EXTENDED NEAR-INFRARED EMISSION FROM CANDIDATE PROTOSTARS IN THE TAURUS-AURIGA MOLECULAR CLOUD

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ABSTRACT

We describe near-IR imaging data for a sample of 23 Class I sources in the Taurus-Auriga dark clouds. Combining our data with previous photometry, we detect brightness variations of ~0.1–0.5 mag in many sources. The near-IR morphologies are consistent with millimeter continuum measurements. Most (~60%) of the sample are true protostars; the rest may be objects in transition between Class I and Class II, T Tauri stars with edge-on disks, or heavily reddened T Tauri stars.

Key words: infrared radiation — reflection nebulae — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Standard models for the formation of a single, low-mass star begin with a slowly rotating cloud of gas and dust with a centrally concentrated density distribution (e.g., Larson 1969, 1972; Stahler, Shu, & Taam 1980, 1981; Shu, Adams, & Lizano 1987; Shu et al. 1993; Safier, McKee, & Stahler 1997; Ciolek & Basu 2000; Whitworth & Ward-Thompson 2001). When the inward gravitational pressure exceeds the outward thermal and magnetic pressures, the cloud collapses. Material near the axis of rotation with low specific angular momentum contracts into a central starlike core. Once the radius of the centrifugal barrier exceeds the radius of the central stellar core, material away from the rotation axis with large specific angular momentum follows a curved infall trajectory, falls onto the equatorial plane, and forms a circumstellar disk (Cassen & Moosman 1981; Terebey et al. 1984; Lin & Pringle 1990; Yorke et al. 1993; Stahler et al. 1994). As the collapse proceeds, the protostellar core becomes more massive and more luminous; the surrounding infalling envelope becomes less massive and less opaque at optical and infrared wavelengths (Lada 1991). Eventually, a wind from the star-disk system begins to clear gas and dust away from the rotational axis, resulting in the production of collimated jets and a bipolar molecular outflow (Adams & Lin 1993; Konigl & Ruden 1993; Konigl & Pudritz 2000; Shu et al. 2000). Once the infalling envelope disperses or falls into the circumstellar disk, the central star-disk system becomes optically visible as a pre–main-sequence star. As the material in the disk accretes onto the central star, dissipates, or condenses into planets, the star moves onto the main sequence (Stahler & Walter 1993; Strom et al. 1993; Cameron 1995).

This picture of star formation generally accounts for an apparent evolutionary sequence in the observed properties of young stars in nearby molecular clouds (Lada 1984; Adams et al. 1987; Lada 1987). Lada (1991) describes three of the classes in this sequence. Class I sources have spectral energy distributions (SEDs) which are broader than a single temperature blackbody function and rise from ~2 μm to ~25–100 μm. Class I sources are star-disk systems still surrounded by massive infalling envelopes. The envelope absorbs optical and near-infrared photons from the central protostar and reemits this radiation at far-IR and millimeter wavelengths, where the envelope is optically thin. Class II sources also have broad SEDs, but the SED falls from ~2 μm to ~25–100 μm. These sources contain a pre–main-sequence star surrounded by a circumstellar disk, which absorbs and reradiates emission from the central star. Class III sources have roughly blackbody SEDs that peak at ~1 μm; radiation from a surrounding disk or envelope contributes negligible emission at 10–100 μm (Lada 1991). André et al. (1993) added the Class 0 sources to this sequence to include very young objects at the beginning of the accretion process. These objects have narrow SEDs that peak at ~100–300 μm (e.g., Motte & André 2001 and references therein). In the current picture the central star of a Class 0 source has accumulated <50% of its final mass; in Class I sources the central star has ≥50% of its final mass.

The Taurus-Auriga cloud is one of the best sites for testing models of isolated, low-mass star formation (see Kenyon & Hartmann 1995 and references therein). This collection of filamentary clouds contains good samples of Class I, II, and III pre–main-sequence stars, a Class 0 source, and several examples of interesting transition objects. The clouds are close enough (d = 140 pc, Kenyon, Dobrzycka, & Hartmann 1994a) to allow high signal-to-noise observations at all wavelengths with moderate to high spectral and spatial resolution. Although the clouds are poor examples of clustered star formation, pre–main-sequence stars in Taurus-Auriga provide interesting constraints on the formation of small close groups of pre–main-sequence stars (Gómez et al. 1993; Armitage & Clarke 1997; Vanhala & Cameron 1998; Scalo & Chappell 1999).

