IDENTIFICATION OF NEW CANDIDATE HERBIG Ae/Be STARS IN EXTREMELY YOUNG GALACTIC CLUSTERS: M8, M16, M17, M42, NGC 2264

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ABSTRACT The youngest known optically visible pre-main sequence stars are the Herbig Ae/Be stars. These objects appear to represent a phase in the pre-main sequence lifetime of intermediate mass stars during which they are surrounded by circumstellar accretion disks. The census of Herbig Ae/Be stars amounts to only some 70 candidate objects scattered throughout the plane of the galaxy. No systematic search, which would enable the identification of a complete sample in a single young cluster, has yet been undertaken. Such an unbiased sample is crucial for establishing the properties of both the stars and the circumstellar accretion disks which are thought to surround them. *Observational determination of the full range of disk parameters (e.g. size, mass, lifetime, accretion rate) is a necessary precursor to understanding the process of disk accretion and, in turn, of high mass star formation.* We examine five young open clusters in order to search for disks around intermediate and high mass stars which are still approaching or which have just reached the main sequence. Recent infrared studies of these clusters reveal that the fraction of early type stars surrounded by disks is only about 10% in clusters of ages $\tau \lesssim 3 \times 10^6$ yr. This suggests that the survival times of disks around $M \gtrsim 5\mathcal{M}_\odot$ stars in young open clusters are shorter than a few 10^5 years, and are thus much shorter than the pre-main sequence lifetime of their central stars.

CHARACTERISTICS OF DISKS SURROUNDING HERBIG Ae/Be STARS

In order to identify new candidate Herbig Ae/Be stars, we search for objects whose near-infrared spectral energy distributions (SEDs) are morphologically similar to those of the known Herbig Ae/Be stars. Figure 1 shows the reddening-corrected $0.36\,\mu$m- $100\,\mu$m SEDs of one Herbig Ae/Be star and, for comparison, one T-Tauri star. The large infrared excesses can be modeled

