

A NEAR-INFRARED MULTIPLICITY SURVEY OF CLASS I/FLAT-SPECTRUM SYSTEMS IN SIX NEARBY MOLECULAR CLOUDS

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ABSTRACT

We present new near-IR observations of 76 Class I/flat-spectrum objects in the nearby ($d \lesssim 320$ pc) Perseus, Taurus, Chamaeleon I and II, ρ Ophiuchi, and Serpens dark clouds. These observations are part of a larger systematic infrared multiplicity survey of self-embedded objects in the nearest dark clouds. When combined with the results of our previously published near-infrared multiplicity survey, we find a *restricted* companion star fraction of 14/79 ($18\% \pm 4\%$) of the sources surveyed to be binary or higher order multiple systems over a separation range of ~ 300 – 2000 AU with a magnitude difference $\Delta K \leq 4$ and with no correction for background contamination or completeness. This is consistent with the fraction of binary/multiple systems found among older pre-main-sequence T Tauri stars in each of the Taurus, ρ Oph, and Chamaeleon star-forming regions over a similar separation range, as well as the combined companion star fraction for these regions. However, the companion star fraction for solar-type, and lower mass M dwarf, main-sequence stars in the solar neighborhood in this separation range ($11\% \pm 3\%$) is approximately one-half that of our sample. Together with multiplicity statistics derived for previously published samples of Class 0 and Class I sources, our study suggests that a significant number of binary/multiple objects may remain to be discovered at smaller separations among our Class I/flat-spectrum sample and/or most of the evolution of binary/multiple systems occurs during the Class 0 phase of early stellar evolution.

Key words: binaries: close — stars: formation — stars: pre-main-sequence

1. INTRODUCTION

Traditional multiplicity search techniques such as direct imaging and spectroscopy have revealed that most field stars are members of binary or higher order multiple systems (Abt & Levy 1976; Duquennoy & Mayor 1991; Fischer & Marcy 1992). Infrared surveys of younger pre-main-sequence (PMS) T Tauri stars (TTSs) in nearby, young dark cloud complexes (i.e., Taurus, Ophiuchus, Chamaeleon, Lupus, Corona Australis) conducted over the past 10 years have shown that the fraction of binary and multiple stars is even higher in these regions (Ghez, Neugebauer, & Matthews 1993; Mathieu 1994; Simon et al. 1995; Ghez et al. 1997; Barsony, Koresko, & Matthews 2003). In contrast, the results of multiplicity studies of the young Trapezium and NGC 2024 clusters in Orion are consistent with what one finds for field stars (McCaughrean & Stauffer 1994; Prosser et al. 1994; Petr et al. 1998; Simon, Close, & Beck 1999; Beck, Simon, & Close 2003).

Each of the above studies samples a different range of separations and companion brightness, making subsequent inter-comparison difficult. However, using a model that accounts for differences in sample completeness, dynamic range, and chance projection of background objects, Duchêne (1999) has reanalyzed and confirmed the previous findings. Thus, the formation of binary and multiple systems appears to be the rule, rather than the exception, in star-forming regions.

However, very little is currently known about the multiplicity of even younger, self-embedded young stellar objects (YSOs). Recently, Reipurth (2000) analyzed the multiplicity of 14 young (ages $\leq 10^5$ yr) sources that drive giant Herbig-Haro flows. Between 79% (separation $\simeq 10$ – 3700 AU) and 86% (separation $\simeq 10$ – 5000 AU) of these sources had at least one companion and, of these, half were higher order multiple systems. In addition, in a millimeter survey of young embedded objects, Looney, Mundy, & Welch (2000) find a very high multiplicity fraction. All surveyed objects were members of small groups or binary systems. These fractions are even larger than those found among either the PMS TTS or field-star populations. In contrast, a significantly lower frequency ($36\% \pm 14\%$; separation $\simeq 300$ – 2000 AU) of binary/multiple stars was observed in a sample of 19 Class I and flat-spectrum YSOs in the ρ Oph and Serpens dark clouds (Haisch et al. 2002). One needs to know with reasonable statistical confidence the multiplicity properties of embedded Class I/flat-spectrum sources, which previous surveys do not provide.

In this paper we present the results of a new near-infrared imaging survey of 76 self-embedded young stars in the ρ Oph

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($d = 125$ pc; Knude & Hog 1998), Serpens ($d = 310$ pc; de Lara, Chavarría-K., & López-Molina 1991), Taurus ($d = 140$ pc; Kenyon & Hartmann 1995), Perseus ($d = 320$ pc; Herbig 1998), and Cha I and II ($d = 160$ pc and $d = 178$ pc, respectively; Whittet et al. 1997) star-forming regions. All of the sources in our survey were selected such that they have either Class I or flat spectral energy distributions, as determined from previous studies using *IRAS*, *ISO*, and ground-based data (e.g., Wilking, Lada, & Young 1989, hereafter WLY; Prusti, Whittet, & Wesselius 1992; Ladd, Lada, & Myers 1993; Greene et al. 1994; Kenyon & Hartmann 1995; Persi et al. 2000; Bontemps et al. 2001; A. A. Kaas 2001, private communication). In defining Class I/flat-spectrum YSOs, the classification scheme of Greene et al. (1994) has been adopted, as it is believed to correspond well to the physical stages of evolution of YSOs (e.g., André & Montmerle 1994). Thus, Class I sources have a spectral index [$\alpha = d \log(\lambda F_\lambda) / d \log(\lambda)$] > 0.3 , and flat-spectrum sources have $0.3 > \alpha \geq -0.3$ in the wavelength range $2 \mu\text{m} \leq \lambda \leq 10 \mu\text{m}$. Combined with the results of our previously published Class I/flat-spectrum multiplicity survey (Haisch et al. 2002), our sample includes 9/21 published known Class I/flat-spectrum sources in Perseus, 11/21 in Taurus, and all known Class I/flat-spectrum YSOs in ρ Oph, Serpens, and Cha I and II.

