Chapter 7

A First Look at Stellar Populations: C-M Diagrams

In our investigation into the nature of the members of the Ae/Be clusters, we have asserted that the partially embedded companion populations are comprised (typically) of young, low mass stars. Thusfar, our only evidence for this claim is the location of stars in various infrared color-color planes, from which we were able to deduce the presence of circumstellar material (Chapter 6). In this Chapter, we take the next step towards deciphering the nature of these sources by studying infrared color-magnitude diagrams, from which we can begin to probe the properties of the stars themselves. Our goal is to determine the distributions of stellar masses and ages in the aggregates associated with Ae/Be stars.

7.1 Presentation of Color-Magnitude Data

We present near-infrared color-magnitude diagrams in Figure 7.1 for all stars with good photometry in four of our sample regions. Superposed are lines indicating pre-main sequence isochrones; we refer to Figure 3.2 for symbols indicating the corresponding mass evolutionary tracks.

Of note in these color-magnitude diagrams is the gap in J-magnitude between the bright early-type star in each region, and the remainder of the stellar population. Although reddening is obviously significant and some contribution at these wavelengths from circumstellar dust emission is likely, the distribution of stellar brightnesses provides at least a first order clue to the distribution of stellar masses. In most cases, the fainter companions appear indeed to be stars of lower mass.

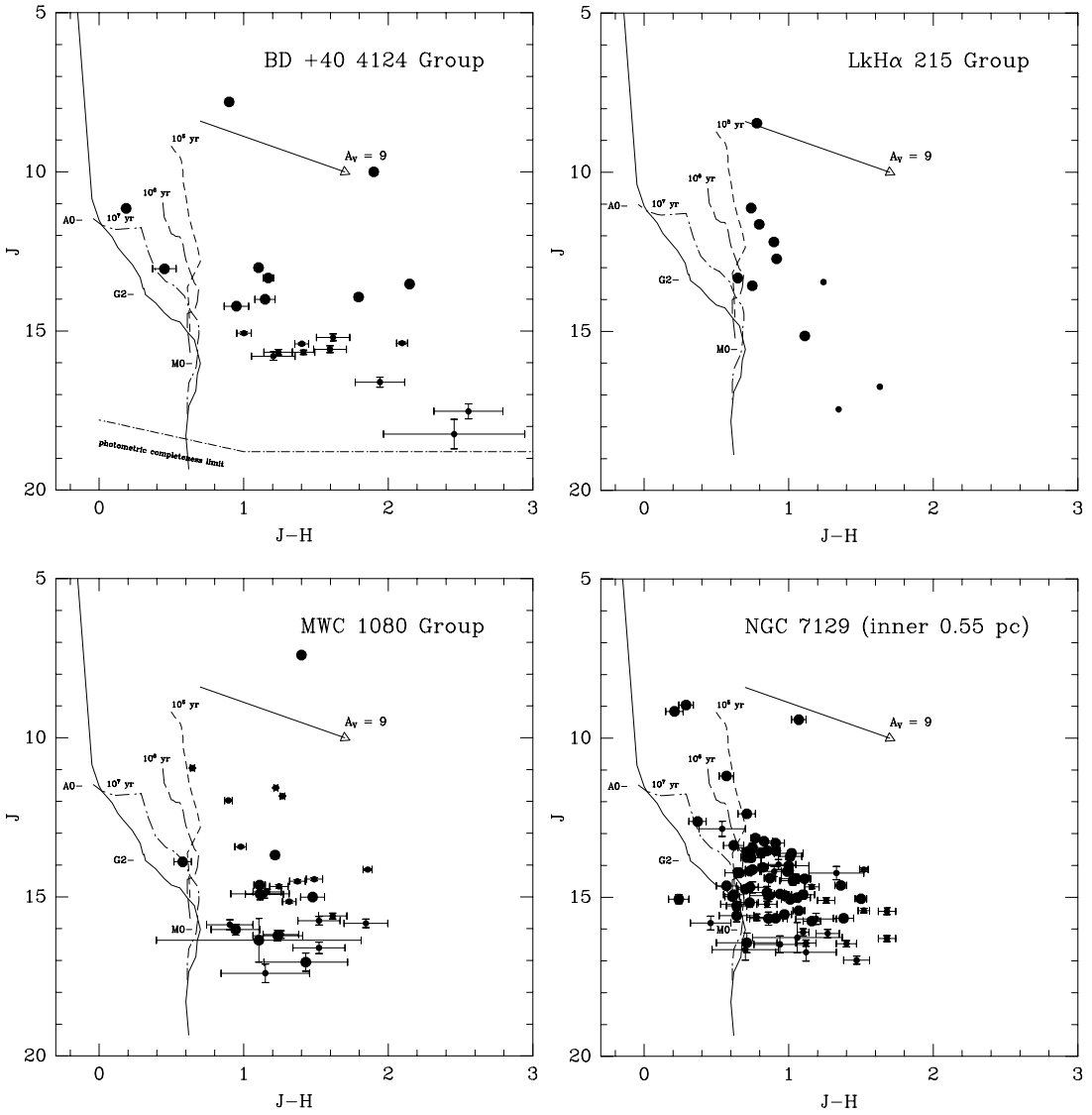

Figure 7.1. *$J-(J-H)$ diagrams for the BD +40° 4124,* Lk Hα *215,* MWC *1080, and* NGC *7129 regions.* These Figures include all sources detected in the inner 0.167 pc of each region, except NGC 7129 for which the radius is 0.55 pc. Optically visible sources are indicated with larger symbols. Photometric errors are shown. Superposed are the zero-age main sequence and the lines of constant (log) age derived by transforming the theoretical pre-main sequence evolutionary tracks of D'Antona & Mazitelli (1994) over the mass range $0.1-2.5$ $M_\odot$ into this color-magnitude plane. We can use this diagram in combination with the $(J-H)-(H-K)$ diagram to deredden embedded sources and estimate stellar masses; see text.

