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SPITZER/IRAC PHOTOMETRY OF THE η CHAMELEONTIS ASSOCIATION

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ABSTRACT

We present IRAC 3.6, 4.5, 5.8, and 8 μm photometry for the 17 A-, K-, and M-type members of the η Chameleontis association. These data show infrared excesses toward six of the 15 K and M stars, indicating the presence of circumstellar disks around 40% of the stars with masses of 0.1–1 $M_{\odot}$. The two A stars show no infrared excesses. The excess emission around one of the stars is comparable to the median excess for classical T Tauri stars in the Taurus association; the remaining five show comparatively weak excess emission. Taking into account published Hα spectroscopy that shows that five of the six stars are accreting, we argue that the disks with weak mid-infrared excesses are disks in which the inner disks have been largely depleted of small grains by grain growth or, in one case, the small grains have settled to the midplane. This suggests that η Cha has a much higher fraction of disks caught in the act of transitioning into optically thin disks than that measured in younger clusters and associations.

Subject headings: infrared: stars — planetary systems: protoplanetary disks — stars: pre–main-sequence

1. INTRODUCTION

The evolution of dusty circumstellar disks is currently the primary observable constraint on planet formation around young stars. Measurements of the properties of disks around stars in young clusters and associations are especially useful since ages can be more reliably determined for the clusters and associations than for individual stars. By comparing the infrared emission from disks in clusters/associations of different ages, disk evolution can be traced as a function of age. This method has been pioneered by ground-based *JHKL*-band observations of young clusters, which can measure excess infrared emission from small dust grains in the inner disk (Lada et al. 2000). By obtaining images at these wavelengths for rich nearby clusters with ages ranging from <1 to 30 Myr, Haisch et al. (2001) measured the fraction of stars that exhibited *L*-band excess emission indicative of small dust grains in the inner regions of disks. They found that this fraction steadily decreased with cluster age, with only half of the stars showing *L*-band excesses by the age of 3 Myr. By 5 Myr, the *L*-band excesses are detected for only 12% of the stars, indicating that the small dust grains in most inner disks have been depleted. The one significant exception may be the 5–9 Myr η Chameleontis association (ECA; Mamajek et al. 1999; Lawson et al. 2001; Luhman & Steeghs 2004); Lyo et al. (2003) reported *L*-band excesses in 60% of the stars in this association. However, Haisch et al. (2005) detected L'-band excesses for only 17% stars in the ECA, which is consistent with the *L*-band excess fractions measured for other clusters by Haisch et al. (2001).

To resolve this inconsistency and obtain a more robust estimate of the fraction of stars with disks in the ECA, we have obtained photometry at wavelengths longer than the previous ground-based *JHKL* measurements by using the Infrared Array Camera (IRAC; Fazio et al. 2004) on the *Spitzer Space Telescope*. This Letter describes these observations, identifies the ECA members that have disks based on the IRAC photometry, and compares the resulting disk frequency to previous measurements of this association and other young associations and clusters.

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2. OBSERVATIONS

As a part of the Guaranteed Time Observation program "Disk Evolution in the Planet Formation Epoch," we obtained images at 3.6, 4.5, 5.8, and 8.0 μm of the 15 known K- and M-type and two known A-type members of the ECA (Mamajek et al. 1999; Lawson et al. 2002; Lyo et al. 2004; Song et al. 2004; Luhman & Steeghs 2004). IRAC on board *Spitzer* observed the targets during a 1 hr period ranging from Julian Date 2,453,167.068 to 2,453,167.111 and obtained 0.6 and 12 s exposures at three dithered position toward each of the targets. We extracted the photometry from the Basic Calibrated Data products (pipeline ver. S11.4.0) using the IDLPHOT package (Landsman 1993). The IDLPHOT routines were integrated into a custom IDL program that uses the world coordinate system information in the image headers to identify the images containing a given star, find the star within the images, and extract the photometry. A 5 pixel radius aperture was used for each star, with a sky annulus extending from 5 to 10 pixels. We used zero points (for units of DN s^{-1}) of 19.6642, 18.9276, 16.8468, and 17.3909 (Reach et al. 2005) and aperture corrections of 1.061, 1.064, 1.067, and 1.089 for the [3.6], [4.5], [5.8], and [8.0] bands, respectively. The photometry was then corrected using position-dependent gain maps available on the *Spitzer* Science Center Web pages. The results are in summarized in Table 1.