We discuss our near-IR observations and data reduction procedures in § 2. In § 3 we present the results of our survey, and we discuss the results in § 4. We summarize our primary results in § 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. OSIRIS-NSFCAM Observations

All near-infrared observations were obtained using two separate facilities. The near-IR *JHKL*-band (1.25, 1.65, 2.2, and $3.5 \mu\text{m}$) observations of all Taurus, Perseus, and Serpens (and follow-up *L*-band data for ρ Oph) Class I/flat-spectrum sources were obtained with the NSFCAM 256×256 pixel InSb facility array camera on the NASA IRTF 3 m telescope on Mauna Kea, Hawaii (Rayner et al. 1993; Shure et al. 1994). Similar *JHK* observations of all Cha I, II, and ρ Oph sources were taken with OSIRIS, the Ohio State 1024×1024 pixel HAWAII HgCdTe infrared imager/spectrometer array on the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope (Atwood et al. 1992; Depoy et al. 1993).

The *J*-, *H*-, and *K*-band observations of the Cha I, II, and ρ Oph sources were made during the period 2002 February 28–March 3. For sources found to be single, only *K*-band data were obtained. The plate scale of OSIRIS on the CTIO 4 m telescope is $0''.161 \text{ pixel}^{-1}$, with a corresponding field of view of approximately $93'' \times 93''$. The average FWHM for all observations was $\sim 0''.6$. Each source was observed in a five-point dither pattern (a 2×2 square with a point at the center) with $12''$ offsets between the corners of the square. Typical total integration times ranged from 1–5 minutes at *J* and *H* bands and 2–3 minutes at *K* band. These integration times yield 5σ sensitivity limits, good to within 0.2 mag, of ~ 20.0 – 20.7 mag at *J* band, ~ 19.0 – 19.7 mag at *H* band, and ~ 18.5 at *K* band.

Similar *J*-, *H*-, *K*-, and *L*-band observations of all Taurus, Perseus, and Serpens sources (as well as *L*-band observations of all ρ Oph sources for which *JHK* data were obtained at CTIO, as described above) were made during the periods 2001 December 8–10, 2002 January 3–5, and 2002 June 13–15 using NSFCAM at the NASA IRTF 3 m telescope. Again, for

single sources, only *K*-band data were taken. For this study, we used a plate scale of $0''.148 \text{ pixel}^{-1}$ with a corresponding field of view of approximately $38'' \times 38''$. The average FWHM for all observations was $\sim 1''$. Each source was observed in a five-point dither pattern (a 2×2 square with a point at the center) with $12''$ offsets between the corners of the square. At each dither position the telescope was nodded to separate sky positions $30''$ north of each target observation. Typical total integration times ranged from 5 to 10 minutes at *J* band, 1–2 minutes at *H* and *K* bands, and 60 s at *L* band. These integration times yield 5σ sensitivity limits, good to within 0.2 mag, of ~ 20.5 – 21.0 mag at *J* band, ~ 19.0 – 19.3 mag at *H* band, ~ 18.5 – 19.0 mag at *K* band, and ~ 14.0 mag at *L* band.

All *JHKL* data were reduced using the Image Reduction and Analysis Facility (IRAF).⁶ The individual sky frames were normalized to produce flat fields for each target frame. All target frames were processed by subtracting the appropriate sky frames and dividing by the flat fields. Finally, all target frames were registered and combined to produce the final images of each object in each filter.

2.2. Source Photometry and Calibration

Aperture photometry was performed using the PHOT routine within IRAF. An aperture of 4 pixels in radius was used for all target photometry, and a 10 pixel radius was used for the standard-star photometry. Sky values around each source were determined from the mode of intensities in an annulus with inner and outer radii of 10 and 20 pixels, respectively. Our choice of aperture size for our target photometry insured that the individual source fluxes were not contaminated by the flux from companion stars; however, they are not large enough to include all the flux from a given source. To account for this missing flux, aperture corrections were determined using the MKAPFILE routine within IRAF. Aperture photometry was performed on all target sources using the same 10 pixel aperture used for the photometry of the standard stars. Fluxes in both the 10 and 4 pixel apertures were compared, and the instrumental magnitudes for all sources were corrected to account for the missing flux.

Photometric calibration was accomplished using the list of standard stars of Elias et al. (1982) for all IRTF data and the *HST*/NICMOS infrared standard stars of Persson et al. (1998) for the CTIO observations. The standards were observed on the same nights and through the same range of air masses as the target sources. Zero points and extinction coefficients were established for each night. All NSFCAM magnitudes and colors were transformed to the CIT system using Mauna Kea to NSFCAM and NSFCAM to CIT photometric color transformation equations.⁷ Following the expectations discussed in the OSIRIS User's Manual, we transformed all OSIRIS magnitudes and colors to the CIT system using the Cerro Tololo Infrared Imager (CIRIM) to CIT transformation equations from the CIRIM Manual. The photometric uncertainty for all observations is typically good to within ± 0.10 , 0.04, 0.02, and 0.06 mag at *J*, *H*, *K*, and *L* band, respectively.

⁶ IRAF is distributed by NOAO, which is operated by AURA, Inc., under cooperative agreement with the NSF.

⁷ From <http://irtfweb.ifa.hawaii.edu/Facility/nsfcam/mkfilters.html>, <http://irtfweb.ifa.hawaii.edu/Facility/nsfcam/hist/color.html>, and the NSFCAM User's Guide.

3. ANALYSIS AND RESULTS

The companion star fraction (CSF) is defined as

$$\text{CSF} = \frac{B + 2T + 3Q}{S + B + T + Q}, \quad (1)$$

where S is the number of single stars, B is the number of binary systems, T the number of triple systems, and Q the number of quadruple systems. In Table 1 we summarize, for each region surveyed, the minimum projected separation to which our observations are sensitive, the number of sources observed, the number of sources found to be binary/multiple, and the CSFs. The quoted uncertainties in the CSFs represent the statistical standard errors (i.e., $[\text{CSF}(1-\text{CSF})/N]^{1/2}$). Our lower limit for detectable separations of 100–140 AU for Taurus, Chamaeleon, and ρ Oph and ~ 300 AU for Perseus and Serpens is set by the seeing ($\sim 0''.6$ at CTIO and $\sim 1''$ at the IRTF). We have imposed an upper limit to the separations of 2000 AU (corresponding to $\lesssim 6''.3$ in Perseus and Serpens, $\lesssim 11''$ in Chamaeleon, $\lesssim 14''$ in Taurus, and $\lesssim 16''$ in ρ Oph) in order to avoid including sources that are not gravitationally bound systems (e.g., Reipurth & Zinnecker 1993; Simon et al. 1995). Within the errors the CSFs are the same for each region, with the exception of Taurus, in which no binary/multiple objects were detected among the surveyed objects. However, it remains possible that the Perseus and Chamaeleon regions may have somewhat lower CSFs ($\sim 10\%$ – 20%) than those found in Serpens and ρ Oph ($\sim 25\%$ – 35%), although this is only marginally significant given the large error bars on the calculated CSFs.

