CONSTRAINTS ON INNER DISK EVOLUTION TIMESCALES: A DISK CENSUS OF THE \( \eta \) CHAMELEONIS YOUNG CLUSTER

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ABSTRACT

We present new \( L' \)-band (3.8 \( \mu \)m) observations of stars in the nearly (~97 pc) young (~6 Myr) compact cluster around \( \eta \) Chamaeleontis, obtained with the European Southern Observatory’s Very Large Telescope in Paranal, Chile. Our data, combined with \( J, H, K \), photometry from the Two Micron All Sky Survey, reveal that only two of the 12 members surveyed harbor \( L' \)-band excesses consistent with optically thick inner disks; both are also likely accretors. Intriguingly, two other stars with possible evidence of ongoing accretion, albeit at very low rates, do not show significant infrared excess: this may imply substantial grain growth and/or partial clearing of the inner disk region, as expected in planet formation scenarios. Our findings suggest that \( \eta \) Cha stars are in an epoch when disks are rapidly evolving, perhaps due to processes related to planet building, and provide further constraints on inner disk lifetimes.

Subject headings: circumstellar matter — infrared: stars — open clusters and associations: general — planetary systems — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

There is growing evidence that circumstellar disks undergo substantial evolution—development of inner disk cavities, grain growth, dust settling, and decrease in accretion rates—within the first several million years of a star’s life (e.g., Haisch et al. 2001b; Jayawardhana et al. 2001; Hogerheijde et al. 2003). Nearby young stellar clusters constitute superb laboratories for detailed studies of the physical processes and the timescales of such disk evolution and planet formation. In particular, the 8 Myr old TW Hydrae association has proven to be a treasure trove: its members exhibit a wide variety of behavior, particularly, the 8 Myr old TW Hydrae association has proven to be a treasure trove: its members exhibit a wide variety of behavior, including a wide variety of behavior, including a wide variety of behavior, including a wide variety of behavior, including a wide variety of behavior, including a wide variety of behavior, including a wide variety of behavior, including a wide variety of behavior, including a wide variety of behavior. The recently identified \( \eta \) Chamaeleontis cluster (Mamajek et al. 1999) provides another superb sample in this interesting age range and offers the prospects of finding other disks “in transition.” The 18 known primaries of this group, first identified by means of their X-ray emission and later confirmed with optical spectroscopy, include three early-type stars and 15 late-type (K5–M5) stars (Lyo et al. 2004; Luhman & Steeghs 2004). Hipparcos measurements place the brighter stars at a distance of ~97 pc. The late-type \( H\alpha \) emission-line stars have the properties of pre–main-sequence T Tauri stars such as large Li abundance, high magnetic activity, and, assuming they are also at ~97 pc, bolometric luminosities 1–2 mag above the main sequence. Recently, Luhman & Steeghs (2004) have derived an age of 6±2 Myr for the cluster, which is consistent with age estimates by Mamajek et al. (1999) and Lawson & Feigelson (2001) within the uncertainties.

Here we report a disk census of the \( \eta \) Chamaeleontis cluster in the \( L' \) band, derive the inner disk fraction, compare it to other clusters and young associations, and discuss constraints on inner disk evolution timescales.

2. OBSERVATIONS

We obtained \( L' \)-band (3.8 \( \mu \)m) images in service mode for 12 known late-type members of the \( \eta \) Chamaeleontis cluster using the Infrared Spectrograph and Array Camera (ISAAC; Moorwood 1997) at the Very Large Telescope (VLT) UT1 during the period 2004 March 4–6. The observations were carried out in the long-wavelength LW4 mode of ISAAC, which is equipped with a 1024 × 1024 InSb ALADDIN array from the Santa Barbara Research Center. This mode yields a pixel scale of 0.071 pixel\(^{-1}\) with a field of view of 73 arcsec\(^2\). The data were acquired in the chop-nod mode with 15º offsets in order to cancel out the variable thermal background. Each observation consisted of two sets of nine co-added frames with integration times of 0.11 s. The total integration time for each star was 1.98 s. The \( J, H, \) and \( K_s \) (1.25, 1.65, and 2.1 \( \mu \)m) observations of each cluster member were taken from the Two Micron All Sky Survey (2MASS) data archive.\(^1\)

All observations were reduced using the standard ISAAC reduction pipeline for long-wavelength imaging data. Flat fields for each night were obtained by subtracting three images taken at 1.0, 2.0, and 2.4 air masses. These flat fields were normalized and divided into the sky-subtracted object frames to produce the final images of each object. The standard star HD106965 was observed on the same nights and through the same range of air masses as the target stars. Zero points and extinction coefficients were established for each night. The photometric accuracy of our observations is typically ±0.05 mag.