3. RESULTS

Mid-infrared colors constructed from the IRAC photometry are a sensitive probe of infrared emission from dusty disks around young stars. Using both models and observations of well-studied classical T Tauri stars, Allen et al. (2004) and Hartmann et al. (2005) have studied the color of young stars in the IRAC color-color diagram ([3.6] − [4.5] vs. [5.8] − [8.0]) and have found that young stars with disks have distinctive mid-infrared colors. Figure 1 shows the IRAC color-color diagram for the 15 stars in the ECA. Six stars show significant infrared excesses in their [5.8] − [8.0] colors, indicating that 6/15 stars with masses of 1–0.1 $M_{\odot}$ have disks.

TABLE 1
IRAC Photometry

ID	Sp.	Magnitude (Uncertainty) 3.6 μm	4.5 μm	5.8 μm	8.0 μm	Other Designation
1	K6	7.17 (0.02)	7.20 (0.02)	7.16 (0.01)	7.11 (0.02)	RECX 1
3	M3.25	9.27 (0.02)	9.21 (0.02)	9.09 (0.05)	9.15 (0.01)	RECX 3
4	M1.75	8.45 (0.02)	8.45 (0.02)	8.37 (0.01)	8.32 (0.02)	RECX 4
5	M4	9.59 (0.03)	9.50 (0.03)	9.37 (0.01)	8.89 (0.01)	RECX 5
6	M3	9.15 (0.04)	9.07 (0.07)	9.04 (0.01)	9.04 (0.01)	RECX 6
7	K6	7.52 (0.01)	7.54 (0.02)	7.49 (0.01)	7.46 (0.01)	RECX 7
8	A7	...	...	5.40 (0.01)	5.40 (0.01)	RS Cha AB
9	M4.5	8.99 (0.02)	8.80 (0.01)	8.57 (0.01)	7.97 (0.02)	RECX 9
10	M1	8.58 (0.01)	8.61 (0.01)	8.55 (0.02)	8.49 (0.01)	RECX 7
11	K5.5	7.09 (0.02)	6.86 (0.01)	6.57 (0.01)	5.97 (0.01)	RECX 11
12	M3.25	8.19 (0.01)	8.15 (0.01)	8.10 (0.02)	8.07 (0.01)	RECX 12
13	A1	6.97 (0.01)	6.97 (0.01)	6.97 (0.01)	6.97 (0.01)	HD 75505
14	M4.75	10.53 (0.01)	10.26 (0.05)	10.04 (0.01)	9.48 (0.01)	J0841.5−7853
15	M3.25	8.38 (0.03)	7.91 (0.01)	7.42 (0.03)	6.51 (0.01)	J0843.3−7905
16	M5.75	11.02 (0.01)	10.75 (0.01)	10.42 (0.01)	9.76 (0.01)	J0844.2−7833
17	M5.25	10.07 (0.02)	10.00 (0.01)	9.92 (0.01)	9.90 (0.01)	J0838.9−7916
18	M5.5	10.57 (0.03)	10.45 (0.01)	10.40 (0.01)	10.37 (0.01)	J0836.2−7908

Note.—Spectral types are from Luhman & Steeghs (2004). The uncertainties are the standard deviations of the magnitudes obtained for each set of three frames.

The two A stars, HD 75505 and the double RS Cha, do not show an excess ($[5.8]-[8.0]\sim 0.0$ for both stars). Infrared excess emission was recently detected in *Spitzer* MIPS 24 μm photometry of the one remaining member that we did not image in our IRAC survey: the B8 star η Cha. This star appears to have a debris disk (Rieke et al. 2005). In total, 7/18 of the member stars in the ECA currently show evidence of disks, although longer wavelength observations may increase this ratio.

The initial estimate of the excess frequency was made by Lyo et al. (2003), who obtained *JHK*-band and *L*-band (3.5 μm) photometry of 11 of the K- and M-type stars and concluded that 7/11 of those stars had infrared excesses on the basis of their $K-L$ colors. More recently, Haisch et al. (2005) combined JHK_s photometry from the Two Micron All Sky Survey (2MASS) with L'-band (3.8 μm) photometry from the Very Large Telescope. By using the spectral types of Luhman & Steeghs (2004) to determine the intrinsic K_s-L' colors, they found that only 2/12 of the stars had significant infrared excesses. Although we find that 6/15 of these stars have significant infrared excesses in the IRAC bands, the $K_s-[3.6]$ color, which is similar to the K_s-L color, only shows significant excesses for two sources: stars 11 and 15 (Fig. 2; Luhman & Steeghs 2004). These are the two infrared excess sources identified by Haisch et al. (2005). At longer wavelengths, stars 5 and 9 show infrared excesses, consistent with the results of Lyo et al. (2003); however, these sources do not show substantial excesses in the $K_s-[3.6]$ color. Finally, sources 3, 6, and 12, which were reported to have excesses by Lyo et al. (2003), do not show infrared excesses in any of the IRAC bands. The IRAC results agree with the conclusion of Haisch et al. (2005): offsets and scatter in their *K*- and *L*-band photometry led Lyo et al. (2003) to overestimate the number of stars with *L*-band excesses. We obtain a higher excess

