

Stellar Properties of Embedded Protostars

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Protostars are precursors to the nearly fully assembled T-Tauri and Herbig Ae/Be type stars undergoing quasi-static contraction towards the zero-age main sequence; they are in the process of acquiring the majority of their stellar mass. Although numerous young stars with spatially extended envelope-like structures appear to fit this description, their high extinction has inhibited observers from directly measuring their stellar and accretion properties and confirming that they are in fact in the main phase of mass accretion (i.e., true protostars). Recently, however, high dispersion spectrographs on large aperture telescopes have allowed observers to begin studying the stellar and accretion properties of a subset of these stars, commonly referred to as Class I stars. In this Chapter, we summarize the newly determined properties of Class I stars and compare them with observations of Class II stars, which are the more optically revealed T Tauri stars, to better understand the relative evolutionary state of the two classes. Class I stars have distributions of spectral types and stellar luminosities that are similar to those of Class II stars, suggesting similar masses and ages. The stellar luminosity and resulting age estimates, however, are especially uncertain given the difficulty in accounting for the large extinctions, scattered light emission and continuum excesses typical of Class I stars. Several candidate Class I brown dwarfs are identified. Class I stars appear to rotate somewhat more rapidly than T Tauri stars, by roughly a factor of 2 in the mean. Likewise, the disk accretion rates inferred from optical excesses and Br γ luminosities are similar to, but larger in the mean by a factor of a few than, the disk accretion rates of T Tauri stars. There is some evidence that the disk accretion rates of Class I stars are more distinct from T Tauri stars within the ρ Ophiuchi star forming region than in others (e.g., Taurus-Auriga), suggesting a possible environmental influence. The determined disk accretion rates are nevertheless 1-2 orders of magnitude less than the mass infall rates predicted by envelope models. In at least a few cases the discrepancy appears to be caused by T Tauri stars being misclassified as Class I stars because of their edge-on disk orientation. In cases where the envelope density and infall velocity have been determined directly and unambiguously, the discrepancy suggests that the stellar mass is not acquired in a steady-state fashion, but instead through brief outbursts of enhanced accretion. If the ages of some Class I stars are in fact as old as T Tauri stars, replenishment may be necessary to sustain the long-lived envelopes, possibly via continued dynamical interactions with cloud material.

1. THE DISCOVERY AND CLASSIFICATION OF PROTOSTARS

The early phases of star and planet formation are difficult to observe because this process occurs while the protostar is buried within its natal molecular cloud material. Nevertheless, infrared and submillimeter observations, which are able to penetrate this high extinction material, have re-

vealed much about the bolometric luminosities, spectral energy distributions (SEDs), and circumstellar material of embedded young stars (e.g., *Lada and Wilking, 1984; Myers et al., 1987; Wilking et al., 1989; Kenyon et al., 1990; André and Montmerle, 1994; Motte and André, 2001; Onishi et al., 2002; Andrews and Williams, 2005*). The earliest of these observations spurred development of the theory of isolated

low mass star formation, advancing initial considerations of the collapse of a singular isothermal sphere (e.g., *Shu, 1977*) to include circumstellar disks and envelopes (*Cassen and Moosman, 1981; Terebey et al., 1984; Adams et al., 1987*).

An easy marriage of observation and theory was found by equating different stages of this theoretical evolutionary process with observed differences in the spectral energy distributions of very young stars. Four classes have been proposed (Class 0, I, II, and III), and are now commonly used to classify young stars. In this proposed scheme, Class 0 stars are cloud cores that are just beginning their protostellar collapse, Class I stars are embedded within an “envelope” of circumstellar material, which is infalling, accumulating in a disk, and being channeled onto the star, Class II stars are nearly fully assembled stars undergoing pure disk accretion with perhaps some evidence for tenuous amounts of envelope material and, finally, Class III stars are post-accretion but still pre-main sequence stars. The Class II and Class III stars are also known as classical T Tauri stars and weak-lined T Tauri stars, respectively. It is believed that the majority of the stellar mass is acquired prior to the Class II phase; these younger stars are thus considered to be the true “protostars.”

Despite the discretization of the Class classification scheme, there is a continuum of circumstellar evolutionary states and thus a continuum of observational properties exhibited by young stars. Fig. 1 illustrates two popular criteria used to segregate the Classes, bolometric temperature (T_{bol} , defined as the temperature of a blackbody with the same mean frequency as the observed SED; *Myers and Ladd, 1993*) and infrared spectral slope ($\alpha = d\log[\lambda F_\lambda] / [d\log\lambda]$, typically determined over the wavelength interval 2 to 25 μm ; *Lada and Wilking, 1984; Lada, 1987*), plotted against one another. Class I stars are distinguished from Class II stars as having $\alpha > 0.0$ or $T_{bol} < 650 \text{ K}$; their SEDs rise into the infrared. A subsample of “flat spectrum” or “transitional Class I/II” stars are often distinguished as those with $-0.3 < \alpha < 0.3$ or $650 < T_{bol} < 1000 \text{ K}$. However, since these criteria are based on observations which typically do not spatially resolve the circumstellar structures, it is not clear that the observed SED differences truly correspond to distinct evolutionary stages. Line of sight orientation or unresolved companions, as examples, can significantly alter the observed SED.

Studies of the emergent SEDs at wavelengths $\gtrsim 10\mu\text{m}$ have provided important, albeit ambiguous, constraints on the circumstellar dust distributions for Class I stars. Although existing data are based on relatively low spatial resolution observations from IRAS and ISO, with the promise of the Spitzer Space Telescope (*Werner et al., 2004*) currently being realized, a single generic representation of Class I and some I/II stars has been developed. Models incorporating infalling, rotating envelopes with mass infall rates on the order of $10^{-6} \text{ M}_\odot/\text{yr}$ predict SEDs that are consistent with observations (*Adams et al., 1987; Kenyon et al., 1993a; Whitney et al., 1997, 2003*). However, only in

a few cases are these mass infall rates supported by kinematic measurements of spatially resolved envelope structures (e.g., *Gregerson et al., 1997*). For some young stars whose SEDs can be explained by spherically-symmetric dust distributions, it has been suggested that nearly edge-on flared disk models may also be able to reproduce the SEDs (e.g., *Chiang and Goldreich, 1999; Hogerheijde and Sandell, 2000*). One additional complication

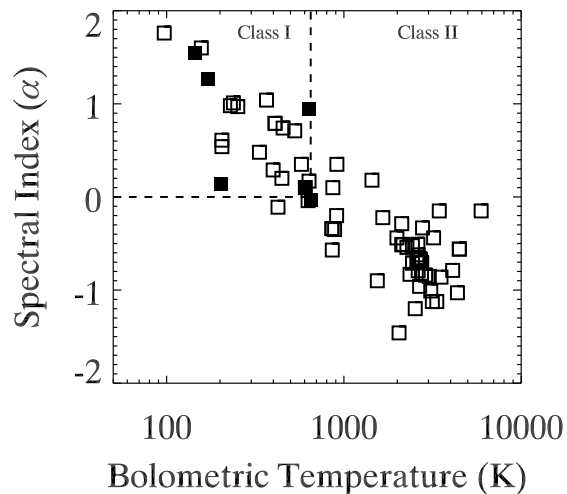


Fig. 1. Spectral index versus bolometric temperature for young stars observed spectroscopically (*White and Hillenbrand, 2004; Doppmann et al., 2005*) in Taurus and ρ Ophiuchi and which have both evolutionary diagnostics determined. Open symbols correspond to stars with detected photospheric features from which stellar properties can be extracted; filled symbols are too heavily veiled to extract these features. Class I stars are bolometrically cold ($T_{bol} < 650 \text{ K}$) and have rising mid-infrared energy distributions ($\alpha > 0.0$). The new spectroscopic observations extend well into the Class I regime.

Whether the observable diagnostics trace distinct evolutionary states bears directly on the issue of whether Class I stars are in fact younger than Class II stars, as is often assumed, or whether they are simply less environmentally developed; they could be T Tauri age stars still (or perhaps just currently) embedded within circumstellar material. What is needed is an understanding of the *stellar* properties of these systems. To date, stellar properties such as mass and age have been derived for Class I stars predicated on the assumption that they are in the main stage of infall (see e.g., *Evans, 1999*), that this material is accumulating in a circumstellar disk, and then accretes onto the star at a rate sufficient to match the bolometric luminosity (defined as the luminosity of a star’s entire energy distribution). Given an assumed mass, the age of the star is then simply the mass divided by the mass infall rate ($0.6 \text{ M}_\odot / 3 \times 10^{-6} \text{ M}_\odot/\text{yr} = 2 \times 10^5 \text{ yr}$). Buttressing the argument for the extreme youth of Class I stars is the relative number of Class I, II, and III stars in clouds such as Tau-Aur. As discussed by

Benson and Myers (1989) and *Kenyon et al.* (1990), the relative ages of stars in different stages can be inferred from their relative numbers, assuming a constant star formation rate. For Taurus-Auriga, there are 10 times fewer Class I stars than Class II and Class III stars, implying the Class I phase must be 10 times shorter, leading to age estimates of $\sim 2 \times 10^5$ yr assuming typical ages of $\sim 2 \times 10^6$ yr for the Class II/III population, as inferred from the Hertzsprung-Russell diagram (e.g., *Kenyon and Hartmann*, 1995).