\(^1\) See http://www.ipac.caltech.edu/2mass/.
TABLE 1

| Star    | $J$  | $H$  | $K_s$ | $L'$ | $(J - H)$ | $(H - K_s)$ | $(K_s - L')$ | $(H - K_s)_b$ | $(K_s - L')_b$ | Sp.  |
|---------|------|------|-------|------|-----------|-------------|--------------|--------------|--------------|-------|
| RECX 1  | 8.15 | 7.50 | 7.37  | 7.18 | 0.65      | 0.13        | 0.19         | 0.02         | 0.07         | K6    |
| RECX 3  | 10.34| 9.65 | 9.45  | 9.31 | 0.69      | 0.20        | 0.14         | -0.06       | -0.19        | M3.25 |
| RECX 4  | 9.52 | 8.78 | 8.65  | 8.45 | 0.74      | 0.13        | 0.20         | -0.08       | -0.03        | M1.75 |
| RECX 5  | 10.77| 10.10| 9.89  | 9.57 | 0.67      | 0.21        | 0.32         | -0.07       | -0.05        | M4    |
| RECX 6  | 10.22| 9.58 | 9.32  | 9.13 | 0.64      | 0.26        | 0.19         | 0.01         | -0.13        | M3    |
| RECX 7  | 8.41 | 7.76 | 7.67  | 7.45 | 0.65      | 0.09        | 0.22         | -0.03        | 0.10         | K6    |
| RECX 9  | 10.26| 9.67 | 9.37  | 8.98 | 0.59      | 0.30        | 0.39         | 0.00         | -0.01        | M4.5  |
| RECX 10 | 9.63 | 8.92 | 8.76  | 8.48 | 0.71      | 0.16        | 0.28         | -0.04        | 0.07         | M1    |
| RECX 11 | 8.73 | 8.04 | 7.69  | 7.03 | 0.69      | 0.35        | 0.66         | 0.24         | 0.55         | K5.5  |
| RECX 12 | 9.31 | 8.68 | 8.44  | 8.05 | 0.63      | 0.24        | 0.39         | -0.01        | 0.06         | M3.25 |
| ECHA J0841.5−7853 | 11.81 | 11.24 | 11.01 | 10.63 | 0.57 | 0.23 | 0.38 | -0.08 | -0.02 | M4.75 |
| ECHA J0843.3−7905 | 10.50 | 9.83 | 9.46  | 8.14 | 0.67      | 0.37        | 1.32         | 0.12         | 0.99         | M3.25 |

* $JHK_s$ magnitudes are taken from the 2MASS database and transformed to the CIT photometric system.

* Intrinsic infrared excess based on 2MASS photometry and spectral type.

* Spectral types taken from Luhman & Steeghs (2004).

### 3. RESULTS

In Table 1 we list the $JHK_sL'$ magnitudes and $J - H$, $H - K_s$, and $K_s - L'$ colors for all members of the η Chamaeleontis cluster. The $JHK_s$ magnitudes and colors have been transformed to the CIT photometric system using 2MASS to CIT transformation equations (see footnote 1). The magnitudes were calibrated in the CIT system. Since all of the η Chamaeleontis members have known spectral types, we have determined their intrinsic photospheric $H - K_s$ and $K_s - L'$ colors, and hence the excesses above the photospheric emission; these are also included in Table 1. In Figure 1 we present the $JHK_sL'$ color-color diagram for the η Chamaeleontis members. Late-type stars are identified by their RECX (ROSAT η Chamaeleon X-ray) number or ECHA (η Cha) number. In the figure, we plot the locus of points corresponding to the unreddened main sequence (which encompasses the range of spectral types of the cluster members) as a solid line and the locus of positions of giant stars as a heavy dashed line. The intrinsic colors of giant and dwarf stars were taken from Bessell & Brett (1988) and transformed into the CIT system. The two leftmost dashed lines define the reddening band for main-sequence stars and are parallel to the reddening vector. The classical T Tauri star (CTTS) locus is plotted as a dot-dashed line (Meyer et al. 1997). The reddening law of Cohen et al. (1981), derived in the CIT system and having a slope of 2.750, has been adopted.

