The Spitzer Spectroscopic Star Formation Survey

I. Motivation

While a great accomplishment of modern astronomy was the development of a robust model of stellar evolution (Hoyle & Schwarzschild 1955), a similarly detailed portrait of the star formation process remains elusive. As stars are the simplest 'atoms' for building luminous structures in the universe, this shortcoming hinders progress in understanding phenomena as far afield as the enrichment of galaxies in heavy elements (Portinari et al. 2004) and the reionization of the universe (Loeb & Barkana 2001). The discovery of extra solar planets (Marcy & Butler 1998) and growing interest in astrobiology makes the need for constraints on the physics of star formation all the more urgent, as star formation sets the initial conditions for planet formation and the emergence of life.

Our current understanding of the star formation process begins with a dense molecular core undergoing gravitational collapse; conservation of angular momentum drives material from the infalling protostellar envelope to form an equatorial circumstellar disk (Terebey et al. 1984). Coupling of the stellar magnetic field to this disk regulates the angular momentum evolution and mass accretion of the protostar until the mass reservoir of the protostar's envelope and disk are fully depleted, resulting in a magnetically active pre-main sequence star (Shu et al. 1994). This theoretical framework predicts observable correlations between stellar properties and signatures of the accretion process (e.g., $\dot{\mathrm{M}} \propto \frac{R_*^4 f_{acc}}{M_* P_{rot}}$; Johns-Krull & Gafford 2002). Unfortunately, the physical properties of heavily embedded protostars have been difficult to measure directly, limiting most observational tests to optically visible T Tauri stars for which mass accretion has largely concluded.

Spitzer surveys are generating homogeneous catalogs of broadband infrared emission from circumstellar disks and embedded protostars (Class 0/I sources in the SED classification scheme of Lada 1987 and Andre et al. 1993) with unprecendented sensitivity and spatial resolution in a variety of star forming environments. **As a Spitzer fellow, I propose to use near infrared multi-object spectroscopy in concert with sub-millimeter interferometry to directly measure stellar and circumstellar properties ($\mathbf{T}_{eff}$, $\dot{\mathbf{M}}$, $\mathbf{F}_{disk}/\mathbf{F}_*$, etc.) of embedded protostars with extant Spitzer photometry.** This work will determine how accurately detailed physical parameters of protostars can be inferred from Spitzer photometry, providing a fundamental calibration for present and future Spitzer star formation studies. I will also use this catalog of derived physical parameters to identify embedded, actively accreting proto-brown dwarfs and to probe the connection between pre-main sequence rotation and circumstellar disks.

II. Observations

The Spitzer Spectroscopic Star Formation Survey (S^3FS) will target nearby star forming regions with IRAC imaging and significant populations of protostars (e.g., Serpens, NGC 1333, ρ Ophiuchus, etc.). Recent studies have demonstrated the ability of near infrared (NIR) spectroscopy to directly measure physical properties of protostars previously inaccessible to detailed spectroscopic analysis (Greene & Lada 2002; Doppmann et al. 2005; Covey et al. 2005a,b). Protostars identified in IRAC cluster surveys will be observed with NIR multi-object spectrographs (MMIRS on Magellan/MMT, or FLAMINGOS II on Gemini; both offer R $\sim$ 3000 and are expected for commissioning in 2006/early 2007). The efficiency of these instruments allow the detection of NIR photospheric features in tens of embedded stars as faint as K $<$ 16.5 in a single night. Observations of optically visible sources with Hectospec and Hectochelle (R $\sim$ 1000 and 40,000 respectively) on the MMT 6.5 m telescope will complete the census of cluster members.

Stellar parameters derived from NIR spectra will be complimentary to measurements of circumstellar material derived by ongoing sub-millimeter interferometric surveys of protostars (the PROtostellar Submillimeter Array Campaign; PROSAC). I will collaborate with the PROSAC team to obtain Submillimeter Array (SMA) observations of protostars amenable to NIR spectroscopy, allowing a complete characterization of protostellar photospheric and circumstellar properties.

III. Analysis

By combining *model independent*, direct physical measurements for each S^3FS source (see Table 1) with archival IRAC imaging data, I will investigate the following outstanding issues concerning the formation and evolution of embedded young stars and brown dwarfs:

A. Testing Protostellar Models: *How accurate are physical parameters of protostars derived from IRAC spectral energy distributions (SEDs) and scattered light morphologies? Are the physical properties of young stars correlated with location in IRAC color-color space?* The difficulty of obtaining direct physical measurements of protostellar cores has led many to infer physical properties from the shape of a protostar's broadband SED. This is typically done either by fitting observations to an SED+scattered light grid generated by detailed radiative transfer codes (Whitney et al. 2003, 2004) or by assuming the SED is dominated by accretion luminosity, revealing the depth of the protostar's gravitational potential. Unfortunately, the accuracy of these methods have yet to be observationally confirmed. As the emergent SED from a protostar depends on the details of scattering within and emission from a geometrically and physically complex environment, parameters inferred from SEDs with ∼7-10 data points are significantly degenerate (see Fig. 1).