A more robust confirmation that Class I stars are bona-fide protostars would be an unambiguous demonstration that they are acquiring mass at a much higher rate than Class II stars. Although the mass infall rates inferred (indirectly, in most cases) for Class I stars are roughly 2 orders of magnitude larger than the disk accretion rates determined for Class II stars ($\sim 10^{-8} M_{\odot}/\text{yr}$; e.g., *Gullbring et al.*, 1998), it has not yet been shown that the infalling material is channeled through the disk and onto the star at this same prodigious rate. Under the assumption that these two rates are the same leads to a historical difficulty with the Class I paradigm - the so-called ‘‘luminosity problem.’’ As first pointed out by *Kenyon et al.* (1990), if the material infalling from the envelope is channeled through the disk via steady-state accretion and onto the star, the accretion luminosity would be dominant at roughly 10 times the luminosity emitted from the photosphere. However, Class I stars, at least in Tau-Aur, do not have integrated luminosities substantially different from those of neighboring T Tauri stars. Several reconciliations have been proposed, including disk accretion which is not steady-state, very low mass (i.e., substellar) central masses, or simply erroneously large mass infall rates. Direct measurement, rather than indirect inference, of both the stellar and the accretion luminosities of Class I stars is needed to distinguish between these.

The most straightforward way to unambiguously determine the stellar and accretion properties of young stars at any age is to observe their spectra at wavelengths shorter than $\sim 3\mu\text{m}$ where the peak flux from the stellar photosphere is emitted. While this has been possible for over five decades for Class II stars, the faintness of Class I stars at optical and near-infrared wavelengths have made it difficult to obtain high resolution, high signal-to-noise observations necessary for such measurements. The development of sensitive spectrographs mounted on moderate to large aperture telescopes now allow direct observations of Class I and I/II photospheres via light scattered through circumstellar envelopes. These observational windows provide an opportunity to study Class I stars with the same tools and techniques developed for the study of Class II stars.

2. PHOTOSPHERES AND ACCRETION

Detailed spectroscopic studies of young stars much less embedded than protostars (e.g., T Tauri stars) have provided much of the observational basis for theories of how stars are assembled and how they interact with their environment. The spectrum of the canonical young, accret-

ing, low-mass star consists of a late-type photosphere with strong emission-lines and excess continuum emission (i.e., veiling) at optical and infrared wavelengths. At optical wavelengths, measurement of this excess emission, which is attributed to high temperature regions generated in the accretion flow, provides a direct estimate of the mass accretion rate and constrains physical conditions of accretion shock models (see the chapter by *Bouvier et al.*). At infrared wavelengths, measurement of the excess thermal emission from warm circumstellar dust reveals structural information of the inner accretion disk (*Najita*, 2004; *Muzerolle et al.*, 2004; *Johns-Krull et al.*, 2003). Additionally, the strengths and profile shapes of permitted emission-lines delimit how circumstellar material is channeled onto the stellar surface (*Calvet and Hartmann*, 1992; *Muzerolle et al.*, 1998, 2001), while density-sensitive forbidden emission lines trace how and how much mass is lost in powerful stellar jets (e.g., *Hartigan et al.*, 1995). Perhaps most importantly, extraction of the underlying photospheric features permit the determination of precise stellar properties (T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$), which can be compared to evolutionary models to determine stellar masses and ages. Doppler broadening of these features also provides a measure of the stellar rotation rate ($v \sin i$), which is important for tracing the evolution of angular momentum. Spectroscopic observations at visible and near-infrared wavelengths are 2 powerful tools for studying a young star’s photospheric properties and its circumstellar accretion, if realizable.

2.1. Visible Light

Although observations at visible or optical wavelengths ($\lesssim 1\mu\text{m}$) are especially challenging for highly extincted stars, there are nevertheless two motivations for pursuing this. First, visible light is dominated by emission from both the photosphere and high temperature accretion shocks; it therefore offers the most direct view of stellar properties and accretion luminosity. Second, for small dust grains ($\lesssim 1\mu\text{m}$), visible light scatters more efficiently than infrared light. Thus, even if the direct line-of-sight extinction is too large for an embedded star to be observed directly, the cavities commonly seen in the envelopes surrounding Class I stars (e.g., *Padgett et al.*, 1999) may permit observations of the photosphere and inner accretion processes through scattered light. This is only feasible in low column density star forming environments like Taurus-Auriga where the young stars are not deeply embedded within the large-scale molecular cloud.

Recognition of faint but nevertheless detectable emission from these embedded stars inspired several low resolution spectroscopic studies with the aim of putting the first solid constraints on the stellar and accretion properties of suspected protostars. This work began even prior to the now established Class classification scheme; some of the first embedded young stars were identified by the strong stellar jets which they powered (e.g., *Cohen and Schwartz*, 1983; *Graham*, 1991). These stars typically had nearly featureless continua with strong emission lines superimposed. *Mundt*

et al. (1985) obtained an optical spectra of the Class I star L1551 IRS 5 in Taurus-Auriga and identified the star as a G or K spectral type (but see *Orosio et al.*, 2003); the emission line features showed P Cygni-like profiles suggestive of a strong outflowing wind. More recently, *Kenyon et al.* (1998) reported spectroscopic observations for 10 of the Class I stars in Taurus-Auriga, detecting M spectral type features (i.e., TiO bands) in several and strong emission line features in all. These initial spectroscopic studies suggested that at least some Class I stars resemble their more evolved T Tauri star counterparts (Class II stars), but with heavily veiled spectra and strong emission lines. Unfortunately, the limited numbers of stars with revealed spectroscopic features, due in part to the low spectral resolution of the observations, precluded accurate determination of stellar properties and specific mass accretion and mass outflow rates for unbiased comparisons with the more optically revealed T Tauri stars.

2.2. Near-Infrared Light

The development of infrared detector technology during the 1980s and 90s has provided another valuable tool for the study of protostars. Since many stars form in high extinction clouds that block nearly all visible light (e.g., ρ Ophiuchi, Serpens), they are not amenable to study at visible wavelengths. It has been recognized for some time that late-type stellar photospheres exhibit a number of atomic and molecular features in the 2 – 2.4 μm wavelength region (K band) which are diagnostic of effective temperatures and surface gravities (*Kleinmann and Hall*, 1986; *Wallace and Hinkle*, 1996), and can be used to measure stellar projected rotational and radial velocities. Interstellar dust is also relatively transparent in this wavelength region, $A_K \simeq 0.1 A_V$ (in magnitudes), permitting spectroscopic observations of even highly extinguished young stars in nearby dark clouds to be obtained. However, the near-infrared spectra of embedded young stars are frequently complicated by the presence of thermal emission from warm dust grains in their inner circumstellar disks or inner envelope regions. This excess circumstellar emission can be several times greater than the photospheric flux of an embedded young star in the K band wavelength region, causing an increased continuum level that veils photospheric features.

Initial near-infrared observations at low resolution found that the CO absorption features at 2.3 μm could be identified less often for Class I stars than Class II stars (*Casali and Matthews*, 1992; *Casali and Eiroa*, 1996). This was interpreted as Class I stars having larger near-infrared excess emission than Class II stars, possibly because of more luminous circumstellar disks caused by larger mass accretion rates or alternatively, envelope emission (*Greene and Lada*, 1996; *Calvet et al.*, 1997). *Muzerolle et al.* (1998) demonstrated that the $\text{Br}\gamma$ (2.166 μm) luminosity correlates well with the total accretion luminosity, and used this relation to measure the the first accretion luminosities for Class I stars. The determined accretion luminosities were only a

small fraction (\sim one-tenth) of the bolometric luminosity; assuming a typical T Tauri star mass and a radius, these accretion luminosities correspond to mass accretion rates that are overall similar to those of T Tauri stars ($\sim 10^{-8} M_{\odot}/\text{yr}$). With regard to stellar features, *Greene and Lada* (1996) and *Luhman and Rieke* (1999) showed that at least $\sim 25\%$ of Class I and flat-spectrum stars exhibited temperature sensitive photospheric features, suggesting that stellar properties could potentially be determined directly (see also *Ishii et al.*, 2004). As with early optical observations, however, low spectral resolution and large infrared excesses prevented accurate extraction of these properties. More recently, *Nisini et al.* (2005) presented spectra of 3 Class I stars in R CrA at moderate resolution ($R \sim 9000$), sufficient to measure the amount of continuum excess and assign spectral types (i.e., temperatures), but (in this case) insufficient to measure radial and rotational velocities.

2.3. The Promise of High Resolution Spectra

Fortunately, high dispersion spectrographs on large aperture telescopes have allowed observers to begin studying the stellar and accretion properties of embedded low mass protostars in detail, at both optical and near-infrared wavelengths. Initial measurements demonstrated that the key to spectroscopically resolving faint photospheric features, given the large continuum excess emission, is high signal-to-noise, high dispersion spectroscopy (*Greene and Lada*, 1997, 2000, 2002; *Doppmann et al.*, 2003). This pioneering work showed that fundamental photospheric diagnostics (temperatures, surface gravities, rotational velocities) and circumstellar features (continuum excesses, emission line luminosities) could be measured nearly as precisely for Class I stars as for Class II stars. The small number of Class I stars “revealed” however, inhibited statistically meaningful comparisons with T Tauri stars to search for evolutionary differences.

Very recently the situation changed dramatically with two large surveys of embedded stars. *White and Hillenbrand* (2004; hereafter *WH04*) conducted a high resolution ($R \simeq 34,000$) optical spectroscopic study of 36 “environmentally young” stars in Taurus-Auriga (Tau-Aur). *WH04* classify stars as “environmentally young” if they are either Class I stars or power a Herbig-Haro flow. Their sample consisted of 15 Class I stars and 21 Class II stars; they detected photospheric features in 11 of the Class I stars and all of the Class II stars. Fig. 2 shows three optical spectra from this survey. *Doppmann et al.* (2005; hereafter *D05*) conducted a complementary high resolution ($R \simeq 18,000$) K band study of 52 Class I and flat-SED stars, selected from 5 nearby star forming regions - Taurus-Auriga (Tau-Aur), ρ Ophiuchi (ρ Oph), Serpens, Perseus, and R Corona Australi (R CrA). Forty-one of the 52 stars were found to have photospheric absorption features from which stellar properties and excess emission could be measured. Fig. 3 shows 3 near-infrared spectra from this survey.