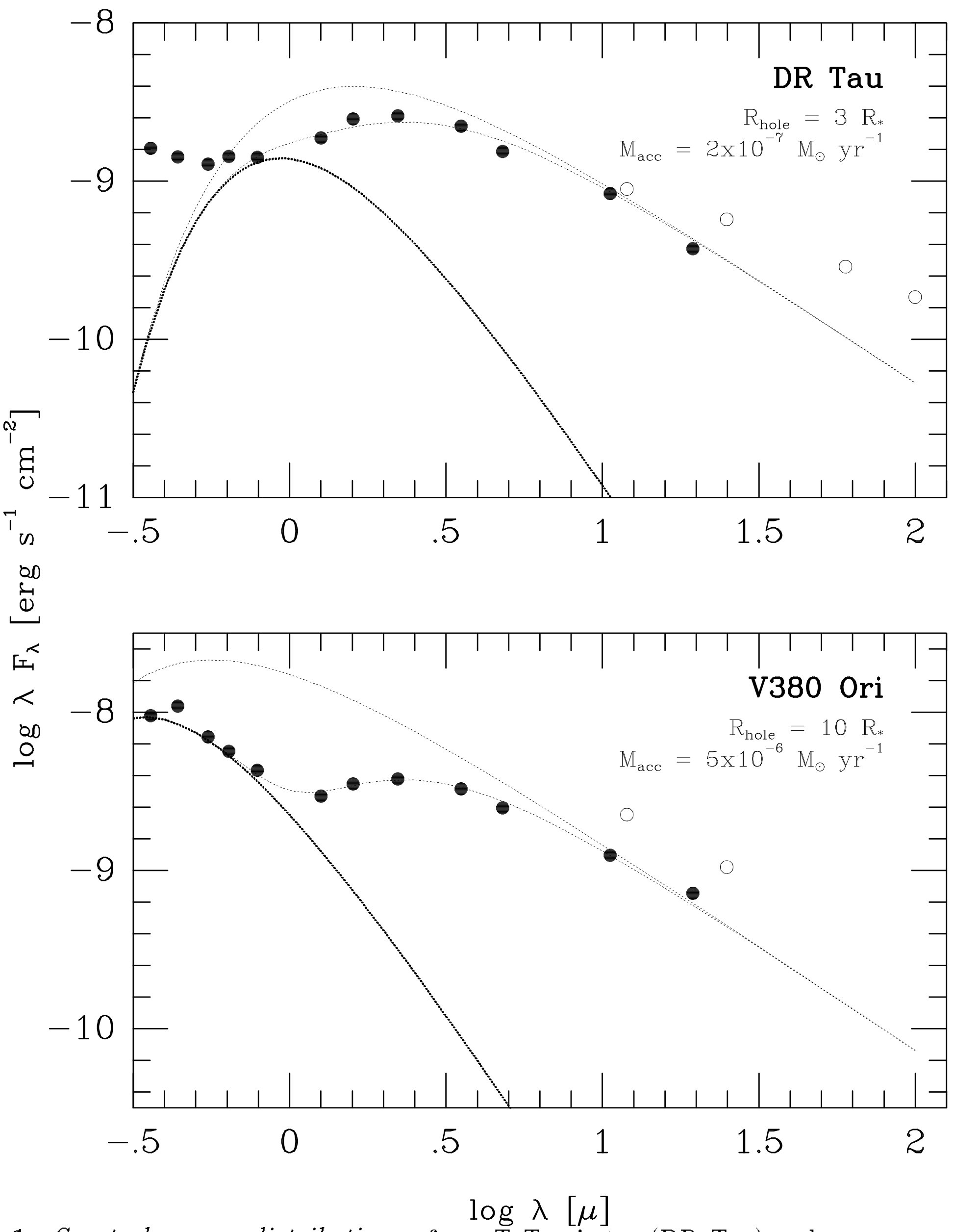


Figure 1. *Spectral energy distributions.* for a T Tauri star (DR Tau) and a Herbig Ae/Be star (V380 Ori). Solid circles are ground-based observations; open circles represent large beam IRAS points. The solid line is the blackbody SED of an appropriate standard main sequence star. Superposed are the spectral energy distributions predicted for (1) a flat, optically thick accretion disk which extends inward to the stellar surface (top dotted curve), and (2) a flat, optically thick accretion disk which extends inward to only $3R_*$ (DR Tau; lower dotted curve) and $10R_*$ (V380 Ori; lower dotted curve); interior to these distances, the disk is assumed to be optically thin. These inner "holes" produce inflections in the near-infrared spectral energy distributions as a direct result of the absence of warm emitting material near the star.

by a central young star surrounded by a dusty, optically thick circumstellar accretion disk with a characteristic infrared spectral slope $\lambda F_\lambda \sim \lambda^{-4/3}$. Our "best fit" disk models include the effects of both disk accretion and inner disk optically thin regions or "holes."

For the sample of Herbig Ae/Be stars studied by Hillenbrand *et al.* (1992), the ranges of disk characteristics are as follows: (1) masses for the disks have upper limits ranging from $0.01 < M_{disk}/M_\odot < 6$; (2) outer disk radii have lower limits ranging from $15 < R_{disk}/AU < 175$; (3) inner optically thin disk regions have sizes $3 < R_{hole}/R_* < 25$; (4) disk mass accretion rates, as diagnosed from the magnitude of the infrared excess, range from $6 \times 10^{-7} < \dot{M}_{acc} < 8 \times 10^{-5}\, M_\odot$ yr^{-1} ; and (5) disk survival times as optically thick structures are less than 1 Myr.

With the positive identification of disks around young intermediate and high mass stars, the presence of circumstellar accretion disks has now been inferred around pre-main sequence stars of all masses ranging from $0.1 - 20\mathcal{M}_\odot$. The disks surrounding Herbig Ae/Be stars appear to be more massive, larger in size, more rapidly accreting, and have shorter lifetimes (*calculated* as $M_*/\dot{M}_{acc}$) than the disks surrounding lower mass T Tauri stars. Our next step is to place *empirical* limits on the disk lifetimes around stars of different mass. This requires identifying the fraction of stars surrounded by optically thick accretion disks as a function of mass and age. Study of a complete, unbiased sample of young stars is necessary, and is most comprehensivly done through imaging surveys of extremely young clusters. Only in this way can the full range of disk properties as a function of stellar mass and age be ascertained.

THE $(J-H)-(H-K)$ COLOR-COLOR DIAGRAM

The identification of young intermediate and high mass stars surrounded by accretion disks (analogs of Herbig Ae/Be stars), and those which are no longer surrounded by disks, can be effected from near-infrared photometry. We employ the $(J-H)-(H-K)$ color-color diagram as a diagnostic in order to statistically study the disk populations of extremely young open clusters. All Herbig Ae/Be stars and many classical T Tauri stars lie outside the region of this diagram populated by normal dwarf and giant stars. Figure 2 shows the location of a sample of Herbig Ae/Be stars and, for comparison, the Taurus sample of classical T Tauri stars in the $(J-H)-(H-K)$ color-color diagram.