Here, we consider a comparison between the millimeter and near-IR properties of Class I sources in Taurus-Auriga. Motte & André (2001) demonstrate that moderate spatial resolution millimeter continuum observations divide these objects into unresolved, pointlike sources with negligible infalling envelopes, extended sources with significant infalling envelopes, and several transition objects with modest infalling envelopes. In this division the unresolved Taurus-
Auriga sources might be edge-on disks similar to those discovered in HH 30 IRS and HK Tau (Burrows et al. 1996; Stapelfeldt et al. 1998). Because the derived lifetimes in each evolutionary phase depend on the relative numbers of objects in each phase (e.g., Kenyon et al. 1990; Hogerheijde 2001), the millimeter continuum data also provide better limits on the Class I lifetime in Taurus-Auriga. Our goal is to test whether near-IR images yield a similar division of sources into extended and pointlike objects. This study extends previous imaging surveys, where near-IR imaging data constrain radiative transfer models for the Class I sample (Kenyon et al. 1993b; Whitney et al. 1997).

We describe the observations in § 2, comment on source variability in § 3, and consider the image morphology in § 4. The paper concludes with a brief summary.

2. OBSERVATIONS

We acquired JHK images of candidate protostars in Taurus-Auriga with Stelircam at the Fred L. Whipple Observatory 1.2 m telescope on 1998 October 5–12 and 1999 November 18–20. Stelircam is a dual-beam IR imager equipped with two 256 × 256 InSb SBRC arrays. The field of view for these images is ~300’’ × 300’’. We took nine 6 × 10 s exposures of each field at HK and later at JK and offset the telescope by 45’’–60’’ after each integration. Poor weather prevented a complete set of J-band observations in photometric conditions; the 1998 HK observations were photometric. We repeated observations of some targets to improve the signal-to-noise ratio of faint nebulosity.

We produce calibrated object frames in each filter using standard techniques in the Interactive Data Language (IDL). After correcting each image for nonlinearity, we construct a nightly flat field for each filter from the median of dark-subtracted image frames. The sky frames for each object image are a median-filtered set of flattened frames scaled to have the same background as the object image. We offset and co-add the nine frames in each filter to make a final deep field image which reveals fainter extended emission without saturating bright stars.

Table 1 lists HK photometry for each source. We use the NOAO IRAF2 routine PHOT to extract magnitudes in three apertures. We analyze the nine HK frames of each source—instead of the co-added frames—to obtain error estimates for the photometry directly from the data. Once we remove bad pixels, the typical standard deviation of nine measurements for one source is ±0.01–0.02 mag at K and ±0.02–0.03 mag at H. Our nightly photometric calibration is based on 15–25 observations of Elias et al. (1982) standard stars. The uncertainty in the calibration is ±0.03 mag in each filter on each night. This uncertainty is comparable to the range in the zero-points and air-mass corrections for the HK filters on each observing run. Adding the calibration error in quadrature with the standard deviations of the source data yields a typical photometric error of less than 0.05 mag in each filter.

To measure morphological information from the individual and co-added frames, we use SExtractor (Bertin & Arnouts 1996). SExtractor is a modern software package which automatically detects, measures, and classifies sources from digital images. For each image, we set up the package to measure the FWHM, elongation, central surface brightness, and the magnitude in 7’’ and 14’’ apertures for each candidate protostar. Table 2 lists the results. The FWHM is the full width at half maximum of the best-fitting one-dimensional Gaussian to the intensity profile of the source; the elongation is the ratio of the major axis to the minor axis of the best-fitting two-dimensional Gaussian to the intensity profile. The fits for both parameters use intensity levels 3 σ or more above the local noise background. We use the central surface brightness and aperture magnitudes to verify that fits for each source reach the same limiting surface brightness and to check the PHOT photometry. The SExtractor photometry agrees with PHOT to ±0.02 mag or better. The limiting surface brightness in the co-added frames is ~19.5 mag arcsec−2.

