Chapter 6

Stars with Circumstellar Disks and Envelopes

As a first step towards addressing the nature of the companions associated with Ae/Be stars, we can look for evidence of circumstellar material (accreting circumstellar disks and/or infalling envelopes) in the form of optical spectroscopic emission features and near-infrared continuum excesses. The survival time for remnant protostellar circumstellar material appears to be short (although a function of stellar mass: $\lesssim 10$ Myr for sub-solar mass stars but $\lesssim 3$ Myr for intermediate-mass stars). Thus, in the absence of fully assembled HR diagrams from which stellar ages can be estimated, identifying stars with significant amounts of circumstellar material serves as a surrogate indicator of stellar youth. The assertion of youthfulness via the observation of indicators of circumstellar material, ensures the physical association of a particular companion star with the molecular core containing the Ae/Be star, thereby eliminating concern about foreground / background contamination.

To investigate the frequency with which disk / envelope signatures are found amongst the Ae/Be cluster members, we consider the diagnostics for cirumstellar material in optically visible stellar populations first, and then optically invisible stellar populations.

6.1 Optically Visible Populations

For those optically visible stars with spectra, we can look for Hα , the Ca II triplet, or the forbidden [O I] or [S II] lines in emission. These lines have been interpreted as indicative of processes associated with ongoing accretion in

nearby, well-studied pre-main sequence stars. In Chapter 4, we noted that many of the Ae/Be cluster members show intrinsic (*i. e.* non-nebular) Hα emission (100% of the optically visible cluster members in the case of the BD +40° 4124 region and 90% in the case of the Lk Hα 215 region – the only two of our sample regions with completed optical spectroscopic surveys to date) and several Ca II triplet emitters were identified as well.

For those optically visible stars without spectra (the majority at the present time), we have only photometric diagnostics of circumstellar material. Photometrically, we can use the $(R_C - I_C) - (H - K)$ plane to distinguish stars with disks/envelopes from normally reddened stars. The (H-K) index is particularly sensitive to heated dust, while the (R_C-I_C) index is generally reddened photospheric – even for early-type star/disk/envelope systems in which the destruction of dust at high temperatures close to the star appears to remove nearly all of the continuum excess at these wavelengths. We show in Figure 6.1 $(R_C - I_C) - (H - K)$ diagrams for all optically visible sources in four of our sample regions, including the color-color relationships followed by unreddened dwarf and giant stars and the reddening vectors appropriate to normal interstellar extinction projected from the extrema of these relationships. From these representative clusters we conclude that amongst optically visible sources in the stellar aggregates defined by Ae/Be stars, the fraction of objects surrounded by disks / envelopes is high ($> 80\%$).

6.2 Optically Invisible Populations

For the optically invisible populations we must rely upon the $(J - H) - (H - K)$ plane to identify star/disk/envelope systems. We show $(J - H) - (H - K)$ digrams for four of our sample regions in Figure 6.2. In addition to the color-color relationships followed by unreddened dwarf and giant

