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EVIDENCE FOR MASS-DEPENDENT CIRCUMSTELLAR DISK EVOLUTION IN THE 5 Myr OLD UPPER SCORPIUS OB ASSOCIATION

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ABSTRACT

We present 4.5, 8, and 16 μm photometry from the *Spitzer Space Telescope* for 204 stars in the Upper Scorpius OB association. The data are used to investigate the frequency and properties of circumstellar disks around stars with masses between ~0.1 and 20 $M_\odot$ at an age of ~5 Myr. We identify 35 stars that have emission at 8 or 16 μm in excess of the stellar photosphere. The lower mass stars (~0.1–1.2 $M_\odot$) appear surrounded by primordial optically thick disks based on the excess emission characteristics. Stars more massive than ~1.8 $M_\odot$ have lower fractional excess luminosities suggesting that the inner ~10 AU of the disk has been largely depleted of primordial material. None of the G and F stars (~1.2–1.8 $M_\odot$) in our sample have an infrared excess at wavelengths ≤16 μm. These results indicate that the mechanisms for dispersing primordial optically thick disks operate less efficiently, on average, for low-mass stars, and that longer timescales are available for the buildup of planetary systems in the terrestrial zone for stars with masses $\lesssim$1 $M_\odot$.

Subject headings: open clusters and associations: individual (Upper Scorpius OB1) — planetary systems: protoplanetary disks — stars: pre–main-sequence

Online material: machine-readable table

1. INTRODUCTION

Most young (~1 Myr) stars embedded within molecular clouds are surrounded by circumstellar accretion disks (Strom et al. 1989) that are potential sites of planet formation. The ubiquity of disks extends to all masses from as high as 10 $M_\odot$ down through brown dwarfs and in all environments from isolated stars in Taurus to dense clusters in Orion (Lada et al. 2000; Bouy et al. 2006).

By an age of 10 Myr, the primordial disks so ubiquitous around young stars change dramatically. The inner disk ($\lesssim$1 AU) dissipates in >90% of stars (Mamajek et al. 2004), accretion rates drop by an order of magnitude (Muzerolle et al. 2000), and the mass contained in small dust grains declines by at least a factor of 4 (Liu et al. 2004; Carpenter et al. 2005). Results from the *Spitzer Space Telescope* (Werner et al. 2004) demonstrate an even more striking degree of evolution, as dust within an ~1 AU orbital radius is found in only a few percent of ~10 Myr stars (Silverstone et al. 2006). MIPS 24 μm surveys have detected dust in 7%–48% of 10–30 Myr stars (Young et al. 2004; Rieke et al. 2005; Chen et al. 2005) but with fractional dust luminosities orders of magnitude below that found in younger sources. Together these observations have established that circumstellar disks are at an advanced evolutionary stage by an age of ~10 Myr.

Key to understanding the formation of planetary systems is examining the evolution of circumstellar disks after the main accretion phase has terminated. To measure the properties of disks during this epoch for stellar masses ranging from 0.1 to 20 $M_\odot$, we have conducted a photometric survey of 205 stars with spectral types between M5 and B0 in the 5 Myr old Upper Scorpius OB association using the IRAC, IRS, and MIPS instruments on *Spitzer*. This letter presents analysis of the IRAC and IRS photometry to probe for terrestrial-zone material across the stellar mass spectrum at a constant age.

2. SAMPLE SELECTION

The parent sample for this program was selected from previous membership studies of the Upper Sco OB association. We compiled members identified based on (1) *Hipparcos* astrometry (B, A, F, and G stars; de Zeeuw et al. 1999), (2) optical color-magnitude diagrams and spectroscopic verification of lithium (G, K, and M stars; Preibisch & Zinnecker 1999; Preibisch et al. 2002), and (3) X-ray sources subsequently verified as lithium-rich, pre-main-sequence stars (G, K, and M stars; Walter et al. 1994; Martín 1998; Preibisch et al. 1998; Kunkel 1999; Köhler et al. 2000). Since these studies identified Upper Sco members based on stellar properties (proper motion, strong lithium, X-ray emission) rather than those linked to circumstellar material (e.g., Hα emission and near-infrared excess), we believe that our sample is not biased for or against the presence of a circumstellar disk.