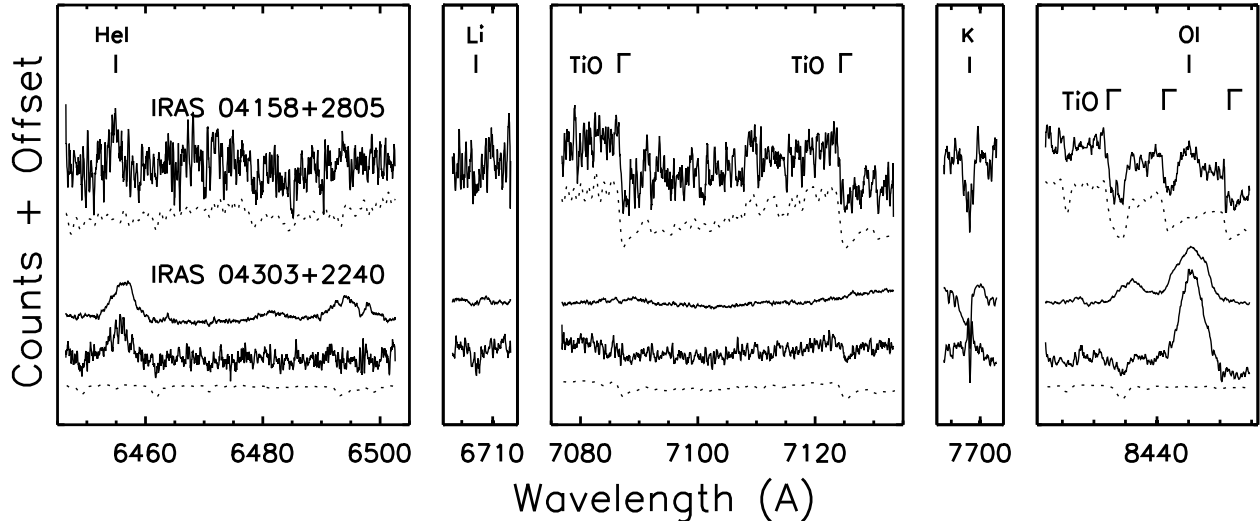


Fig. 1.— Fig. 2. Portions of the Keck/HIRES spectra from *White and Hillenbrand* (2004). IRAS 04158+2805 ($\alpha = +0.71$) has a very cool spectral type ($\sim M6$) and possibly a substellar mass. The two epochs of IRAS 04303+2240 ($\alpha = -0.35$) show dramatic variations in the veiling and the inferred mass accretion rate; the heavily veiled spectrum is less noisy because the star was also much brighter. Spectra of the best fit dwarf stars, veiled and rotationally broadened, are shown as dotted lines.

3. SPECTROSCOPIC PROPERTIES OF PROTOSTARS REVEALED

In this section, we present a combined assessment of the stellar and accretion properties of Class I and transitional Class I/II stars as inferred in the *WH04* and *DO5* studies, including other results when applicable. We note that the two primary studies were able to determine astrophysical properties for 6 of the same stars, permitting a direct comparison of the two techniques. Agreement is good for 5 of the 6 overlapping stars (in $v \sin i$ and effective temperature); the 1 discrepancy occurs in a heavily veiled, very low signal-to-noise (optical) observation; the infrared properties are adopted in this case.

To identify how stellar and circumstellar properties change as a star evolves through the proposed evolutionary scheme, we present the inferred properties as a function of the evolutionary diagnostic α , the infrared spectral index. We adopt this diagnostic simply because it is available for most of the stars observed. In addition to the primary samples of *WH04* and *DO5*, we include a sample of accreting Class II stars from Tau-Aur (as assembled in *WH04*) and ρ Ophiuchi (assembled in *Greene and Lada, 1997* and *Doppmann et al., 2003*), whose properties have been determined from high dispersion spectra as well. When available, we selected values of α calculated from observations at 2 and 25 μm ; when such measurements are not available, we use α values calculated over a smaller wavelength interval (typically based on ISO observations extending to 14 μm). Specifically, stars in Tau-Aur, NGC 1333 and R CrA have 2-25 μm α values determined from IRAS observations by *Kenyon and Hartmann* (1995), *Ladd et al.* (1993), and *Wilking et al.* (1992), respectively. Serpens and ρ Oph stars have 2-14 μm α values from the work of *Kaas et al* (2004)

and *Bontemps et al* (2001). As emphasized in the introduction, however, all evolutionary diagnostics are subject to significant biases, which can mask subtle trends. Thus, we will primarily make ensemble comparisons between stars classified as Class I stars ($\alpha > 0.0$) and stars classified as Class II stars.

3.1. Stellar Masses

Historically, the masses of embedded young stars have been poorly determined by observations, since in most cases, the only measurable property was the bolometric luminosity from the (often poorly determined) SED. IRAS surveys of the Tau-Aur, ρ Oph, R CrA, and Chamaeleon I dark clouds revealed populations of Class I embedded stars in each region with bolometric luminosities spanning from below $0.1 L_{\odot}$ to approximately $50 L_{\odot}$, with a median value near $1 L_{\odot}$. (*Kenyon et al., 1990; Wilking et al., 1989, 1992; Prusti et al., 1992*). Converting these luminosities to mass estimates requires an assumed mass-luminosity relation, which strongly depends upon age, and an assumed accretion luminosity. If the embedded Class I stars in these regions have luminosities dominated by accretion, then their masses can be approximated by applying the spherical accretion luminosity relation $L_{\text{bol}} = L_{\text{acc}} = GM_* \dot{M} / R_*$. Adopting an infall rate of $2 \times 10^{-6} M_{\odot}/\text{yr}$ and a protostellar mass-radius relation (e.g., *Adams et al., 1987; Hartmann, 1998*) leads to a mass of $0.5 M_{\odot}$ (at a radius of 3 R_{\odot}) for a $10 L_{\odot}$ star. Thus, only the most luminous Class I stars would have inferred masses consistent with those of T Tauri stars ($0.1 - \text{a few } M_{\odot}$; *Kenyon and Hartmann, 1995; Luhman and Rieke, 1999*); the majority would have masses $\lesssim 0.1 M_{\odot}$. Although there remain considerable uncertainties in the calculated bolometric luminosities and the prescription for accretion for Class I stars, the emerging census

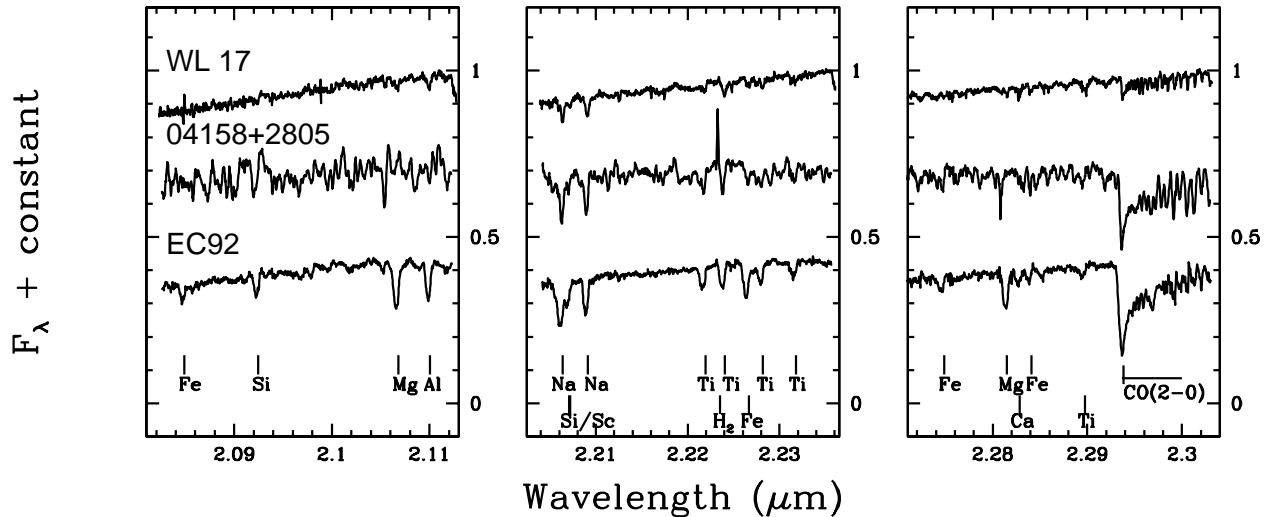


Fig. 2.— Fig. 3. High resolution near-infrared spectra of the embedded protostars from *Doppmann et al. (2005)*. WL 17 ($\alpha = +0.42$) is heavily veiled, IRAS 04158+2805 ($\alpha = +0.71$) has a very cool spectral type ($\sim M6$) and possibly a substellar mass, and EW 92 is moderately rapidly rotating ($v \sin i = 47$ km/s).

suggests a "luminosity problem" as described in Section 1; the typical Class I star is under-luminous relative to what is expected for a canonical T Tauri size star (in mass and radius) accreting at the predicted envelope infall rates. The luminosity problem is most severe in the Tau-Aur star forming region (*Kenyon et al., 1990*); there is tentative evidence for a regional dependence upon the distribution of bolometric luminosities of Class I stars. One proposed solution to the luminosity problem is that Class I stars are in fact much lower in mass than T Tauri stars (i.e., brown dwarfs), either because they are forming from less massive cores/envelopes or because they have yet accreted only a small fraction of their final mass. These possible solutions introduce yet additional problems, however. If almost all Class I "stars" are producing brown dwarfs, then "star" formation in most regions must have already ceased, implying an unexpected mass dependent formation time-scale. Alternatively, the hypothesis that Class I stars have accreted only a small fraction of their final mass is inconsistent with their relatively low envelope masses ($\sim 0.1 M_{\odot}$), estimated from millimeter wavelength observations (e.g., *Motte and André, 2001*). Accurately determined stellar mass estimates are needed to test this proposed yet problematic solution to the luminosity problem.