Figure 1 gives examples of contour maps derived from co-added K-band images for Taurus-Auriga protostars (see also Tamura et al. 1991; Kenyon et al. 1993b; Whitney et al. 1997; Lucas & Roche 1997). The images have a variety of morphologies, ranging from apparent point sources (04108+2803 and 04295+2251) to monopolar (04287+1801 and 04288+1802) and bipolar (04325+2402 and 04361+2547) nebulae with central point sources. Two objects are faint patches with no obvious point source (04166+2706 and 04368+2557). Whitney et al. (1997) measure large near-IR polarizations for sources with extended nebulae, confirming models where dust grains within the nebulosity scatter radiation from the central star into our line-of-sight (see also Lucas & Roche 1998a). Gómez et al. (1997) identify optical and near-IR jets on [S ii] and H2 images of many Taurus-Auriga protostars (see also Lucas & Roche 1998b); Kenyon et al. (1998) note [S ii] emission on optical spectra of several other sources. Jet emission and bipolar outflows are characteristic of embedded protostars (e.g., Reipurth 1991; Moriarty-Schieven et al. 1992; Bontemps et al. 1996; Tamura et al. 1996; Reipurth & Bally 2001).

The IRAS source 04166+2706 deserves special mention. Kenyon et al. (1990) discovered a near-IR counterpart with raster scans on the single-channel MMT photometer. From near-IR imaging data, Kenyon et al. (1993b) identified a point source with very red colors near the IRAS position. This object is ~2 mag brighter than the Kenyon et al. (1990) source and lies near the reddening band in the J–K, H–K color-color diagram. Our images recover the Kenyon et al. (1990) source as a patch of low surface brightness nebulosity similar to the nebula of 04368+2557 (see Whitney et al. 1997). This object is 52” north and 44” west of the Kenyon et al. (1993b) point source, with J2000.0 coordinates of R.A. = 04h19m43.2s and decl. = +27º13’39”.

1 IDL is distributed by Research Systems, Inc., of Boulder, Colorado.
2 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
### TABLE 1
Photometry of Taurus-Auriga Candidate Protostars

| IRAS Name | Other ID | JD | 8° Aperture | 13° Aperture | 26° Aperture |
|-----------|----------|----|-------------|--------------|--------------|
|           |          |    | 8°           | 13°          | 26°          |
|           |          |    | H–K         | H–K          | H–K          |
|           |          |    | K            | K            | K            |
|           |          |    |              |              |              |
|           |          |    |            |              |              |
|           |          |    | Sigma       | Sigma        | Sigma        |
|           |          |    |              |              |              |

### TABLE 2
Morphological Data for Taurus-Auriga Class I Sources

| Source Name | $f_\lambda$ (arcsec) | $e_\lambda$ | $f_H$ (arcsec) | $e_H$ | $f_K$ (arcsec) | $e_K$ | Comment |
|-------------|----------------------|-------------|----------------|-------|----------------|-------|---------|
| 04016 + 2610 | 5.23                 | 1.15        | 11.76          | 1.19  | 6.04           | 1.27  | Transition |
| 04108 + 2803A | 1.44                 | 1.09        | 1.89           | 1.05  | 2.00           | 1.06  | Reddened TTS |
| 04108 + 2803B | 1.86                 | 1.17        | 1.84           | 1.06  | 1.99           | 1.07  | Transition? |
| 04158 + 2805 | 1.93                 | 1.21        | 1.90           | 1.10  | 2.10           | 1.10  | Reddened TTS |
| 04166 + 2706 | 1.44                 | 1.09        | 1.89           | 1.05  | 2.00           | 1.06  | Reddened TTS |
| 04181 + 2655 | 1.44                 | 1.09        | 1.89           | 1.05  | 2.00           | 1.06  | Reddened TTS |
| 04260 + 2642 | 15.30                | 2.80        | 11.20          | 2.45  | 11.68          | 2.43  | Protostar |
| 04239 + 2436 | 14.27                | 2.50        | 11.20          | 2.45  | 11.68          | 2.43  | Protostar |
| 04288 + 1802 | 4.17                 | 1.48        | 2.77           | 1.18  | 3.63           | 1.34  | Protostar |
| 04325 + 2402 | 4.94                 | 1.36        | 2.27           | 1.06  | 3.19           | 1.19  | Protostar |
| 04361 + 2547 | 1.57                 | 1.09        | 2.28           | 1.18  | 2.44           | 1.32  | Protostar |
| 04368 + 2537 | 1.57                 | 1.09        | 2.28           | 1.18  | 2.44           | 1.32  | Protostar |

a The columns list the FWHM $f$ and elongation $e$ of Gaussian fits to the intensity profile of each source at each wavelength. Based on multiple measurements of each source, the typical error in $f$ is $\pm 0.02$; the typical error in $e$ is $\pm 0.1$.

