STELLAR AND CIRCUMSTELLAR PROPERTIES OF CLASS I PROTOSTARS

L. Prato¹, K. E. Lockhart¹, Christopher M. Johns-Krull², and John T. Rayner³

¹ Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA; lprato@lowell.edu
² Department of Physics and Astronomy, Rice University, MS-108, 6100 Main Street, Houston, TX 77005, USA; k.e.lockhart@gmail.com, cmj@rice.edu
³ Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA; rayner@ifa.hawaii.edu

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ABSTRACT

We present a study of the stellar and circumstellar properties of Class I sources using low-resolution (R ∼ 1000) near-infrared (near-IR) K- and L-band spectroscopy. We measure prominent spectral lines and features in eight objects and use fits to standard star spectra to determine spectral types, visual extinctions, K-band excesses, and water ice optical depths. Four of the seven systems studied are close binary pairs; only one of these systems, Haro 6-10, was angularly resolvable. For certain stars, some properties found in our analysis differ substantially from published values; we analyze the origin of these differences. We determine extinction to each source using three different methods and compare and discuss the resulting values. One hypothesis that we were testing, that extinction dominates over the K-band excess in obscuration of the stellar photospheric absorption lines, appears not to be true. Accretion luminosities and mass accretion rates calculated for our targets are highly uncertain, in part the result of our inexact knowledge of extinction. For the six targets we were able to place on a Hertzsprung–Russell diagram, our age estimates, <2 Myr, are somewhat younger than those from comparable studies. Our results underscore the value of low-resolution spectroscopy in the study of protostars and their environments; however, the optimal approach to the study of Class I sources likely involves a combination of high- and low-resolution near-IR, mid-IR, and millimeter wavelength observations. Accurate and precise measurements of extinction in Class I protostars will be key to improving our understanding of these objects.

Key words: infrared: stars – stars: evolution – stars: formation

1. INTRODUCTION

Class I sources represent one of the earliest stages of star formation and are identified by a rising spectral energy distribution (SED) at wavelengths longer than 2 μm (Lada 1987). These sources are deeply embedded within molecular clouds and are very faint or undetectable at visible wavelengths because of a thick envelope of circumstellar dust. This material effectively envelops the whole star and as a result, the light from these young stellar objects (YSOs) is absorbed and re-radiated in the infrared (IR). Therefore, most studies of Class I objects employ observations in the near-IR or longer wavelength regimes where these sources are relatively bright (e.g., Greene & Lada 1996, 2002; Dopmann et al. 2005; Beck 2007).

Following the suggestion of Lada (1987), it has been commonly thought that Class I objects inhabit an earlier evolutionary stage relative to Class II sources (classical T Tauri stars, or CTTSs). However, showing that the central YSOs in Class I sources display signatures indicative of an earlier evolutionary phase compared to CTTSs has not been straightforward. Kenyon et al. (1998) conducted a visible light, low spectral resolution survey of Class I YSOs in the Taurus star-forming region (SFR). They identified preliminary spectral types and luminosities and determined that for Class I sources these properties were similar to those of the Class II objects in Taurus. However, these investigators did find a greater frequency and intensity of outflows as deduced from forbidden line emission in the Class I objects. White & Hillenbrand (2004) used high spectral resolution data in the visible to measure the stellar properties of several dozen Class I objects and reached similar conclusions, although they argue that the larger equivalent width values observed in forbidden emission lines from Class I sources might be attributable to the effect of circumstellar disk orientation causing obscuration of the central continuum source (White et al. 2007) rather than to a higher incidence of strong jets. White & Hillenbrand (2004) also found that the veiling and derived accretion rates were similar for Class I and Class II sources; however, using high-resolution IR spectra, Dopmann et al. (2005) found that the veiling and associated accretion rates of Class I and flat-spectrum YSOs are higher than those of the Class II objects. As a result of these discrepancies, it is unclear how much of the final mass of a YSO is accreted during the Class I phase. Episodic events have been proposed to account for significant growth over short periods (e.g., Kenyon et al. 1998); however, White et al. (2007) argue that the process by which protostars acquire the majority of their mass is still unconfirmed.

From an evolutionary point of view, another property that is expected to differ between the two classes of YSOs is their rotation rates, but again unambiguous observational evidence for this is lacking. White & Hillenbrand (2004) determined that their sample of Class I objects in Taurus is rotating at v sin i < 35 km s⁻¹ on average, which makes them generally indistinguishable from Class II sources in this SFR. However, Covey et al. (2005) found that Class I and flat-spectrum objects (apparently transitioning from Class I to Class II; Greene & Lada 1997) in the Taurus and Ophiuchus SFRs do rotate more quickly than Class II objects in the same regions. To account for rotational slowing between the Class I and Class II phases, Montmerle et al. (2000) invoked the onset of magnetic disk braking (e.g., Koenigl 1991; Shu et al. 1994) over the protostellar lifetime. In the framework of this paradigm, once disk locking has fully engaged, the star has evolved to the Class II stage and its rotation has slowed accordingly. Alternatively, Matt &
Pudritz (2005) proposed accretion-driven winds to account for angular momentum changes in young stars.

It seems unlikely that all Class I objects could be Class II systems with irregular appearances attributable to geometric effects. Some Class I sources no doubt are simply CTTs seen through edge-on disks, but the rest may well be part of an overall evolutionary sequence from Class 0/I to Class I/II YSOs. Untangling the evolutionary state and geometric effects influencing these classifications is, however, apparently quite complex.

Following the early, low-resolution (~600) near-IR spectroscopy studies of Greene & Lada (1996, 1997) on Class I sources, there has been a shift to primarily high spectral resolution (R ∼ 18,000) studies of protostars (e.g., Greene & Lada 2000, 2002; White & Hillenbrand 2004; Doppmann et al. 2005; Covey et al. 2005, 2006) as the requisite instrumentation has become available on large telescopes. High-resolution spectra permit the measurement of $v \sin i$, magnetic fields, and other detailed properties. Although this work has proved valuable, the wide wavelength coverage available with low dispersion spectrographs provides unique leverage in the study of these very embedded young stars, allowing for the simultaneous determination of the extinction and the examination and characterization of many spectral features. For objects in common with high dispersion studies, the results we obtain here, based on low-resolution IR data, are not always the same, suggesting that the two approaches are complementary.