The S^3FS K band spectra obtained in these clusters will produce the first complete survey of the physical state of protostellar populations, extending for the first time to magnitudes fainter than K $\sim$ 11. These spectra will break the degeneracies in fits to radiative transfer models and will allow physical properties (T_{eff}, $\dot{M}$, M_{env}) for each source to be mapped directly into IRAC color-color space. This exercise will determine if protostellar SEDs and scattered light morphologies are *physically* degenerate, or if model degeneracies are a signature of incomplete input physics. In either case, S^3FS will provide a robust observational estimate of the typical scatter between measured properties and those predicted from model fits to IRAC colors. Finally, a comparison of the physical properties ($\dot{M}$, M_*) of the embedded sample and the optically visible sample will reveal the amount of physical evolution occuring between the protostellar and Classical T Tauri stages.

B. Finding Embedded Brown Dwarfs: *How does mass accretion depend on protostellar mass at the earliest ages?* Young brown dwarfs appear to pass through an evolutionary stage analogous to the Classical T Tauri phase (Muzerolle et al. 2003; Luhman et al. 2005), but only a handful of candidate proto-brown dwarfs have been identified (White & Hillenbrand 2004). Spitzer is well suited for identifying candidate proto-brown dwarfs; one protostar has already been discovered whose SED has been interpreted as implying a sub-stellar mass (Young et al. 2004; Bourke et al. 2005; Huard et al. 2005), highlighting the promise of fully calibrated protostellar SED models.

This discovery, however, would be well served by spectroscopic confirmation; assuming an accretion dominated luminosity for the SED of Haro 6-33 predicts a substellar mass (Young et al. 2003), but follow-up spectroscopy reveals a spectral type (M0; White & Hillenbrand 2004) indicative of a stellar mass core. Additionally, at faint magnitudes (where proto-brown dwarfs will be found) some extragalactic sources have IRAC colors similar to protostars. With a K magnitude of 16.3 at 200 pc, L1014-like objects will fall within the S^3FS sample in nearby star forming regions. S^3FS spectroscopy will identify bona fide protostars and track T_{eff} well below the substellar limit at these young ages (Covey et al. 2005c). SMA observations of Keplerian rotation in disks around candidate proto-brown dwarfs will provide dynamical mass estimates (Simon et al. 2000), testing the dependence of $\dot{M}$ on M_* and constraining protostellar models at the lowest masses and ages.

C. Investigating Disk Locking: *What controls the angular momentum evolution of young stars?* Angular momentum must be extracted from stars during their formation; if this were not the case, stars would be observed to rotate more rapidly on the zero age main sequence (Hartmann et al. 1989). The interaction of a young star with its circumstellar disk via magnetospheric accretion columns (disk locking; Ostriker & Shu 1995) is expected to extract angular momentum, though some suggest accretion powered stellar winds may be the solution to the 'angular momentum problem' (Matt & Pudritz 2005a,b). Observations show stars hosting circumstellar disks rotate more slowly than stars without (Edwards et al. 1993; Herbst et al. 2001), with recent work showing that rotational braking must begin prior to the optically visible phase (see Fig. 2).

The optically visible S^3FS sample will produce a comprehensive set of homogeneous rotation rates for young stars as a function of age and environment. The presence of circumstellar disks around these stars will be diagnosed with Spitzer photometry, and mass accretion rates will be measured directly from S^3FS spectra. Coupling the kinematics and morphology of circumstellar disks and protostellar envelopes provided by SMA observations with recent measurements of angular momenta for embedded young stars (Covey et al. 2005a) will complete the angular momentum inventory of the protostellar phase. Using these combined S^3FS data products, I will test the relationships between stellar rotation, mass accretion and circumstellar disks predicted by theories of angular momentum dissipation via magnetospheric accretion or stellar winds.

IV. Benefits to Spitzer Science and Justification of Host Institution

The S^3FS program will refine the community's ability to infer protostellar properties (such as T_{eff} & $\dot{M}$) from Spitzer photometry, enabling more accurate photometric studies of clusters too distant for direct spectroscopic followup. As more Spitzer survey data becomes public, quantifying the reliability of protostellar parameters inferred from IRAC colors will grow increasingly important. S^3FS will also provide a homogeneous catalog of direct physical measurements for young stars in nearby clusters with IRAC imaging; these complimentary spectroscopic parameters, as well as the calibrated observations from which they were measured, will be made publicly available following a brief data verification period, providing added value to the Spitzer archive. Lastly, the role S^3FS will play in identifying proto-brown dwarfs and investigating disk locking will advance two of Spitzer's four core science themes: understanding the formation and evolution of brown dwarfs and protoplanetary disks (Werner et al. 2004).