The CSFs quoted in Table 1 assume that there are no restrictions on either separations between companions or magnitude differences between components, an assumption that is clearly unattainable in practice. The quantity that one can measure is a *restricted* CSF, that is the CSF over a given physical separation range to a stated component K -magnitude difference (ΔK). In calculating the overall restricted CSF for our sample, we restrict the physical separation range to 300–2000 AU, since 300 AU corresponds to our lower limit for detectable separations in Perseus and Serpens. In addition, sensitivity calculations from our data indicate that we can detect a $K = 4$ mag difference between the primary and companion at a separation of $1''$ at the 5σ confidence level. Thus, we restrict our analysis to component magnitude differences $\Delta K \leq 4$ mag.

In combination with our previously published results for ρ Oph and Serpens (in which we find a restricted CSF of 5/13; $38\% \pm 13\%$ over a separation range of 300–2000 AU), we find

a *restricted* CSF of 14/79 ($18\% \pm 4\%$) for separations between ~ 300 – 2000 AU and $\Delta K = 4$ mag, with no correction for background contamination or completeness. In the calculation of our restricted CSF the sources WL 1 and EC 82/EC 86 are excluded since their separations (103 and ~ 2700 AU, respectively) are outside of our restricted separation range. Furthermore, the sources IRS 54, GY 51, EC 129, GY 91, WL 22, GY 197, EC 121, EC 40, EC 37, EC 28, and DEOS are not included in the calculation of the overall restricted CSF, as their component ΔK values are either not within $\Delta K \leq 4$, or any potential companions would be fainter than our 5σ sensitivity limit.

Table 2 lists the separations (in both arcseconds and astronomical units) and position angles (P.A.'s) (measured with respect to the brightest source at K band) for the sources in our survey that were found to be binary/multiple. In Tables 3–8, we present the right ascension and declination coordinates (J2000.0), K -band magnitudes, or in the case of the multiple objects in Table 3 $JHKL$ magnitudes and near-IR colors, for all surveyed sources (the exception being in Chamaeleon, where L -band data were not taken).

None of the sources in the Ced 110 IRS 6, HB 1, and GCNM 53 systems were detected at J band, and neither component in the HB 1 and GCNM 53 systems was detected at H band. This was not likely due to the smearing out of faint sources in these relatively long (90 s) exposures, since this effect was not observed in other equally long J - and H -band images in which faint sources were detected. Furthermore, the mean object sizes were the same in all bands. Upper limits for the J - and H -band magnitudes for these sources were determined by adding artificial stars to the respective J - and H -band images and counting the number of sources recovered by DAOFIND. Artificial stars were added at random positions to each image in 20 separate half-magnitude bins, with each bin containing 100 stars. The 20 bins covered a magnitude range from 15.0 to 25.0. The artificial stars were examined to ensure that they had a similar FWHM of the point-spread function as the sources detected in other J - and H -band images. Aperture photometry was performed on all sources to confirm that the assigned magnitudes of the added sources agreed with those returned by PHOT. All photometry agreed to within 0.1 mag. DAOFIND and PHOT were then run and the number of identified artificial sources within each half magnitude bin was tallied. This process was repeated 20 times. For Ced 110 IRS 6, HB 1, and GCNM 53, our 5σ J -band magnitude limit, good to within ± 0.2 mag, is 20.0. Similarly, our 5σ H -band magnitude limit is 19.0. We list our 5σ J - and H -band limits in Table 3 where appropriate.

TABLE 1
COMPANION STAR FRACTION FOR EACH REGION

Region	Separation ^a (AU)	No. Observed ^b	No. Binary/Multiple ^c	CSF (%)
Perseus	320	9	1	11 \pm 10
Taurus.....	140	11	0	0 \pm 0
Cha I and II	100	17	3	18 \pm 9
Serpens.....	310	19	6	32 \pm 11
ρ Oph.....	125	37	9	27 \pm 7

^a Denotes the minimum separation to which our observations are sensitive.

^b Number of sources observed in each region.

^c Number of sources found to be binary/multiple.

TABLE 2
SEPARATIONS AND POSITION ANGLES FOR THE BINARY/MULTIPLE SOURCES

Source	Region	Separation (arcsec)	Separation (AU)	P.A. ^a (deg)
03260+3111.....	Perseus	3.62	1160	47.9
Cha I T33B.....	Cha I	2.38	380	285.2
Ced 110 IRS6.....	Cha I	1.95	310	95.6
Cha I T14a.....	Cha I	2.35	375	51.9
IRS 48.....	ρ Oph	15.13	1890	121.1
IRS 54.....	ρ Oph	7.25	905	324.0
GY 51.....	ρ Oph	1.16	145	67.5
Third source.....	...	5.66	710	97.7
WL 2.....	ρ Oph	4.15	520	343.2
IRS 37.....	ρ Oph	8.55 ^b	1070	65.8 ^b
IRS 43/GY 263.....	ρ Oph	6.99	875	322.0
WL 1.....	ρ Oph	0.82	103	321.2
GY 23/GY 21.....	ρ Oph	10.47	1310	322.6
L1689 SNO2.....	ρ Oph	2.92	365	240.3
SVS 20.....	Serpens	1.51	468	9.9
EC 95/EC 92.....	Serpens	5.03	1560	352.1
EC 129.....	Serpens	6.22	1930	323.4
HB 1.....	Serpens	1.46	450	28.9
GCNM 53.....	Serpens	4.31	1340	159.4

^a Measured with respect to the brightest source at *K* band.