While a number of continuum and line emission processes likely play a role in shaping the emergent spectra of Class I objects, we undertook the current study to test the hypothesis that extinction is the dominant factor, as indicated by analysis of the protostar YLW 15A (Prato et al. 2003). In this current paper, we determine the properties of a small sample of eight Class I YSOs using a number of techniques such as measuring the equivalent width of key spectral absorption and emission line features, placing sources in a color–color diagram using photometric data obtained from the literature, and fitting our observed spectra to standard star spectra to determine effective temperature ($T_{\text{eff}}$), extinction, and $K$-band excess. Our goal is to understand better the properties of protostars and the characteristics of their surrounding environments using photometry in combination with low-resolution spectroscopy of atomic and molecular lines, as well as of solid-state features such as water ice absorption at 3.1 μm (Beck 2007). We examine several approaches to measuring extinction in our targets and compare these with each other and with estimates found in the literature. In this study we find a wide range in the strength and shape of protostar spectral features, both emission and absorption lines, from source to source, even in our relatively small sample of eight objects. The principal unifying feature to the entire set is a rising spectrum across the $K$ band. The observations and data reduction procedures are described in Section 2. In Section 3, we present the analysis of the data. A discussion appears in Section 4 and the results are summarized in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

Our sample consists of eight Class I YSOs in the Taurus SFR, two of which comprise a relatively wide binary, Haro 6-10. Three of the YSOs were unresolved binaries, IRAS 04239+2456, L1551 IRS 5, and IRAS 04361+2547. The objects are listed in Table 1, along with coordinates and observing dates. The coordinates reported here were determined using the Two Micron All Sky Survey (2MASS) interactive image service.

### Table 1

| Object Name | α (J2000.0) | δ (J2000.0) | UT Date of Observation |
|-------------|-------------|-------------|------------------------|
| IRAS 04016+2610 | 04 04 43.0 | +26 18 57 | 2000 Nov 18 |
| IRAS 04181+2654A | 04 21 11.5 | +27 01 09 | 2000 Nov 18 |
| IRAS 04239+2436 | 04 26 57.1 | +24 43 36 | 2000 Nov 18 |
| Haro 6-10 | 04 29 24.2 | +23 33 00 | 2000 Nov 19 |
| L1551 IRS 5 | 04 31 34.0 | +18 08 05 | 2000 Nov 18 |
| IRAS 04361+2547 | 04 39 13.9 | +25 53 21 | 2000 Nov 19 |
| IRAS 04489+3042 | 04 52 06.7 | +30 47 18 | 2000 Nov 20 |

Notes.

- Binary of separation 0′′.30 (Reipurth et al. 2000).
- Binary of separation 1′′.2 (Leinert & Haas 1989; listed as Haro 6-10 S (visible light primary) and N in subsequent tables. Haro 6-10 S is a radial velocity variable and thus possibly a spectroscopic binary (Doppmann et al. 2008).
- Binary of separation 0′′.35 (Looney et al. 1997).
- Binary of separation 0′′.31 (Terebey et al. 1999).

### Table 2

| Object Name | Spectral Type | $K_s$ (mag) | UT Date of Observation |
|-------------|---------------|-------------|------------------------|
| HR 996 | G5 V | 3.0 | 2000 Nov 19 |
| HR 995 | G6 IV | 4.1 | 2000 Nov 20 |
| HR 7957 | K0 IV | 1.4 | 2000 Nov 20 |
| HR 166 | K0 V | 4.0 | 2000 Nov 19 |
| HR 753 | K3 V | 3.5 | 2000 Nov 19 |
| GL 846 | M0.5 V | 5.3 | 2000 Nov 19 |
| GL 908 | M1 V | 5.0 | 2000 Nov 18 |
| GL 15A | M1.5 V | 4.0 | 2000 Nov 20 |
| GL 806 | M2 V | 6.5 | 2000 Nov 19 |
| GL 752A | M3 V | 4.7 | 2000 Nov 19 |
| HR 9064 | M3 III | −0.1 | 2000 Nov 20 |
| GL 876 | M4 V | 5.0 | 2000 Nov 20 |
| GL 83.1 | M4.5 V | 6.6 | 2000 Nov 19 |

Initially, using coordinates in SIMBAD, 2MASS images were found to show a displacement of sometimes 10′′ or more between the coordinate center and the stellar image. By iterating the coordinates until these matched, we determined the best values for our sample targets. Haro 6-10 is unresolved in 2MASS images. The sample was drawn from the study of Greene & Lada (1996) and selected on the basis of steeply rising $K$-band spectra; Greene & Lada identified seven of the eight systems as Class Is and IRAS 04489+3042 as a flat-spectrum source. In addition, 13 spectral type standard stars were observed and are listed in Table 2 along with their spectral types, $K$-band magnitudes, and dates of observation. These standards were selected to cover a wide range of low-mass spectral types for use in the model fitting described below.

The data were obtained at the NASA Infrared Telescope Facility on Mauna Kea in 2000 November 18–20 (UT), using SpeX, the facility low-resolution near-IR spectrograph (Rayner et al. 2003). A 1024 × 1024 InSb array was used to record the spectra. Simultaneous observations of the $K$ and $L$ bands (~2.0–4.2 μm) were acquired by means of a prism cross-disperser. A slit width of 0.8″ was used for all observations, yielding a spectral resolution of $R \equiv \lambda / \delta \lambda = 1000$. The seeing ranged from 0.5″ to 0.9″. The data were acquired in pairs, nodded along the slit between frames. Exposure times varied between 0.51 s and 30 s, and multiple exposures were taken in each nod position.
Stars of spectral type A0 were also observed for the removal of telluric features. Exposures of an argon lamp were taken for wavelength calibration. Flat field and dark exposures were also acquired.