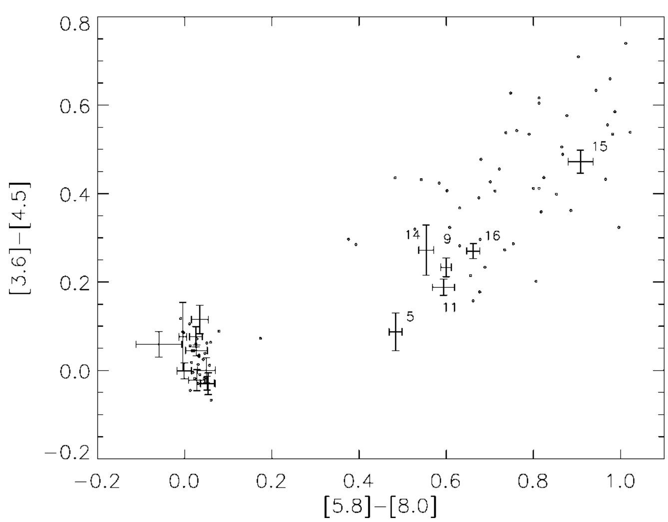

Fig. 1.—IRAC color-color diagram for the 15 known K- and M-type members of the η Cha association and the A star HD 75505. The dots shows the colors of pre–main-sequence stars observed in the Taurus regions (Hartmann et al. 2005). Pure photospheres are clustered around (0, 0), with the M stars showing colors of $[5.8]-[8.0]\approx 0.03$ and $[3.6]-[4.5]$ ranging from 0.15 to −0.05. The excess sources are labeled using the identification numbers from Luhman & Steeghs (2004).

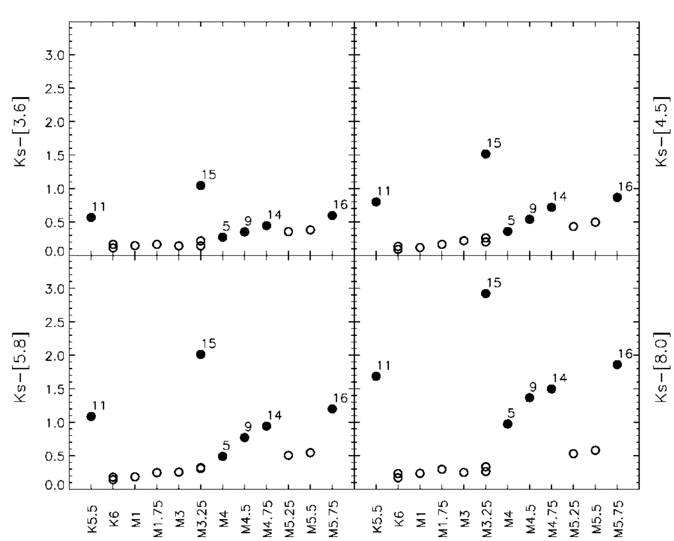

Fig. 2.—Infrared excess as a function of spectral type using the spectral types from Luhman & Steeghs (2004). We display the color for all four IRAC bands. The filled circles are infrared excess sources; the open circles do not show excesses. The K_s magnitudes are taken from the 2MASS point source catalog.

