Scientific Justification

Young Brown Dwarfs Harbor Disks - 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 same sequence as the standard star formation model (cloud-core fragmentation, collapse, and subsequent accretion of material onto a hydrostatic core). Most alternate theories lead 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. Such theories are 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 which occurs at much lower rates than found for comparably aged stellar mass objects. Disks around young substellar objects are thus common.

Although brown dwarfs are therefore likely to form in a manner analogous to stars, young circum-brown dwarf disks may be remarkably different than the disks surrounding higher mass young stellar objects. 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, and lead to longer disk lifetimes with corresponding effects on the potential of brown dwarfs to form planetary systems.

Role and Uniqueness of Spitzer - The near-infrared imaging surveys that have been successful at diagnosing large numbers of disks around pre-main sequence stars and brown dwarfs are sensitive to warm circumstellar gas and dust. Measured near-infrared excesses are modest for cool objects whose 1–3 μm emission is dominated by the stellar photosphere (Figures 1,3). Findings to date on disk frequency for young brown dwarfs are therefore only lower limits. 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 (Figure 3). Smaller irradiating flux from cooler photospheres means that the temperature range probed by infrared observations is closer to the source, allowing us to infer inner disk structure in finer detail around young brown dwarfs than is possible for hotter stellar objects. Previous ISO spectroscopic studies only had the sensitivity to explore high and intermediate mass objects. Limited ISO photometric study of brown dwarf disks provided mid-infrared detection but no real constraints on models (Testi et al. 2002; Figure 4) . Because *Spitzer* has >10-1000× the sensitivity of any previous mid- to far-infrared instrument, it allows us for the first time to study in detail disks around young brown dwarfs. Several of the existing Legacy and GTO programs will probe properties and evolution of disks around young stars, largely in the range 0.8-3 $M_{\odot}$. We will obtain a complementary set of data in the unique substellar mass regime.

Sample Description - We propose to observe a sample of 20 spectroscopically confirmed young substellar objects: 10 in the Taurus dark cloud (1–3 Myr) and 10 in the Upper Scorpius OB association (10 Myr). Objects were selected to be cooler than M6 (Taurus) and M5.5 (Upper Scorpius) which at the relevant ages corresponds to masses less than 0.1 $M_\odot$ (Figure 2). Taurus and Upper Sco are two of the closest recently star forming regions to the Sun (D=140 pc and D=145 pc, respectively). The factor of ten age range spanned by these two clusters will allow us to explore disk evolution, which is expected to proceed rapidly from 1–10 Myr (Hillenbrand et al. 2004). They also provide two distinct star-forming environments: Taurus is sparsely populated and does not contain any massive stars while the more evolved, dense OB association Upper Sco provides targets whose disks may have been influenced by external sources of ionizing radiation.

Upper Sco objects were selected from Ardila et al 2000. Four potential candidates were rejected based on surface gravity analysis and/or Li I equivalent widths (Slesnick et al. 2004; Muzerolle et al. 2003; White & Hillenbrand 2004) indicating they are not likely members of the association. Two others were excluded due to lack of spectroscopic data to confirm temperature and membership. The remaining sample of 10 objects is a complete survey of confirmed brown dwarfs in Upper Sco. Spectroscopically confirmed targets in Taurus are from White & Basri (2003), Luhman et al. (2003), Briceño et al. (2002), and Martín et al. (2001). Two potential candidates are already scheduled to be observed in IRS/GTO programs and were removed from our sample. We have chosen 10 of the remaining confirmed brown dwarfs to complement our 10 objects in Upper Sco. For each cluster the objects span a broad range in spectral type (M6–M9.5).

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 using atmosphere models, and project it into the mid-infrared (see Figure 1 for blackbody photospheric approximations). The *Spitzer* observations will reveal either this photosphere or excess emission from circumstellar disk material. Our existing high resolution spectra allow us to measure more accurate temperatures (crucial for determining masses), derive mass accretion rates onto the photospheres, and assess short-period binarity. In addition, all objects are part of an HST Cycle 12 program (PI White) to search for long period binaries. The effect of binarity on circumstellar material is to truncate circumstellar disks and partially disrupt circumbinary disks (Jensen et al. 1996).