Data were reduced using the REDSPEC code. Normalized flat fields were created by taking the median of the set of three flat-field exposures taken for each star. The effects of subtracting median dark frames from the flat were insignificant so this differencing was not performed. Target exposures were medianed to create a single image of the spectrum of each star at each nod position. For each object these medianed nod pairs were differenced and divided by the corresponding flat. The images were spatially rectified using fourth-order fits to bright A0 star traces in each order. When the REDSPEC code could not fit the traces automatically, as occurred in an L-band order where there was significant atmospheric contamination, manual fits to the traces were performed. Wavelength calibration was accomplished by fitting a second-order polynomial to the positions of identified lines in the argon lamp line spectrum. Several rows containing the stellar spectral data in the rectified, differenced image, one positive trace and one negative trace, were then summed. By subtracting the resulting negative spectrum from the positive, we accomplished a double-difference procedure that eliminated OH night sky emission line residuals. A0 calibrator star spectra, observed at similar airmasses as the standard and target stars, were used for the removal of telluric absorption lines. Intrinsic atomic hydrogen lines were interpolated over in the calibrator star spectrum, which was then divided into the standard and target star spectra. The ratio was multiplied by a featureless 9500 K blackbody curve to restore the original shape of the continuum of the standard or target star. After reduction, cosmetic improvements (such as interpolation over bad pixels) were made to the spectra. The reduced K-band spectra of the standard stars appear in Figures 1 and 2. The reduced K- and L-band spectra of the Class I objects appear in Figures 3 and 4.

Four of our target systems are binaries; however, only Haro 6-10 was angularly resolvable. When extracting the Haro 6-10 S and N spectra, the number of extracted rows was chosen so as to avoid contamination by the companion star. The spectra of IRAS 04239+2436, L1551 IRS 5, and IRAS 04361+2547 are composed of the blended light of their primary and secondary components.

3. ANALYSIS

3.1. Target Colors and Corresponding Extinction

Near-IR magnitudes for the Class I sample (Table 3) were obtained from the 2MASS point source catalog (Skrutskie et al. 2006) and used to construct a J−H versus H−K color–color diagram (Figure 5). Haro 6-10 N lacks a J-band measurement and hence is not shown. The location of Haro 6-10 S on the diagram implies strong contamination from circumstellar scattered light. All other targets show evidence for a large near-IR excess and most are highly extinguished.

To measure the extinction from the color–color diagram, we used the relation $A_V = 13.83(J−H)_{\text{obs}}−8.29(H−K)_{\text{obs}}−7.43$, derived in Prato et al. (2003). This dereddens the targets to the

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5 See http://www2.keck.hawaii.edu/inst/nirspec/redspec.
Figure 4. $K$- and $L$-band spectra for the spectroscopic sample; the region around 2.7 $\mu m$ contaminated by terrestrial water absorption is not shown. The spectra were extracted from five overlapping orders and scaled to match in the overlap regions. The overall spectrum was normalized at 2.25 $\mu m$ and shifted by a constant for presentation. The ice band feature and hydrogen lines are indicated.

Figure 5. $J-H, H-K$ color–color diagram of the Class I sample, except for Haro 6-10 N. Magnitude data were obtained from 2MASS and from the literature. The dotted line separates objects with (to the right and below) and without a near-IR excess. The dwarf (dash-dotted line) and giant (solid line) star loci are overplotted at the bottom left. The CTTS locus and $A_v = 10$ mag reddening vector from Meyer et al. (1997) are also shown.

3.2. Equivalent Widths and Surface Gravity

Equivalent widths for spectral features in the $K$ band were measured for the standard stars and for the Class I YSOs and are given in Tables 4 and 5, respectively. The equivalent width of the Br$\alpha$ emission line for the Class I sources is also given in Table 5. Equivalent width uncertainties were determined by varying the location at which the relative continuum was measured. For the $K$ band, this yielded uncertainties of $\sim 0.5$ Å and for the $L$ band, $\sim 2$ Å. When no value is given in Table 4 or 5, the equivalent width is less than the uncertainty or the line is not detected at all.

Only two targets in our sample, L1551 IRS 5 and IRAS 04489+3042, showed Na $\text{i}$, Ca $\text{i}$, and CO (2–0) all in absorption. We compared the locations of these two stars with the dwarf (from our data) and giant (from Wallace & Hinkle 1997) star Na $\text{i}$+Ca $\text{i}$ versus CO (2–0) equivalent width loci (similar to the loci data in Prato et al. 2003) and find that the Class I sources are consistent with giant star surface gravities. We conclude that, for Class I protostars, at least in some cases, low surface gravity standards would be preferable as spectroscopic templates.

3.3. Spectral Types, $K$-band Excess, and Extinction Revisited

To determine the underlying spectral type, $K$-band excess, $r_K$, and extinction down to the protostellar photosphere, we compared the $K$-band YSO spectra to a suite of dwarf, subgiant, and giant spectral type standards (Figures 1 and 2). We initially followed the same procedure described in Prato et al. (2003) which we briefly review. For a range of trial $A_V$ and $r_K$ values, the Class I target spectra are dereddened using the reddening law of Rieke & Lebofsky (1985) and the veiling continuum is removed. This modified spectrum is then fit to spectral type standard templates by determining the multiplicative scale factor that minimizes $\chi^2$. The combination that gives the lowest overall value of $\chi^2$ then gives us an estimate of $A_V$, $r_K$, and the spectral type appropriate for each Class I source. This procedure provided initial estimates of these key properties; however, additional experimentation with wavelength-dependent veiling and visual examination of the resulting fits was used to arrive
YSO fits to the comparison standard stars. Some comments on order of 5%–15% were estimated from visual inspection of the depths of the Ca\textsuperscript{i} identify a K star spectral type, and Doppmann et al. (2005)\textsuperscript{−}\textsuperscript{−}L1551 IRS 5\textsuperscript{−}\textsuperscript{−}IRAS 04239+2436\textsuperscript{−}\textsuperscript{−}μ-band excess for this protostar. Given the similar Haro 6-10 Sc 11.54 ± 0.03\textsuperscript{d}\textsuperscript{−}\textsuperscript{−}IRAS 04181+2654A 16.44 ± 0.12 13.02 ± 0.04 10.72 ± 0.03 8.9\textsuperscript{a} 5 20.8 ± 1.8 IRAS 04489+3042 14.43 ± 0.03 12.02 ± 0.02 10.38 ± 0.02 1.5\textsuperscript{a} 6 12.3 ± 0.6