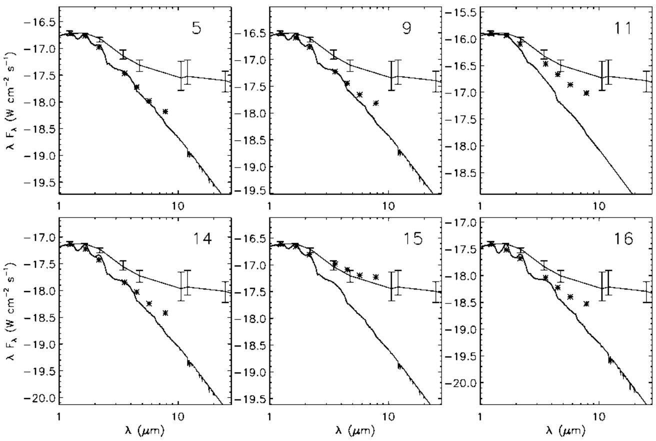

FIG. 3.—Spectral energy distributions for the six infrared excess sources. The *J*, *H*, and K_s fluxes are from the 2MASS point source catalog. The upper line shows the median classical T Tauri locus from D'Alessio et al. (1999). For comparison, we show the NextGen models for stars with the effective temperatures of Luhman & Steeghs (2004) and a surface gravity of $g = 4.0$ (Hauschildt et al. 1999); these models are smoothed to a resolution of 0.1 μm and are scaled to the *J*-band flux of the observed stars.

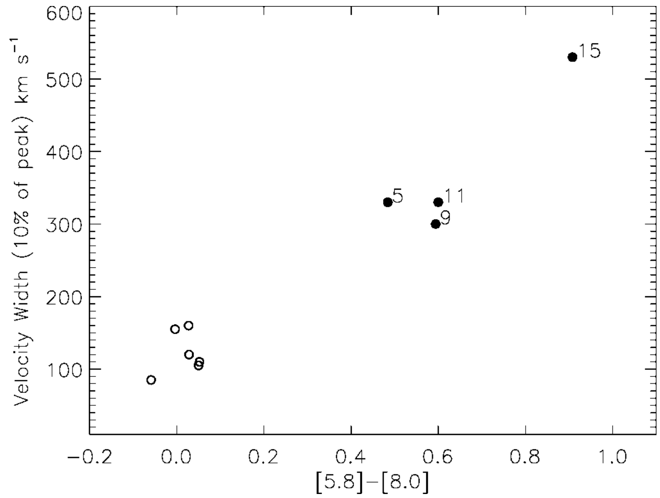

FIG. 4.—Infrared excess as a function of accretion, using the velocity width of the Hα line measured by Lawson et al. (2004) as a diagnostic of the accretion rate. Stars with velocity widths greater than 270 km s^{-1} are accreting gas, and the Hα emission in the remaining stars arises in active chromospheres (White & Basri 2003). The filled circles are IRAC excess sources; open circles do not show excess.

fraction of stars with excesses than Haisch et al. (2005), but only because most of the stars with disks show significant IR excesses at wavelengths longward of 4 μm.

4. DISCUSSION

The ECA provides an important opportunity to study disk evolution in an age range (5–9 Myr) that has been poorly probed so far. Our finding that 40% of the systems with masses of 0.1–1 $M_\odot$ show dust emission from disks is very similar to the frequency found using *Spitzer* photometry of stars with similar masses in the ~4 Myr old cluster Tr 37 (e.g., Sicilia-Aguilar et al. 2005) but much higher than the ~10% frequency found using *N*-band photometry of the 10 Myr old TW Hya association (Jayawardhana et al. 1999) or the <10% frequency found using *Spitzer* photometry of the ~12 Myr old cluster NGC 7160 (Sicilia-Aguilar et al. 2005). The two stars with detectable excesses at 3.6 μm yields a frequency similar to the ~12% *L*-band excess frequency found for the ~5 Myr old cluster NGC 2362 (Haisch et al. 2001). These observations illustrate the importance of longer wavelength observations in detecting disks and the necessity of comparing infrared excess frequencies only within similar wavelength bands. These data also suggest that the disks in small associations like the ECA evolve similarly to disks in large associations with massive stars, such as Tr 37.

Of the stars with IR excesses, one (star 15) has an infrared spectral energy distribution that is essentially the same as that of typical classical T Tauri stars (CTTS) with an optically thick disk extending inward close to the stellar surface (Fig. 3). The other four show greatly reduced or absent infrared excess emission, particularly at wavelengths $\lesssim$6 μm. This is apparent in both the [3.6] − [4.5] and [5.8] − [8] colors as compared to the colors of CTTS in Taurus (Fig. 1), and the spectral energy distributions compared to the median Taurus spectral energy distribution (Fig. 3).