The parent sample was cross-matched with the *Hipparcos* (Perryman et al. 1997), Tycho-2 (Høg et al. 2000), and UCAC2 (Zacharias et al. 2004) proper-motion catalogs where possible. Using the Madsen et al. (2002) kinematic model for Upper Sco, we computed the probability that a given star has a proper motion consistent with membership in the association (see, e.g., Mamajek et al. 2002). Any star that deviated more than 2 σ from the proper-motion model was removed, as was any star with an inferred cluster parallax distance more than 45 pc from the mean Upper Sco distance (where the line-of-sight depth of the association is ~30 pc; Preibisch & Zinnecker 1999). We also removed stars located in projection against the ρ Oph molecular cloud, which is near Upper Sco and contains stars with ages of $\lesssim$1 Myr. These criteria yielded 341 Upper Sco members with spectral type M5 and earlier.

The aim was to populate five quasi-logarithmically spaced mass bins with 50 stars each. In paring the list, we (1) removed stars requiring >20 cycles with MIPS to detect the photosphere at 24 μm, (2) dropped sources for which a nearby star compromised the Two Micron All Sky Survey (2MASS) photometry, (3) removed stars with the highest 70 μm background levels, and (4) avoided sources observed by other *Spitzer* pro-

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TABLE 1

Observed IRAC and IRS Fluxes

Source	Spectral Type	Spectral Type Ref.	IRAC 4.5 μm[a]		IRAC 8 μm[b]		IRS 16 μm[c,d]		Excess?	
			S_ν (mJy)	σ (mJy)	S_ν (mJy)	σ (mJy)	S_ν (mJy)	σ (mJy)	8 μm	16 μm
Upper Sco Sources from This Study										
HD 142987 ……	G4	MML	181.3 (13867264)	2.2	67.9 (13867264)	0.4	19.9 (13888000)	0.1	N	N
HD 147810 ……	G1	MML	228.9 (13864704)	2.8	82.0 (13864704)	0.8	26.3 (13885952)	0.2	N	N
HD 149598 ……	G0	MML	113.0 (13870336)	1.4	41.4 (13870336)	0.3	12.9 (13889280)	0.1	N	N

Note.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal Letters*. A portion is shown here for guidance regarding its form and content.

[a] IRAC 4.5 μm photometry measured using a flux calibration factor of 0.1388 MJy $\mathrm{sr}^{-1}/(\mathrm{DN\ s}^{-1})$.

[b] IRAC 8 μm photometry measured using a flux calibration factor of 0.2021 MJy $\mathrm{sr}^{-1}/(\mathrm{DN\ s}^{-1})$.

[c] IRS 16 μm PUI photometry measured using a flux calibration factor of 0.01375 MJy $\mathrm{sr}^{-1}/(e^{-}\ \mathrm{s}^{-1})$.

[d] Saturated sources are listed as "sat."

grams. The final source list consists of 205 stars:[4] 48 stars with masses between 0.1 and 0.2 $M_\odot$ (corresponding to spectral types of ~M3–M5), 50 between 0.2 and 0.4 $M_\odot$ (M0.5–M3), 42 between 0.4 and 1.8 $M_\odot$ (F0–M0.5), 50 between 1.8 and 3.0 $M_\odot$ (B5–F0), and 15 more massive than 3 $M_\odot$ (earlier than B5). The final source list does not constitute a complete sample of stars but should be a representative population of Upper Sco.

Preibisch & Zinnecker (1999) estimated an age of 5 Myr for an X-ray-selected sample of stars in Upper Sco as inferred from D'Antona & Mazzitelli (1994) pre-main-sequence evolutionary tracks after allowing for binaries. This age is consistent with the nuclear (5–6 Myr; de Geus et al. 1989) and dynamical (4.5 Myr; Blaauw 1991) age of the high-mass stars. Moreover, Preibisch & Zinnecker (1999) find that the intrinsic age spread within the association is less than 2 Myr. We therefore adopt an age of 5 Myr for Upper Sco but recognize that the age is uncertain by at least 1–2 Myr, depending on the choice of model evolutionary tracks.