Table 3
Sample Photometry

| Object Name | J (mag) | H (mag) | K\textsubscript{s} (mag) | L (mag) | L Band References | Color–Color Diagram A\textsubscript{v} (mag) |
|-------------|---------|---------|----------------|--------|------------------|-----------------------------|
| IRAS 04016+2610 | 14.01 ± 0.07 | 12.16 ± 0.08 | 9.84\textsuperscript{a} | 6.8\textsuperscript{a} | 1 0.0 ± 1.6 |
| IRAS 04181+2654A | 16.22 ± 0.08 | 12.65 ± 0.02 | 10.34 ± 0.03 | 8.5\textsuperscript{b} | 2 22.8 ± 1.2 |
| IRAS 04239+2436 | 15.75 ± 0.09 | 12.35 ± 0.04 | 9.99 ± 0.02 | 7.2\textsuperscript{b} | 2 20.0 ± 1.4 |
| Haro 6-10 S\textsuperscript{c} | 11.54 ± 0.03\textsuperscript{d} | 10.6 ± 0.1 | 8.6 ± 0.1\textsuperscript{a} | 6.1 ± 0.1\textsuperscript{b} | 3 0 ± 1.9 |
| Haro 6-10 N\textsuperscript{c} | ... | 13.5 ± 0.1 | 8.7 ± 0.1\textsuperscript{a} | 4.9 ± 0.1\textsuperscript{b} | 3 ... |
| L1551 IRS 5 | 13.71 ± 0.06 | 11.51 ± 0.05 | 9.82 ± 0.04 | 7.4\textsuperscript{a} | 4 9.1 ± 1.2 |
| IRAS 04361+2547 | 16.44 ± 0.12 | 13.02 ± 0.04 | 10.72 ± 0.03 | 8.9\textsuperscript{a} | 5 20.8 ± 1.8 |
| IRAS 04489+3042 | 14.43 ± 0.03 | 12.02 ± 0.02 | 10.38 ± 0.02 | 1.5\textsuperscript{a} | 6 12.3 ± 0.6 |

Notes.
Data are from 2MASS unless otherwise specified.
\textsuperscript{a} No uncertainty available.
\textsuperscript{b} L' magnitude.
\textsuperscript{c} H, K, and L' magnitudes quoted for the highly variable Haro 6-10 system are from reference (3) and correspond to the date of their observations closest in time to our spectroscopy.
\textsuperscript{d} All J-band flux from Haro 6-10 is assumed to come from the "primary," southern component; the J magnitude is from 2MASS and was not observed concurrently with the H, K, and L data.

References, (1) Benson et al. (1984); (2) Beck (2007); (3) Leinert et al. (2001); (4) Cohen & Schwartz (1983); (5) Kenyon et al. (1990); (6) Myers et al. (1987).

Table 4
Standard Star K-band Equivalent Widths (Å)

| Name | Spectral Type | 2.166 μm CO(2–0) Hα | 2.208 μm Na I | 2.264 μm Ca I | 2.281 μm Mg I | 2.294 μm CO(3–1) | 2.323 μm CO(3–1) |
|------|---------------|-----------------------|----------------|----------------|----------------|------------------|------------------|
| HR 996 G5 V | 3.2 | 1.3 | 1.2 | 1.1 | 1.5 | 6.6 |
| HR 995 G6 IV | 2.2 | 0.9 | 1.1 | 0.7 | 4.7 | 5.0 |
| HR 7957 K0 IV | 2.1 | 0.9 | 1.4 | ... | 5.9 | 7.1 |
| HR 166 K0 V | 2.1 | 1.5 | 1.6 | 1.7 | 4.5 | 6.5 |
| HR 753 K3 V | 1.4 | 2.2 | 2.1 | 1.9 | 6.6 | 6.6 |
| GL 846 M0.5 V | ... | 4.4 | 4.3 | 1.1 | 7.4 | 6.2 |
| GL 908 M1 V | ... | 1.9 | 2.7 | ... | 4.8 | 5.1 |
| GJ 15A M1.5 V | ... | 3.3 | 3.2 | ... | 5.6 | 5.3 |
| GL 806 M2 V | ... | 3.8 | 3.9 | ... | 6.6 | 6.3 |
| GL 752A M3 V | ... | 4.6 | 4.5 | ... | 7.4 | 7.1 |
| HR 9064 M3 III | ... | 2.2 | 2.8 | 2.0 | 20.9 | 13.7 |
| GJ 876 M4 V | ... | 6.2 | 4.2 | ... | 4.5 | 6.2 |
| GL 83.1 M4.5 V | ... | 5.1 | 2.4 | ... | 6.0 | 4.3 |