Proposed Observations - We request a total of 30 hours for this project using the IRAC, MIPS, and IRS instruments. Together these data enable us to construct finely sampled (and cross-calibrated) spectral energy distributions out to 40 μm. We have chosen exposure times which reach photospheric levels at 10σ with IRAC and IRS-SL. Sensitivity of the IRS-LL modules is generally not sufficient to detect young brown dwarf photospheres; thus for all but the brightest targets we will integrate to a level of ~10× the expected photosphere (see Technical Justification). The increased sensitivity at equivalent wavelengths of MIPS 24 μm observations over IRS LL observations will allow us to reach with photometry to photospheric levels at 5-10σ for all targets.

The wavelength regime covered by *Spitzer* is particularly important for constraining circumstellar disk models. Compared to the sparsely sampled spectral energy distributions available (at any mass) thus far, *Spitzer* will provide *spectrophotometry* in the critical 5-40μm region supplemented in our study by photometry. 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 CO_2 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 for objects not detected with the LL modules of IRS.

A Detailed Study of Brown Dwarf Disks - For our 1-10 Myr brown dwarfs we will probe the inner few tenths of an AU in the disk, closer to the central object than is possible from analysis of spectral energy distributions for hotter (higher mass) central sources. We will first create a model of the underlying stellar photosphere using e.g. Allard et al. (2000) models which will be subtracted from the the assembled spectral energy distributions to reveal the dust re-emission spectrum. In our simplest analysis we will compute the integrated infrared excess and fractional excess (L_{IR} and L_{IR}/L_*), and the wavelength at which sustained significant departure from the predicted photosphere first occurs. Simple blackbody modelling will provide initial characterization of the dust excess (e.g. inner radius) with a minimal number of parameters. More detailed modelling that accounts for both radial and vertical structure in the disk as well as grain properties will be implemented following the Dullemond et al. (2002) prescriptions, with which we already have experience (e.g. Eisner et al. 2004).

The Spitzer data combined with our previous work on young brown dwarf stellar parameters, accretion rates, and binarity will allow us to address with the Taurus and Upper Sco samples several fundamental questions regarding brown dwarf disk properties and evolution. Does disk chemistry evolve in the same manner and on similar time scales as for disks around higher mass stellar objects? What are the respective roles of accretion vs. irradiation for disk heating? How is the inner disk truncation radius affected by the temperature of the central object and of the accretion shocks? How does binarity affect disks and disk evolution? Assembly of spectral energy distributions for young brown dwarfs at ages <1-10 Myr will determine for the first time an evolutionary sequence for the circumstellar material surrounding young substellar objects. 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.

For objects in which we do not detect disks, we will still be able to place limits on the inner disk truncation radius and, unprecedentedly, with IRS assess the *photospheric spectra* of young brown dwarfs in the mid-infrared which may be compared to model atmospheres (e.g. Burrows et al. 1997, Saumon et al. 2004).

Technical Plan

Target Selection - We propose to use the *Spitzer* Space Telescope to observe a sample of 20 spectroscopically confirmed substellar objects: 10 members of the sparsely populated Taurus T association (1–3 Myr) and 10 members of the dense, more evolved OB association Upper Scorpius (10 Myr); see Observations Summary Table for details. Because both Taurus and Upper Scorpius are large clusters and our targets are spread over > 3 degrees within each region, we are requesting all observations as fixed single targets.

IRAC Observations - We request a total of 1.13 hours for IRAC photometry observations of Upper Sco targets. Objects in Taurus are scheduled to be observed as part of large maps in existing GTO programs and we will include these data in our analysis when they become available. Because most of the sources in Taurus have known L-band magnitudes, IRAC observations in this region are not as critical for initial disk characterization. Exposure times in Upper Sco were set by requiring detection of photospheric emission at S/N $\sim$10 in a single pointing in all four bands (3.6, 4.5, 5.8 & 8 μm) for each object. In the high background limit (as it is defined by the relevant tables available on the *Spitzer* web-site this limit pertains to both Taurus and Upper Sco) a 2 second exposure results in 10σ sensitivities sufficient to achieve the desired S/N for most sources. The faintest 6 targets require a 12 second exposure time. We have opted to observe in full array mode to reduce the number of telescope shifts required. Observations will be taken in a five-point Gaussian pattern with medium scale factor which provides us sufficient coverage for cosmic ray rejection (as recommended by Chapter 6 in the *Spitzer* Observer's Manual) in the minimum amount of time. All objects were examined visually using the SPOT imaging tools to verify that bright objects do not fall in regions which could scatter light into the IRAC field of view.