^b IRS 37 forms a binary with WL 5. Separation and P.A. are measured with respect to IRS 37, the Class I YSO.

TABLE 3
POSITIONS AND *JHKL* MAGNITUDES AND COLORS FOR MULTIPLE SOURCES

Source	R.A. (J2000.0)	Decl. (J2000.0)	<i>J</i>	<i>H</i>	<i>K</i>	<i>L</i> ^a	<i>J</i> − <i>H</i>	<i>H</i> − <i>K</i>	<i>K</i> − <i>L</i> ^a
03260+3111.....	03 29 10.40	+31 21 58.0	9.36	8.08	7.29	6.75	1.28	0.79	0.54
...	...	...	13.61	12.07	11.04	10.22	1.54	1.03	0.82
Cha I T33B.....	11 08 15.69	−77 33 47.1	9.32	8.10	6.93	...	1.22	1.17	...
...	...	...	9.98	9.16	8.85	...	0.82	0.31	...
Ced 110 IRS6.....	11 07 09.80	−77 23 04.4	>20.00	15.18	10.86	...	>4.82	4.32	...
...	...	...	>20.00	17.57	12.86	...	>2.43	4.71	...
Cha I T14a.....	11 04 24.32	−77 18 07.2	16.42	14.32	12.54	...	2.10	1.78	...
...	...	...	18.43	15.66	13.85	...	2.77	1.81	...
IRS 48.....	16 27 37.20	−24 30 34.0	10.40	8.72	7.71	6.12	1.68	1.01	1.59
IRS 50.....	16 27 38.10	−24 30 40.0	12.54	10.94	9.92	9.24	1.60	1.02	0.68
IRS 54.....	16 27 51.70	−24 31 46.0	16.38	12.22	10.15	7.74	4.16	2.07	2.41
...	...	...	>20.00	16.13	14.29	13.14	>3.87	1.84	1.15
GY 51.....	16 26 30.49	−24 22 59.0	16.41	12.22	10.16	8.16	4.19	2.06	2.00
...	...	...	16.98	12.99	11.09	9.42	3.99	1.90	1.67
...	...	...	>20.00	17.27	15.51	>13.50	>2.73	1.76	<2.01
WL 2.....	16 26 48.56	−24 28 40.4	19.26	13.95	11.15	9.24	5.31	2.80	2.80
...	...	...	20.07	15.15	12.42	10.60	4.92	2.73	1.82
IRS 37.....	16 27 17.54	−24 28 56.5	19.22	14.46	10.94	8.54	4.76	3.52	2.40
WL 5.....	16 27 18.00	−24 28 55.0	>20.50	15.03	10.21	7.94	>5.47	4.82	2.27
EC 129 ^b	18 30 02.80	+01 12 28.0	...	...	10.07	...	...	...	...
...	...	...	...	...	15.88	...	...	...	...
HB 1.....	18 29 59.50	+01 11 59.0	>20.00	>19.00	15.67	10.89	>1.00	>3.53	4.78
...	...	...	>20.00	>19.00	16.98	11.77	>1.00	>2.22	5.21
GCNM 53.....	18 29 52.90	+01 14 56.0	>20.00	>19.00	16.75	12.95	>1.00	>2.45	3.80
...	...	...	>20.00	>19.00	18.22	>13.50	>1.00	>0.98	<4.72

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a *L*-band magnitudes, and hence *K*−*L* colors, not available for Chamaeleon sources.

^b EC 129 is a binary source; however, no *J*, *H*, or *L* observations were taken since the binarity of this source could not be determined prior to the reduction of the data.

TABLE 4
POSITIONS AND K MAGNITUDES FOR SINGLE PERSEUS SOURCES

Source	R.A. (J2000.0)	Decl. (J2000.0)	K Mag.
03382+3145	03 41 22.70	+31 54 46.0	8.22
03259+3105	03 29 03.70	+31 15 52.0	8.53
03262+3114	03 29 20.40	+31 24 47.0	8.56
03380+3135	03 41 09.10	+31 44 38.0	8.63
03220+3035	03 25 09.20	+30 46 21.0	10.21
03254+3050	03 28 35.10	+31 00 51.0	10.28
03445+3242	03 47 41.60	+32 51 43.5	11.41
03439+3233	03 47 05.00	+32 43 09.0	12.73

4. DISCUSSION

4.1. Multiplicity Characteristics

For the Class I/flat-spectrum sources surveyed, we find a restricted CSF of 14/79 ($18\% \pm 4\%$). This consistent with the restricted CSFs derived for PMS T Tauri stars in each of the Taurus, ρ Oph, and Chamaeleon star-forming regions over a separation range of ~ 300 – 1800 AU (Leinert et al. 1993; Simon et al. 1995; Ghez et al. 1997; Allen et al. 2002; Barsony et al. 2003), as well as the combined restricted CSF ($19\% \pm 3\%$) for these regions. In contrast, however, the CSF for solar-type and lower mass M dwarf, main-sequence stars in the solar neighborhood in this separation range ($11\% \pm 3\%$; Duquennoy & Mayor 1991; Fischer & Marcy 1992) is approximately one-half that of our sample.

Reipurth (2000) found that 79%–86% of young (ages $\leq 10^5$ yr) stellar objects driving giant Herbig-Haro flows were multiple, with half being triple or even higher order systems. This CSF is considerably higher than the restricted CSF found in the present study. However, the Reipurth work was based on adaptive optics, *HST* NICMOS, and VLA data, all having higher spatial resolution than our present Class I/flat-spectrum study. We have determined that we would have detected four of these sources as binaries (no triples) given the spatial resolution, dynamic range, and physical separation limits of our present survey. This results in a restricted CSF = $29\% \pm 12\%$, statistically identical to the restricted CSF of our Class I/flat-spectrum sample.