Table 5
Target Star Equivalent Widths (Å)

| Name | 2.059 μm CO(2–0) Hα | 2.122 μm CO(3–1) Hα | 2.166 μm CO(3–1) Hα | 2.208 μm CO(2–0) Na I | 2.264 μm CO(2–0) Ca I | 2.281 μm CO(3–1) Mg I | 2.294 μm CO(3–1) CO(2–0) Br α |
|------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| IRAS 04016+2610 | ... | −2.2 | −2.3 | 1.0 | 1.0 | 2.0 | 2.3 | ... | −11.5 |
| IRAS 04181+2654A | −1.4 | −1.9 | −9.9 | 1.3 | 1.6 | −0.8 | ... | 4.0 | −23.0 |
| IRAS 04239+2436 | −2.6 | −2.3 | −15.3 | −2.4 | 1.4 | ... | −11.9 | −10.5 | −25.0 |
| Haro 6-10 S | ... | −2.1 | −4.1 | ... | 1.0 | 1.0 | ... | ... | −33.0 |
| Haro 6-10 N | ... | −2.5 | −3.1 | −1.1 | ... | ... | −6.7 | −2.2 | ... |
| L1551 IRS 5 | ... | −2.5 | −1.7 | 2.4 | 1.9 | ... | 16.7 | 14.8 | −4.5 |
| IRAS 04361+2547 | ... | −2.8 | −2.6 | ... | 0.5 | 1.4 | ... | ... | −2.0 |
| IRAS 04489+3042 | −2.6 | ... | −2.7 | 2.0 | 1.7 | ... | 4.6 | 4.5 | ... |

at the final values shown in Table 6. Crude uncertainties on the order of 5%–15% were estimated from visual inspection of the YSO fits to the comparison standard stars. Some comments on the fitting process for each target are as follows.

3.3.1. IRAS 04016+2610

White & Hillenbrand (2004) and Doppmann et al. (2005) identify a K star spectral type, and Doppmann et al. (2005) find a large K-band excess for this protostar. Given the similar depths of the Ca I, Mg I, and first CO bandhead evident in the spectrum of IRAS 04016+2610, an early K spectral type appears to provide the best match. The K-band excess has a positive slope of F\textsubscript{r}/\lambda ∼ 0.5 and a y-intercept of 0.1. Unfortunately, the subtraction of such a large K-band excess from the observed spectrum results in a noisier spectrum that the original; higher signal-to-noise data would improve the accuracy of the fit. Experimenting with multiple spectral type standard spectra, a range of extinctions from 43 to 53 mag, and veiling at 2.2 μm of 0.5–1.5, we conclude that IRAS 04016+2610 is best fit with a K3 spectral type, A\textsubscript{v} = 45 mag, and r\textsubscript{K} = 1.3. This spectral
type and excess are consistent with the results of Doppmann et al. (2005) using high-resolution ($R = 18,000$) $K$-band spectra.

### 3.3.2. IRAS 04181+2654A

The data of Beck (2007) taken of this source $\sim 3$ years after our spectra, and at higher signal to noise, show better-defined stellar absorption features. However, both the shape of the continuum and the depth of absorption lines, shown in Figure 3, provide important limits from which to determine the best fit. The presence of water vapor in the atmospheres of M type objects produces a break in the slope of the spectrum at about $2.3 \, \mu m$ (Wilking et al. 1999). Thus, objects with such a break (Figures 1 and 3) are unambiguously of later spectral type. In lieu of clearly detectable stellar absorption lines, we estimated an upper bound for the extinction by assuming a zero $K$-band excess and fitting the slope of the continuum to an M star. The continuum spectrum of IRAS 04181+2654A is consistent with an early M star and an $A_v$ upper limit of 34 mag. Beck (2007) found an $A_v$ of 18 mag and an M3$^+$ spectral type.

### 3.3.3. IRAS 04239+2436

All spectral features, including Na I and CO, observed in the $K$ band for this target are in emission. No break in the continuum is detected, thus a spectral type later than K7 (Figure 1) is unlikely. Using a K0 V standard and setting the $K$-band excess to zero, we estimate an upper limit for the visual extinction of $\sim 45$ mag.

### 3.3.4. Haro 6-10 S

We found a constant $K$-band excess of $\sim 0.5$ for Haro 6-10 S and an extinction of 30 mag. No break in the continuum was observed, implying a spectral type earlier than M0. Small absorption lines of Na I, Ca I, and Mg I are clearly visible; however, the CO is probably in emission, filling in what would otherwise be fairly deep absorption features (see Doppmann et al. 2008). We assign Haro 6-10 S an early K spectral type and use a K3 type to estimate an approximate temperature, although this is highly uncertain.

### 3.3.5. Haro 6-10 N

Setting the $K$-band excess to zero, we estimated an upper limit for the extinction and the spectral type of the emission line object Haro 6-10 N. We find an upper limit of 59 mag for the extinction and a spectral type consistent with an early K or G type star.
and 3.88 μm. Once we have fit each observed spectrum, we divide that spectrum by the fit and set the minimum value of the ratio equal to $e^{-\tau_{\text{ice}}}$ and solve for $\tau_{\text{ice}}$. An example of our fit to IRAS 04016+2610 appears in Figure 7.

Whittet et al. (1988) found a linear correlation between $\tau_{\text{ice}}$ and the visual extinction, $A_V$, for the interstellar medium. Sato et al. (1990) examined this correlation for a sample of protostars, assuming the ice to be in the circumstellar material surrounding the star itself, and used the same relation as Whittet et al. (1988), $\tau_{\text{ice}} = 0.093(A_V - A_{Vc})$, adopting a critical visual extinction of $A_{Vc} = 1.6$ mag. We use this modified relation to calculate the extinction as traced by the circumstellar ice feature. The results appear in Table 7.

The combination of near-simultaneous moderate resolution spectroscopy from the near-IR to the mid-IR allows for the comparison of solid-state features and hence reveals physical and compositional properties of Class I envelopes (e.g., Furlan et al. 2008). We examined the correlation of the 10 μm silicate absorption feature strength, $F_{\lambda}$, from Kessler-Silacci et al. (2005), calculated from a Gaussian fit to the normalized mid-IR spectra, with optical depths we determined for the 3.1 μm water ice feature (Table 7). Figure 8 shows a trend toward higher ice optical depths for strong silicate absorption sources only; no significant correlation is obvious.