One direct way to estimate the mass of a young star is to observationally determine its stellar effective temperature and luminosity and then compare them with the predictions of pre-main sequence (PMS) evolutionary models. The recent optical and near-IR spectroscopic studies of WH04 and D05 have been able to achieve this for the first time for several dozen embedded young stars in nearby dark clouds. Since low mass, fully-convective stars primarily evolve in luminosity while young (e.g., *Baraffe et al., 1998*), temperature is especially important in determining a young star's mass. In most cases, the temperature estimates for the Class

I stars are as precisely determined as those for T Tauri stars (~ 150 K), which translates into similar uncertainties in the inferred stellar masses (a few tens of percent), but large systematic uncertainties remain (e.g., temperature scale - see the chapter by *Mathieu et al.*; effects of accretion - *Siess et al., 1999*; *Tout et al., 1999*). The uncertainties in the stellar luminosities of embedded stars are, on the other hand, typically much larger than those for T Tauri stars. *WH04* estimated stellar luminosities by performing a bolometric correction from near-infrared *J*-band ($\lambda \simeq 1.25 \mu\text{m}$) photometric data, which is expected to be least contaminated by circumstellar excesses (see, however, *Cieza et al. 2005*); extinctions were determined by comparing the observed *J - H* colors to that expected for a dwarf-like photosphere. *D05* estimated luminosities by performing a bolometric correction to near-infrared *K*-band ($\lambda \simeq 2.3 \mu\text{m}$) photometric data, after accounting for *K*-band veilings determined from their spectra; extinctions were determined by comparing the *H - K* colors to a typical value for a T Tauri star. However, much of the flux detected from embedded young stars at visible and near-infrared wavelengths has been scattered from their circumstellar environments. The physical nature of circumstellar dust grains (sizes, shape, composition), distribution of material in disks and envelopes, and system inclination all change how the photospheric flux is scattered into our line of sight, changing both a star's brightness and color. Comparisons of luminosities determined via different techniques differ by factors of 2-3, and we suggest this as a typical uncertainty. In addition to this, stars with edge-on disk orientations often have calculated luminosities that can be low by factors of 10 to 100; the preferential short-wavelength scattering leads to artificially low extinction estimates. With these uncertainties and possible systematic errors in mind, in Fig. 4 are shown all the Class I and flat-spectrum stars ($\alpha > -0.3$) in Tau-Aur, ρ Oph,

and Serpens observed in the *D05* and the *WH04* surveys on a Hertzsprung-Russell diagram. The PMS evolutionary models of *Baraffe et al.* (1998) are shown for comparison.

Several points can be extracted from Fig. 4 regarding the masses of Class I and flat-spectrum stars. First, the stars generally span a similar range of effective temperatures and stellar luminosities in all regions, though there is a slightly narrower range of temperatures in ρ Oph. Second, based on comparisons with the *Baraffe et al.* (1998) PMS evolutionary models, the combined distribution of stellar masses span from substellar to several solar masses. This is similar to the distributions of Class II stellar masses in Tau-Aur and ρ Oph (*Kenyon and Hartmann, 1995; Luhman and Rieke, 1999*), while little has been reported on the masses of Class II stars in the Serpens clouds. Other studies corroborates these findings. *Nisini et al.* (2005) determine masses spanning from 0.3 to 1.2 M_{\odot} for 3 Class I stars in R CrA, based on spectral types determined from moderate resolution spectra. *Brown and Chandler* (1999) determine masses of 0.2 - 0.7 M_{\odot} for 2 Class I stars in Tau-Aur based on disk kinematics under the assumption of Keplerian rotation.

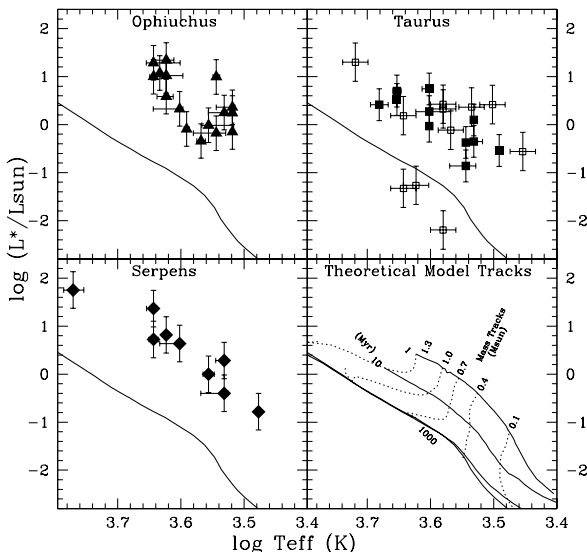


Fig. 4. Stellar luminosities and effective temperatures of Class I and flat-SED stars ($\alpha > -0.3$) in ρ Oph, Tau-Aur, and Serpens are shown on an H-R diagram. Filled symbols are from *D05* and unfilled symbols are from *WH04*. The evolutionary models of *Baraffe et al.* (1998) are also shown for comparison.

Apparently the majority of Class I stars have stellar masses that are similar to those of T Tauri stars. The present spectroscopic data does not support the notion that the majority of the low luminosity ($L < 1L_{\odot}$) Class I stars are substellar. This proposed resolution to the luminosity problem can now be excluded. Nevertheless, it is particularly notable that there are several Class I stars which have masses that are close to or below the substellar boundary (0.075 M_{\odot} ; *Baraffe et al.*, 1998). *WH04* identified 3 Class I stars with spectral types of M5.5 or M6, and considered them candidate Class I brown dwarfs. Two of these stars,

IRAS 04158+2805 and IRAS 04489+3042 were also observed and analyzed by *D05*. The *D05* infrared spectra also indicate a M6 spectral type for IRAS 04158+2805, but yield a slightly earlier M4 spectral type for IRAS 04489+3042. It is very encouraging that both optical and infrared spectra are yielding very similar results for these stars, and strengthens the case for the existence of a Class I object at or below the substellar boundary.

On the other hand, some Class I stars which had been previously interpreted as accreting brown dwarfs from photometric data are now revealed to be low mass stars instead. For example, *Young et al.* (2003) interpreted the very complete photometric data on the Class I star IRAS 04385+2250 as evidence that it is a brown dwarf of only 0.01 M_{\odot} ($\sim 10 M_{\text{Jup}}$) by assuming an accretion rate of $2 \times 10^{-6} M_{\odot}/\text{yr}$. As pointed out by *Kenyon et al.* (1990; 1994), such an assumption implies that all low luminosity ($L < 1L_{\odot}$) Class I stars are actually substellar. However, *WH04* find that IRAS 04385+2250 (also known as Haro 6-33) has a spectral type of M0, placing it squarely in the regime of low mass stars and not brown dwarfs.

3.2. Stellar Ages

In addition to providing stellar masses, comparisons of observationally determined stellar properties with the predictions of evolutionary models can provide useful age estimates. Comparisons of Class II stars in nearby dark clouds consistently yield ages spanning from less than 1 to a few million years (e.g., see *Kenyon and Hartmann, 1995; Luhman and Rieke, 1999*). If Class I stars are really the precursors to Class II stars, as their less evolved circumstellar environments suggest, then they should have younger ages.

As emphasized above, the calculated luminosities of Class I stars are especially uncertain given the large extinctions, uncertain scattered light contributions, and continuum excesses; they are also occasionally subject to large systematic errors caused by orientation effects. These large uncertainties bear directly upon how well the stellar ages can be determined, since low mass stars evolve primarily along vertical evolutionary tracks at ages less than a few $\times 10^7$ yr. Nevertheless, comparisons of the observed luminosities and temperatures with the predictions of pre-main sequence evolutionary models, as shown in Fig. 4, provide a large ensemble of ages estimates. The range of ages is broadest for Tau-Aur and narrowest for Serpens, though these regions have the largest and smallest samples measured, respectively. Several stars in Tau-Aur appear to have unrealistically old ages (below the main-sequence), likely a consequence of the stellar luminosity being severely underestimated because of an edge-on disk orientation (see *WH04*). The absence of low luminosity stars in ρ Oph and Serpens suggests they may be more difficult to identify in regions of high extinction.

Despite these possible regional differences and large uncertainties, calculating a median age in all 3 regions yields a consistent value of ~ 1 Myr. This is remarkably similar to

the average age of Class II stars in ρ Oph and Tau-Aur; few are known in Serpens. This suggests that most Class I stars are not systematically younger than Class II stars. Unfortunately the large uncertainties in the luminosity estimates of Class I stars, as well as current evolutionary models at early ages (Baraffe et al., 2002), limits the robustness of this comparison at this time.

Finally, we note that a comparison of the inferred stellar luminosities with calculated bolometric luminosities for Class I stars suggests that in most cases studied here, the stellar luminosity is the dominant source of luminosity in the system ($L_{Star}/L_{Bol} > 0.5$). Most Class I stars with detected photospheric features do not have accretion dominated luminosities as had been initially proposed. We caution, however, that the observational biases in the sample studied here (revealed at $< 3\mu\text{m}$, with moderate veiling or less) prevent extrapolation of this finding to Class I stars in general. The most bolometrically luminous stars for which photospheric features are detected are IRS 43 ($L_{bol} = 7.2 L_{\odot}$) and YLW 16A ($L_{bol} = 8.9 L_{\odot}$; see D05). Thus it is not yet known if the most luminous Class I stars ($L_{bol} > 10 L_{\odot}$) have accretion dominated luminosities or are simply more massive stars.