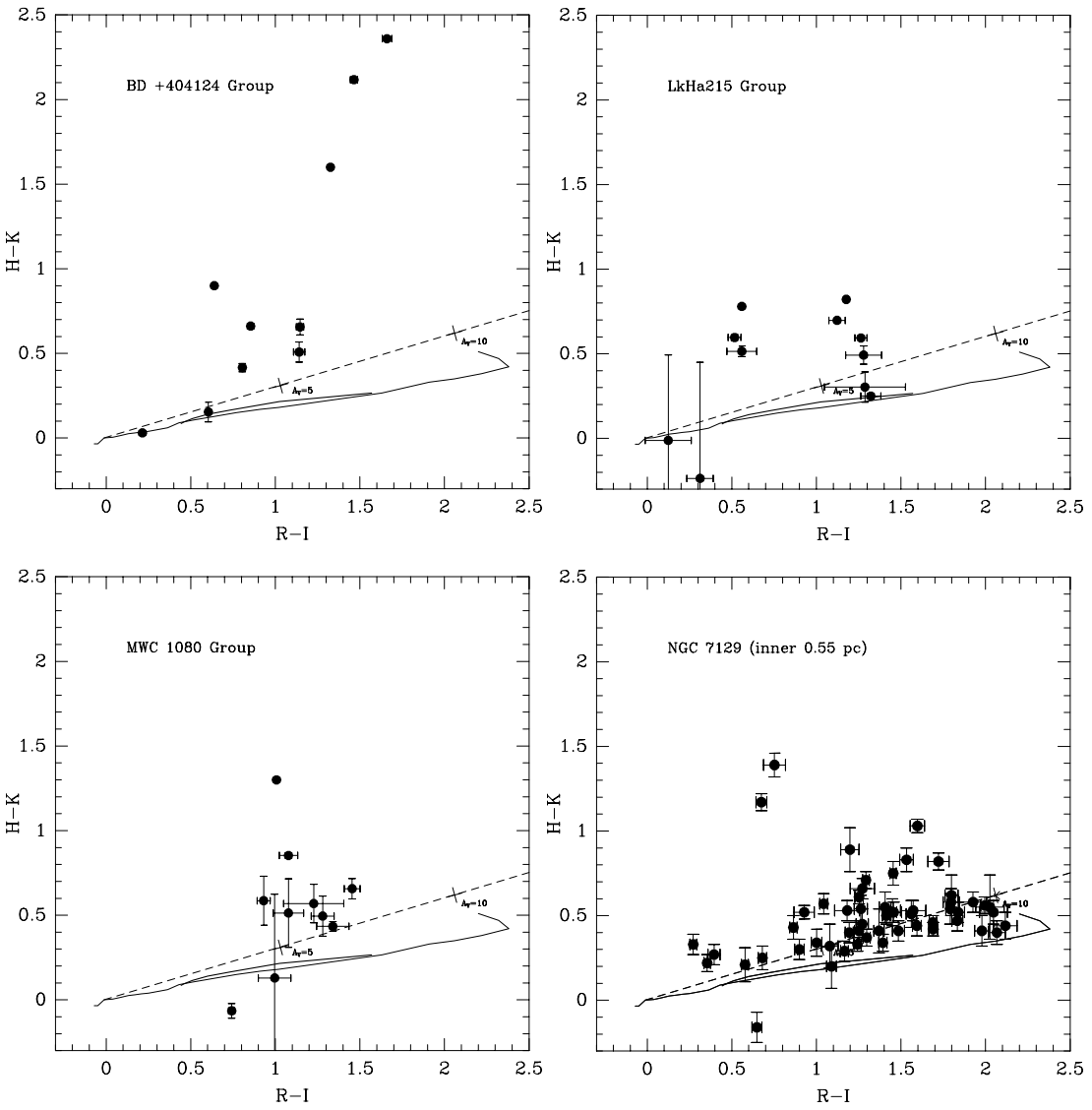

Figure 6.1. $(R_C - I_C) - (H - K)$ *diagrams for the BD +40° 4124,* Lk Hα *215,* MWC *1080, and* NGC *7129 regions.* These Figures include all optically visible sources in the inner 0.167 pc of each region, except NGC 7129 for which the radius is 0.55 pc. Photometric errors are indicated. The color-color relationships followed by unreddened dwarf and giant stars are shown as are the reddening vectors appropriate to normal interstellar extinction with $A_V = 5$ mag intervals marked. We use this diagram to identify stars with infrared spectrophotometric signatures for dusty circumstellar disk/envelope material, and infer that amongst optically revealed stars the disk fractions are high ($> 80\%$).