### 3.5. H–R Diagram

To compare the relative masses and ages of our Class I sources with those of Class II objects, we plotted stars for which we have the most reliable spectral types, determined from both absorption lines and continuum shape, on the Hertzsprung–Russell (H–R) diagram (Figure 9). For four targets, we used luminosity estimates from Furlan et al. (2008). For two others, IRAS 04016+2610 and Haro 6-10 S, we used values from Doppmann et al. (2005) either because the value from Furlan et al. (2008) was anomalously low (implying a main-sequence age for IRAS 04016+2610) or because Furlan et al. (2008) did not observe the source (Haro 6-10 S). We used our spectral type estimates (Table 6) combined with the dwarf conversion (Table 2) given in Johnson (1966), to determine $T_{\text{eff}}$. Interestingly, Johnson’s spectral type to $T_{\text{eff}}$ conversion closely parallel those derived for young stars by Luhman et al. (2003), from G through mid-M spectral types. In Table 8 we list our $T_{\text{eff}}$, and for comparison the luminosity of each star given by Furlan et al. (2008), Doppmann et al. (2005), and/or White & Hillenbrand (2004). The resulting mass and age from the pre-main-sequence tracks of Palla & Stahler (1999) are provided in Table 8 for the six targets for which these data were possible to derive.

Of the seven systems studied in this paper (taking Haro 6-10 S and N as one system), four are close binaries (Table 1).
The three single systems in our sample along with Haro 6-10 S and two of the unresolved binaries appear in Figure 9. There is an inherent overestimate of the stellar luminosity for the unresolved pairs, which are treated as single objects by Furlan et al. (2008). Also, geometrical effects produced by the relative orientations of the circumstellar disks of each binary component could lead to anomalous measurements of extinction and excesses, for example, in the case of a configuration in which one star is obscured by the disk of the other. To the extent that circumstellar disks (flared or seen nearly edge-on) contribute to the extinction, it is quite possible the extinction is very different to the two members of the binary. Without angularly resolved observations of the component objects in these systems, the degree to which binarity distorts the results of Class I studies, specifically the effective temperature and luminosity estimates and thus a source’s location in the H–R diagram, is unknown.

The unresolved binaries are located far above the evolutionary model tracks in Figure 9, suggesting unrealistically young ages for these systems.

3.6. Accretion Luminosity and Mass Accretion Rate

For comparison with other studies of Class I objects as well as with Class II targets, we calculated the accretion luminosity, \( L_{\text{acc}} \), of the eight stars in our sample using the correlation between \( L_{\text{acc}} \) and Br\( \gamma \) line luminosity found by Muzerolle et al. (1998). Our calculation is based on the \( K \)-band magnitude, the Br\( \gamma \) emission line strength, and the overall extinction, for which we used the value determined by model fitting to standard stars as described in Section 3.3. The results appear in Column 2 of Table 9. In most cases, the measurement is significant only at the 1\( \sigma \) level because the inherent uncertainties in the relationship between the accretion luminosity and the Br\( \gamma \) line luminosity (Muzerolle et al. 1998) are large. For half of our sample, we use upper limits for the extinction; if instead we use the values for extinction determined from the ice feature (Table 7), we obtain lower values for \( L_{\text{acc}} \) in the cases of IRAS 04181+2654A (\( \log(L_{\text{acc}}) = -0.84 \pm 1.12 \)), IRAS 04239+2436 (\( \log(L_{\text{acc}}) = -0.19 \pm 1.06 \)), and Haro 6-10 N (\( \log(L_{\text{acc}}) = -0.94 \pm 1.14 \)). For IRAS 04361–2547, the other system with an upper limit only for \( A_v \), in Table 6, the ice feature \( A_v \) (24.2 mag) is similar to the upper limit (less than 30 mag).

For the six targets in our sample for which we have estimates of both \( T_{\text{eff}} \) and the luminosity (Furlan et al. 2008), we calculated the stellar radius, \( R_\star \), and hence the mass accretion rate, \( \dot{M} \), following Gullbring et al. (1998): \( \dot{M} = 1.25 \frac{L_{\text{acc}}}{R_\star (GM_\odot)} \) (Table 9). Stellar mass (\( M_\star \)) was estimated from the location of the targets in the H–R diagram. Primarily as a result of the very large uncertainties in the calculated accretion luminosity, \( L_{\text{acc}} \), uncertainties in our mass accretion rates are all approximately an order of magnitude.

4. DISCUSSION

4.1. Comparison with Previous Results from the Literature

4.1.1. Extinction

As demonstrated here and also shown in Beck (2007), different approaches to measuring the extinction along the line
of sight to Class I protostellar photospheres produce widely different results. We have used the position of sources in a near-IR color–color diagram, fitting to absorption features and the continuum shape of the $K$-band spectra, and fitting to the $L$-band water ice feature to determine $A_v$. and have found values that differ significantly. Figure 10 shows the extinctions determined from de-reddening objects plotted on the color–color diagram and from $K$-band spectral fitting as a function of $A_v$ determined from fitting the $L$-band water ice feature (Figure 7). Color–color diagram determined extinctions appear to scatter randomly, whereas extinctions measured from our $K$-band spectra, excluding the upper limits, show some positive correlation with the ice $A_v$. This suggests that the color–color diagram approach does not trace the same material along the line of sight. The color–color approach was based on the possibly flawed premise that the circumstellar envelope present in a Class I system contributes only reddening and assumes that the intrinsic colors of Class I protostars are the same as those of CTTSs. As a counterexample, consider objects that fall below the CTTS locus in the color–color diagram, i.e., IRAS 04016+2610 and Haro 6-10 S. These are no doubt extinguished; however, the effect of scattered light in the surrounding circumstellar environment yields unusual colors. Measurements of the extinction from the optical depth of the water ice feature in the $L$ band probes the extinction through the region where this feature forms, while possibly missing extinction caused by dust in inner, warmer regions of an envelope or disk where it is too hot for water ice to survive. This could explain the systematically higher $A_v$ values from the $K$-band spectroscopic fit approach (again, excluding the upper limits) which show a similar slope as the one-to-one correlation and presumably take into account all sources of extinction along the entire line of sight to the target system.