Furthermore, in most Ae/Be regions the fainter companion stars lie above a lower envelope defined by the reddening vector as projected from the 0.1 $M_{\odot}$ point on the 3 Myr isochrone. From a comparison of the distributions of sources in these diagrams to the photometric completeness levels in the $J-(J-H)$ plane shown in Figure 3.2, we see that our survey completeness limits are deeper than this for low values of extinction. Thus, we also have a first order estimate for the upper limit on stellar ages.

7.2 Methods for Estimating Interstellar Extinction

In order to more accurately determine stellar mass and age distributions, we need to correct the observed photometry for the effects of interstellar extinction and, in doing so, account for the presence of infrared continuum excesses when significant.

Our methods for dereddening young stars necessarily differ between optically visible and optically invisible populations. We have indicated optically visible stars ($R_C, I_C \lesssim 18.5$ mag) in Figure 7.1 with slightly larger symbols. These objects are accessible to ground-based optical spectroscopy, as described in Chapter 4, and thus we can deredden these stars by comparing their observed colors to those of standard stars of the same spectral types (see Chapter /refchap:hrd). What about optically invisible stars? Sources for which we have only near-infrared photometry (smaller symbols in Figure 7.1) are more inaccurately dereddened as, in order to do so, we must 1) use purely infrared photometric methods; 2) make some assumptions regarding the relative contributions of photospheric and circumstellar emission to our infrared photometry; and 3) estimate a cluster age and therefore an isochrone in the $J-(J-H)$ plane to which sources dominated by photospheric emission are dereddened.

To apply this method to individual sources, we distinguish between those with and without evidence for hot circumstellar dust in the $(J-H)-(H-K)$ diagram (Figure 6.2). We assume that the sources uncovered in our infrared surveys have stellar and circumstellar characteristics similar to those of nearby, well-studied young (accreting) star/disk/envelope systems and proceed as follows: (1) Sources lying within the reddening vectors in the $(J-H)-(H-K)$ plane have colors consistent with normal interstellar extinction and are dereddened in the $J-(J-H)$ plane to intersect the isochrone corresponding to the assumed cluster age. (2) Sources displaying near-infrared excesses in the $(J-H)-(H-K)$ plane and having colors redder than $(J-H) \approx 1$ mag but located within 0.6 mag in $(H-K)$ of the reddening vector are assumed to be similar in nature to classical T Tauri stars and are dereddened in the $(J-H)-(H-K)$ color-color diagram to intersect the locus defining the domain occupied by classical T Tauri stars (see Figure 6.2). (3) Sources displaying near-infrared excesses in the $(J-H)-(H-K)$ plane and having colors bluer than $(J-H) \approx 1$ mag are assumed to be similar in nature to Ae/Be stars and are not dereddened. (4) Sources displaying extreme near-infrared excesses, located well to the right of even "the classical T-Tauri locus," are not dereddened. In cases (1) and (2) we have extinction estimates for the stars; in cases (3) and (4) we are unable to derive extinction estimates from infrared photometry alone, since we do not know the extinction-free colors.

7.3 Turning Dereddened Photometry into Stellar Masses

With the aid of set of pre-main sequence evolutionary tracks, stellar masses can be derived from dereddened photometry, where we have been able to obtain it.

For optically visible populations, we use optical photometry and spectroscopy to locate stars in the traditional HR diagram and determine their masses *and* ages.

For optically invisible populations, we use absolute J magnitudes to estimate masses based on *assumed* ages (those derived from the optically visible surface stellar populations; see Chapter 8). Absolute J magnitudes are computed using the cluster distance, the observed J magnitudes, and the extinction values derived according to the above method. What about the two cases given above where no extinction value can be determined? In case (3), we assign masses $M > 1$ $M_{\odot}$ to the stars, since the vector described by the color excesses in the $(J-H)-(H-K)$ plane seems nonphysical for lower-mass stars. In case (4), we assign no mass estimate, although we might expect most of these objects also to have masses $M > 1$ $M_{\odot}$.

The errors associated with deriving stellar masses using this infrared photometric dereddening procedure are discussed by Meyer (1995). Summarizing their results, comparisons between masses derived from this procedure and from traditional HR diagrams constructed with optical photometry and spectroscopy in the Lupus and Taurus dark clouds, suggest that the dereddening technique just described is accurate to within 50% in mass, if the assumed age is correct. As we will find in Chapter 8, this uncertainty is no worse than the uncertainty in the predictions of pre-main sequence evolutionary theory itself, on which the dereddening technique is based. For completeness, we note that if the assumed age is incorrect, we introduce the bias (due to the relative positions of the isochrones in the $J-(J-H)$ plane) that a younger assumed age yields systematically lower absolute J magnitudes translating into systematically lower mass stars, than if an older age is assumed. We take advantage of this bias in our discussion of cluster mass spectra in Chapter 9.

7.4 Preliminary Conclusions on Stellar Populations

Based only upon the observed infrared color-magnitude diagrams (Figure 7.1), we conclude that the aggregates accompanying Ae/Be stars appear to be comprised of stars which are young (< 3 Myr) in age and which extend down to the hydrogen burning limit (0.08 $M_{\odot}$) in mass. Specific constraints on stellar ages will be discussed in Chapter 8, from traditional HR diagram analysis of the optically visible members of the Ae/Be aggregates. Specific constraints on stellar mass distributions will be discussed in Chapter 9, during our analysis of initial mass function issues.