IRS Staring Observations - We request a total of 21.76 hours using all four SL and LL modules of IRS in staring mode. Exposure times were estimated to detect photospheric emission at S/N $\sim$10 with the SL modules. The sensitivity of the LL modules is not sufficient to detect photospheric emission (at 10σ) for objects fainter than $\sim$1.78 mJy at 17.6 μm corresponding to an M7 star with $K_S \sim 11.8$. For objects less luminous than this limit we integrate to a maximum exposure time of 1200 seconds which allows us to detect even our faintest object at $10\times$ the photospheric flux (which should be sufficient to study disk emission; see Figures 3 & 4) with 8.5σ and 2.5σ sensitivities for the LL2 (17.6 μm) and LL1 (30.3 μm) modules, respectively. The 3σ sensitivity limits for a 1200 second exposure are $\sim$30% better than those shown in Figure 1 for a 500 second integration. We chose to use the longest ramp durations possible within the needed total exposure time to maximize efficiency in telescope moves and signal detected (backgrounds were checked to ensure there is no possibility of saturation). Each cycle provides a spectrum at two positions along the slit to reduce the effects of cosmic ray hits and allow for more accurate background subtraction. All positions were verified visually using the image tools in SPOT to ensure that no bright object would fall in the peak-up array windows during SL integrations. Despite success of the blind pointing of the telescope (0.5"–1.0") which should certainly put all targets into even the narrowest SL slit (3.6"), we choose to utilize the IRS peak-up option. We are requesting relatively long exposure times (up to 20 minutes for a single module) and it is therefore important to calibrate *Spitzer*'s inertial frame after pointing to ensure that the object does not drift out of the slit during integration. Our targets are too faint to use as peak-up objects and we use offset stars found from the 2MASS catalog identified with the interactive SPOT tools. Moderate peak-up with the blue IRS peak-up sub-array provides sufficient accuracy for our purposes (1.0" plus an additional 0.2" rms from moving to the target from an offset star) while requiring the least amount of overhead.

MIPS Photometry - We request a total of 7.33 hours for MIPS 24 μm observations in small aperture photometry mode. Exposure times were determined to detect photospheric emission with S/N $\sim$5 in the high background limit. A maximum exposure time was set at 2240 seconds which will detect *photospheric* emission at S/N $\sim$3, even for the faintest objects. However, because we expect the majority of our targets to have circumstellar material, we anticipate higher detection signals for most objects. The 3σ sensitivity limit for a 2240 second exposure at 24μm in a region of high background is $\sim$50% better than that shown in Figure 1 for a 500 second integration with medium background. Because all of our targets are located in regions of high background we cannot use the longest exposure per pointing time of 30 seconds and instead use 10 second exposures despite slight increases in overhead. Each cycle results in 14 dithered exposures providing ample redundancy for cosmic ray rejection even when relatively few cycles are requested.

Data Analysis Plan - We anticipate using the Basic Calibrated Data (BCD) products from the SSC pipeline, which will include flat-fielding, dark subtraction, droop corrections and other calibrations specific to the *Spitzer* instruments. However, because we are exploring objects located in regions with high and possibly structured backgounds, we expect that the most accurate photometric and spectral data will be achieved via interactive analysis. Therefore, we plan to perform photometry and extract spectra by hand using tools within IRAF to help confirm the final post-BCD data which will come out of the automated processes in the SSC pipelines. We may also take advantage of Legacy/FEPS software development efforts once released to the community. We have previous experience dealing with near- and mid-infrared data, and with extracting both photometric and spectral data from challenging regions (cf., Hillenbrand & Carpenter 2000; Metchev et al. 2003; Slesnick et al. 2004).