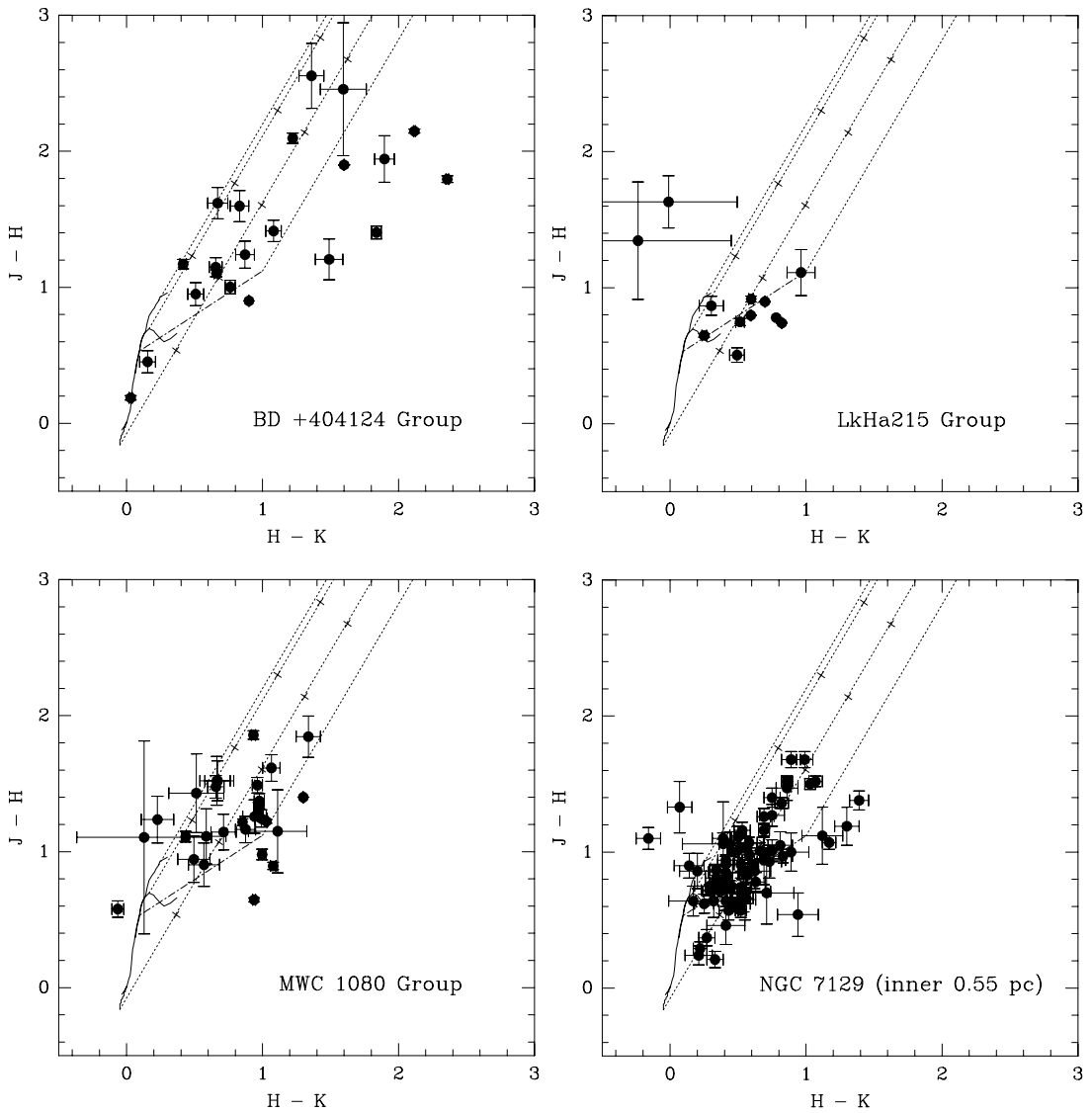

Figure 6.2. $(J-H)-(H-K)$ *diagrams for the BD +40° 4124,* Lk Hα *215,* MWC *1080, and* NGC *7129 regions.* These Figures include all sources with JHK photometry in the inner 0.167 pc of each region, except NGC 7129 for which the radius is 0.55 pc. Photometric errors are indicated. The color-color relationships followed by unreddened dwarf and giant stars are shown as are the reddening vectors appropriate to normal interstellar extinction with $A_V = 5$ mag intervals marked. Also shown (dash-dot line) is the locus of colors occupied by dereddened classical T Tauri stars and the reddening vector projected from its extreme. We use this diagram to identify stars with dusty circumstellar disk/envelope material, and infer based on this plane that the disk fractions are high ($> 50\%$) although not as high as those inferred for the same data from the $(R_C - I_C) - (H - K)$ plane ($> 80\%$).

stars and the reddening vectors appropriate to normal interstellar extinction projected from the extrema of these relationships, we also show in Figure 6.2 the locus of colors occupied by dereddened classical T Tauri stars (Meyer *et al.* 1995) and the reddening vector projected from the extreme of this relationship. We draw attention to four domains of the $(J-H)-(H-K)$ diagram: (1) Sources lying within the standard reddening vectors as projected from the main sequence and giant branches have small or absent near-infrared excesses, although a comparison of our two color-color diagrams for the optically visible stars shows that even sources which lie within the reddening vectors in the $(J-H)-(H-K)$ plane can have significant near-infrared excesses evident in the $(R_C-I_C)-(H-K)$ plane. (2) Sources displaying moderate excesses with colors redder than $(J-H) \approx 1$ mag are assumed to be similar in nature to the classical T Tauri stars , objects which can be modelled successfully as young low-mass stars with circumstellar (accretion) disks and whose dereddened colors occupy a well-defined locus (see Figure) in this color-color plane. (3) Sources displaying moderate excesses with colors bluer than $(J-H) \approx 1$ mag are assumed to be similar in nature to the Ae/Be stars, a subset of which can be modelled successfully as young intermediate- and high-mass stars with circumstellar (accretion) disks and whose near-infrared colors are produced, in part, by destruction of dust close to the star. (4) Sources displaying extreme near-infrared excesses, located well to the right of even "the classical T-Tauri locus," are typically those with flat or rising spectral energy distributions out into the mid- and far-infrared (although Ae/Be stars with large dust destruction radii but falling spectral energy distributions also can be found here); the circumstellar environments of these sources are presumed to include extended envelopes of varying geometries. In summary, from the $(J-H)-(H-K)$ diagrams of these representative clusters we conclude that the fraction of stars surrounded by disks/envelopes is typically $> 50\%$.