In order for an object to lie to the right of the reddened main sequence in the $(J-H)-(H-K)$ diagram, a high $\dot{M}_{acc}$ accretion disk seems to be required. Additionally, as is seen in the SEDs of Herbig Ae/Be stars, the presence of an inner disk hole moves objects even further away from the standard color-color relationships (also see Lada & Adams, 1992). All Herbig Ae/Be stars and some T Tauri stars can be distinguished from normal stars in the $(J-H)-(H-K)$ plane – even if they are heavily reddened. Thus, locating

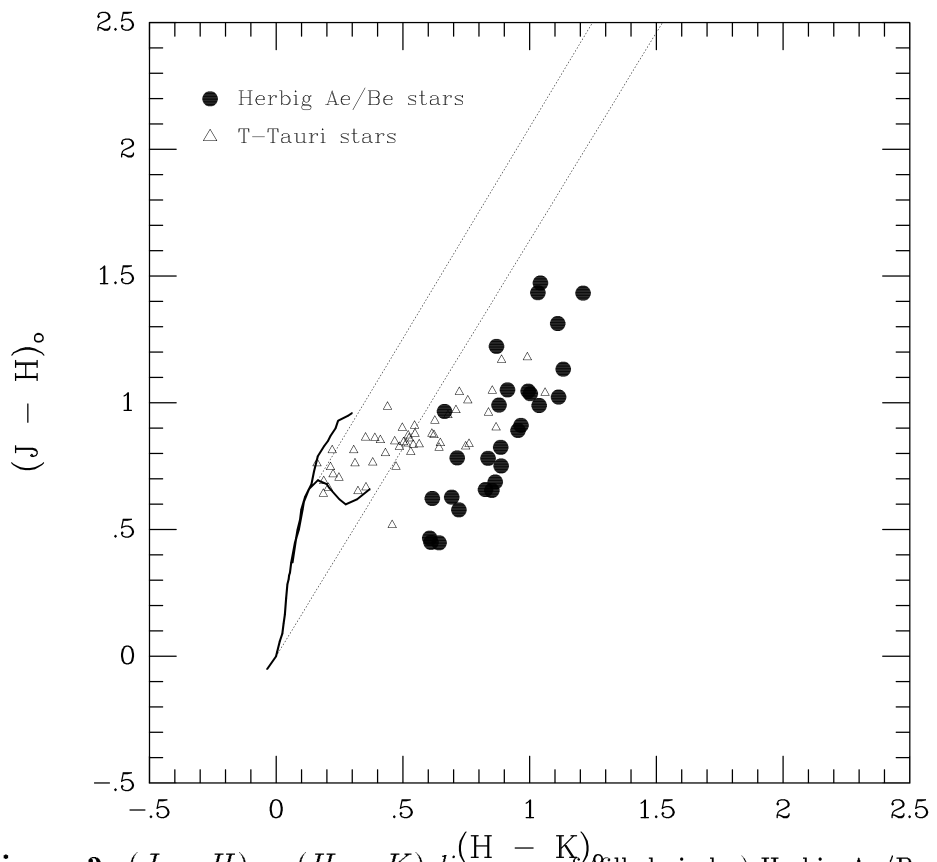


Figure 2. $(J - H) - (H - K)$ *diagram.* of (filled circles) Herbig Ae/Be stars with SEDs similar to that illustrated in Figure 1 and (triangles) classical T Tauri stars in Taurus-Auriga. The solid lines are the standard relations for unreddened luminosity class V and class III stars (Bessell & Brett, 1988); the dotted lines indicate the effects of normal reddening from the main sequence. Note that the Herbig Ae/Be stars lie well to the right of the domain occupied by normal reddened stars, and reflect the presence of both an inner disk "hole" and disk accretion. Most of the T Tauri stars lie within the region occupied by normal reddened stars. The exceptions are those like DR Tau (see Figure 1) which are believed to have unusually high accretion rates.

stars in the $(J - H) - (H - K)$ diagram can provide the means for rapid classification of optically obscured, luminous pre-main sequence stars with accretion disks and inner disk holes discovered, for example, in the course of infrared imaging surveys of star-forming regions.

Classical Be stars, which are found to populate young open clusters, also lie slightly to the right of the reddened main sequence in the $(J - H) - (H - K)$ diagram. However, their small (H-K) excesses relative to their (J-H) colors arise due to free-free emission in a *gaseous* circumstellar disk or shell.

INFRARED SURVEYS OF YOUNG GALACTIC CLUSTERS

We are in the process of diagnosing the fraction of intermediate and high mass stars with disks as a function of stellar mass and age. To search for candidate Herbig Ae/Be systems and establish the disk lifetimes, we have undertaken a study of the young clusters M8, M16, M17, M42, and NGC 2264. Intermediate mass pre-main sequence populations appear in these clusters with ages of only 1×10^5 years. Thus they are prime arenas in which to search for the presence of circumstellar disks associated with the formation of high mass stars - even if the disk lifetimes are extremely short. As a first step in this study, in order to identify candidate stars surrounded by disks, we have obtained JHK photometry using the SQIID camera and the OTTO InSb detector at the KPNO 1.3m telescope.