Project Summary: Mid-infrared spectrophotometry of young substellar objects will provide information regarding the composition, structure, heating, and evolutionary time scales for circum-brown dwarf disks, which will add to our currently limited knowledge of substellar formation. We have carefully selected our sample to span a range of evolutionary stages and star-forming environments and already possess the ancillary information which will greatly strengthen the scientific return from the proposed *Spitzer* observations. The IRS observations are the most critical part of this program. Our data set is complementary to existing approved (GTO/Legacy) *Spitzer* programs which will explore the circumstellar environments of young objects at masses higher by a factor of >10, and the photospheric properties of comparably low mass but much older, nearby field brown dwarfs. Follow-up observations including MIPS 70, 160, and/or SED observations as well as numerous ground investigations may be motivated by our results.

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Figure 1 - Observed optical and near-infrared flux levels for our sources shown with blackbody photospheres normalized at *K*-band and projected into the mid- and far-infrared. Many of our sources have near-infrared *L*-band excesses indicative of circumstellar material. The sensitivity and uniqueness of *Spitzer* compared to previous infrared observatories is illustrated by 3σ detection limits for 500 second *Spitzer* exposures in a region of medium background.

Figure 2 - HR diagram for substellar sample to be observed with *Spitzer*. Targets in Taurus and Upper Sco are shown as circles and squares, respectively. Pre-main sequence stellar and brown dwarf evolutionary models are from D'Antona & Mazzitelli (1997). Our targets are < 0.1 $M_\odot$ and span ages from <1–10 Myr.

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 actively accreting objects and objects with small inner disk radii we expect disk emission to be many times the photospheric level.

Figure 4 - Figure 4 of Testi et al. (2002). The thick grey line shows a model photosphere ($T_* = 2400$ K) taken from the work of Allard et al. (2000). Solid and dotted lines show combined photosphere plus flared disk model predictions for inner disk radii equal to 1 and 3 R_*. Data points are mid-infrared ISOCAM observations from Comerón et al. (1998) and Bontemps et al. (2001). Photometric accuracies of $\lesssim$10% for all three *Spitzer* insruments will allow us to constrain disk model parameters with much higher precision than was possible with observations from previous infrared observatories.