In a $\lambda = 2.7$ mm interferometric survey of 24 YSOs Looney et al. (2000) found that all of the embedded objects were members of small groups or binary systems. All but four of these objects are Class 0 or Class I sources. Together with the multiplicity statistics found among older T Tauri and main-sequence stars, our study suggests that a significant number of

TABLE 5
POSITIONS AND K MAGNITUDES FOR SINGLE TAURUS SOURCES

Source	R.A. (J2000.0)	Decl. (J2000.0)	K Mag.
Haro 6-13	04 32 15.61	+24 29 02.3	7.77
GV Tau B	04 29 23.61	+24 34 06.8	7.86
Haro 6-28	04 35 55.87	+22 54 35.5	9.60
04489+3042	04 52 06.90	+30 47 17.0	9.98
04016+2610	04 04 42.85	+26 18 56.3	10.23
04108+2803	04 13 52.90	+28 11 23.0	10.25
04361+2547	04 39 13.87	+25 53 20.6	10.32
04365+2535	04 39 35.01	+25 41 45.5	10.80
04295+2251	04 32 32.10	+22 57 30.0	11.01
04264+2433	04 29 30.30	+24 39 54.0	11.60

TABLE 6
POSITIONS AND K MAGNITUDES FOR SINGLE CHAMAELEON SOURCES

Source	R.A. (J2000.0)	Decl. (J2000.0)	K Mag.
Cha I T32	11 08 04.61	-77 39 16.9	6.13
Cha I T44	11 10 01.35	-76 34 55.8	6.43
Cha I T41	11 09 50.39	-76 36 47.6	6.99
Cha I T42	11 09 54.66	-76 34 23.7	7.02
Cha I T29	11 07 59.25	-77 38 43.9	7.19
ISO-Cha I 26	11 08 04.00	-77 38 42.0	8.25
Cha I C1-6	11 09 23.30	-76 34 36.2	8.43
Cha I C9-2	11 08 37.37	-77 43 53.5	8.62
Cha II 8	12 53 42.88	-77 15 05.7	8.76
Cha I T47	11 10 50.78	-77 17 50.6	8.77
ISO-Cha I 97	11 07 18.30	-77 23 13.0	11.20
ISO-Cha I 225	11 09 55.00	-76 31 12.0	12.38
ISO-Cha I 138	11 08 19.20	-77 30 41.0	12.90
ISO-Cha I 86	11 06 57.20	-77 22 51.0	13.12

binary/multiple objects may remain to be discovered at smaller separations among our Class I/flat-spectrum YSOs and/or most of the evolution of binary/multiple systems occurs during the Class 0 phase of early stellar evolution.

4.2. Notes on the Multiple Sources

03260+3111: This source forms a wide binary system with a $3''.62$ separation at P.A. $\simeq 48^\circ$. Clark (1991) determined fluxes in all four *IRAS* bands for 03260+3111, although it was noted that several sources were present in the *IRAS* images. Subsequently, Ladd et al. (1993) obtained *H*- and *K*-band photometry of this source and determined a total luminosity of $L = 318 L_\odot$. Based on an optical and near-infrared imaging survey, Magnier et al. (1999) have classified 03260+3111 as a transitional YSO (i.e., flat-spectrum), consistent with the near-infrared colors derived in the present survey.

TABLE 7
POSITIONS AND K MAGNITUDES FOR SINGLE ρ OPHIUCHI SOURCES

Source	R.A. (J2000.0)	Decl. (J2000.0)	K Mag.
Elias 29	16 27 09.43	-24 37 18.5	7.54
IRS 42	16 27 21.45	-24 41 42.8	8.56
GSS 30/IRS 1	16 26 21.50	-24 23 07.0	9.03
VSSG 18	16 27 28.44	-24 27 21.9	9.20
GSS 26	16 26 10.28	-24 20 56.6	9.38
IRS 34	16 27 15.48	-24 26 40.6	10.26
WL 17	16 27 06.79	-24 38 14.6	10.31
WL 12	16 26 44.30	-24 34 47.5	10.43
IRS 46	16 27 29.70	-24 39 16.0	10.57
WL 6	16 27 21.83	-24 29 53.2	10.77
WL 3	16 27 19.30	-24 28 45.0	11.50
CRBR 15	16 26 19.30	-24 24 16.0	11.73
GY 312	16 27 38.91	-24 40 20.1	11.94
CRBR 12	16 26 17.30	-24 23 49.0	12.08
GY 344	16 27 45.81	-24 44 53.7	12.33
IRS 33	16 27 14.60	-24 26 55.0	12.34
GY 245	16 27 18.50	-24 39 15.0	12.54
CRBR 85	16 27 24.68	-24 41 03.7	14.45
GY 91	16 26 40.60	-24 27 16.0	15.76
WL 22	16 26 59.30	-24 35 01.0	17.58
GY 197	16 27 05.40	-24 36 31.0	18.33

TABLE 8
POSITIONS AND K MAGNITUDES FOR SINGLE SERPENS SOURCES

Source	R.A. (J2000.0)	Decl. (J2000.0)	K Mag.
EC 94.....	18 29 57.80	+01 12 37.0	11.67
EC 73.....	18 29 55.13	+01 13 19.2	12.20
EC 38.....	18 29 49.50	+01 17 07.0	12.42
EC 125.....	18 30 02.10	+01 14 00.0	12.90
EC 91.....	18 29 57.80	+01 12 28.0	13.67
EC 80.....	18 29 56.60	+01 12 40.0	14.92
EC 121.....	18 30 01.10	+01 13 26.0	15.44
EC 40.....	18 29 49.70	+01 14 57.0	15.98
EC 37.....	18 29 49.10	+01 16 32.0	16.01
EC 28.....	18 29 47.00	+01 16 26.0	16.47
DEOS.....	18 29 49.30	+01 16 19.0	16.82