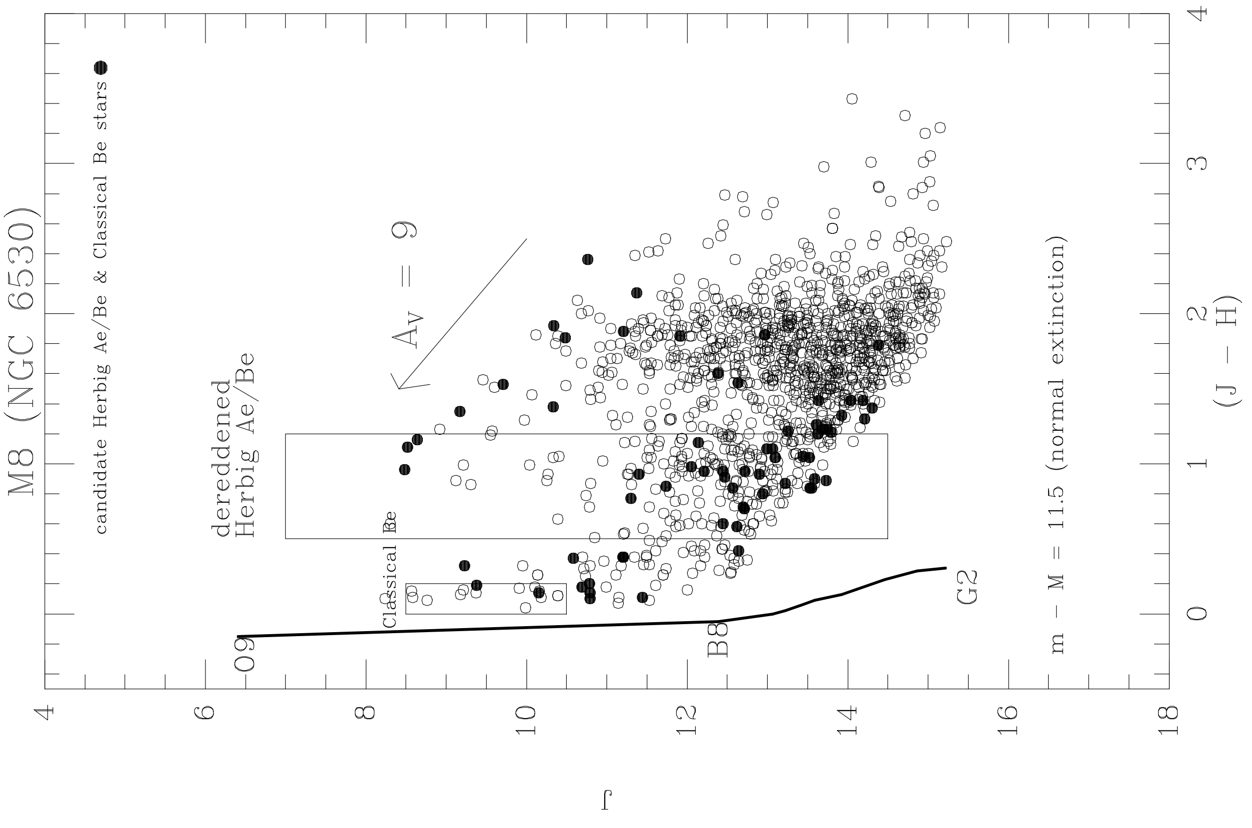
SQIID Studies of M8, M16, and M17 (d = 1.5 - 3.2 kpc)
The estimated completeness limit in a 180 second SQIID exposure is to magnitude 15 at J (15σ dectection) which, assuming the flux at J to be photospheric in origin, corresponds roughly to a spectral type of B8 and a mass of $5\mathcal{M}_\odot$ at the cluster distances. The sample is unbiased and includes all detected objects within a central $15' \times 15'$ field for M8 and M16, and within a central $5'.5 \times 5'.5$ field for M17.

The $(J-H)-(H-K)$ diagrams of these young clusters (see Figures 3,4,5) show the presence of a significant number of objects lying to the right of the region populated by normal reddened stars. We suggest that these objects are either (1) candidate Herbig Ae/Be stars - intermediate mass pre-main sequence stars surrounded by accretion disks or (2) candidate classical Be stars - early B stars of unknown evolutionary state surrounded by gaseous circumstellar disks.

Lower limits to the fraction of objects considered to be candidate Herbig Ae/Be stars or candidate classical Be stars are as follows:

M8 : 5% in a cluster whose age estimates range from $2-5$ Myr.
M16 : 13% in a cluster whose age estimates range from $3-10$ Myr.
M17 : 13% in a cluster whose age estimate is 1 Myr.