3. OBSERVATIONS AND DATA REDUCTION

IRAC (4.5 and 8 μm; Fazio et al. 2004) observations for 204 stars and IRS peak-up-imaging (PUI; 16 μm; Houck et al. 2004) data for 195 stars were obtained with the *Spitzer Space Telescope*. IRS PUI observations were not attempted for nine B stars, since the detector would have saturated on the stellar photosphere. Exposure times ranged from 0.02 to 12 s for IRAC and from 6 to 30 s for IRS PUI, depending on the stellar brightness estimated from 2MASS photometry. At least nine dither positions were obtained per band, and the number was increased as needed to achieve a minimum signal-to-noise ratio on the stellar photosphere of 50 for IRAC and 20 for IRS PUI.

Data analysis was performed on the basic calibrated data images produced by the S14 pipeline for IRAC and S13 for IRS PUI. Photometry was measured on individual frames using a modified version of IDLPHOT. For IRAC, we adopted an aperture radius of 3 pixels (1 pixel $= 1''.22$) and a sky annulus between 10 and 20 pixels. For IRS PUI, we used an aperture radius of 2 pixels (1 pixel $= 1''.8$) and a sky annulus between 5 and 8 pixels. A multiplicative aperture correction of 1.110, 1.200, and 1.316 was applied to the IRAC 4.5 μm, IRAC 8 μm, and IRS 16 μm flux densities, respectively, to place the photometry on the calibration scale described in the IRAC and IRS data handbooks. Photometric corrections at the few percent level were applied to the IRAC data to account for distortion and variations in the effective bandpass across the detector (Reach et al. 2005). Internal photometric uncertainties were computed as the standard deviation of the mean of measurements made on individual frames. We adopted a minimum uncertainty of 1.22%, 0.66%, and 0.58% for 4.5, 8, and 16 μm, respectively, based on repeatability achieved for bright stars.

We incorporated into the analysis 14 solar-type stars in Upper Sco from the Formation and Evolution of Planetary Systems (FEPS) *Spitzer* Legacy Program (Meyer et al. 2006) that were selected for that study based on criteria similar to those stated in § 2. We excluded the FEPS source HD 143006, since this star was recognized as a Upper Sco member based on an *IRAS* excess (Odenwald 1986) and thus would bias the sample. The FEPS IRAC data were processed using the above procedures. FEPS did not obtain IRS PUI observations.

Table 1 lists the sources, spectral types, *Spitzer* fluxes, and internal uncertainties for the 218 stars analyzed here. The uncertainties do not include calibration uncertainties of 2% for IRAC (Reach et al. 2005) and 6% for IRS PUI, as quoted in the IRS data handbook. Five sources are flagged in Table 1 where the curve of growth at 16 μm deviates from a point source by more than 4% for the adopted aperture radius, indicating that the flux measurement may include contributions from a second source.

4. SOURCES WITH INFRARED EXCESSES

Color-color diagrams for the Upper Sco sources are presented in Figure 1. The top panel shows the 8 to 4.5 μm flux ratio ($\equiv R_8$) as a function of the $J-H$ color, and the bottom panel shows the 16 to 4.5 μm flux ratio ($\equiv R_{16}$). In both panels, most sources lie along a tight locus that is assumed to represent emission dominated by reddened stellar photospheres. However, several sources have large values of R_8 or R_{16} diagnostic of 8 or 16 μm emission in excess of the photosphere.

Since the scatter in the observed colors is likely dominated by factors not easily quantified on a star-by-star basis, we empirically determined a threshold to identify sources with intrinsic infrared excesses. A linear relation was fitted between $\log R_{16}$ and $J-H$. Any outliers more distant than 4 times the rms of the fit residuals were removed, and the fit was repeated until no additional outliers were identified. A similar fit was performed between $\log R_8$ and $J-H$ after removing all R_{16} outliers.

The rms residuals from the final linear fit were 1.9% and 5.7% for R_8 and R_{16}, respectively. A source was identified with an infrared excess if R_8 or R_{16} exceeded the fitted relation by both 4 times the rms of the fit residuals and 4 times the internal uncertainty in the flux ratio. We further required that a large value of R_8 or R_{16} not result from extinction as determined from *B*, *V*, and 2MASS photometry, spectral types, and the Mathis (1990) extinction law.