b The comment column lists our best estimate of the evolutionary class of each object: true protostars (protostar), objects in transition between Class I and Class II (transition), edge-on disks, or reddened T Tauri stars.
2654A, R.A. = 04°21'10.5" and decl. = +27°01'38" for 04181+2654B, and R.A. = 04°21'08.1" and decl. = +27°02'22" for 04181+2655.

3. VARIABILITY

Most pre–main-sequence stars vary at optical and infrared wavelengths (e.g., Joy 1945; Bouvier et al. 1993; Choi & Herbst 1996; Stassun et al. 1999). Many systems have regular variations with amplitudes of 0.1–1.0 mag and periods of 2–10 days (Eaton, Herbst, & Hillenbrand 1995; Herbst et al. 1994, 2000). Other objects vary irregularly with similar amplitudes on similar or longer timescales. The periodic variations yield information on stellar rotational periods and the sizes, temperatures, and lifetimes of dark and bright spots on the stellar photosphere (Bouvier et al. 1993; Stassun et al. 1999). These data also provide tests of models for the inner disks and magnetospheres of low-mass pre–main-sequence stars (e.g., Mahdavi & Kenyon 1998; Wood & Whitney 1998; Wood et al. 2000).

To test whether any of the candidate protostars are variable, we compare with previous measurements obtained with single-channel photometers (Kenyon et al. 1990) and near-IR imagers (Kenyon et al. 1993b, 1994b; Whitney et al. 1997). For sources where we have only one or two of our own measurements, we supplement the photometry with data from the compilation of Kenyon & Hartmann (1995). We derive the average brightness and the standard deviation for the candidate protostar and for another stellar source in the same field using 8" and 13"–14" apertures. Although there are too few measurements for each source to construct a robust average, the standard deviation provides a reasonable first estimate of source variability.

The observations in this study use different instruments; we use the comparison stars to verify that the photometry from each instrument is on the same magnitude scale. We could not perform this test with single-channel photometry; previous comparisons show that the differences between photometric systems are small compared to the source variations in our sample (Kenyon & Hartmann 1995). As a final test, we check whether the mean variation of a protostar from one observing run to the next is zero. Using data from Kenyon et al. (1993b), Whitney et al. (1997), and this paper, the average change in brightness of the complete sample is $0.11 \pm 0.37$ from 1991 to 1993–1994 and $0.05 \pm 0.31$ from 1993–1994 to 1998–1999.

Our analysis indicates that candidate protostars in Taurus-Auriga are variable. Histograms of standard deviations $\sigma$ in $K$ and in $H-K$ (Fig. 2) demonstrate that candidate protostars have larger variations than comparison stars in the same field. The variation of a typical source has an amplitude of 0.2–0.3 mag at $K$. These fluctuations are similar to
variations observed in optically visible T Tauri stars (e.g., Kenyon & Hartmann 1995; Choi & Herbst 1996; Stassun et al. 1999). Many sources have variable colors. Roughly half of the sample varied by 0.1–0.3 mag in H–K. Although large color variations are observed in some T Tauri stars, the variations are less than 0.1–0.2 mag in more than 70% of pre–main-sequence stars in Taurus-Auriga (Kenyon & Hartmann 1995; see also Carpenter, Hillenbrand, & Skrutskie 2001).

Without repeat observations on short timescales, we are unable to analyze the variability of Taurus-Auriga protostars in detail. The large brightness and color changes are consistent with the behavior expected from bright spots, dark spots, and obscuration models (see also Carpenter et al. 2001 and references therein). There is no correlation between brightness and color changes; some sources become bluer as they brighten while others become redder. Most models predict strong correlations between color and brightness evolution, but our observations are too few in number to discriminate between possible models.