The J – (J-H) diagrams of these clusters (see Figures 3,4,5) show that the fraction of objects which are possibly surrounded by disks increases with decreasing J luminosity. Assuming that the flux at J is dominated by photospheric emission, stars of lower J luminosity should have lower mass. Hence, it appears that the disks may survive longer around stars of lower mass. If so, then the disks surrounding high mass stars must evolve on shorter timescales than those surrounding low mass stars. This result is consistent with the finding in Hillenbrand *et al.* (1992) that disk accretion rates are higher for disks around stars of higher mass ($\dot{M}_{acc} \sim M_*^{2.2}$), and that disk accretion times ($M_*/\dot{M}_{acc}$) are shorter for disks around stars of higher mass.



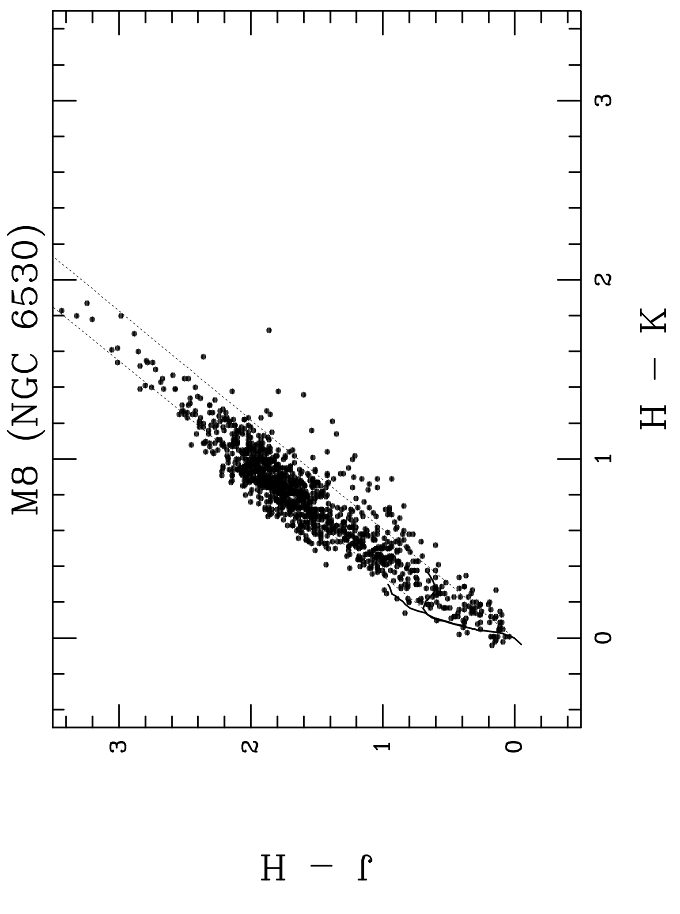


Figure 3. *Infrared Color-Color and Color-Magnitude Diagrams for stars in the young cluster M8 (NGC 6530).*. All objects have J $<$ 15 and are located within the central 8$'$ of the cluster. The photometry is from SQIID observations obtained at the KPNO 1.3m telescope; color errors are all less than $0^m.1$. *Upper panel:* The $(J-H)-(H-K)$ standard relations and reddening vectors are the same as in Figure 2. Note the presence of a modest number (5%) of stars which lie to the right of the region occupied by normal reddened stars. These objects cover the domain occupied by ordinary Be stars and Herbig Ae/Be stars, and we regard them as candidate members of these classes. *Right panel:* The heavy solid line indicates the zero-age main sequence in the J - (J-H) diagram, and the vector appropriate to normal interstellar reddening is shown. Also indicated are the domains of the diagram occupied by (1) known members of the Herbig Ae/Be class with IR spectral energy distributions similar to those expected for stars surrounded by accretion disks with inner disk holes (see Figure 1); and (2) classical Be stars whose IR excesses appear to arise from free-free emission in a gaseous circumstellar disk or envelope. Solid circles are those stars which fall outside the normal $(J-H)-(H-K)$ relationship for reddened main sequence stars. The behavior of these diagrams at $(J-H) > 1.6$ may indicate that a large number of stars background to the cluster are included in our sample, thus increasing the fraction of cluster members with circumstellar disks.