The ECA is remarkable for the relatively large fraction of stars exhibiting both disk gas accretion, although at a reduced rate, and very reduced hot dust emission (Fig. 4). Lawson et al. (2004) inferred that stars 5, 9, 11, and 15 are accreting on the basis of Hα profiles. The Hα emission-line equivalent widths of stars 14 and 16 are −12 and −58 Å, respectively (Lawson et al. 2002; Song et al. 2004); the analysis of White & Basri (2003) suggests that star 16 is accreting while star 14 probably just exhibits chromospheric Hα emission. Thus, five of the six stars with IRAC excesses exhibit gaseous accretion detectable in Hα.

While longer wavelength observations will be needed to assess outer disk properties, the presence of gas accretion leads us to suspect that the four ECA stars with weak short-wavelength excesses (5, 9, 14, and 16) are "transition" T Tauri disk systems such as TW Hya (Calvet et al. 2002; Uchida et al. 2004) and CoKu Tau 4 (Forrest et al. 2004; D'Alessio et al. 2005). These disks are thought to be transitioning from optically thick accretion disks into optically thin planetesimal and debris disks; in this transition phase, the inner disks are optically thin, and the outer disk is still optically thick. Transition disks exhibit very low or no dust emission at shorter wavelengths and strong emission at wavelengths $\gtrsim$10 μm, implying the presence of an inner disk "hole" largely cleared of small dust grains and a substantial outer disk of gas and dust. In such disks, the dust detected by IRAC is transported into the inner disk by accretion from the outer disk. In contrast, "debris disk" systems, in which small dust grains are produced by the collisions of planetesimals, rarely show excesses at wavelengths $\lesssim$10 μm, and they do not show evidence of significant continuous gas accretion onto the central star (as distinct from infalling bodies; e.g., Grady et al. 2000 and references therein). Star 11, which does show a significant 3.6 μm excess, may have an optically thick flat disk due to dust settling and/or grain growth in the inner disk (Calvet et al. 2005a).

Current *Spitzer* Infrared Spectrometer (IRS) studies indicate that the number of transition disk systems in Taurus (ages ~2 Myr) is relatively small, $\lesssim$5% of the number of classical T Tauri star/disk systems (Calvet et al. 2005b). If all CTTS in Taurus pass through a transition disk stage, this suggests that the transition phase lasts 5% of the total disk lifetime. In sharp contrast, the ECA appears to show a transition disk fraction of 4/6 of all systems with infrared excesses. Although the ECA contains a higher fraction of low-mass mid-M–type stars than Taurus, of the eight CTTS and 10 weak line T Tauri stars with spectral types of M3–6 in Taurus, none show transition disks. This suggests that the difference between the ECA and Taurus is not due to the different distribution of masses in the two associations. Whether this remarkable difference results from a slowing of disk transitions with increasing age or some other, possibly environmental, factor is not clear.

We now estimate the size and gas surface density in the inner disk holes. To estimate the sizes of the inner disk holes, we scale a model for TW Hya, which has a significant dust excess in the IRAC [8] band but little at shorter wavelengths, and has been modeled as having a disk "wall" at 4 AU with a relatively evacuated region at smaller radii (Calvet et al. 2002). TW Hya has a luminosity of about 0.25 $L_\odot$ (Webb et al. 1999), and the ECA disk systems have luminosities of ∼0.1–0.02 $L_\odot$; so our observations suggest evacuated regions of ∼2–0.4 AU in size.

The presence of accretion indicates that the inner disk hole does contain gas, and the amount of gas in the inner disk hole can be estimated from the accretion rates inferred from the Hα velocity widths (Fig. 4). Lawson et al. (2004) estimated mass accretion rates of $\sim 10^{-10.4}$ $M_\odot$ yr^{-1} for stars 5, 9, and 11 and an accretion rate of $\sim 10^{-9}$ $M_\odot$ yr^{-1} for star 15. The lowest rates are well below those observed in Taurus and other young regions (see summary in Calvet et al. 2005a). This is not surprising, given the advanced age of the ECA and the observational indications of decreasing accretion rates with age, although the estimated ECA accretion rates appear to fall a bit below a simple model of a viscously evolving disk (Calvet et al. 2005a).