The variations of several objects deserve special mention. 

**04018+2803B**: This source is the more embedded of a pair of IRAS sources separated by 17" on the sky. The large variation is based on a single observation in 1998 October. 

**04181+2655**: The brightest of a triplet of IRAS sources, this object has varied consistently from one observing run to the next. The color variation of this source is among the largest in our sample.

**04239+2436**: This source has a large nebulosity at J which is nearly invisible at K. It has one of the largest amplitudes in our sample, with a variation of more than 0.7 mag at K during the past decade.

Six other sources—04016+2610, 04181+2654A, 04287+1801 (L1551 IRS 5), 04361+2547, 04365+2535, and 04381+2540—vary by 20% or more in brightness and in color. All other sources change by less than 0.1–0.2 mag (Table 1; cols. [10]–[11]). The historical variation of L1551 IRS 5 is difficult to quantify because of large differences in observing techniques, but published data are consistent with the variation in our data.

### 4. MORPHOLOGY

Image morphology provides a good constraint on models for embedded protostars. Whitney et al. (1997) demonstrate that the size of synthetic near-IR images correlates with the centrifugal radius $R_c$ and the infall rate $M$ in the Terebey et al. (1984) infalling envelope model. The elongation correlates with the inclination of the source and the size of the outflow cavity (see also Whitney & Hartmann 1993). Both parameters vary with the grain albedo. Grains with large albedo produce larger and more elongated near-IR images of protostars. Whitney et al. (1997) emphasize that the size and elongation provide better constraints on models when combined with polarization measurements.

The image morphology also provides a good comparison with millimeter continuum observations. Motte & André (2001) describe moderate spatial resolution millimeter-wave observations of the Taurus-Auriga sample. They divide the sources into two groups based on the ratio of the flux $F$ in 11" and 60" beams. Extended sources have $F_{11}/F_{60} \lesssim 0.5$–0.7; point sources have $F_{11}/F_{60} \approx 1$. Roughly half of the Taurus-Auriga sample is extended by this criterion.

To compare the near-IR morphology with millimeter continuum morphology, we use two measures to divide objects into extended sources and pointlike sources. We follow Motte & André (2001) and define extended sources as objects where the flux in a 26" aperture exceeds the fluxes in 13" and 8" apertures (Table 1). Larger apertures yield poor quality photometry on our images. In a sample of ~2000 field stars with moderate signal-to-noise photometry, the mean aperture corrections for our data are $m_b - m_{13} = 0.09 \pm 0.02$ and $m_{13} - m_{26} = 0.11 \pm 0.02$. The aperture corrections are independent of the filter. With this result, extended sources have $m_b - m_{13} > 0.15$ and

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**Fig. 2.—Variability of K and H–K in pre–main-sequence stars. The left panel shows the distribution of standard deviations $\sigma_K$ about the mean K magnitude for candidate protostars with two or more K measurements (solid line) and for comparison stars in the same field (dot-dashed line). The right panel shows the distribution $\sigma_{H-K}$ for H–K of candidate protostars (solid line) and of comparison stars (dot-dashed line).**
Motte & André (2001) define the concentration \( c \) as the ratio of the fluxes in \( 11'' \) and \( 60'' \) apertures expressed as a percentage. Highly concentrated sources have \( c = 100 \); very extended sources have \( c < 30 \). Our near-IR measures \( f_K \) and \( e_K \) are inversely correlated with \( c \) (Fig. 4, middle panels). The relation between \( c \) and \( e_K \) is significant at the 3 \( \sigma \) level, with \( p_s \approx 4 \times 10^{-3} \); the size is more weakly correlated with \( e \) (\( p_s \approx 10^{-5} \)). Motte & André (2001) use the concentration and the absolute fluxes to measure the envelope mass, \( M_{\text{env}} \). Our \( K \)-band measures are more strongly correlated with \( M_{\text{env}} \) than with \( c \) (Fig. 4, top panels); \( p_s \approx 2 \times 10^{-3} \) is the Spearman rank probability for the correlation between \( f_K \) and \( M_{\text{env}} \) and \( p_s \approx 10^{-3} \) is the probability for the correlation between \( e_K \) and \( M_{\text{env}} \).