Comparison of our extinction results with those of White & Hillenbrand (2004) and Beck (2007) reveals that these studies are generally consistent with our smaller estimates of extinction based on fitting of the $L$-band ice absorption feature. White & Hillenbrand (2004) provide extinctions determined from $J−H$ colors and Beck (2007) derives extinctions using several different approaches, including a spectral fitting procedure similar to the $K$-band fits employed here. In their Section 3.8, Dopmann et al. (2005) describe an approach to estimating extinction, based on $K$-band magnitudes, in order to derive stellar luminosities; however, they do not provide values of extinction in their paper. It is difficult to know which approach yields the “correct” extinction to a protostar. Ideally, a combination of near-simultaneous high- and low-resolution spectroscopy could provide careful measurements of underlying absorption line ratios as well as a measurement of the continuum slope. Even relatively small uncertainties in extinction can have a strong impact on derived Class I object properties, particularly accretion rates, and hence studies of these targets can be significantly improved with more attention to this problem.

4.1.2. Spectral Types, Surface Gravity, and $K$-band Excesses

Three of our targets, IRAS 04016+2610, Haro 6-10 S, and IRAS 04489+3042, for which we determined $T_{\text{eff}}$, $A_v$, and $r_k$, were also analyzed by White & Hillenbrand (2004), Dopmann et al. (2005, 2008), and Luhman (2006). Another, L1551 IRS 5, was analyzed by Dopmann et al. (2005). Our results for spectral types, surface gravities, and $K$-band excesses typically agree to within 1σ−2σ with those from the literature with the exception of Haro 6-10 S and L1551 IRS 5, discussed below. For IRAS 04489+3042, Luhman (2006) found a spectral type of M3.5−M4.5 on the basis of visible light observations, and M3−M4 on the basis of IR observations, in excellent agreement with our determination of an M3.5 spectral type for this source.

For Haro 6-10 S, Dopmann et al. (2008) used high-resolution, high signal-to-noise $K$-band spectra to derive a $T_{\text{eff}}$ of 3800 K, cooler than our value of ~4800 K, a surface gravity (log $g$) of 4.0, and a $K$-band excess of 2.5, substantially larger than our uncertain estimate of 0.5. Based on the appearance of their spectra, these values for Haro 6-10 S are more reliable than our findings and result in a mass estimate smaller than ours by a factor of $>3$; both studies result in similar ages (2–3 Myr).

For L1551 IRS 5, we find an excellent match to an M3 III spectral type. Dopmann et al. (2005) find a $T_{\text{eff}}$ of 4800 K, corresponding to an early K spectral type, and a log $g$ of 4.0. In both our analysis and theirs, the $K$-band veiling is ~1. Figure 6 shows our M3 III fit of the modified young star spectrum, with $A_v$ = 28 mag and a constant $K$-band excess taken into account. Inspection of the spectra presented in Dopmann et al. (2005) shows an inconsistency with their earlier spectral type and higher gravity, possibly as the result of a degeneracy between the equivalent widths of the Na i and Mg i/Al i lines as a function of $T_{\text{eff}}$ and log $g$ (G. W. Dopmann 2007, private communication). The lower surface gravity found in our fit is also consistent with our comparison of the location of L1551 IRS 5 on a plot of the Na i + Ca i versus CO (2−0) equivalent widths (Section 3.2); it clearly lies along the giant star locus.

In general, from our $K$-band spectral fits, we find higher extinctions and lower excesses than those derived in previous Class I studies. We have used arbitrary slopes for fitting the $K$-band excess, with no physical basis in a realistic model of circumstellar disk and/or envelope radiation. A combination of high signal-to-noise ratio, low- and high-resolution spectra, and detailed modeling of the SED, as in Furlan et al. (2008), will be necessary to improve these uncertain results.
4.1.3. Accretion Luminosities and Mass Accretion Rates

For six of our targets, published accretion luminosities are available for comparison in Muzerolle et al. (1998) and Beck (2007); these are provided in Table 9. Although the procedure for measuring the mass accretion rates followed in this paper and in the work of Muzerolle et al. (1998) and Beck (2007) was the same, i.e., based on the \( \text{Br}\gamma \) emission line, our values are all larger by \( >1\sigma\sim2\sigma \). Four objects have upper limits only for the spectroscopically determined \( A_v \). We recalculated the accretion luminosities for the three largest upper limits using the \( A_v \) values based on the 3.1 \( \mu \)m ice feature (see Section 3.6). The recalculated \( L_{\text{acc}} \) values are much closer to the values found by Muzerolle et al. (1998) and Beck (2007) for the same targets, illustrating that the relatively large values and upper limits for the extinction determined from our \( K \)-band spectra are responsible for our relatively large accretion luminosities (Table 6). The impact of these larger accretion luminosities propagates into our calculation of the mass accretion rates, which range from \( \sim5\times10^{-7}M_\odot\text{yr}^{-1} \) to \( \sim2\times10^{-8}M_\odot\text{yr}^{-1} \) (Table 9), calculable for six of our targets. For the targets with published accretion rates, our estimates are equivalent or larger by up to 2 orders of magnitude (Table 9), however, with an uncertainty of approximately an order of magnitude. Given this large uncertainty, our small sample size, and the ambiguity in the determination of \( A_v \), it is impossible to draw definitive conclusions regarding potential-enhanced accretion in Class I versus Class II objects. Class II mass accretion rates are typically \( >10^{-8} \) (Herczeg & Hillenbrand 2008). Our results point to larger accretion luminosities and mass accretion rates than those of Class II objects, suggesting an evolutionary progression from protostars to CTTSs, as discussed in Doppmann et al. (2005) for example, but without the signal to noise to support this conclusion at a significant level.