Extrapolation of the steady accretion disk models by D'Alessio et al. (1999) to somewhat lower stellar luminosities and masses suggests that at accretion rates of $\sim 10^{-10}$ $M_\odot$ yr^{-1}, the disk gas surface density would be of order 1 g cm^{-2} at 1 AU and scale roughly as R^{-1} for a typical viscosity parameter of $\alpha = 10^{-2}$. Taking a dust opacity (per gram of gas) for interstellar medium (ISM) dust in the IRAC 4.5 μm band of order 9 cm^2 g^{-1} (derived from Indebetouw et al. 2005), a vertical optical depth of unity requires a surface density of ∼0.1 g cm^{-2}. For ISM dust, the accretion rates imply a 4.5 μm optical depth of order 10 at 1 AU and about 100 at 0.1 AU. To make the disk optically thin within the 0.1–1 AU range, as required by the observations of the ECA transition disks, the opacity would have to be reduced by $\sim 10^1$–10^2 from the ISM case. While there are substantial uncertainties in several parameters, this result suggests that the dust opacity per unit gas mass in the ECA transition disks has declined substantially from the initial value. Thus, it appears likely that the ECA has an unusually large proportion of stars in which the inner disks have had substantial dust growth, reducing mid-infrared opacities to low values while still maintaining a significant flow of accreting gas at radii $\lesssim 1$ AU. These data are further evidence that in at least some disks, the primordial dust grains in the inner disk are collected into larger dust grains and planetesimals in the first 10 Myr of stellar evolution, while gas is still present in the disk.

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REFERENCES

Allen, L. E., et al. 2004, ApJS, 154, 363
Calvet, N., Briceño, C., Hernandez, J., Hoyer, S., Hartmann, L., Sicilia-Augilar, A., Megeath, S. T., & D'Alessio, P. 2005a, AJ, 129, 935
Calvet, N., D'Alessio, P., Hartmann, L., Wilner, D., Walsh, A., & Sitko, M. 2002, ApJ, 568, 1008
Calvet, N., et al. 2005b, ApJ, submitted
D'Alessio, P., Calvet, N., Hartmann, L., Lizano, S., & Cantó, J. 1999, ApJ, 527, 893
D'Alessio, P., et al. 2005, ApJ, 621, 461
Fazio, G. G., et al. 2004, ApJS, 154, 10
Forrest, W. J., et al. 2004, ApJS, 154, 443
Grady, C. A., Sitko, M. L., Russell, R. W., Lynch, D. K., Hanner, M. S., Perez, M. R., Bjorkman, K. S., & de Winter, D. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 613
Haisch, K. E., Jayawardhana, R., & Alves, J. 2005, ApJ, 627, L57
Haisch, K. E., 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, in press
Hauschildt, P H., Allard, F., & Baron, E. 1999, ApJ, 512, 377
Indebetouw, R., et al. 2005, ApJ, 619, 931
Jayawardhana, R., Hartmann, L., Fazio, G., Fisher, R. S., Telesco, C. M., & Piña, R. K. 1999, ApJ, 521, L129
Lada, C. J., Muench, A. A., Haisch, K. E., Jr, Lada, E. A., Alves, J. F., Tollestrup, E. V., & Willner, S. P. 2000, AJ, 120, 3162
Landsman, W. B. 1993, in ASP Conf. Ser. 52, Astronomical Data Analysis Software and Systems II, ed. R. J. Hanisch, R. J. V. Brissenden, & Jeannette Barnes (San Francisco: ASP), 246
Lawson, W. A., Crause, L. A., Mamajek, E. E., & Feigelson, E. D. 2001, MNRAS, 321, 57
———. 2002, MNRAS, 329, L29
Lawson, W. A., Lyo, A.-R., & Muzerolle, J. 2004, MNRAS, 351, L39
Luhman, K. L., & Steeghs, D. 2004, ApJ, 609, 917
Lyo, A.-R., Lawson, W. A., Feigelson, E. D., & Crause, L. A. 2004, MNRAS, 347, 246
Lyo, A.-R., Lawson, W. A., Mamajek, E. E., Feigelson, E. D., Sung, E.-C., & Crause, L. A. 2003, MNRAS, 338, 616
Mamajek, E., Lawson, W. A., & Feigelson, E. D. 1999, ApJ, 516, L77
Reach, W. T., et al. 2005, PASP, in press
Rieke, G. H., et al. 2005, ApJ, 620, 1010
Sicilia-Aguilar, A., et al. 2005, ApJ, submitted
Song, I., Zuckerman, B., & Bessell, M. S. 2004, ApJ, 600, 1016
Uchida, K. I., et al. 2004, ApJS, 154, 439
Webb, R. A., Zuckermann, B., Platais, I., Patience, J., White, R. J., Schwartz, M. J., & McCarthy, C. 1999, ApJ, 512, L63
White, R. J., & Basri, G. 2003, ApJ, 582, 1109