3.3. Stellar Rotation

Studies of stellar rotation at very young ages have revealed clues regarding the evolution of angular momentum from the epoch of star formation through to the young main sequence. Conservation of angular momentum during the collapse of a molecular core to form a low-mass star should lead to rotation velocities near break-up ($v_{break-up} = \sqrt{(GM_{star}/R_{star})} \sim 200$ km/s). However, the small projected rotation velocities of Class II stars ($v_{sin i} \lesssim 20$ km/sec; Bouvier et al., 1986, 1993; Hartmann et al., 1986; Stassun et al., 1999; Rhode et al., 2001; Rebull et al., 2002; see the chapter by Herbst et al.) show that angular momentum must be extracted quickly, on time scales of $< 1 - 10$ Myr. A number of theories have been proposed to rotationally “brake” young stars. One favored model for involves magnetic linkage between the star and slowly rotating disk material at a distance of several stellar radii (Königl, 1991; Collier Cameron and Campbell, 1993; Shu et al., 1994; Armitage and Clarke, 1996). Initial observational evidence supported this picture. T Tauri stars without disks were found to rotate somewhat more rapidly than stars with disks (Edwards et al., 1993; Bouvier et al., 1993, 1995), which was interpreted as evidence that disk presence keeps stars rotating at fixed angular velocity while disk absence allows stars to conserve angular momentum and spin up as they contract towards their main sequence radii. Since then, the observational case for disk locking has become less clear-cut (e.g., Stassun et al., 2001; but see Rebull et al., 2004), while detailed theoretical and magnetohydrodynamical considerations suggest that disk locking in and of itself is unable to extract sufficient amounts of angular momentum (Safier, 1998). Strong stellar winds are one

possible alternative (e.g., Matt et al., 2005).

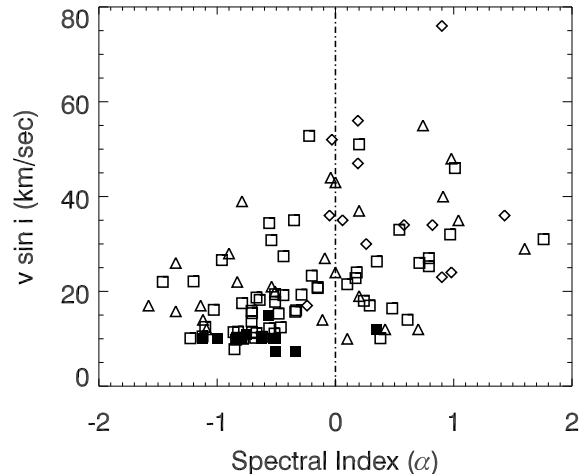


Fig. 5. Projected rotational velocity ($v_{sin i}$) versus spectral index. Triangles are stars in ρ Oph, squares are stars in Tau-Aur and diamonds are stars in Serpens. $v_{sin i}$ measurements are shown as open symbols while upper limits are shown as filled symbols. The dashed vertical line separates Class I stars from Class II stars. Data originally presented in WH04, Covey et al. (2005) and references therein.

The uncertainties in our understanding of *how* angular momentum is extracted from young stars provide motivation for determining *when* it is extracted, since knowing the appropriate time scale could help distinguish between proposed models. The rotation velocities of Class I stars as revealed by spectroscopic studies provide the earliest measurements of stellar angular momentum; Fig. 5 shows the distribution of $v_{sin i}$ values for Class I and Class II stars in Tau-Aur, ρ Oph, and R CrA versus the evolutionary diagnostic α . The largest $v_{sin i}$ value observed for a Class I star is 77 km/s, while the remainder have $v_{sin i} \leq 56$ km/s. These values are only a few tenths of the typical break-up velocity. Comparing Class I ($\alpha > 0.0$) to Class II ($\alpha < 0.0$) stars, Class I stars have slightly higher rotation rates. Although the distributions of rotation rates are statistically different (Covey et al., 2005), the difference in the mean is only a factor of two. The distributions are less distinct for any particular region (e.g., Tau-Aur, WH04), likely from smaller number statistics, though global properties of a region could lead to correlated biases (e.g., age). Although the distributions of Class II rotational velocities in some star forming regions have been shown to be statistically different (e.g., Orion versus Tau-Aur; Clarke and Bouvier, 2000; White and Basri, 2003), the evidence for this at the Class I stage is still tentative ($\sim 2\sigma$); Covey et al. (2005) found Tau-Aur to have the lowest mean observed rotation velocity for the three regions in their study (30.1 km/s versus 31.1 km/s in ρ Oph and 36.8 km/s in Serpens). These comparisons are likewise limited by small number statistics. Overall, the observational evidence demonstrates that Class I stars are rotating somewhat more rapidly than

Class II stars, but at rates that are well below break-up velocities. If Class I stars are indeed in the main phase of mass accretion (Section 4.3), this implies that angular momentum is removed concurrently with this process.

3.4. Circumstellar Accretion

If Class I stars are to acquire the majority of their mass (e.g., $0.6 M_{\odot}$) on a timescale of $\sim 2 \times 10^5$ yr, they must have time-averaged mass accretion rates that are $\sim 3 \times 10^{-6} M_{\odot}/\text{yr}$, assuming a simple spherical infall model (e.g., Hartmann, 1998). For comparison, this mass accretion rate is at least 2 orders of magnitude larger than what is typically observed for T Tauri stars (e.g., Gullbring *et al.*, 1998). The newly available high dispersion spectra of Class I stars permit measurements of the mass accretion rate (from the disk onto the star), by 2 independent methods. The first of these comes from measurements of optical excess emission in high dispersion optical spectra under the assumption that the liberated energy is gravitational potential energy (see the chapter by Bouvier *et al.*). Unfortunately there remain considerable uncertainties in measuring the total liberated energy, which typically requires a large bolometric correction from an optical measurement; the majority of the accretion luminosity is emitted at ultra-violet wavelengths. Additionally, estimating the potential energy requires estimates of stellar and inner disk properties, which have large uncertainties themselves. Nevertheless, by calculating mass accretion rates for Class I stars following the same assumptions used for T Tauri stars, many of these systematic uncertainties can be removed, thereby permitting a more robust comparison if the same accretion mechanism applies.

WH04 have measured optical excess emission at 6500 Å for 11 Class I stars, and several borderline Class I/II stars, all within the Tau-Aur star forming region. These measurements, along with a sample of excess measurements of accreting T Tauri stars from Hartigan *et al.* (1995; as compiled in WH04), are shown in Fig. 6. Similar to the T Tauri stars, the Class I stars have continuum excesses that range from not detected (< 0.1) to several times the photosphere; in the general case, their optical emission is not dominated by accretion luminosity. Class I stars have veiling values that are only modestly larger in the mean ($\times 1.3$) than those of Class II stars. WH04 proceed to convert these continuum excesses to mass accretion rates, and find values of a few $\times 10^{-8} M_{\odot}/\text{yr}$, which are again similar to those of Class II stars. Further, by accounting for other components to the star’s luminosity, they find that the accretion luminosity only accounts for $\sim 25\%$ of the bolometric luminosity, on average.

A second measure of the mass accretion rate comes from emission line luminosities. Emission-line studies, in combination with radiative transfer models of circumstellar accretion, suggest that many of the permitted lines originate in the infalling magnetospheric flow (Hartmann *et al.*, 1994; Muzerolle *et al.*, 1998), and that the line strengths are proportional to the amount of infalling mass. Muzerolle *et al.*

(1998a, 1998b) demonstrated this to be true for the Ca II infrared triplet and Br γ by correlating these emission-line luminosities with mass accretion rates determined from blue excess emission. As emphasized by the authors, accurate corrections for extinction and scattered light are critical for this. The near-infrared emission-line Br γ is of special interest in the study for Class I stars since the high extinction often inhibits observations at shorter wavelengths. Using the Br γ correlation, Muzerolle *et al.* (1998) found that the Br γ luminosities of Class I stars, with assumed stellar properties, are similar to those of Class II stars. The implication is that they have similar mass accretion rates.

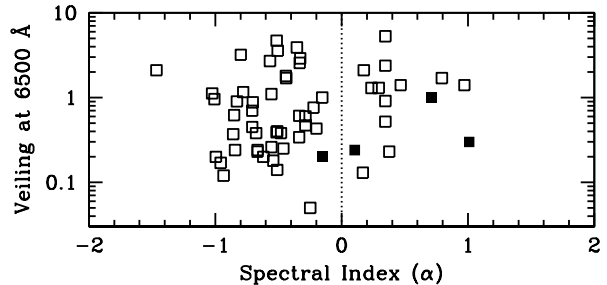


Fig. 6. Optical veiling versus spectral index for stars in Tau-Aur. Measurements are from WH04 and Hartigan *et al.* (1995). Veiling measurements are shown as open symbols while upper limits are shown as filled symbols. The dashed vertical line separates Class I stars from Class II stars.

Fig. 7 shows a compilation of logarithmic Br γ luminosities from Muzerolle *et al.* (1998) and D05 (also includes measurements from Luhman and Rieke, 1999; Folha and Emerson, 1999; Doppmann *et al.*, 2003), plotted versus spectral index. As with optical excess emission, the Br γ luminosities of Class I stars span a similar, though slightly broader range than the Class II stars, but are larger in the average by a factor of a few; the distributions are different at approximately the 3σ level according to a K-S test. Much of the difference between the Class I and Class II stars appears to be driven by stars in the ρ Oph region, where the Br γ luminosities of Class I stars are systematically larger than those of Class II stars by a factor of ~ 5 in the mean; the distributions are different at the $\sim 2\sigma$ level, or $\gtrsim 3\sigma$ if the low Br γ luminosity (-4.58), $\alpha = 0.0$ star GY21 is considered a Class II. Stars in Tau-Aur show no difference between the 2 classes ($< 1\sigma$).