The Center for Astrophysics is an ideal host institution for this research program. The CfAs access to multi-object spectrographs (MMIR, Hectospec/Hectochelle) on 6.5m class telescopes (MMT, Magellan) make a complete spectroscopic survey of multiple stellar clusters a tractable observational program, while collaboration with the SMA PROSAC team allows constraints to be placed on the geometric and kinematic structure of circumstellar material around young stars. Lori Allen and Phil Myers, as well as the CfA components of the IRAC instrument and GTO science teams, will provide invaluable expertise with Spitzer data products, particularly concerning the embedded clusters most central to this work. The broader community of CfA star formation scientists (including my sponsor, Charles Lada) with strong connections to Spitzer will be well suited to make fullest use of the S^3FS dataset, increasing the ultimate scientific output of this research program.

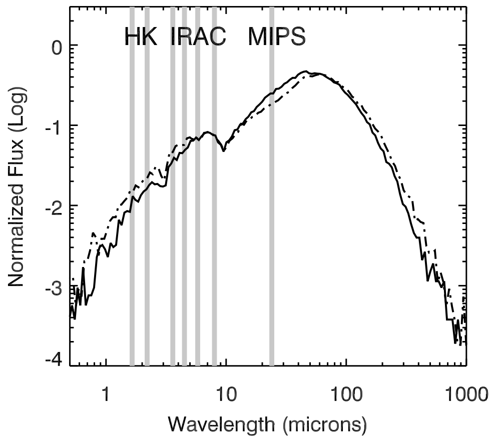
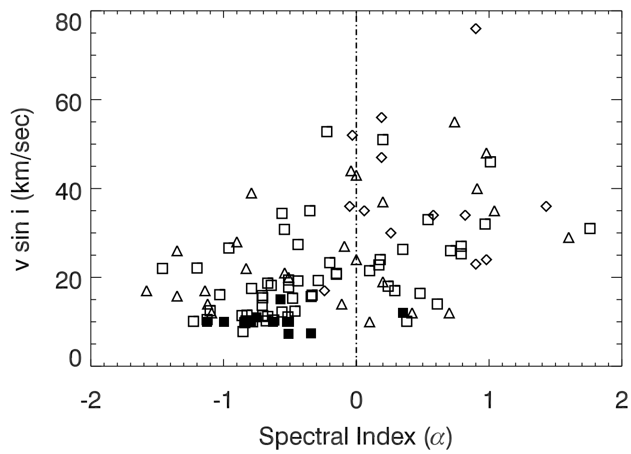


Figure 1 (left) – A demonstration of degeneracies in model SEDs of young stars. Sources shown have effective temperatures, mass accretion rates, inclinations and envelope centrifugal radii (a proxy for envelope mass) differing by factors of 2 to 100 (solid – T_{eff} = 3500 K, $\dot{M} = 10^6 M_\odot$/yr, R_{cent} = 200 AU, $i = 70°$; dashed – T_{eff} = 5000 K, $\dot{M} = 10^8$ $M_\odot$/yr, R_{cent} = 75 AU, $i = 40°$; Whitney et al. 2004). Differences in measured SEDs for these sources would be ∼20%, near the level of intrinsic photometric variability for young stars. S^3FS will break degeneracies in Spitzer protostellar SEDs by directly measuring T_{eff} and $\dot{M}$ for young stars, with sub-mm interferometry providing disk inclinations and mm maps measuring envelope mass (see Table 1).

Figure 2 (right) – Observed projected rotation velocity as a function of mid-infrared SED slope (α). Larger values of α indicate redder, more deeply embedded, stars. Symbols show objects in the Taurus (squares), ρ Ophiuchi (triangles) and Serpens (diamonds) star forming regions; filled symbols indicate a rotation velocity upper limit. The dashed vertical line divides embedded objects on the right from optically revealed sources on the left. While a range of rotation rates are seen at every evolutionary stage, the mean and maximum observed rotation velocities decline as sources become more optically visible, indicating angular momentum must be extracted from these sources as they emerge from their protostellar envelopes. Data from White & Hillenbrand (2004); Covey et al. (2005a) and references therein.



Measurements inside parentheses below indicate parameters requiring sub-mm/mm data.

Table 1. Constraining the physical state of young embedded stars

Physical Parameter	Near IR measurement	Method reference	Optical measurement	Method reference
T_{eff}	K band line ratios [CO, Ca, Na, Mg, Al]	Doppmann et al. (2005)	optical line ratios [CaI,Na,CaH_3,TiO,VO]	Le Borgne et al. (2003)
$\dot{M}_{disk}$	HI Br γ emission	Muzerolle et al. (1998)	Hα, CaII emission	Muzerolle et al. (2001)
F_{disk}/F_*	veiling of T_{eff} features	Doppmann et al. (2005)	···	···
$v \sin i$	(High-res followup?)	Covey et al. (2005a)	Doppler line broadening	Hartmann et al. (1989)
inclination	(sub-mm imaging of disk)	Qi et al. (2004)	method as in	embedded sample
M_*	(sub-mm imaging of disk)	Simon et al. (2000)	method as in	embedded sample
M_{env}	(Cores to Disks mm maps)	Motte et al. (1998)	method as in	embedded sample
$R_* \sin i$	···	···	$v \sin i$ & phot. period	Rhode et al. (2001)
$\log g$	···	···	fit to TiO, NaI, KI	Mohanty et al. (2004)

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