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[4] One source, HIP 80112, was observed only with MIPS and is not further discussed.

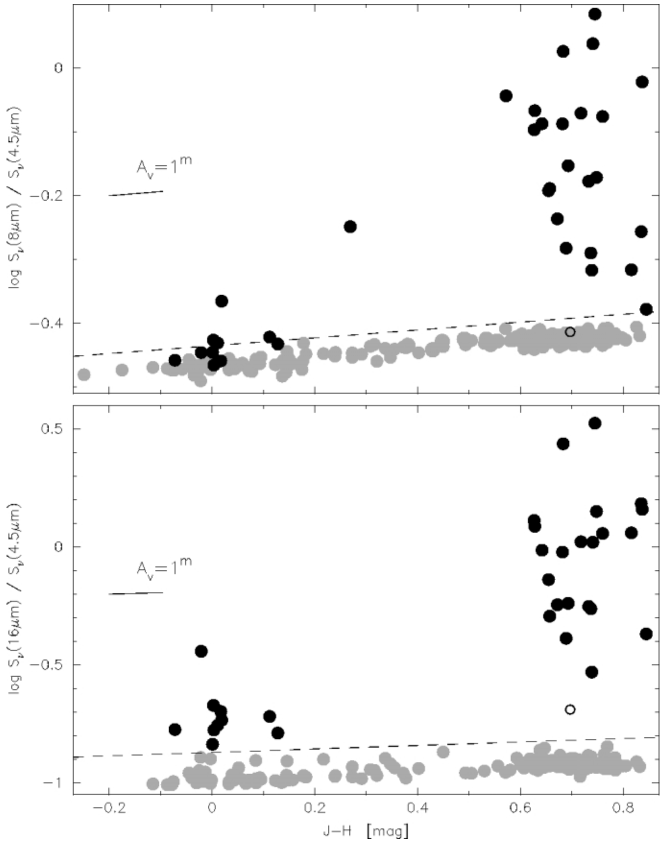

FIG. 1.—Color-color diagrams showing $J-H$ along the abscissa, tracing the stellar photosphere, and the 8 to 4.5 μm flux ratio (*top*) and 16 to 4.5 μm flux ratio (*bottom*) along the ordinate, diagnostic of circumstellar disks. Dashed lines indicate the thresholds adopted to identify sources with infrared excesses, corresponding to a color excess above the photosphere of 8% (*top*) and 25% (*bottom*). Black circles represent sources identified with an 8 or 16 μm excess, and gray circles represent sources without a detectable excess. The open circle represents Sco PMS 17, for which the 16 μm excess is questionable based on possible source confusion (see Table 1). The internal uncertainties in the *Spitzer* flux ratios are all smaller than the symbol size, and the median $J-H$ uncertainty is 0.036 mag. The source [PBB2002] USco J161420.2−190648, which has an excess at both 8 and 16 μm, is offscale on these plots. The reddening vector from Mathis (1990) is indicated.

Excesses were inferred toward 35 sources as indicated in Table 1: 29 at 8 μm and 33 at 16 μm. The 16 μm excess sources include [PBB2002] USco J161420.2−190648, which saturated the IRS detector. HIP 78207 and [PZ99] J161411.0−230536 have 8 μm excesses but were not observed at 16 μm. An IRS spectrum of the latter source shows a clear excess at this wavelength (J. M. Carpenter et al. 2006, in preparation), and HIP 78207 exhibits *IRAS* excesses at 12 and 25 μm (Oudmaijer et al. 1992).

5. DISCUSSION

The excess properties of the Upper Sco sources are not uniform across spectral type as demonstrated in Figure 1. The 8 μm excess fraction for K+M stars (24 of 127) is higher than that for B+A stars (5 of 61) at the 92% confidence level and for F+G stars (0 of 30) at 99.2% confidence, as determined from the two-tailed Fisher's Exact Test. At 16 μm, the K+M excess fraction (23 of 121) is similar to that for B+A stars (10 of 52) but higher than that for F+G stars (0 of 22) at 97.5% confidence.