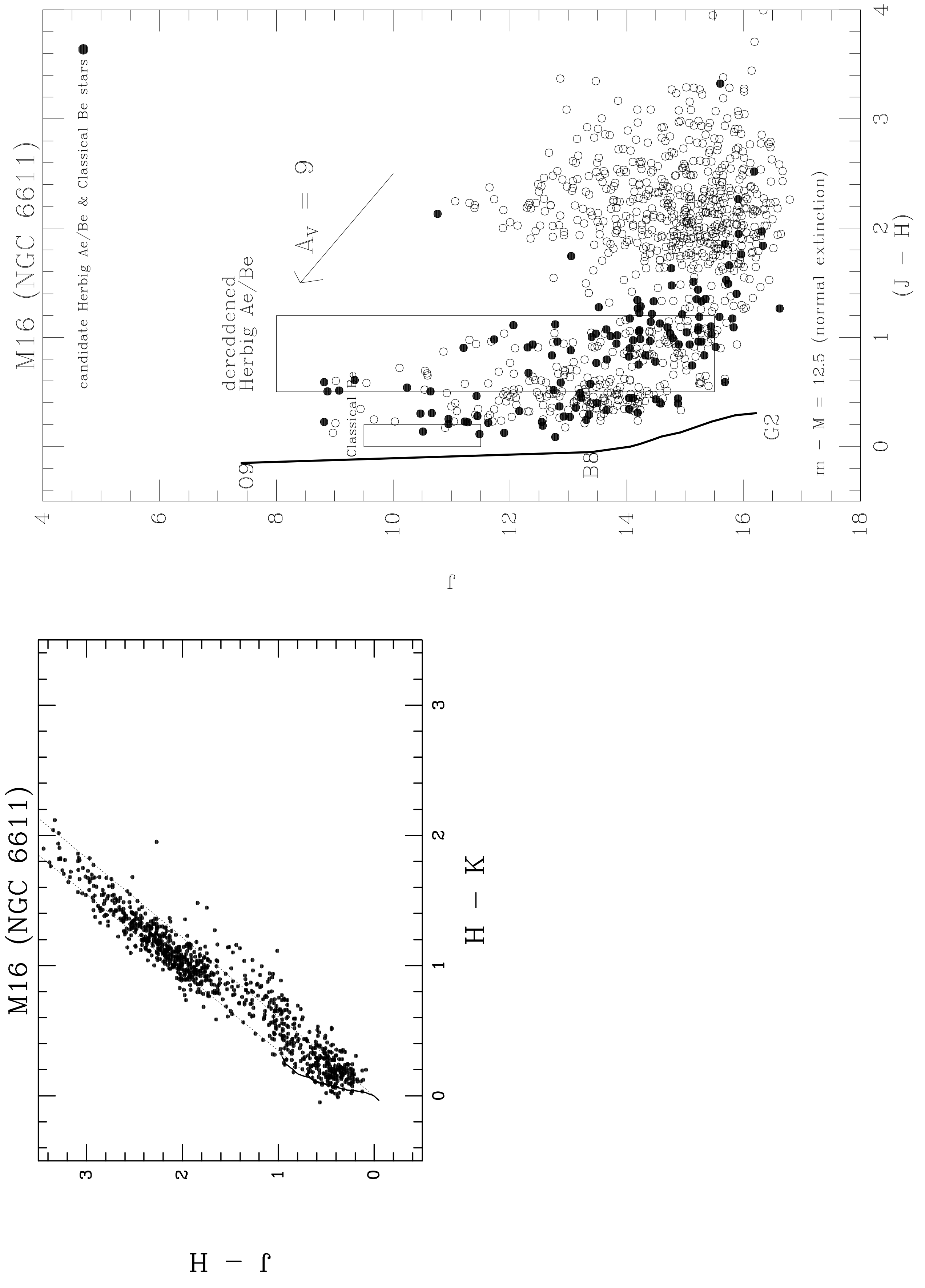


Figure 4. *Infrared Color-Color and Color-Magnitude Diagrams for stars in the young cluster M16 (NGC 6611).*. All objects have J $<$ 16 and are located within the central $8'$ of the cluster. Otherwise, the Figure is the same as Figure 3. Approximately 13% of the sample lies to the right of the region occupied by normal reddened stars in the $(J-H)-(H-K)$ diagram.