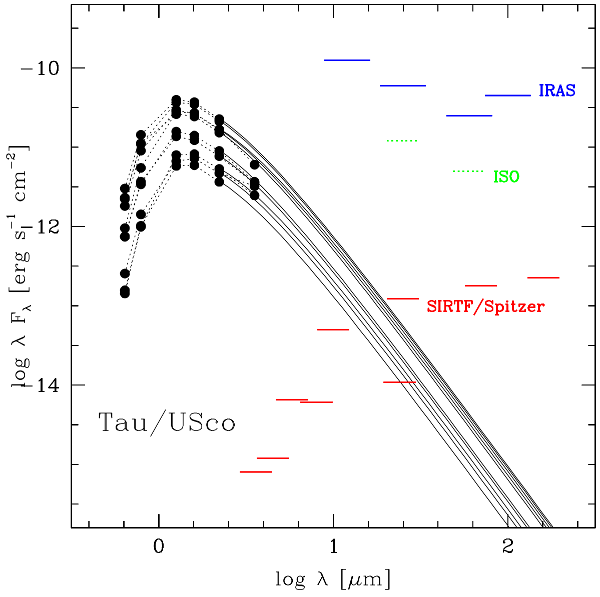

Figure 1

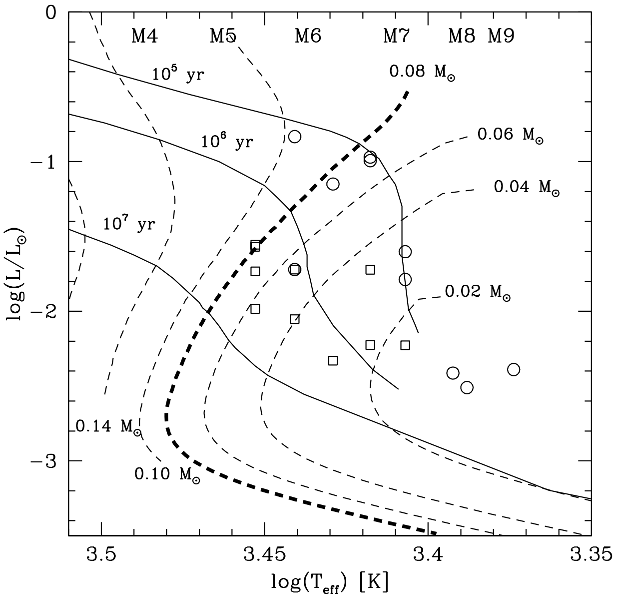

Figure 2

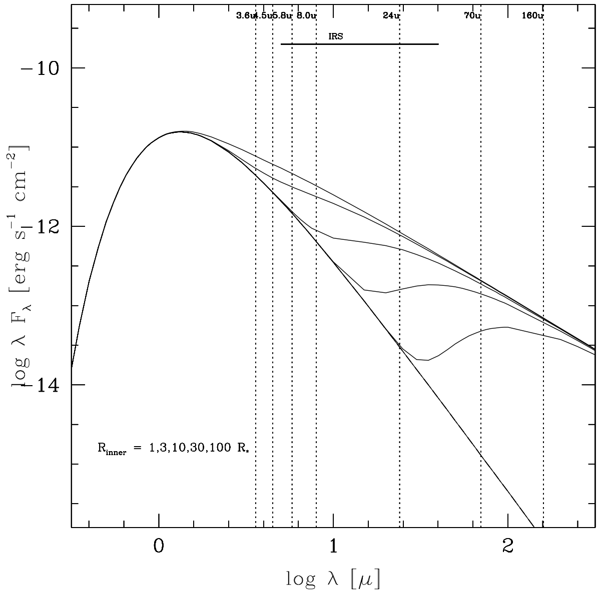

Figure 3

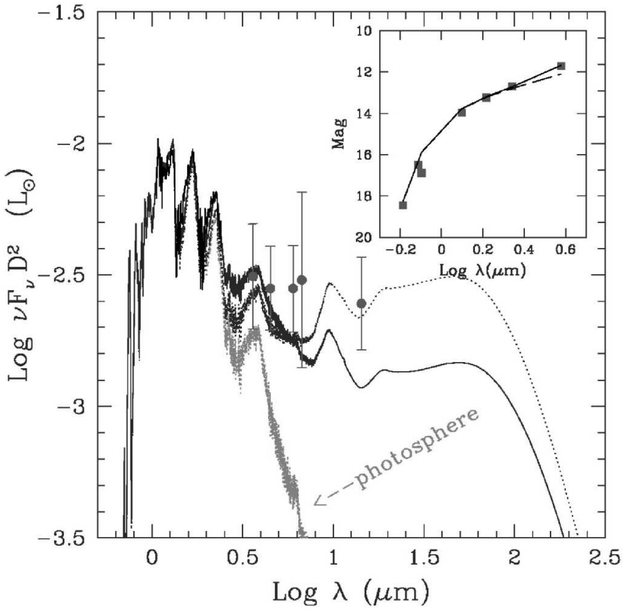

Figure 4

Table 1. Observations Summary

					Time [sec]					
					IRAC Photometry[a]		IRS Staring[b]		MIPS Photometry[c]	
ID	RA [deg]	DEC [deg]	Sp Type	K_s [mag]	Exp	AOR	Exp	AOR	Exp	AOR
KPNO-Tau3	66.622	26.404	M6	12.079	···	···	2770	3916	459	725
KPNO-Tau4	66.867	26.201	M9.5	13.281	···	···	3649	4975	2424	2943
KPNO-Tau5	67.440	26.513	M7.5	11.536	···	···	2097	3120	313	571
KPNO-Tau6	67.530	26.139	M8.5	13.689	···	···	3889	5258	2424	2943
KPNO-Tau7	67.738	25.944	M8.25	13.272	···	···	3649	4959	2424	2943
MHO-5	68.067	18.213	M7	10.063	···	···	1513	2396	92	351
MHO-8	68.258	24.350	M6	9.726	···	···	1513	2419	92	351
CFHT-Tau2	69.043	22.999	M7.5	12.169	···	···	2648	3779	459	725
GMTau	69.589	26.154	M6.5	10.632	···	···	2034	3046	92	351
CFHT-Tau4	69.948	26.028	M7	10.332	···	···	1757	2705	92	351
UScoCTIO128	239.797	-23.633	M7	13.207	240	479	3649	5243	2424	2943
UScoCTIO67	239.858	-23.086	M5.5	11.568	40	374	2619	3720	313	571
UScoCTIO130	239.932	-20.244	M7.5	13.075	240	479	3166	4375	1799	2183
UScoCTIO131	240.081	-22.941	M6.5	13.481	240	479	3771	5390	2424	2943
UScoCTIO112	240.111	-20.942	M5.5	12.507	40	374	2926	4087	1047	1341
UScoCTIO75	240.126	-23.579	M6	11.841	40	374	2619	3719	459	725
UScoCTIO109	240.330	-23.111	M6	12.672	40	374	2926	4093	1212	1567
UScoCTIO66	240.456	-23.852	M5.5	11.927	40	374	2619	3719	459	725
UScoCTIO100	240.518	-20.845	M7	11.827	40	374	2619	3739	313	571
UScoCTIO55	240.691	-23.081	M5.5	11.502	40	374	2619	3733	313	571
			Total Number of AORs		10		20		20	
			Total AOR time		1.13 hr		21.76 hr		7.33 hr	

[a] On source integration times estimated to detect photospheric emission at SNR ∼ 10.

[b] On source integration times estimated to detect photospheric emission at SNR ∼ 10 for SL modules and set to 1200 sec for LL modules (except for sources bright enough to detect photospheric emission at SNR ∼ 10 in less time).

[c] On source integration times estimated to detect photospheric emission at SNR ∼ 5.

Personnel:

Hillenbrand (Professor of Astronomy, Caltech) is experienced in general research on young stellar populations including optical/infrared photometric surveys, optical/infrared spectroscopy, the initial mass function, stellar age diagnostics, disk accretion indicators (Muzerolle et al. 2000, ApJL, 545, 141; Muzerolle et al. 2003, ApJ, 592, 266), and most relevant to the analysis required for this proposal SED modelling (Hillenbrand et al 1992, ApJ, 397, 613; Wolf & Hillenbrand 2003, ApJ, 596, 603; Eisner et al. 2004, ApJ, submitted). In terms of *Spitzer* science she is involved as deputy PI in the Meyer et al Legacy program FEPS which aims to study late-stage primoridal disk evolution as well as debris disk evolution in a sample of solar-mass stars ranging from 3 Myr to 3 Gyr in age. Several publications from ground-based ancillary work (Williams et al. 2004, ApJ, in press; Metchev, Hillenbrand, & Meyer 2004, ApJ, 600, 435; Metchev, Hillenbrand, & White, 2003, ApJ, 582, 1102; White, Hillenbrand, & Gabor, 2004, in preparation) have already resulted. At present the FEPS team have obtained and analyzed our 1% *Spitzer* validation observations, have released our program for execution, and are preparing an ApJ Letter for the *Spitzer* special issue.

Slesnick is a third year graduate student in good standing at Caltech. The proposed project is a major component of her PhD thesis work which also includes a paper (Slesnick, Hillenbrand, and Carpenter, ApJ, submitted) on spectroscopic confirmation of a young brown dwarf population in the Orion Nebula Cluster (whose backgrounds are too high to enable follow up in the manner proposed here for Taurus and Upper Sco young brown dwarfs), and an optical variability survey of Upper Sco to identify new cluster members, in particular new 10 Myr old brown dwarfs.

White (Post-doctoral Scholar, Caltech) is experienced in optical high dispersion spectroscopy and related science including accretion indicators, age diagnostics, rotational and radial velocities, and spectroscopic binary orbits. He is an expert on young star multiplicity. Particularly relevant to this proposal is his work on the photospheric and accretion characteristics of our sample (White & Basri 2003, ApJ, 582, 1109; White & Hillenbrand, 2004, in preparation) and his nearly completed HST Cycle 12 program on the wide binary characteristics of our target stars.

Financial:

We anticipate requesting support for graduate student stipend and tuition at the California Institute of Technology. Our budget will also include ancillary requests for the student such as AAS and topical meeting travel, computing charges, and page charges.

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