A very small fraction of the sources falls outside and to the right of the reddening lines in the infrared excess region of the $JHK_sL'$ color-color diagram. Indeed, 2/12 (17% ± 11%) of the sources in the η Chamaeleontis cluster have colors exhibiting $JHK_sL'$ infrared excess emission indicative of circumstellar disks. This low fraction is supported by the intrinsic excesses for these stars calculated in Table 1. The quoted uncertainty represents the statistical standard error (i.e., $\sqrt{\text{DF}^2 + \text{DF}^2}$; $\text{DF}$ = disk fraction) in our derived excess/disk fraction. We note that this excess fraction depends on the adopted reddening law and, to a lesser extent, on the photometric system used to plot the positions of the main-sequence stars and the reddening bands. We have calculated the $JHK_sL'$ infrared excess fraction for two other reddening laws obtained in different photometric systems (Koornneef 1983; Rieke & Lebofsky 1985) and find excess fractions identical to that derived above. This is perhaps not surprising given the absence of measured extinctions among the cluster members (Luhman & Steeghs 2004). Additionally, we have considered the effects of binarity on the derived excess fractions, since a number of cluster members are known (RECX 1, RECX 7, and RECX 9; Köhler & Petr-Gotzens 2002; Lyo et al. 2003, 2004) or suspected (RECX 12; Köhler & Petr-Gotzens 2002; Lawson et al. 2001; Haich et al. 2005) to be binary systems. Examining three different sets of pre–main-sequence models (Baraffe et al. 1998; Palla & Staehler 1999; Seiss et al. 2000), we calculate that the presence of a binary will change our photometry by <0.04 mag, within our measured photometric error. Therefore, we conclude that binarity will not affect our calculated excess (disk) fraction.

### 4. DISCUSSION

The disk fraction we derive for the η Chamaeleontis cluster is significantly smaller than that (60% ± 13%) found by Lyo et al. (2003). Figure 2 shows the $JHK_sL'$ color-color diagram of Lyo et al. after transforming their $JHK_sL'$ photometry to the CIT system.
The large difference in the derived disk fraction between our study and that of Lyo et al. is only apparent when the $L$-band data are included in the analysis. In Figure 3a we plot the $JHK$ color-color diagram using the 2MASS photometry adopted in our study, and in Figure 3b we plot the $JHK$ photometry of Lyo et al. As one can see, none of the $\eta$ Chamaeleontis members in the present survey show $JHK$ excesses using the 2MASS colors, while $2/14$ ($14\% \pm 9\%$) show $JHK$ excesses in the Lyo et al. survey. These results are similar to those obtained from examining the intrinsic $H - K$ excesses for each member (Table 1) and from published surveys of other clusters with a similar age (Haisch et al. 2001b). We note that, in many cases, the $J$, $H$, and/or $K$-band magnitudes observed by Lyo et al. are $\sim$0.05–0.20 mag fainter than the photometry in our survey, even after transforming all photometry to the same photometric system. Similarly, the Lyo et al. $L$-band magnitudes are typically 0.10–0.30 mag brighter than our $L'$ data. Thus, the $K - L$ colors in the Lyo et al. study are typically 0.15–0.50 mag redder than those derived in our study, thereby leading to a higher calculated $JHKL$ disk fraction.

There are six additional known members of the $\eta$ Chamaeleontis cluster that are not covered in our survey. Three of these ($\eta$ Cha, RS Cha, and HD 75505) were observed at $JHKL$ by Lyo et al. (2004) and were not found to possess infrared excesses. The remaining three cluster members have no published $L$-band photometry. They do not exhibit infrared excess emission in a photometric system. Late-type stars are identified by their RECX number or ECHA number, and early-type stars are identified by name.

$JHK$ color-color diagram; however, future $L$-band observations of these stars may show that they are indeed surrounded by disks. If so, this would still imply an upper limit on the disk fraction in the $\eta$ Chamaeleontis cluster of $28\% \pm 13\%$.

Based on H$\alpha$ emission-line profiles in high-resolution optical spectra, Lawson et al. (2004) claimed that four of the $\eta$ Cha stars...
are accreting from circumstellar disks. One of them—ECHA J0843.3−7905—has an Hα equivalent width of ≈90 Å, characteristic of classical T Tauri stars, and also exhibits a clear L′ excess in our data. According to these authors, the other L′ excess star in our census, RECX 11, may also be accreting, given its Hα profile, although the equivalent width is only 3 Å. We note that it is difficult to distinguish between weak accretion and stellar chromospheric activity, sometimes even with high-resolution spectra (e.g., Walter & Barry 1991; Jayawardhana et al. 2003b). Intriguingly, two other stars—RECX 5 and 9—that Lawson et al. claim to be accretors based on their Hα profiles, albeit at very low rates, do not harbor L′ excesses consistent with optically thick disks in our survey. This could be the result of substantial grain growth and/or partial clearing of the inner disk region, as expected in theories of planet formation (e.g., Bryden et al. 1999). A similar situation has been found for two stars and one brown dwarf in the 8 Myr old TW Hydrae association. TW Hya itself and Hen 3-600A appear to be accreting at low and one brown dwarf in the 8 Myr old TW Hydrae association.

The L′-band emission from circumstellar disks is produced very close (≤0.1 AU) to the stellar surface. However, some millimeter studies of stars in young clusters suggest that the rapid decline in the circumstellar disk fraction with cluster age observed in the inner disk regions may also apply to the outer disk regions (>1 AU) where most planet formation is likely to occur (Haisch et al. 2001a; Carpenter 2002; Lada & Haisch 2005). This places important constraints on the timescale allowed for building gas giant planets around such stars.

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