The near-IR measurements at \( J \) and \( H \) also correlate with the millimeter continuum data. Because the short wavelength images have a lower signal-to-noise ratio, the correlations at \( J \) and \( H \) are 10% to 20% weaker than at \( K \). These results exclude the deeply embedded source 04368+2557 (L1527 IRS) from the analysis. Including this source with a nominal size of \( f_K \approx 25'' \) and an elongation of \( e_K \approx 2 \) yields smaller Spearman rank probabilities by a factor of 2–3. These correlations provide additional confirmation of infall models for protostars. In the standard infall picture (Terebey et al. 1984; Adams et al. 1987), an optically thick envelope absorbs radiation from the central object and reradiates this energy at millimeter wavelengths. Protostars with massive infalling envelopes are therefore more extended at millimeter continuum wavelengths than Class II or Class III sources with little or no infalling envelope. Once the central object generates a bipolar outflow, optical and near-IR radiation from the central object can escape through the optically thin cavity (e.g., Whitney & Hartmann 1993; Kenyon et al. 1993b; Whitney et al. 1997). Some of this radiation scatters off material in the cavity and in the outer envelope, producing an extended, elongated, and highly polarized optical or near-IR image (Whitney et al. 1997). As material from the envelope continues to fall onto the disk, the envelope opacity declines and more optical and IR radiation from the central star can reach the observer directly. This process reduces the amount of millimeter continuum emission and scattered optical and near-IR emission. These objects thus appear more concentrated and more symmetrical at all wavelengths than more highly

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**Fig. 3.** — Size and elongation histograms for the fields of Taurus-Auriga Class I sources. Left: Size histogram for 3176 sources detected on \( K \)-band images of Taurus-Auriga protostars. Right: Elongation histogram. The dot-dashed line in each panel indicates the division between point sources and extended sources.
embedded objects. Our data confirm this general trend: Class I sources that are extended at millimeter continuum wavelengths are extended and more elongated on near-IR images than their pointlike counterparts.

These correlations may also offer a test of infalling envelope models. To the best of our knowledge, there are few quantitative predictions of the relationship between the optical or near-IR properties and the millimeter continuum properties of protostars. Published radiative transfer models have successfully modeled independently the spectral energy distributions, density distributions, and near-IR images of individual protostars. However, we are not aware of models that predict the observed correlations between the concentration or envelope mass derived from millimeter data and the size or elongation derived from optical or near-IR data. Our results suggest that observations can now test these predictions.

The near-IR data divide Taurus-Auriga Class I sources into nearly the same two groups as the millimeter continuum data. We base this conclusion on Table 3, which compares our results with those of Motte & André (2001). Nine sources are extended at millimeter and near-IR wavelengths; eight sources are not extended at these wavelengths. Two sources—04016+2610 and 04302+2247—have large near-IR nebulae with little evidence for extended millimeter continuum emission from a massive envelope3 (Hogerheijde 2001; Motte & André 2001). Three sources—04181+2654A, 04181+2654B, 04365+2535, and 04381+2540—are extended at millimeter continuum wavelengths but are not extended at near-IR wavelengths based on our measurements of size and elongation. Three of these—04181+2654A, 04365+2535, and 04381+2540—show some evidence for an extended nebula at K from \( K_8-K_{13} \) and a visual inspection of the co-added images (see Fig. 1). Higher signal-to-noise K-band images would provide definitive tests for extended emission in these sources.

Our data confirm the Motte & André (2001) conclusion that most (~60%) of the Taurus-Auriga Class I sources are embedded protostars with massive infalling envelopes (see also Hogerheijde et al. 1998; Hogerheijde & Sandell 2000; Chandler & Richer 2000, and references therein). Because these objects are definitely extended in the millimeter continuum and probably extended at K, we include 04181+2654A, 04181+2654B, and 04381+2540 in this group (see Table 2). The envelope masses inferred from the