Cha I T33: Also known as Glass 1, Cha I T33 (catalog designation from Whittet et al. 1987) was first found to exhibit a strong near-infrared excess by Glass (1979). Chelli et al. (1988) identified Cha I T33 as a binary source (separation = $2''.67$; P.A. = 285°) for the first time using near-infrared narrow-slit scan observations. Most of the total system luminosity ($L \simeq 5 L_\odot$) was found to be associated with the very red companion, while the optically dominant primary is a non-emission-line K4 star. Since the companion is much brighter in the near-infrared than the primary, the *IRAS* fluxes of T33 have been assigned to this component (Prusti et al. 1992). The binarity of Cha I T33 has also been noted by Feigelson & Kriss (1989) and Reipurth & Zinnecker (1993). The former authors have found Cha I T33 to be an *Einstein* X-ray source (CHX 12), with the red companion being a weak-line H α spectral type G5 star. Model fits to the spectral energy distributions (SEDs) of both components by Koresko, Herbst, & Leinert (1997) suggest that the primary is consistent with its classification as a “naked” T Tauri star by Feigelson & Kriss (1989) with an implied mass of $M = 1 M_\odot$ and an age of 3×10^6 yr. The observed spectral type of the companion was also found to be consistent with that derived from the SED modeling. Finally, ISOPHOT spectra suggest a strong mid-infrared variability of Cha I T33 (Gürtler et al. 1999), already suggested by a variability flag in the *IRAS* fluxes of this object. Comparably strong near-infrared variability was also noted previously by Chelli et al. (1988), who concluded that the primary is the variable component. The near-infrared variability of T33 has also been noted more recently by Carpenter et al. (2002). The ISOPHOT spectra of Gürtler et al. (1999) suggest that the primary may also be variable at mid-infrared wavelengths or that the infrared companion is a variable also.

Ced 110 IRS 6: Detected as an embedded *IRAS* source by Prusti et al. (1991), Ced 110 IRS 6 is located in the direction of a dense molecular core discovered by Mattila, Liljeström, & Toriseva (1989) at the edge of the Cederblad 110 optical reflection nebula. Using *IRAS* fluxes in conjunction with near-infrared photometry, Prusti et al. (1991) have classified IRS 6 as a Class I YSO with a luminosity of $L = 1 L_\odot$. Ced 110 IRS 6 was detected as an X-ray source with $L_X \simeq 10^{29-30}$ ergs s $^{-1}$ in archived *ROSAT* PSPC pointed observations (Carkner, Kozak, & Feigelson 1998) and is thus one of the lowest X-ray luminosity Class I objects yet detected. Ced 110 IRS 6 has also been detected as an unresolved mid-infrared excess source in ISOCAM images of the Ced 110 dense core (Persi

et al. 2000). More recently, subarcsecond near-infrared images of IRS 6 have revealed the binarity of this object (Persi et al. 2001). In contrast to the previous system luminosity determination of Prusti et al. (1991), the primary component is found to have a luminosity of $L = 6 L_\odot$, with the secondary source having a luminosity about a factor of 7 lower, although with similar $H-K$ colors. This suggests that most of the observed mid- and far-infrared ISOCAM and ISOPHOT (Lehtinen et al. 2001) flux densities are associated with the primary component of Ced 110 IRS 6.

Cha I T14a: Cha I T14a is also known as Herbig-Haro (HH) 48. The binary nature of this object was suggested initially by Schwartz (1977), who noted that HH 48 consisted of two close condensations, the northeast component being the fainter. Indeed, our resolved (separation = $2''.35$; P.A. = 52°) near-infrared photometry of Cha I T14a confirms that the secondary (northeast) source is the fainter component of the binary. A subsequent spectrum of Cha I T14a implied that it is a T Tauri star with relatively strong forbidden emission lines (Schwartz, Jones, & Sirk 1984). Cha I T14a has been detected at both mid- and far-infrared wavelengths by ISOCAM and *IRAS*, respectively (Prusti et al. 1992; Persi et al. 2001), and exhibits a flat-spectrum composite SED.

IRS 48: IRS 48 forms a wide ($\sim 15''$) binary with IRS 50. IRS 48 has been classified as a Class I YSO (WLY), although recent ISOCAM observations suggest a flat-spectrum object (Bontemps et al. 2001). IRS 50 remains unclassified, however our *JHKL* imaging data suggest infrared colors consistent with a Class II YSO. IRS 48 and IRS 50 exhibit very different spectral types of less than F3 and M4, respectively (Luhman & Rieke 1999). IRS 48 has been detected at 1.3 mm (André & Montmerle 1994) and is also a CO outflow driving source exhibiting a bipolar morphology and high-velocity wings (Bontemps et al. 1996).

IRS 54: We find IRS 54 to be a binary source with a separation of $\simeq 7''.3$ at a P.A. of 324° . IRS 54 itself is a Class I YSO (WLY; Bontemps et al. 2001), while the companion has *JHKL* colors indicative of a heavily reddened ($A_V > 25$) Class III or background object. IRS 54 was detected as a *ROSAT* X-ray source with $L_X = 10^{30.7}$ ergs s $^{-1}$ (Casanova et al. 1995); however, subsequent *ROSAT* PSPC (Carkner et al. 1998) and *Chandra* X-ray (Imanishi, Koyama, & Tsuboi 2001) observations resulted in nondetections.

GY 51: GY 51 was first discovered to be a binary object with a separation of $1''.15$ (very similar to our derived separation of $1''.16$) by Strom, Kepner, & Strom (1995). We find GY 51 to be in fact a triple system with a separation of $5''.66$ and a P.A. of $97''.7$. ISOCAM observations reveal GY 51 to be a flat-spectrum source (Bontemps et al. 2001); however, its dereddened spectral index suggests a Class II YSO (Wilking et al. 2001). GY 51 is also a known radio source (LFAM 9; Leous et al. 1991).

WL 2: WL 2 was discovered by Wilking & Lada (1983) and was subsequently found to be binary by Barsony et al. (1989). Barsony, Ressler, & Marsh (2004) find a spectral index of +0.21 for the primary and -0.46 for the secondary, making this a flat-spectrum and Class II pairing. WL 2 has been detected at 1.3 mm (André & Montmerle 1994) and is a *Chandra* X-ray source (Imanishi, Koyama, & Tsuboi 2001).