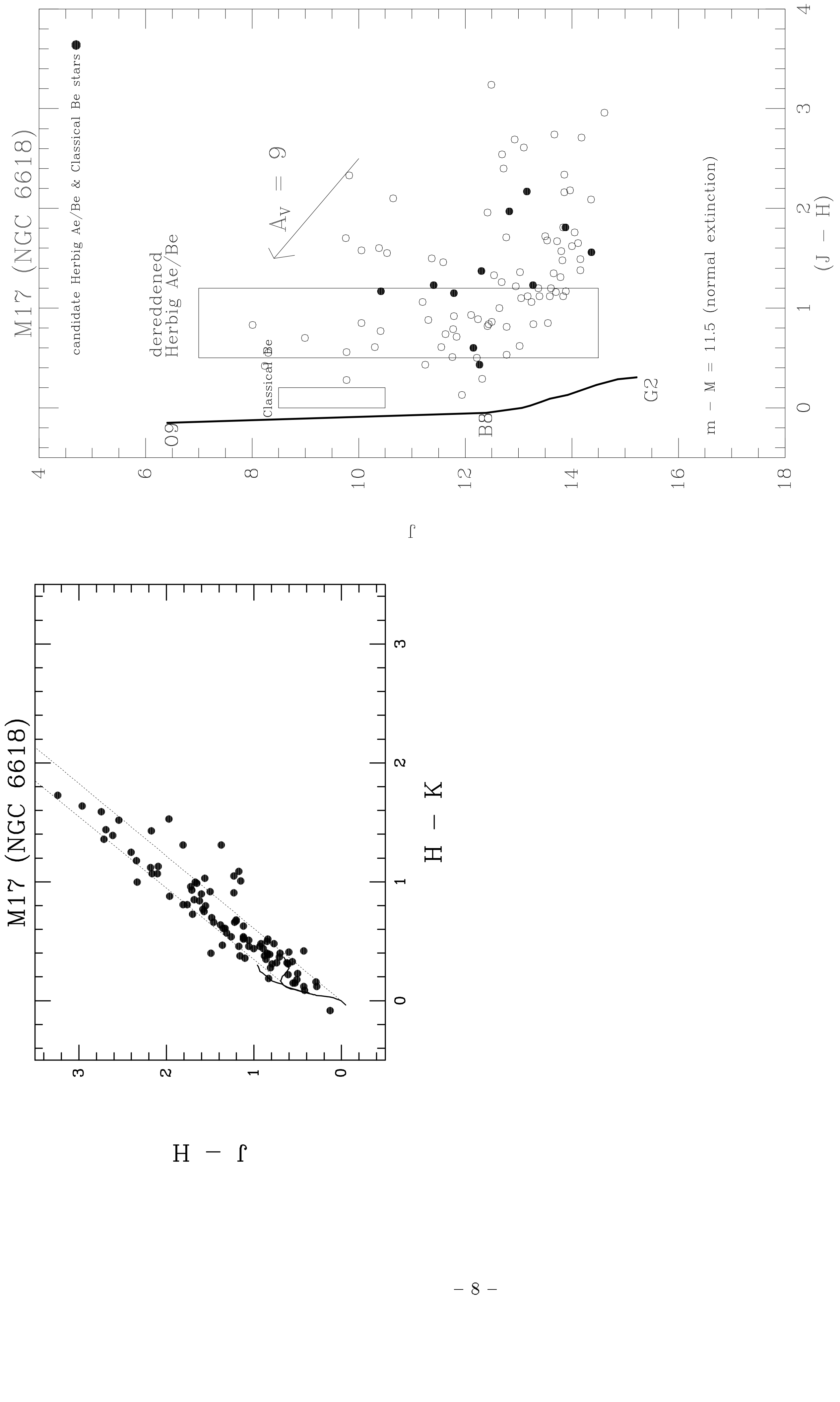


Figure 5. *Infrared Color-Color and Color-Magnitude Diagrams for stars in the young cluster M17 (NGC 6618).*. All objects have J $<$ 14 and are located within the central $3'$ of the cluster. Otherwise, the Figure is the same as Figure 3. Approximately 13% of the sample lies to the right of the region occupied by normal reddened stars in the $(J-H)-(H-K)$ diagram.

The J – (J-H) diagrams also seem to indicate the presence of a large number of background objects in our samples. If we assume that all stars with $(J-H) > 1.6$ are in fact background sources, then the fraction of candidate Be and Herbig Ae/Be stars rises to 13% in M8 and to 30% in M16.

OTTO Studies of M42 and NGC 2264 (d = 460 pc; 800 pc)
The sample is optically selected and includes only proper motion cluster members brighter than B = 14. The estimated range in spectral type is from early B to middle G in both clusters.

The fraction of objects considered to be candidate Herbig Ae/Be stars or candidate classical Be stars (see Figure 6) is as follows:

M42: 13% in a cluster whose age estimates range from $3-5$ Myr.
NGC 2264: 15% in a cluster whose age estimates range from $3-20$ Myr.

Consequences for Disk Lifetimes and Disk Accretion Rates
Evidence is rapidly accumulating that stars of all masses seem to be surrounded by dusty circumstellar disks at "birth." If so, then our empirical results indicate that most of the disks initially surrounding intermediate and high mass stars have disappeared by ages of less than 10^6 yr. Strict limits on disk survival times, however, await the construction of proper HR diagrams for these young clusters. We suggest that because the disk lifetimes for early type stars appear to be short, the accretion rates through the disks $(\dot{M}_{acc} = \varepsilon\, M_{disk}/\tau_{disk})$ must be high.