Conversion of these luminosities to mass accretion rates leads to values for Class I stars that are similar to Class II stars, and corroborates the initial study of Muzerolle *et al.* (1998). The largest mass accretion rates are $\sim 10^{-7} M_{\odot}/\text{yr}$, and many of these are in the ρ Oph star forming region. The larger mean accretion luminosities in ρ Oph is consistent with its larger mean near-infrared excess for Class I stars relative to Class II stars ($\langle r_K \rangle = 2.2$ versus 0.94), compared with other regions. Overall it appears that the mass accretion rate during the majority of the Class I phase is similar to that of T Tauri stars, and 1 – 2 orders of magnitude less than the envelope infall rates inferred from

SED modeling ($\text{few} \times 10^{-6} M_{\odot}/\text{yr}$). We note that there is tentative evidence that the mass accretion rate is extremely time variable during the embedded phase. As one example, the borderline Class I/II star IRAS 04303+2240 changed its mass accretion rate dramatically ($> 4\times$) during 2 observational epochs (Fig. 2). Little observational work has been done to characterize the amplitudes or timescales of candidate protostar variability.

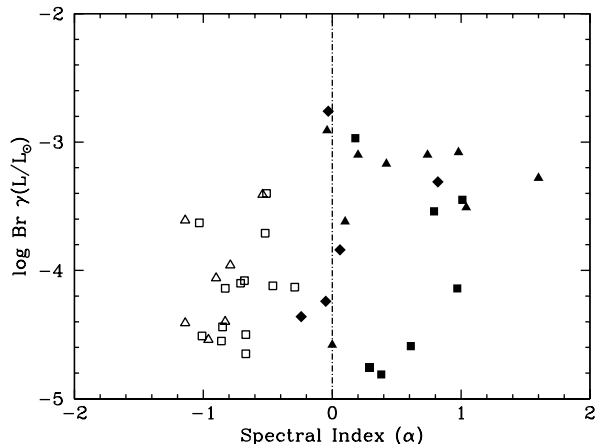


Fig. 7. $\text{Br}\gamma$ luminosity versus spectral index. Triangles are stars in ρ Oph, squares are stars in Tau-Aur and Diamonds are stars in Serpens. Filled symbols are from *D05* while open symbols are from *Muzerolle et al.* (1998). The dashed vertical line separated Class I stars from Class II stars.

3.5. Jet Emission

Optically thin forbidden emission-lines are believed to originate in an outflowing jet or wind. Their intensity is expected to be directly proportional to the amount of material being funneled along the jet, as viewed through the slit of the spectrograph. The luminosity of these emission lines can therefore be used to estimate the mass outflow rate in a young stellar jet (see the chapter by *Bally et al.*). Since jets are believed to be powered by circumstellar accretion, the mass outflow rate should correlate with the mass accretion rate.

In Fig. 8 are shown equivalent width measurements of the forbidden line $[\text{SII}] 6731 \text{ \AA}$ for stars in Tau-Aur versus spectral index. Measurements are from *WH04* and *Hartigan et al.* (1995; as compiled in *WH04*). Unlike the optical excess and $\text{Br}\gamma$ luminosity accretion diagnostics, which are only slightly enhanced among Class I stars relative to Class II stars, Class I stars systematically have larger $[\text{SII}]$ equivalent widths by roughly a factor of 20 in the mean. The implication is that Class I stars power much more energetic outflows than Class II stars. *Kenyon et al.* (1998) found similar results based on some of the same stars presented here.

However, as emphasized by *WH04*, many of the Class I stars they observed show signatures of having an edge-on disk orientation. In such a case, the emission-line region may be more directly observable than the partially embed-

ded central star is. The preferentially attenuated continuum flux will consequently produce artificially large equivalent width values, and biased mass outflow rates. Without accurate geometric information for these stars, however, it is difficult to tell the significance of this bias in the average case. If these larger forbidden line equivalent widths indeed correspond to larger mass outflow rates, perhaps it is because their spatially extended location make them a better tracer of the time-averaged mass outflow rate. As is considered below, the mass accretion rate (and corresponding mass outflow rate) for Class I stars could be T Tauri-like for the majority of the time, with occasional large outbursts. In such a case, Class I stars would then have a larger time-averaged mass accretion and mass outflow rates. The alternative to this, in the absence of any significant continuum attenuation bias, is that the ratio of mass loss to mass accretion rate is dramatically different between Class I and Class II stars ($> 10\times$), possibly suggesting a different accretion mechanism.

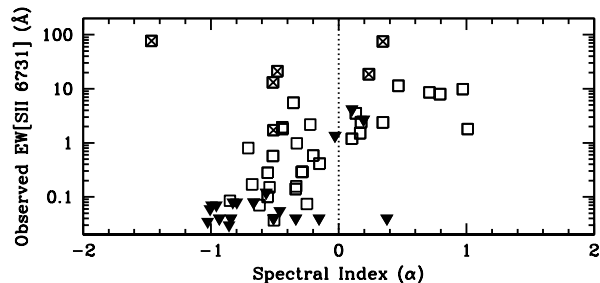


Fig. 8. Equivalent width measurements of $[\text{SII}] 6731 \text{ \AA}$ versus spectral index for stars in Tau-Aur. Measurements are from *WH04* and *Hartigan et al.* (1995). Detections are shown as open squares while upper limits are shown as filled triangles; stars with an x have a known or suspected edge-on orientation. The dashed vertical line separates Class I stars from Class II stars.

4. IMPLICATIONS FOR CLASS CLASSIFICATION SCHEMES AND FORMATION THEORY

A broad comparison of the properties derived for Class I stars and Class II stars from spectroscopy reveals some surprising similarities and differences. Class I stars appear to occupy the same ranges of effective temperature and (photospheric) luminosity as Class II stars; applying our current theoretical understanding of PMS evolution to these observations implies that Class I stars have similar stellar masses as Class II stars. If Class I stars are indeed precursors to T Tauri stars, this means that by the Class I stage a young star has accreted the majority of its final stellar mass. Although the inferred stellar luminosities of Class I stars are, on average, similar to those of Class II stars, implying similar ages, the large uncertainties and systematic biases in these estimates prevent strict age comparisons at this time. Class I stars appear to be more rapidly rotating, on average, than Class II stars, though there are many Class I stars with low projected rotational velocities. Spectroscopic indicators of

mass accretion, such as optical veiling and Br γ luminosity, do appear slightly elevated in Class I stars relative to Class II stars, but still well below predicted mass infall rates ($\sim 10^{-6} M_{\odot}/\text{yr}$). Although Class I stars have larger forbidden line emission strengths, implying larger mass outflow rates, there is a yet unaccounted for continuum attenuation bias in these measurements. Here we use the combined results to investigate possible regional differences among Class I stars, to assess whether Class I stars are being properly classified, and to improve our understanding of how mass is acquired during the main phase of mass accretion.

4.1. Are There Regional Differences Among Class I Stars?

Initial studies of Class I stars suggested that their properties may differ in different regions. *Kenyon et al.* (1990) noted that although the Tau-Aur and ρ Oph clouds both contain similar numbers of Class I stars, ρ Oph contains many more with $L_{\text{bol}} > 10L_{\odot}$. If stars in both regions have similar stellar masses, then this luminosity difference should translate into ρ Oph stars having mass accretion rates 3 – 10 times higher than those in Tau-Aur (and correspondingly larger mass infall rates, if the accretion is steady-state). This is expected according to classical star formation theory (*Shu, 1977*), which predicts that the infall rate should scale as the cube of the isothermal sound speed. The warmer gas in ρ Oph, relative to Tau-Aur (*Myers and Benson, 1983*), should consequently yield large mass infall rates, and larger time-averaged mass accretion rates. However, more recent work suggests that cloud turbulence may primarily set the initial infall rates (e.g., *Mac Low and Klessen, 2004*), and possibly even the initial mass function (e.g., *Goodwin et al., 2004*), and the resulting binary fraction and rotational distribution (*Jappsen and Klessen, 2004*). Searching for possible differences in the stellar and accretion properties of stars produced in regions with different global properties (temperature, turbulence, density) can therefore help distinguish between proposed scenarios for mass assembly and early evolution.

The distributions of effective temperatures shown in Fig. 4 indicate that there are no significant differences in the masses of Class I stars in either the Tau-Aur, ρ Oph, or Serpens star forming regions ($< 1\sigma$, according to K-S tests). While the stellar luminosities and ages are also similar among the 3 regions (given their large uncertainties), Serpens is somewhat distinct in that all of its Class I and flat-SED members appear coeval at an age younger than 1 Myr, as would be expected for bona-fide protostars. The larger scatter in stellar luminosity in ρ Oph and Tau-Aur is not well understood, though some apparently low luminosity stars are a consequence of their edge-on disk orientation (Section 3.2).