IRS 37: IRS 37 (also known as GY 244) forms a wide ($\sim 8''.5$) binary with WL 5 (=IRS 38), and is part of an asterism that also includes WL 3 and WL 4. Both objects were discovered in *IRAS* and near-infrared observations of WLY and

Wilking & Lada (1983), respectively. Barsony et al. (1989) subsequently found the near-infrared counterpart to IRS 37. The exact spectral classification of IRS 37 has been the subject of some debate. WLY cite IRS 37 to be a Class I YSO, a classification supported by Bontemps et al. (2001), while André & Montmerle (1994) assign a Class II designation. WL 5, however, is considered to be an extinguished Class III YSO (André & Montmerle 1994 and references therein; Bontemps et al. 2001). Indeed, it is one of the most heavily extinguished infrared sources in the ρ Oph cloud core (André et al. 1992). As was the case with IRS 48/IRS 50, IRS 37 and WL 5 have very different spectral types of M4 (Luhman & Rieke 1999) and F7 (Greene & Meyer 1995), respectively. Both objects are known X-ray flare sources; however, the flares observed in IRS 37 are significantly stronger (Imanishi, Koyama, & Tsuboi 2001).

EC 129: EC 129 appears to be the brightest component of a wide binary system, although the physical separation (1930 AU) is almost at our imposed upper limit for a bound system. First detected by Eiroa & Casali (1992), EC 129 exhibits 3.08 μm H₂O-ice absorption ($\tau = 0.08$) and has an extinction corrected luminosity of $L = 3.29 L_{\odot}$. Casali & Eiroa (1996) found that its 2 μm $\delta v = 2$ CO bands were in absorption with a CO index of 2.4. EC 129 may be associated with the *IRAS* source PS 2 identified in Hurt & Barsony (1996). This source exhibits polarization consistent with scattering in the bipolar/cometary nebula associated with the object (Sogawa et al. 1997). Testi & Sargent (1998) detected 3 mm continuum emission from EC 129, and *ISO-LWS* spectra have identified EC 129 as a point source of $\sim 5''$ size at a dust temperature of $T_d \simeq 24$ K (Larsson et al. 2000).

HB 1: HB 1 was identified as an *IRAS* source by Hurt & Barsony (1996) and is coincident with a 3 mm continuum source detected by Testi & Sargent (1998). Kaas (1999) identified a near-infrared source associated with HB 1, which we have subsequently found to be binary (separation = $1''.46$; P.A. = 29°) in the present study.

GCNM 53: Identified in a deep optical and infrared imaging survey by Giovannetti et al. (1998), we find GCNM 53 to be a wide binary with a separation of $4''.31$ at a P.A. of 159° .

5. SUMMARY AND CONCLUSIONS

1. We have obtained new near-IR observations of 76 Class I/flat-spectrum objects in the Perseus, Taurus, Cha I and II, ρ Oph, and Serpens dark clouds. The observations presented here are part of a larger systematic infrared multiplicity survey of self-embedded objects in the nearest dark clouds.

2. When combined with our previously published Class I/flat-spectrum multiplicity survey, we find a *restricted* CSF of 14/79 ($18\% \pm 4\%$) over a separation range of ~ 300 – 2000 AU and $\Delta K \leq 4$ mag. This is consistent with the restricted CSFs derived for T Tauri stars in each of the Taurus, ρ Oph, and Chamaeleon star-forming regions over a similar separation range, as well as the combined restricted CSF ($19\% \pm 3\%$) for these regions. In contrast, the CSF for solar-type, and lower mass M dwarf, main-sequence stars in the solar neighborhood in this separation range ($11\% \pm 3\%$) is approximately one-half that of our sample.

3. Accounting for differences in spatial resolution between the present study and that of Reipurth (2000), we find the restricted CSFs for our Class I/flat-spectrum sample and young (ages $\leq 10^5$ yr) stellar objects driving Herbig-Haro flows to be statistically identical. Furthermore, in a millimeter survey of young embedded objects, Looney et al. (2000) found that all of the Class 0 and Class I objects surveyed were members of small groups or binary systems. When compared with previously published results, our survey suggests that a significant number of binary/multiple objects may remain to be discovered at smaller separations among our Class I/flat-spectrum YSOs and/or most of the evolution of binary/multiple systems occurs during the Class 0 phase of early stellar evolution.

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REFERENCES

- Abt, H. A., & Levy, S. 1976, *ApJS*, 30, 273
 Allen, L. E., Myers, P. C., Di Francesco, J., Mathieu, R., Chen, H., & Young, E. 2002, *ApJ*, 566, 993
 André, P., Deeney, B. D., Phillips, R. B., & Lestrade, J.-F. 1992, *ApJ*, 401, 667
 André, P., & Montmerle, T. 1994, *ApJ*, 420, 837
 Atwood, B., Byard, P., Depoy, D. L., Frogel, J., & O'Brien, T. 1992, *Prog. Telesc. Instrum. Technol.*, 693
 Barsony, M., Burton, M. G., Russell, A. P. G., Carlstrom, J. E., & Garden, R. 1989, *ApJ*, 346, L93
 Barsony, M., Koresko, C., & Matthews, K. 2003, *ApJ*, 591, 1064
 Barsony, M., Ressler, M. E., & Marsh, K. 2004, in preparation
 Beck, T. L., Simon, M., & Close, L. M. 2003, *ApJ*, 583, 358
 Bontemps, S., et al. 2001, *A&A*, 372, 173
 Bontemps, S., André, P., Terebey, S., & Cabrit, S. 1996, *A&A*, 311, 858
 Carkner, L., Kozak, J. A., & Feigelson, E. D. 1998, *AJ*, 116, 1933
 Carpenter, J. M., Hillenbrand, L. A., Skrutskie, M. F., & Meyer, M. R. 2002, *AJ*, 124, 1001
 Casali, M. M., & Eiroa, C. 1996, *A&A*, 306, 427
 Casanova, S., Montmerle, T., Feigelson, E. D., & André, P. 1995, *ApJ*, 439, 752
 Chelli, A., Zinnecker, H., Carrasco, L., Cruz-Gonzalez, I., & Perrier, C. 1988, *A&A*, 207, 46
 Clark, F. O. 1991, *ApJS*, 75, 611
 de Lara, E., Chavarria-K. C., & Lopez-Molina, G. 1991, *A&A*, 243, 139
 Depoy, D. L., Atwood, B., Byard, P. L., Frogel, J., & O'Brien, T. P. 1993, *Proc. SPIE*, 1946, 667
 Duchêne, G. 1999, *A&A*, 341, 547
 Duquennoy, A., & Mayor, M. 1991, *A&A*, 248, 485
 Eiroa, C., & Casali, M. M. 1992, *A&A*, 262, 468
 Elias, J. H., Frogel, J. A., Matthews, K., & Neugebauer, G. 1982, *AJ*, 87, 1029
 Feigelson, E. D., & Kriss, G. A. 1989, *ApJ*, 338, 262
 Fischer, D. A., & Marcy, G. W. 1992, *ApJ*, 396, 178
 Ghez, A. M., McCarthy, D. W., Patience, J., & Beck, T. 1997, *ApJ*, 481, 378
 Ghez, A. M., Neugebauer, G., & Matthews, K. 1993, *AJ*, 106, 2005