More telling differences between early and late spectral types are observed in the magnitude of the excesses. Nine B+A stars have a R_{16} color excess less than twice the stellar photosphere, while all K+M sources exceed this limit with excesses up to 27 times the photospheric level. Similarly, at 8 μm, all but two B+A excess sources have a R_8 excess less than 10% of the photosphere, while 23 of the 24 K+M excess sources have larger color excesses.

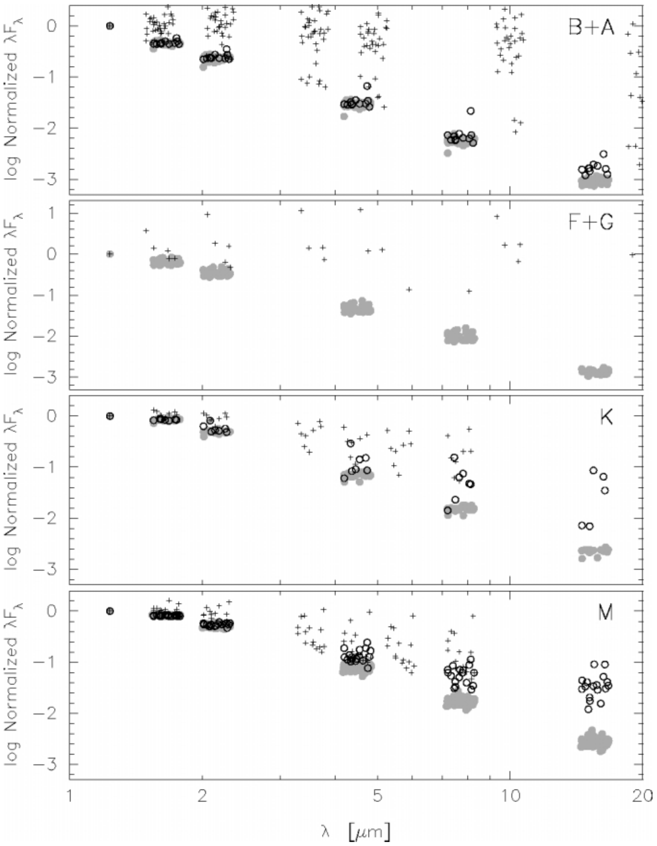

FIG. 2.—Dereddened SEDs for B+A (*top*), F+G (*second from top*), K (*third from top*), and M (*bottom*) stars. Filled circles represent Upper Sco sources that do not have a detectable excess at wavelengths ≤16 μm, and open circles represent sources with an excess in one or more bands. Plus signs represent Herbig Ae/Be stars (B, A, and F spectral types) and class II sources in Taurus (G, K, and M spectral types) listed in Hillenbrand et al. (1992) and Hartmann et al. (2005). The SEDs have been normalized to the J band, and a random offset has been added to the wavelengths to illustrate the distribution of points.

In Figure 2, we assess the evolutionary state of the circumstellar disks in Upper Sco by comparing normalized, dereddened spectral energy distributions (SEDs) for stars in Upper Sco with a sample of well known T Tauri (Hartmann et al. 2005) and Herbig Ae/Be (Hillenbrand et al. 1992) stars that have tabulated photometry. The Taurus and Herbig Ae/Be objects are expected to represent young stars surrounded by primordial, optically thick, circumstellar accretion disks.

As shown in Figure 2, the SEDs for B and A stars in Upper Sco differ substantially from most Herbig Ae/Be stars. Herbig Ae/Be stars typically have excesses at wavelengths as short as 2 μm and fractional excess luminosities that are 10–100 times the photosphere at 10–20 μm. By comparison, only one B or A star in Upper Sco has a *K*-band excess (HIP 78207), and the fractional excess luminosity at 16 μm is typically less than twice the photosphere.

Surprisingly, none of the F and G stars in our Upper Sco sample exhibit a detectable excess. While Chen et al. (2005) identified a 24 μm excess around one of five F+G stars in Upper Sco, and the G6 V star HD 143006 is surrounded by an optically thick disk (Sylvester et al. 1996), overall infrared excesses at wavelengths ≤16 μm are relatively rare for this spectral type range at the age of Upper Sco.