The analysis of accretion diagnostics in Section 3.4 partially supports a scenario in which Class I stars in ρ Oph are accreting at higher rates than those in Tau-Aur. The Br γ luminosities of Class I stars in ρ Oph are systematically larger than those in Tau-Aur, implying larger mass

accretion rates. This is also supported, though less directly, with the larger near-IR veiling and higher bolometric luminosities of Class I stars in ρ Oph relative to Tau-Aur (*D05*). In a case study of the luminous ($L_{\text{bol}} = 10 L_{\odot}$) protostar YLW 15, *Greene and Lada, (2002)* determine that 70% of the star’s luminosity is due to mass accretion and infer a rate of $2 \times 10^{-6} M_{\odot}/\text{yr}$. At least in this one case, the disk accretion rate appears consistent with the mass infall rate inferred from envelope models (though these infall rates are derived primarily from Class I stars in Tau-Aur, because of less confusion with cloud material in that region). Given the small number and broad range of Br γ luminosities for Class I stars in Serpens, this distribution is consistent with the distributions of either ρ Oph or Tau-Aur Class I stars.

Finally, the present data do not reveal any notable differences in the distributions of rotation velocities, or angular momenta, of embedded protostars in different regions. *Covey et al.* (2005) found that Class I and flat spectrum stars in Serpens had a somewhat larger mean $v \sin i$ rotation velocity than those in Tau-Aur or ρ Oph, but this difference is not statistically significant ($< 2\sigma$). We caution that any orientation bias present in the samples studied (e.g., edge-on disk systems), will also bias the distribution of projected rotational velocities.

4.2. Are Class I Stars Properly Classified?

In the traditional classification scheme, Class I stars are true protostars – stellar embryos surrounded by an infalling envelope – while Class II stars are pre-main sequence stars surrounded by circumstellar disks only. Here we consider the ability of popular evolutionary diagnostics to unambiguously distinguish between these 2 classes. Radiative transfer models of still-forming stars find that the SED shape typically used to distinguish Class I and Class II stars (as parametrized by T_{bol} and α) has an important dependence on the orientation of the disk and envelope relative to the observer’s line of sight (*Kenyon et al., 1993a, 1993b; Yorke et al., 1993; Sonnhalter et al., 1995; Whitney et al., 2003, 2004*). As an example, the models of *Whitney et al. (2003)* show that mid-latitude ($i \sim 40^{\circ}$) Class I stars have optical, near- and mid-infrared characteristics similar to those of more edge-on disk ($i \sim 75^{\circ}$) Class II stars. The effects of edge-on disk orientation are most severe for evolutionary diagnostics determined in the near- and mid-infrared such as the 2 – 25 μm spectral index. Bolometric temperatures are also biased, but less so, while diagnostics based at much longer wavelengths, such as the ratio of sub-millimeter to bolometric luminosity (*André et al., 1993*), are the least affected. Unfortunately longer wavelength SEDs are not yet available for Class I stars in many star forming region. Consequently, we conclude that current samples of Class I stars defined by either spectral index or bolometric temperature are contaminated with at least a few edge-on disk Class II stars.

Other observable characteristics, however, can be helpful in identifying Class II stars that have been mistakenly

classified as Class I stars due to orientation effects. The radiative transfer models of *Whitney et al.* (2003) show that edge-on Class II stars are nearly 5 times fainter than ‘true’ Class I stars with the same value of α , suggesting that misclassified edge-on systems should appear significantly lower in an H-R diagram. *WH04* identified several likely disk edge-on systems in their sample of optically revealed Class I stars in Tau-Aur, several of which (but not all) appear under-luminous relative to other cluster members. Unfortunately the large luminosity spread of Class I stars inhibit identifying edge-on disk systems based on this criterion alone, unless the system is almost precisely edge-on (e.g. HH 30). Column-density sensitive spectral features (e.g., Si at $9.7\mu\text{m}$; *Kessler-Silacci et al.*, 2005) or high spatial resolution imaging may provide less ambiguous orientation information.

The presence of spatially extended envelope material, as determined from image morphology at infrared and millimeter wavelengths, has been proposed as a more direct way to constrain the evolutionary Class. Such features are only expected during the main accretion phase. Based on criteria put forth by *Motte and Andre* (2001), only 58% (15/26) of the Class I stars in Tau-Aur are true protostars. The remaining 42% (11 stars) have envelope masses $\lesssim 0.1 M_{\odot}$ and are spatially unresolved at 1.3 mm wavelengths (referred to as “unresolved Class I sources” in *Motte and Andre*, 2001). *Motte and Andre* (2001) suggest that these stars are more likely transitional Class I/II stars or highly reddened Class II stars (e.g., edge-on disk systems). The complementary near-infrared morphology survey by *Park and Kenyon* (2002) supports the claim that these stars are not bona fide Class I stars. However, we note that the morphological criteria used in these studies do not account for the luminosity and mass of the central star. For example, IRAS 04158+2805 may appear more evolved and point-like because it is a lower luminosity Class I brown dwarf with a smaller disk and envelope.

André and Montmerle (1994) present a similar morphological study based 1.3 mm continuum observations of Class I and Class II stars in the ρ Oph star forming region. They found that Class I and Class II stars, as classified by the $2.2 - 10\mu\text{m}$ spectral index, have similar 1.3 mm flux densities. Class I stars, however, were more often spatially extended, consistent with a significant envelope component, though of relatively low mass ($\lesssim 0.1 M_{\odot}$). Thus, it appears that a much smaller fraction of Class I stars in ρ Oph, relative to Tau-Aur, are candidate misclassified Class II stars. Nevertheless, their low envelope masses imply that they have already acquired the majority of their stellar mass (discussed below), like Class II stars. Complementary comparisons of Class I and Class II stars in the Serpens and R CrA star forming region have not yet been carried out.

Based on this mostly indirect evidence, we conclude that between one-third and one-half of the Class I stars in Tau-Aur are candidate misclassified Class II stars; the emission-line profiles and image morphology suggests that in some cases the misclassification is caused by a nearly edge-on

orientation. There is less evidence for significant misclassification in other regions (e.g., ρ Oph).

4.3. Are Class I Stars in the Main Accretion Phase?

Although the absolute values of the circumstellar disk accretion rates have large systematic uncertainties, the rates inferred for Class I stars and Class II stars, under the same assumptions, are similar. However, these values are typically 1-2 orders of magnitude less than both the envelope infall rates inferred from SED modeling of Class I stars (e.g., few $\times 10^{-8} M_{\odot}/\text{yr}$ vs. few $\times 10^{-6} M_{\odot}/\text{yr}$) and the time-averaged accretion rate necessary to assemble a solar mass star in a few $\times 10^5$ years. Here we explore possible ways to reconcile this apparent discrepancy.

The first possibility to consider is that either the disk accretion rates or the mass infall rates are wrong, or both. Given the large uncertainty in determining the total accretion luminosity from an observed excess, which is roughly an order of magnitude (see e.g., *Gullbring et al.*, 1998; *WH04*), the average disk accretion rate could be as large as $10^{-7} M_{\odot}/\text{yr}$. Much larger disk accretion rates would invoke statistical problems since classical T Tauri stars are accreting at this rate as well, for 1-10 Myr, and would consequently produce a much more massive population than what is observed. Larger rates would also be inconsistent with emission-line profile analyses (*Hartmann et al.*, 1994; *Muzerolle et al.*, 1998). Assessing possible errors in the mass infall rates is more challenging since most are not determined directly from kinematic infall signatures. Instead, they are primarily set by the density of the envelope material; denser envelopes yield higher mass infall rates and redder SEDs. However, effects such as orientation (*Whitney et al.*, 2003) and disk emission (*Kenyon et al.*, 1993a; *Wolf et al.*, 2003) can also shift the SED towards redder wavelengths, if unaccounted for. Using sophisticated envelope plus disk models combined with spatially resolved images to constrain orientation, *Eisner et al.* (2005) and *Terebey et al.* (2006) nevertheless find that mass infall rates of a few $\times 10^{-6} M_{\odot}/\text{yr}$ still provide the best fits to the SED and image morphology. How low these infall rates could be and still provide reasonable fits is unclear; a factor of ~ 10 decrease in the assumed infall rate could potentially reconcile the discrepancy, if disk accretion rates are correspondingly increased by a factor of 10. It is important to keep in mind, as highlighted by *Terebey et al.* (2006), that the amount of envelope material which actually reaches the star may be only one-fourth of the infalling mass because of mass lost to stellar jets/winds and companions. With all this in mind, we conclude that it is possible to reconcile the infall/disk accretion rate discrepancy based on systematic errors and model assumptions alone. However, since the current best estimates strongly favor values that are ~ 2 orders of magnitude discrepant, we will also consider other possibilities for reconciling these rates.

One possibility, as first suggested by *Kenyon et al.* (1990), is that the infalling envelope material is not trans-

ferred to the star via disk accretion in a steady-state fashion. Instead, the accreting envelope mass accumulates in the circumstellar disk until it becomes gravitationally unstable (e.g., *Larson, 1984*) and then briefly accretes at a prodigious rate ($\sim 10^{-5} M_{\odot}/\text{yr}$; see *Calvet et al., 2000*). This scenario is consistent with the small population of young, often embedded stars which dramatically increase their luminosity for a few years to a few centuries (e.g., FU Ori, *Hartmann and Kenyon, 1987*; V1647 Ori, *Briceño et al., 2004*). If Class I stars intermittently accrete at this rate, they must spend 5-10% of their lifetime in the high accretion state to achieve typical T Tauri masses within 1 Myr. Statistically, 5-10% of Class I stars should then be accreting at this rate. The sample of Class I stars with mass accretion rates is now becoming large enough to suggest a possible problem with these expected percentages; none appear to accrete at this high of a rate (Section 3.4). However, there is a strong observational bias in that stars accreting at this rate are likely to be too heavily veiled, at both optical and infrared wavelengths, to identify photospheric features from which the amount of excess can be measured. Indeed, several stars observed by *WH04* and *D05* are too veiled to measure mass accretion rates. L1551 IRS 5, for example, which is the most luminous Class I star in Tau-Aur, has been proposed to be a young star experiencing an FU Ori-like outburst (*Hartmann and Kenyon, 1996*; *Osorio et al., 2003*). Without a more accurate measure of its stellar properties this is difficult to confirm; its larger luminosity could be a consequence of it being a somewhat more massive star.