- Giovannetti, P., Caux, E., Nadeau, D., & Monin, J.-L. 1998, *A&A*, 330, 990
Glass, I. 1979, *MNRAS*, 187, 305
Greene, T. P., & Meyer, M. R. 1995, *ApJ*, 450, 233
Greene, T. P., Wilking, B. A., André, P., Young, E. T., & Lada, C. J. 1994, *ApJ*, 434, 614
Gürtler, J., Schreyer, K., Henning, T., Lemke, D., & Pfau, W. 1999, *A&A*, 346, 205
Haisch, Jr., K. E., Barsony, M., Greene, T. P., & Ressler, M. 2002, *AJ*, 124, 2841
Herbig, G. H. 1998, *ApJ*, 497, 736
Hurt, R. L., & Barsony, M. 1996, *ApJ*, 460, L45
Imanishi, K., Koyama, K., & Tsuboi, Y. 2001, *ApJ*, 557, 747
Kaas, A. A. 1999, *AJ*, 118, 558
Kenyon, S. J., & Hartmann, L. 1995, *ApJS*, 101, 117
Knude, J., & Hog, E. 1998, *A&A*, 338, 897
Koresko, C. D., Herbst, T. M., & Leinert, C. 1997, *ApJ*, 480, 741
Ladd, E. F., Lada, C. J., & Myers, P. C. 1993, *ApJ*, 410, 168
Larsson, B., et al. 2000, *A&A*, 363, 253
Lehtinen, K., Haikala, L. K., Mattila, K., & Lemke, D. 2001, *A&A*, 367, 311
Leinert, C., Zinnecker, H., Weitzel, N., Christou, J., Ridgway, S. T., Jameson, R., Haas, M., & Lenzen, R. 1993, *A&A*, 278, 129
Leous, J. A., Feigelson, E. D., André, P., & Montmerle, T. 1991, *ApJ*, 379, 683
Looney, L. W., Mundy, L. G., & Welch, W. J. 2000, *ApJ*, 529, 477
Luhman, K. L., & Rieke, G. H. 1999, *ApJ*, 525, 440
Magnier, E. A., Volp, A. W., Laan, K., van den Ancker, M. E., & Waters, L. B. F. M. 1999, *A&A*, 352, 228
Mathieu, R. D. 1994, *ARA&A*, 32, 465
Mattila, K., Liljeström, T., & Toriseva, M. 1989, in *Low Mass Star Formation and Pre-Main Sequence Objects*, ed. B. Reipurth (Garching: ESO), 153
McCaughrean, M. J., & Stauffer, J. R. 1994, *AJ*, 108, 1382
Persi, P., Marenzi, A. R., Gómez, M., & Olofsson, G. 2001, *A&A*, 376, 907
Persi, P., et al. 2000, *A&A*, 357, 219
Persson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, *AJ*, 116, 2475
Petr, M. G., Coude Du Foresto, V., Beckwith, S. V. W., Richichi, A., & McCaughrean, M. J. 1998, *ApJ*, 500, 825
Prosser, C. F., Stauffer, J. R., Hartmann, L., Soderblom, D. R., Jones, B. F., Werner, M. W., & McCaughrean, M. J. 1994, *ApJ*, 421, 517
Prusti, T., Clark, F. O., Whittet, D. C. B., Laureijs, R. J., & Zhang, C. Y. 1991, *MNRAS*, 251, 303
Prusti, T., Whittet, D. C. B., & Wesselius, P. R. 1992, *MNRAS*, 254, 361
Rayner, J. T., et al. 1993, *Proc. SPIE*, 1946, 490
Reipurth, B. 2000, *AJ*, 120, 3177
Reipurth, B., & Zinnecker, H. 1993, *A&A*, 278, 81
Schwartz, R. D. 1977, *ApJS*, 35, 161
Schwartz, R. D., Jones, B. F., & Sirk, M. 1984, *AJ*, 89, 1735
Shure, M., et al. 1994, *Exp. Astron.*, 3, 239
Simon, M., Close, L. M., & Beck, T. L. 1999, *AJ*, 117, 1375
Simon, M., et al. 1995, *ApJ*, 443, 625
Sogawa, H., Tamura, M., Gatley, I., & Merrill, K. M. 1997, *AJ*, 113, 1057
Strom, K. M., Kepner, J., & Strom, S. E. 1995, *ApJ*, 438, 813
Testi, L., & Sargent, A. I. 1998, *ApJ*, 508, L91
Whittet, D. C. B., Kirrane, T. M., Kilkenney, D., Oates, A. P., Watson, F. G., & King, D. J., 1987, *MNRAS*, 224, 497
Whittet, D. C. B., Prusti, T., Franco, G. A. P., Gerakines, P. A., Kilkenney, D., Larson, K. A., & Wesselius, P. R. 1997, *A&A*, 327, 1194
Wilking, B. A., Bontemps, S., Schuler, R. E., Greene, T. P., & André, P. 2001, *ApJ*, 551, 357
Wilking, B. A., & Lada, C. J. 1983, *ApJ*, 274, 698
Wilking, B. A., Lada, C. J., & Young, E. T. 1989, *ApJ*, 340, 823