3 04016+2610 is resolved at 2 cm and 3.5 cm (Lucas, Blundell, & Roche 2000); this emission probably traces radiation from an ionized jet or inner disk as in L1551 IRS 5 (Rodriguez et al. 1986).
millimeter data range from \( \sim 0.09 \, M_\odot \) for 04239+2436 to \( \sim 0.9 \, M_\odot \) for L1551 IRS 5. The density distributions for these sources, \( \rho(r) \propto r^{-n} \) with \( n = 1.5 - 2 \), agree with the predictions of infall models on scales of \( \sim 10,000 \) AU (Terebey et al. 1984; Chandler, Barsony, & Moore 1998; Hogerheijde et al. 1992; Hogerheijde & Sandell 2000; Motte & André 2001). The SEDs and the near-IR morphologies and polarizations of these sources also agree with model predictions (Kenyon et al. 1993a, 1993b; Whitney et al. 1997; Motte & André 2001). All of these sources have molecular outflows (e.g., Bontemps et al. 1996) and 66% have emission from optical or near-IR jets (e.g., Gómez et al. 1997).

At least two Taurus-Auriga Class I sources without extended millimeter emission might be transition objects between Class I protostars and Class II T Tauri stars. In addition to their large near-IR nebulae, 04016+2610 and 04302+2247 have molecular outflows, optical or near-IR emission from a jet, and large near-IR polarization as in true protostars (see also Heyer et al. 1990; Tamura et al. 1991; Kenyon et al. 1993b; Gómez et al. 1997; Whitney et al. 1997). However, both sources fail to meet the “true protostar” criterion of Motte & André (2001), \( M_{\text{env}}/M_* \gtrsim 0.1 \). To estimate these ratios in 04016+2610 and 04302+2247, we assume the central star in each source lies on the birth line of Palla & Stahler (1999). The observed bolometric luminosities then yield approximate stellar masses of \( M_* \sim 0.6 \, M_\odot \) for 04016+2610 and \( M_* \lesssim 0.1 \, M_\odot \) for 04302+2247. Motte & André (2001) estimate envelope masses \( M_{\text{env}} \leq 0.04 \, M_\odot \) for 04016+2610 and \( M_{\text{env}} \lesssim 0.01 \, M_\odot \) for 04302+2247. Thus, both sources have \( M_{\text{env}}/M_* \lesssim 0.1 \) and are not true protostars.

Based on millimeter aperture synthesis observations, Hogerheijde (2001) previously proposed that 04016+2610 is a transition object between true protostars and Class II sources. The millimeter data are consistent with a Keplerian disk with a radius of \( \sim 2000 \) AU surrounding a 0.65 \( M_\odot \) central star (see also Saito et al. 2001). Our mass estimate favors this interpretation over the proposal of sub-Keplerian motion around a more massive star. If 04016+2610 is a transition object, several common near-IR properties suggest that 04302+2247 might also be a transition object.4 Aperture synthesis observations at millimeter wavelengths would test this proposal.

Other Taurus-Auriga Class I sources are peculiar in having Class I SEDs but little or no extended near-IR or millimeter continuum emission. The properties of this group differ significantly from the true protostars. Most do not have molecular outflows, optical/near-IR jet emission, or large near-IR polarization. As a group, these objects thus appear older, with smaller extended envelopes and less accretion activity than the protostars (see also Reipurth & Bally 2001). There are several exceptions to this statement. Four sources—04181+2654, 04181+2655, 04264+2433, and 04489+3042—have [S ii] emission; 04264+2433 has large near-IR polarization; near-IR spectra of 04295+2251 and 04489+3042 more closely resemble spectra of Class I sources than T Tauri stars Greene & Lada (1996). This diversity of properties suggests that the peculiar Class I sources do not belong to a single class of objects.

Table 2 lists our best estimates for the nature of these peculiar Class I sources. We consider 04016+2610, 04260+2642, 04264+2433, and 04302+2247 as transition objects between Class I and Class II. Extended, highly polarized near-IR nebulae demonstrate that 04016+2610 and 04302+2247 are not Class II sources; 04181+2654, 04260+2642 and 04264+2433 have similar spectral energy distributions for 04302+2247. Thus, both sources have \( M_{\text{env}}/M_* \lesssim 0.1 \) and are not true protostars.