6.3 Success Rate of Various Diagnostics of Circumstellar Material

As noted above, many of the optically revealed sources which lie within the reddening vectors in the $(J-H)-(H-K)$ plane are seen to have infrared excesses in the $(R_C-I_C)-(H-K)$ plane. This is due to the nearly perpendicular behavior in the $(R_C-I_C)-(H-K)$ plane of 1) reddening and 2) heated dust radiation, while in the $(J-H)-(H-K)$ plane, these two effects are not as clearly distinguishable. This is particularly true in cases where circumstellar dust is heated to temperatures comparable to those of the central stars (*e. g.* in late-type systems). Thus, for embedded stellar populations we can use the $(J-H)-(H-K)$ diagram to diagnose rapidly accreting low-mass star / disk / envelope systems and all high-mass star/disk/envelope systems (both active and passive); however, diagnosis of slowly accreting and passive low-mass star / disk / envelope systems is more accurately done from the $(R_C-I_C)-(H-K)$ diagram.

In order to assess the true fraction of Ae/Be cluster members with evidence for circumstellar material, we estimate the success rates of the various diagnostics available from our data set (an unbiased imaging survey combined with a biased spectroscopic survey) by determining the frequency with which these diagnostics are found to characterize well-studied optically visible young stellar objects in the nearby Taurus molecular cloud. The sample of stars discussed photometrically by Strom *et al.* (1989) and spectroscopically by Edwards *et al.* (1993) is used for this purpose (see also Hartigan *et al.* , 1995).

Definitive identification of accreting systems is accomplished via the observation of optical spectral veiling (indicative of accretion directly onto the star) and / or forbidden line-emission (indicative of accretion-driven stellar or disk winds). In Taurus, 100% of the stars with measured veiling and with forbidden line-emission have (H-K) continuum excesses (Edwards *et al.* ; 1993), which reflect the presence of heated circumstellar dust. Ideally, measuring an (H-K) excess

entails removing the contributions of the stellar flux and of interstellar extinction from an observed color, leaving the intrinsic color excess which is attributed to dust continuum-emission. However, in this and in most studies of partially embedded young clusters, only color-color diagrams of reddened stars of unknown spectral type are available. Thus we cannot measure dust continuum excesses properly and must depend on the robustness of these color-color diagrams as diagnostics.

How well do the $(R_C - I_C) - (H - K)$ and the $(J - H) - (H - K)$ diagrams do in identifying stars with circumstellar material? Of the set of objects in Taurus with spectroscopic accretion signatures, all described above to have intrinsic (H-K) color excesses, only approximately 60% are unambiguously identified as having infrared excess emission from the $(J - H) - (H - K)$ diagram, while 80% are unambiguously identified as having infrared excess emission from the $(R_C - I_C) - (H - K)$ diagram. Although not relevant to the current analysis, moving to longer wavelengths, for example to the $(H - K) - (K - L)$ diagram, increases the fraction of infrared-identifiable objects with spectroscopic accretion signatures to 100%. In summary, while color-color diagrams allow us to pick out *most* of the objects with circumstellar material, the assumed disk / envelope frequencies serve only as lower limits to the actual disk / envelope fractions, which may be up to 40% higher than those derived from simple analysis of these commonly used diagrams.

6.4 Conclusions on the Presence of Circumstellar Material

In this Chapter, we have provided evidence that the fraction of objects with circumstellar activity signatures in the dense stellar groups identified with Ae/Be stars, is high ($> 50 - 80\%$). However, we have also discussed our belief that these numbers are necessarily only lower limits to the true disk / envelope fractions, due

to the inaccuracy of our diagnostics. Fully assembled, dereddened optical and infrared spectral energy distributions would be required for any further analysis.

Although we have presented data for only four of the regions in our sample, our suspicion is that the featured regions are representative. That the assumed fraction of objects with circumstellar material is high confirms that the stars found projected within several tenths of a pc of young high-mass Ae/Be stars are, typically, also young and therefore likely physically associated stars. We turn now towards investigation of these young stellar populations.