Sizeable accretion rates are not only suggested, but are required in the simple argument that for a star of mass $5\mathcal{M}_\odot$ to be built during its pre-main sequence lifetime of 5×10^5 yr, it must accumulate material at the time-averaged rate of $1 \times 10^{-5} \mathcal{M}_\odot$ yr^{-1}. Such high accretion rates imply short disk lifetimes, consistent with our observations. We note that the required steady-state accretion rates are similar to those derived by Hillenbrand *et al.* (1992) from the magnitude of the infrared excesses in Herbig Ae/Be stars. Finally, if the disk survival time is comparable to the pre-main sequence lifetime of the star, these accretion rates imply that a significantly large percentage of the material which makes up the final mass of the star passes through its disk during the pre-main sequence phase.

CONCLUSIONS AND FUTURE DIRECTIONS

Because some of the Be and Herbig Ae/Be candidates we have identified will, in fact, turn out to be classical Be stars, and will not show the large excess infrared emission expected from analogs of Herbig Ae/Be stars, we conclude that *by the age of just a few* 10^5 *years, less than* 10% *of pre-main sequence O and B stars are surrounded by optically thick accretion disks.* If these stars were all initially surrounded by disks of mass comparable to that

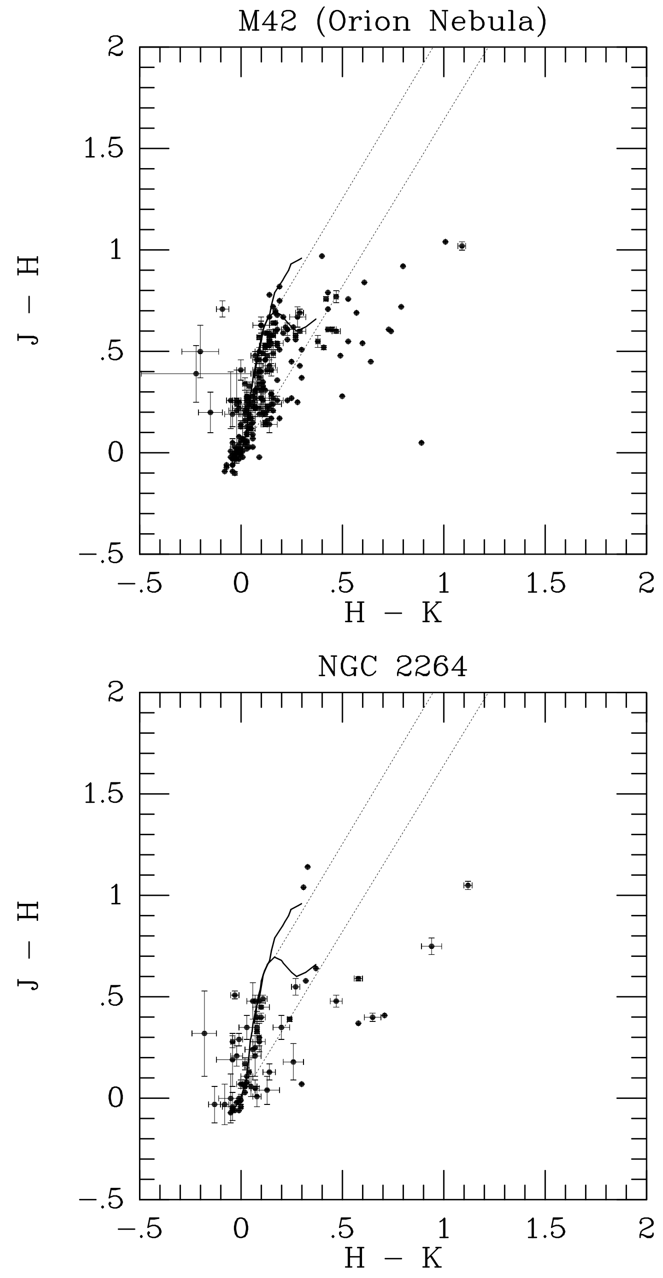


Figure 6. $(J-H)-(H-K)$ *diagram for all known proper motion members.* with B < 14 located (*upper panel*) within the central 45′ of the Orion Nebula and (*lower panel*) within the central 20′ of NGC 2264 . These observations were obtained with the OTTO single channel InSb photometer mounted on the 1.3m telescope at KPNO; error bars are indicated. In Orion, of a sample of 225 stars, 30 fall in the domain occupied by classical Be or Herbig Ae/Be stars. In NGC 2264, of a sample of 65 stars, 10 fall in the domain occupied by classical Be or Herbig Ae/Be stars. We note that our survey sample in these regions includes stars of spectral types ranging from early B though middle G.

of the current star, then the accretion rates for these disks must be on the order of $10^{-5}\mathcal{M}_{\odot}$ yr^{-1}.

For the SQIID surveyed regions, CCD imaging in combination with our IR imaging allows the objects to be properly dereddened and placed in an $M_V - (B-V)_0$ observational HR diagram. Using theoretical evolutionary tracks, we can then estimate the number of stars surrounded by disks as a function of stellar mass and age. We are currently carrying out such investigations.

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