Table 3 lists our best estimates for the nature of these peculiar Class I sources. We consider 04016+2610, 04260+2642, 04264+2433, and 04302+2247 as transition objects between Class I and Class II. Extended, highly polarized near-IR nebulae demonstrate that 04016+2610 and 04302+2247 are not Class II sources; 04181+2654, 04260+2642 and 04264+2433 have similar spectral energy distributions for 04302+2247. Thus, both sources have \( M_{\text{env}}/M_* \lesssim 0.1 \) and are not true protostars.

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4 Padgett et al. (1999) detect an edge-on disk on HST near-IR images of 04302+2247, but our ground-based near-IR images of 04302+2247 show more near-IR nebulosity than Class II sources with edge-on disks such as HH 30 IRS and HK Tau.
distributions but no obvious near-IR nebulosity. The Class I sources 04108+2803B, 04295+2251, and 04489+3042 have larger optical to far-IR flux ratios than 04016+2610 and other “transit candidates.” These sources could be transition objects viewed along the rotational axis of the disk. The strong [S II] emission in 04295+2251 recalls similar emission in the edge-on disk systems HK Tau and HH 30 IRS. Finally, 04108+2803A and 04158+2805 are more similar to Class II sources and are probably heavily reddened T Tauri stars.

5. SUMMARY

Our near-IR observations provide a first detection of near-IR variability in a sample of Class I protostars. The variations are similar in amplitude to those observed in T Tauri stars (Kenyon & Hartmann 1995; Carpenter et al. 2001). The poor time coverage of the imaging data for this sample does not provide a useful measure of the timescale for these variations. If the variations are similar to those in T Tauri stars, observations on successive nights over weeks or months can measure the timescales. As an example, Hillenbrand et al. (2001) derive an 8 day period for the variation in the Becklin-Neugebauer object, an embedded protostar in Orion (see also Wood et al. 2000).

The near-IR morphologies of Taurus-Auriga Class I sources are consistent with the millimeter continuum measurements of Motte & André (2001). Most (~60%) of these objects are true protostars, with massive envelopes surrounding a young star with ~50% of its final mass. Some (~25%) of the Class I sources are probably transition objects between true protostars and optically visible T Tauri stars; one or two of these might have edge-on disks similar to those observed in HH 30 IRS and HK Tau. Two other Class I sources are probably heavily reddened T Tauri stars.

Making accurate classifications for the “peculiar” Class I sources requires additional data. Radio observations of some Class I sources using higher spatial resolution might reveal compact nebulae or large disks as in 04016+2610 (Hogerheijde 2001). Deeper near-IR images may also reveal extended nebulosity. We have marginal detections of faint nebulosity on co-added near-IR images of 04181+2655 and 04264+2433; higher signal-to-noise observations might provide a better indication of the extended nature of these and other pointlike Class I sources. Because molecular outflows and optical/near-IR jets are more common among Class I sources and transition objects than among T Tauri stars with Class II SEDs (Gómez et al. 1997; Kenyon et al. 1998; Reipurth & Bally 2001), deeper optical and near-IR surveys for jet emission and more extensive outflow surveys can also help to classify these objects. These new data would provide a better understanding of the evolution from Class I to Class II among low mass protostars.

Finally, our results offer a new test of infall models for Class I protostars. In the standard picture, a massive envelope produces millimeter and far-IR continuum emission; near-IR and optical radiation from the central object escape through the optically thin outflow cavity. As the infalling envelope becomes less massive and less opaque, the angular size of the outflow cavity should shrink. Because optical and near-IR radiation can escape the envelope more easily, protostars should become less elongated as the optical depth through the envelope decreases. Our near-IR morphological data confirm this expectation: $f_K$ and $e_K$ of Class I sources correlate with $M_{env}$. The standard model also predicts a general anticorrelation between the near-IR measurements $f_K$ and $e_K$ and millimeter measurement $c$ of Motte & André (2001). As the envelope mass declines, the unresolved central star and the disk produce more of the millimeter continuum flux; sources thus become more concentrated at millimeter wavelengths as they become less elongated and less extended at optical and near-IR wavelengths. To the best of our knowledge, however, theoretical radiative transfer models of protostars do not make specific predictions for the variation of $f_K$ or $e_K$ as a function of $c$ or $M_{env}$. Our results demonstrate that near-IR and millimeter continuum data can test these predictions.

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