4.2. Accreting Protostars or Misclassified T Tauris?

Recent studies of Class I protostars differ in their conclusions regarding the nature of these objects. White & Hillenbrand (2004) suggest that most Class Is have moved beyond their main accretion phase and might actually be Class II stars seen edge-on through circumstellar accretion disks. Doppmann et al. (2005) conclude that Class I objects are indeed actively accreting protostars, albeit spanning a range of accretion activity. Since the publication of both papers, their authors have reached some consensus and conclude in White et al. (2007) that, at least for the Taurus SFR, one-third to one-half of the Class I objects are likely to be misclassified Class II stars seen through optically thick disks. White et al. (2007) and Doppmann et al. (2005) also conclude that most Class I sources possess disk accretion rates below the expected envelope infall rates. Misclassified T Tauri stars would certainly show low disk accretion rates; however, such objects would typically be subluminous by a factor of 5 compared to bona fide Class Is (Whitney et al. 2003).

Another possibility raised in White et al. (2007) is that our knowledge of disk accretion rates and mass infall rates is incomplete. The uncertainties in these calculations are significant: in this paper as well as in the literature these values are only known to a precision of about an order of magnitude. Our finding of relatively large accretion rates (Table 9) compared to previously derived values for Class I objects is not significant. Objects that are found to be highly extinguished, such as our results suggest, naturally have large accretion luminosities. However, the large uncertainties associated with the mass accretion rate estimates mean that we cannot be confident that our results indicate that these protostars are currently experiencing a particularly active accretion phase. Our targets do, however, lie relatively far up on the evolutionary tracks in the \( H-R \) diagram (Figure 9), with ages \( <2\text{Myr} \), consistent with a population younger than that of the Class II T Tauri stars with ages of \( \sim1 \) to several Myr.

Another source of uncertainty in the determination of Class I protostar properties is their variability. Class I YSOs show considerable variation in their spectra, fluxes, colors, and excess IR emission. Leinert et al. (2001) studied the variability of the Haro 6-10 system over a 12 year period and found substantial change in the magnitudes and colors of the two components, especially at shorter wavelengths. \( K \)-band veiling measurements for the Class I protostar YLW 15A (IRS 43) varied significantly over \( \sim5 \) years, possibly on timescales as short as weeks (Luhman & Rieke 1999; Greene & Lada 2002; Prato et al. 2003). These results suggest that the geometry of the obscuring material in front of the protostellar surface may be shifting rapidly, perhaps producing variations in the extinction along the line of sight to the protostar (e.g., Leinert et al. 2001; Beck et al. 2001).

Consistent with a younger evolutionary stage for the Class I sources is the ubiquitous atomic and molecular hydrogen emission in all but one of our targets (Figure 3; Doppmann et al. 2005). The atomic hydrogen emission is likely associated with disk accretion onto the central star and the molecular emission with shocks created by infalling or outflowing gas interacting with the circumstellar environment. IRAS 04489+3042 shows only a small Br\( \gamma \) emission line and does not reveal any molecular hydrogen emission, either in our study or in that of Doppmann et al. (2005). All other targets have the \( H_2\nu=1-0\ S(1) \) line in emission and about half also show emission in the \( H_2\nu=1-0\ S(0) \) line.

5. SUMMARY

We obtained \( K \)- and \( L \)-band spectra of a sample of eight Class I sources in the Taurus SFR with the SpeX spectrometer on the NASA IRTF 3 m telescope. We measured absorption and emission line equivalent widths, determined the optical depth of the \( L \)-band water ice feature, and, where possible, estimated the spectral type, visual extinction, and \( K \)-band excesses for each of our targets. Our analysis and results are summarized below.

1. Using our derived spectral types in combination with 2MASS photometry and luminosity estimates available in the literature, we placed our targets in the \( H-R \) diagram and used evolutionary tracks of Palla & Stahler (1999) to estimate stellar masses and ages. In addition, we calculated accretion luminosities from the Br\( \gamma \) line luminosity and determined the associated mass accretion rate for our targets. The six objects which we were able to place on the \( H-R \) diagram show ages of \( <2\text{Myr} \) and clump into two groups with masses \( \sim0.2\ M_\odot \) and \( 1.9\ M_\odot \).

2. For two objects, we obtain significantly different results from those presented in the literature: Haro 6-10 S and L1551 IRS 5. The majority of our targets are multiples; although we resolved Haro 6-10 S and N, Doppmann et al. (2008) suggest that the southern component is a spectroscopic binary. The high-resolution, very high signal-to-noise data of Doppmann et al. (2008) indicate a later spectral type, closer to M0, than the early K type found by us. The companion to L1551 IRS 5 is seen only at very long wavelengths (greater than submillimeter; Looney et al. 1997) and it is thus unlikely that this
component contaminates the primary spectrum in our analysis. However, we found a robust fit for this target to an M3 III spectral type standard, a significantly lower gravity and later spectral type than the ~K3 V type of Doppmann et al. (2005).

3. Our experimental hypothesis, that obscuration of the photospheric absorption lines in Class I targets is dominated by extinction local to the sources, is not correct. Veiling of lines from the near-IR excess also plays a key role. It is likely that emission, for example from warm CO in a circumstellar disk, also fills in spectral absorption lines in some cases, hampering the determination of the underlying protostellar characteristics.

4. We compared our derived properties with values from the literature and find that our larger estimates of extinction lead to larger accretion luminosities and larger mass accretion rates. We stress that the very large uncertainties, inherent in the relationship between emission line luminosities and accretion luminosities (Muzerolle et al. 1998) as well as in our observations, render these estimates highly uncertain, not only in our study but also in numerous examples in the literature.

5. The higher mass accretion rates we find are more consistent with the interpretation that Class I protostars are undergoing a relatively active mass accretion phase; however, because of the large uncertainties in these results, additional observations are required to confirm this interpretation. High-resolution, high signal-to-noise IR spectroscopy provides a promising approach, however, low-resolution data across the near-IR may be particularly useful for the evaluation of extinction.

6. The visual extinction to protostars appears to be an extremely important and poorly determined property, impacting estimates of all the key stellar properties including luminosity, mass, age, accretion luminosity, and mass accretion rate. It therefore represents a critical area for improvement.

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