The results for the B, A, F, and G stars imply that the reservoir of small dust grains in a primordial, optically thick inner disk has been largely depleted by an age of 5 Myr for ~1–20 $M_\odot$ stars.

The inner-disk radius inferred by the weak (or lack of) excess emission at 16 μm is ∼4–10 AU for 6000–10,000 K photospheres, assuming optically thin, blackbody dust emission (Jura 2003). These results are consistent with the low fraction of accreting B and A stars found in the 4 Myr old Trumpler 37 cluster (Sicilia-Aguilar et al. 2006) and the 5 Myr old Orion OB1b association (Hernández et al. 2006). However, Hernández et al. (2006) found that 7 out of 11 F stars in Orion OB1b contain 24 μm excesses consistent with a debris disk, suggesting that the excess fraction for F and G stars in Upper Sco may increase once our longer wavelength observations are obtained.

In contrast to the massive stars, the K and M stars in Upper Sco with infrared excesses have characteristics similar to those of optically thick primordial disks. As discussed above and demonstrated in Figure 2, the K+M stars have larger fractional excesses than the B+A stars, and the magnitude of the excesses overlaps with that observed toward class II stars in Taurus. A further connection between the disks in Upper Sco and Taurus is found by considering evidence for disk accretion as traced by Hα emission. Of the 100 stars in our sample with measured Hα line strengths (see references in § 2), nine have Hα equivalent widths consistent with accretion according to the criteria recommended by White & Basri (2003). Eight of these nine sources have an infrared excess and are likely surrounded by accretion disks. These similarities suggest that many of the K+M stars in Upper Sco remain surrounded by optically thick disks. Assuming optically thick blackbody emission, the 4.5 and 8 μm excesses may imply the presence of dust at radii as small as ∼0.05 AU (Jura 2003).

Differences in the excess characteristics between the ∼1–2 Myr old Taurus and 5 Myr Upper Sco populations are notable, since they may reflect temporal evolution in the disk properties. While the magnitude of the excesses overlaps between the two samples, the excesses are larger, on average, for Taurus, as seen in Figure 2. Furthermore, about half of the stars in Taurus exhibit a *K*-band excess (Strom et al. 1989) compared to only two (1.5%) K+M stars in Upper Sco ([PBB2002] USco J161420.2−190648 and [PZ99] J160421.7−213028). Similarly, while 68% of the stars in Taurus exhibit a 3.6 μm excess (Haisch et al. 2001), only $19\%^{+5\%}_{-4\%}$ of K+M stars in Upper Sco have an 8 μm excess. Therefore, not only are there fewer sources with disks in Upper Sco, but the disks that remain lack the hot dust found in younger stars. Sicilia-Aguilar et al. (2006) found similar tendencies for the low-mass population in Trumpler 37 compared to Taurus.

To summarize, 19% of K0–M5 stars in Upper Sco possess infrared excesses similar to class II sources in Taurus, indicating that primordial disks last around an appreciable number of 0.1–1 $M_\odot$ stars for at least 5 Myr. By contrast, only $\lesssim$1% of the more massive stars in Upper Sco contain such disks within an orbital radius of ∼4–10 AU. Similar results have been reported for Trumpler 37 (Sicilia-Aguilar et al. 2006), IC 348 (Lada et al. 2006), and η Cha (Megeath et al. 2005). Our observations of Upper Sco extend these conclusions to the full range of stellar masses down to the hydrogen-burning limit at an age of ∼5 Myr. These results establish that warm dust in the terrestrial zone persists for longer times around stars with masses $\lesssim 1\ M_\odot$.