An independent test of the episodic accretion hypothesis is the relative masses of Class I disks compared to Class II disks. If the envelope material of Class I stars is accumulating in their circumstellar disks, they should be more massive than Class II stars. *WH04* investigated this using 1.3 mm continuum observations from *Beckwith et al. (1990)*, *Osterloh and Beckwith (1995)*, and *Motte and André (2001)*, and restricted to beam sizes of 11 – 12'' to avoid contamination from envelope emission of Class I stars. This comparison showed that the 1.3 mm flux densities of Class I and Class II stars in Tau-Aur are indistinguishable, implying similar disk masses if the Class I and Class II disks have similar dust opacity and dust temperature (*Henning et al., 1995*). However, *Andrews and Williams (2005)* drew a different conclusion based on sub-millimeter observations at 450 μm and 850 μm (with beam sizes of 9'' and 15'', respectively). They showed that the distribution of sub-millimeter flux densities and disk masses of Class I stars are statistically different from those of Class II stars (being more massive), though Class I and Class II samples nevertheless span the same range of disk masses. Unfortunately biases introduced by stellar mass, multiplicity, envelope emission, and low spatial resolution evolutionary diagnostics, inhibit robust comparisons of these samples. We conclude there is at most marginal evidence for Class I stars having more massive disks than Class II stars, as would be expected if they undergo FU Ori-like outbursts more often than Class II stars.

Given the overall similarities of Class I and Class II stars, *WH04* put forth the still controversial suggestion that many (but not all) Class I stars are no longer in the main accretion phase and are much older than traditionally assumed; *WH04* focus their study on Class I stars in Tau-Aur, where the case for this is most compelling. This proposal does not eliminate the luminosity problem for bona-fide Class I stars, but minimizes the statistical significance of it in general. Support for this idea originates in the known biases introduced by current classification criteria which are inadequate to unambiguously identify young stars with infalling envelopes. The two largest biases are the low spatial resolution mid-infrared measurements upon which most SEDs are based and the effects of an unknown orientation on the SED. These biases likely explain why $\sim 42\%$ of stars classified as Class I stars in Tau-Aur do not appear to be bona fide protostars (Section 4.2). Indeed, some authors have claimed that Class I stars like IRAS 04016+2610 and IRAS 04302+2247 have morphologies and kinematics that are better described by a rotating disk-like structure (*Hogerheijde and Sandell, 2000*; *Boogert et al., 2002*; *Wolf, 2003*) than a collapsing envelope model (*Kenyon et al., 1993b*; *Whitney et al., 1997*), though more recent work still favors massive envelopes (e.g., *Eisner et al., 2005*). However, the limitation of all of these models is that they only account for the spatial distribution of circumstellar material, which can be confused with diffuse cloud emission (*Motte and André, 2001*) or companion stars with $\sim 10^3$ AU separations (*Haisch et al., 2004*; *Duchêne et al., 2004*). A convincing case for a massive infalling envelope can only be established by spatially mapping molecular line profiles and accounting for the effects of outflows and rotations (*Evans, 1999*). Currently the Class 0 star IRAS 04368+2557 (L1527) is the only star in Tau-Aur that has been shown to retain a massive extended envelope with unambiguous evidence for infall (*Gregersen et al., 1997*).

In regions outside Tau-Aur, there is less evidence as well as less motivation for Class I stars being older than presumed and past the main phase of mass accretion. As discussed in Section 3.4, the higher disk accretion rates of many Class I stars in ρ Oph, for example, are within a factor of ~ 10 of predicted mass infall rates, and thus easier to reconcile given current uncertainties in observations and models assumptions. Additionally, there is less evidence that these Class I stars are misclassified Class II stars, compared with Tau-Aur Class I stars. However, we strongly caution that it is not yet possible to tell if the apparent differences between the Class I population in Tau-Aur and other regions reflects real differences in their evolutionary state or is simply a consequence of Tau-Aur being a lower density environment and its members being more optically revealed. One important similarity of Class I stars in all star forming regions is their relatively low mass envelopes (e.g. *André and Montmerle, 1994*; *Motte and André, 2001*), suggesting that at this phase they have already acquired the majority of their stellar mass.

If the ages of Class I stars are indeed as old as T Tauri

stars ($\gtrsim 1$ Myr) as the comparisons tentatively suggest (Section 3.2), there is a potential dynamical timescale problem. In such a case the envelope is surviving nearly a factor of 10 longer than its dynamical collapse timescale, which seems unlikely. However, it is well known that there is nearly an order of magnitude spread in the *disk* dispersal timescale of Class II stars (e.g., *Hillenbrand et al.*, 1998); a similar spread in the envelope dispersal timescale seems plausible. One possibility for generating a large spread in the envelope dispersal timescale is that in some cases the envelopes are replenished. Recent simulations of cluster formation (e.g., *Bate et al.*, 2003) suggest that even after the initial phase of mass accretion, a young star continues to dynamically interact with the cloud from which it formed, and in some cases even significantly increase its mass. Thus some embedded stars could in fact come from an older population. These would be difficult to distinguish from younger stars in their initial main accretion phase based on circumstellar properties alone. More accurately determined age estimates is likely the best way to test this intriguing hypothesis.

Summarizing, we find that in most cases the disk accretion rates of Class I stars are well below predicted envelope infall rates. In some cases this may be a consequence of misclassification. In the more general case, it implies that if the envelope material is indeed infalling, it is not transferred to the star efficiently (e.g., *Terebey et al.*, 2006) or at a steady rate (e.g., *Kenyon et al.*, 1990), or both. While it is known that some young stars dramatically increase in brightness, presumably due to enhanced accretion (e.g., FU Ori), the idea that this is process by which stars acquire the majority of their mass is still unconfirmed. If the ages of some Class I stars are indeed as old as T Tauri stars, the long-lived envelope lifetimes may stem from envelope replenishment, possibly caused by continued interactions with the cloud after formation. Overall, it appears that most of Class I stars, as currently defined, have already acquired the majority of their final stellar mass.

5. FUTURE PROSPECTS

The ensemble of newly determined stellar and disk accretion properties of Class I stars offer powerful constraints on how and when young stars (and brown dwarfs) are assembled. However, many unknowns still remain. Here we highlight 7 key areas of research that would help resolve the remaining uncertainties and advance our understanding of the earliest stages of star formation.

More Accurately Determined Circumstellar Properties - Much of the suspected misclassification of Class I stars could be confirmed or refuted with more accurately determined SEDs based on observations over a broad wavelength range which spatially resolve features (e.g., edge-on disks) and nearby neighbors. In concert with this, more accurate and less orientation dependent criteria for identifying Class I stars needs to be established.

Extensive Surveys for Class I Stars - Larger, more complete

(and less flux limited) surveys for Class I stars in multiple star forming regions will help confirm or refute tentative trends identified with the small samples studied so far, and may likewise reveal real environmental (e.g., turbulence, gas temperature) and/or (sub)stellar mass dependencies upon the formation process.

Improved Models of the Circumstellar Environment - With larger, more accurately determined samples of Class I stars, there will be a need for more sophisticated envelope-plus-disk models of embedded stars which can fit the observed SED and scattered light and polarization images (e.g., *Osorio et al.*, 2003; *Whitney et al.*, 2005; *Eisner et al.*, 2005; *Terebey et al.*, 2006). This work is important for directly determining the density of the envelope material (which constrains the mass infall rate), estimating the extinction to the central star (which is often in error because of scattered light), and can potentially determine the system orientation.

Detailed Kinematic Mapping - The case for massive infalling envelopes can be unambiguously resolved using interferometric techniques that kinematically map the surrounding envelope-like material. In addition, these techniques offer the most direct and accurate way to determine the envelope infall rate, which can be compared to the newly determined disk accretion rates.

Improved Models of Disk Accretion - Unfortunately there remain considerable uncertainties in observationally determining disk accretion rates (e.g. bolometric correction), and these uncertainties are magnified for embedded stars with high extinction and scattered light. Consequently the absolute value of the disk accretion rates and their agreement with infall model predictions are difficult to assess. Observations of emission-line profiles and continuum excess measurements over a broad range of wavelengths are promising methods to help resolve this. Additionally, observational monitoring to determine the timescale and magnitude of variations in the mass accretion rate may yield important constraints on how and how quickly mass is acquire during this stage.

More Sensitive Spectroscopic Surveys - While the recent spectroscopic observations focused upon here have revealed much about the pre-T Tauri evolutionary stage, the data suffer from rather severe observational biases. These include biases in flux, extinction, and mass accretion rate. More sensitive spectrographs and/or larger aperture telescopes may be needed to address the first two biases, while higher signal-to-noise observations of "featureless" Class I stars may help reveal their stellar and accretion properties. Specifically, particular attention should be paid to the most luminous Class I stars in a given region, to establish better if they are more luminous because they have accretion dominated luminosities, or if they are simply more massive stars (e.g., L1551 IRS 5).

Comparisons with Synthetically Generated Spectra - Fortunately in the last decade there has been considerable progress in the area of synthetically generated spectra of stars. The implication is that stellar properties (e.g., temperature and surface gravity), can be directly extracted from

the spectra (e.g., *Johns-Krull et al.*, 1999, 2004; *Doppmann et al.*, 2003, 2005), as opposed to indirectly determined by historic spectral-comparison techniques. The most exciting application is the determination of surface gravities, as the inferred stellar radii from these measurements can be used to establish more precise age estimates, and perhaps unambiguously determine the age of Class I stars, even if only relative to T Tauri stars.

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