resolution spectroscopy is available for all objects, either from our own work or the literature. These data allow us to construct the energy distribution for each underlying photosphere, and project it into the mid-infrared. The *Spitzer* observations will reveal either this photosphere or excess emission from circumstellar disk material. We will observe spectral features diagnostic of disk composition and grain size, particularly the expected 9.7 and 18.5 μm amorphous silicate features and perhaps crystalline silicates or PAH's which may be present depending on the heating history of the disk. The presence of water-ice and solid CO₂ absorption features at 6 μm and 15 μm would, for the youngest sources, inform us regarding the thermal history of their proto-brown dwarf envelopes. IRAC photometry will sample the short wavelength spectral energy distribution, closest to the central heating source, while MIPS photometry will place constraints on inner disk truncation radii

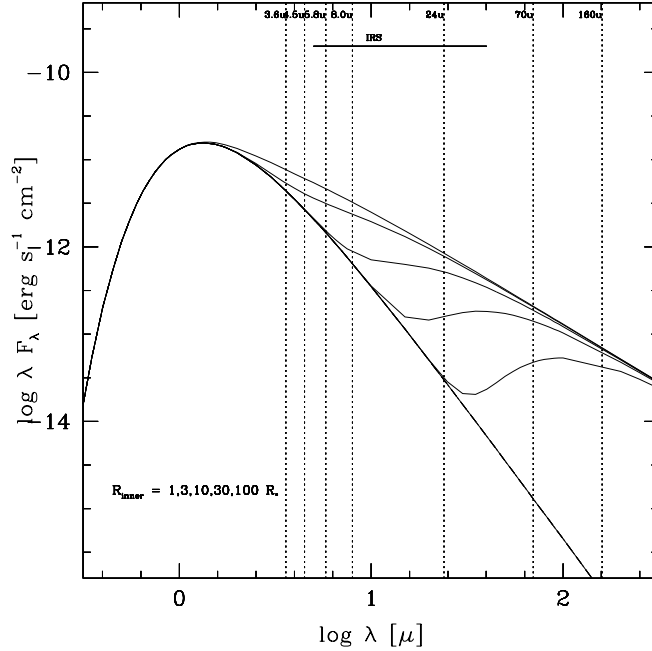


Figure 3: Blackbody photosphere for a 1 Myr $0.06 M_{\odot}$ star and model emission from a flat circumstellar disk with inner disk truncation radii of 1.3, 10, 30 & 100 R_{*} ($100 R_{*} = 0.23$ AU). Vertical lines indicate the *Spitzer* photometric bands. For objects with small inner disk radii we expect disk emission to be many times the photospheric level.

for objects not detected with IRS. Simple blackbody modeling will provide initial characterization of the dust excess (e.g. inner radius) with a minimal number of parameters.

Work done by Johnstone et al. (1998) indicates that disks around low mass stars near hot OB stars in the ONC will be significantly disrupted. Comparison between our two samples, Taurus and Upper Sco will enable us to assess whether star formation environment (e.g. density and massive star content within the cloud) might play a role in disk evolution around brown dwarfs.

We are aware of the possibility that the *Spitzer* proposal may not be awarded time. We have been allocated time this May at Keck on LWS to obtain ground-based $10 \mu\text{m}$ fluxes for a small number of brown dwarfs in Upper Sco. Even with this data alone we will be able to construct SEDs for objects into the mid-IR and place limited constraints on inner disk truncation radii. We will immediately be able to compare our results for 5 Myr brown dwarfs with those of Natta et al. (2002) for the 1 Myr ρ Oph stars, thereby gaining new insights into how circum-brown dwarf disks evolve from 1–5 Myr.

4 Summary and Timeline

The combined data discussed in Section 3 will explore mid-IR disk properties, accretion signatures, and chromospheric activity for the Taurus and Upper Sco substellar populations. From this information we will be able to address questions regarding the early evolution of brown dwarfs. Do dust properties and composition in circum-brown dwarf disks evolve in the same manner and on similar time scales as in disks around higher mass stellar objects? How is the inner disk truncation radius

affected by the temperature of the central object? Assembly of spectral energy distributions and accretion signatures for young brown dwarfs at ages 1–5 Myr will determine for the first time an evolutionary sequence for the circumstellar material surrounding young substellar objects. We will be able to further analyze this sequence in light of environmental conditions (ie., density, OB star presence). Our completed (Slesnick et al. 2004) and on-going (QUEST-2 survey) studies of the mass, age and spatial distributions of young brown dwarfs in clusters (Section 2) will help answer fundamental but as yet unresolved questions regarding brown dwarf formation. What is the role of primordial mass segregation in cluster formation? Does it depend on star formation environment? Is the substellar IMF universal? Together the investigations in my thesis will bring new insights into the processes involved in young brown dwarf formation and early evolution and how they are affected by external environmental factors.

Timeline:

- Fall 2002-Winter 2004: Begin and complete a spectroscopic study of the substellar ONC population. Slesnick, Hillenbrand, & Carpenter 2004, ApJ, in press (astro-ph/0404292).
- Spring 2004: Begin work on QUEST-2 variability survey of Taurus and Upper Sco. Obtain LWS 10 μ m photometry for brown dwarf objects in Upper Sco.
- Summer 2004: Determine if we have been allocated *Spitzer* time. Continue working on QUEST-2 Data. Begin reducing LWS data.
- Fall 2004: Begin obtaining optical spectroscopy of QUEST-2 candidates. Propose for Double Spec follow-up observations of Upper Sco QUEST-2 candidates. Analyze and write-up LWS data.
- Winter 2004: Analyze data from Double Spec and GALEX.
- Spring 2005: Write up QUEST-2, Double Spec and GALEX data. Analyze *Spitzer Data*
- Summer 2005: Write up *Spitzer* data.
- Fall 2005: Apply for jobs.
- Winter 2005: Write Thesis.
- Spring 2006: Defend.

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