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REFERENCES

Blaauw, A. 1991, in The Physics of Star Formation and Early Stellar Evolution, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 125
Bouy, H., Heélama, N., Martín, E. L., Barrado y Navascués, D., Sterzik, M., & Pantin, E. 2006, A&A, in press (astro-ph/0608395)
Carpenter, J. M., Wolf, S., Schreyer, K., Launhardt, R., & Henning, T. 2005, AJ, 129, 1049
Chen, C. H., Jura, M., Gordon, K. D., & Blaylock, M. 2005, ApJ, 623, 493
D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467
de Geus, E. J., de Zeeuw, P. T., & Lub, J. 1989, A&A, 216, 44
de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354
Fazio, G., et al. 2004, ApJS, 154, 10
Haisch, K. E., Jr., Lada, E. A., & Lada, C. J. 2001, ApJ, 553, L153
Hartmann, L., Megeath, S. T., Allen, L., Luhman, K., Calvet, N., D'Alessio, P., Franco-Hernandez, R., & Fazio, G. 2005, ApJ, 629, 881
Hernández, J., Briceño, C., Calvet, N., Hartmann, L., Muzerolle, J., & Quintero, A. 2006, ApJ, in press (astro-ph/0607562)
Hillenbrand, L. A., Strom, S. E., Vrba, F. J., & Keene, J. 1992, ApJ, 397, 613
Høg, E., et al. 2000, A&A, 355, L27
Houck, J., et al. 2004, ApJS, 154, 18
Houk, N. 1982, Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 3 (Ann Arbor: Univ. Mich.)
Houk, N., & Smith-Moore, M. 1988, Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 4 (Ann Arbor: Univ. Mich.)
Jura, M. 2003, ApJ, 584, L91
Köhler, R., Kunkel, M., Leinert, C., & Zinnecker, H. 2000, A&A, 356, 541
Kunkel, M. 1999, Ph.D. thesis, Julius-Maximilians-Univ., Würzburg
Lada, C. J., Muench, A. A., Haisch, K. E., Lada, E. A., Alves, J. F., Tollestrup, E. V., & Willner, S. P. 2000, AJ, 120, 3162
Lada, C. J., et al. 2006, AJ, 131, 1574
Liu, M. C., Matthews, B. C., Williams, J. P., & Kalas, P. G. 2004, ApJ, 608, 526
Madsen, S., Dravins, D., & Lindegren, L. 2002, A&A, 381, 446
Mamajek, E. E., Meyer, M. R., Hinz, P. M., Hoffmann, W. F., Cohen, M., & Hora, J. L. 2004, ApJ, 612, 496
Mamajek, E. E., Meyer, M. R., & Liebert, J. 2002, AJ, 124, 1670
Martín, E. L. 1998, AJ, 115, 351
Mathis, J. S. 1990, ARA&A, 28, 37
Megeath, S. T., Hartmann, L., Luhman, K. L., & Fazio, G. G. 2005, ApJ, 634, L113
Meyer, M. R., et al. 2006, PASP, submitted
Muzerolle, J., Calvet, N., Briceño, C., Hartmann, L., & Hillenbrand, L. 2000, ApJ, 535, L47
Odenwald, S. F. 1986, ApJ, 307, 711
Oudmaijer, R. D., van der Veen, W. E. C. J., Waters, L. B. F. M., Trams, N. R., Wailkens, C., & Engelsman, E. 1992, A&AS, 96, 625
Perryman, M. A. C., et al. 1997, The *Hipparcos* and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA)
Preibisch, T., Brown, A. G. A., Bridges, T., Guenther, E., & Zinnecker, H. 2002, AJ, 124, 404
Preibisch, T., Guenther, E., Zinnecker, H., Sterzik, M., Frink, S., & Roeser, S. 1998, A&A, 333, 619
Preibisch, T., & Zinnecker, H. 1999, AJ, 117, 2381
Reach, W. T., et al. 2005, PASP, 117, 978
Rieke, G. H., et al. 2005, ApJ, 620, 1010
Sicilia-Aguilar, A., et al. 2006, ApJ, 638, 897
Silverstone, M. D., et al. 2006, ApJ, 639, 1138
Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451
Sylvester, R. J., Skinner, C. J., Barlow, M. J., & Mannings, V. 1996, MNRAS, 279, 915
Walter, F. M., Vrba, F. J., Mathieu, R. D., Brown, A., & Myers, P. C. 1994, AJ, 107, 692
Werner, M., et al. 2004, ApJS, 154, 1
White, R., & Basri, G. 2003, ApJ, 582, 1109
Young, E. T., et al. 2004, ApJS, 154, 428
Zacharias, N., Urban, S. E., Zacharias, M. I., Wycoff, G. L., Hall, D. M., Monet, D. G., & Rafferty, T. J. 2004, AJ, 127, 3043