Chapter 11

Summary and Future Investigations

In his original paper identifying the class of early-type emission-line stars associated with nebulosity on which the current study is based, Herbig (1960) noted the presence of groups of objects in the vicinity of the Ae/Be stars which also displayed Hα -emission spectra. Herbig's objective prism survey of these regions was limited to bright, optically visible sources and, furthermore, was not conducted with the purpose of uniformly sampling various regions in either space or depth. In this work, we have described a molecular mapping, optical and infrared imaging, and spectroscopic stellar classification survey of star-forming sites producing young ($\tau < 1$ Myr), intermediate- and high-mass ($M > 3/M_{\odot}$) Herbig Ae/Be stars. We have confirmed the local clustering of low-mass stars in the vicinity of Ae/Be stars and attempted to characterize further their properties. Our survey has focussed on uncovering embedded and partially embedded populations and, although not strictly uniform between regions, is sensitive in most cases to young stars of all masses down to near the hydrogen-burning limit, over the range of extinction values $A_{\rm V} < 10$ mag.

We summarize below our procedures and results on the stellar populations and molecular environments of young, massive Ae/Be stars.

11.1 Summary of this Thesis Presentation

- We have defined a "star-forming event" to be the sequence of star formation occuring on spatially and temporally coherent scales, which we take to mean 1) within molecular cores which are isolated from large complexes of extensive

star formation; 2) over size scales of several tenths of a pc or less; 3) over temporal scales of 3 Myr or less.

- We have investigated the molecular properties of the Ae/Be cores via a CO and CS survey and found cloud sizes of 0.1-0.8 pc and cloud masses of $150 - 2000$ $M_{\odot}$. Visual extinction through the cores *at the positions of the stars* ranges from 2-50 mag. We have also found from simple inspection of morphological structure, that the molecular clouds with which Ae/Be stars are associated are typically asymmetric structures with large column density gradients (several tens of magnitudes in some cases) near the positions of the central massive stars. This is due, most likely, either to interaction of the young star itself with the ambient cloud, or to external dynamical processes which perhaps aided in the production of the high-mass stars.

- We have identified small, dense, partially - obscured aggregates of size a few to several tens of stars (mean = 10) projected onto the same molecular cores as the Ae/Be stars. The number densities estimated within the central 0.167 pc of these clusters, range from several hundred to several thousand stars per cubic parsec (mean = 1350).

- We have found an apparent correlation between the aggregate stellar surface densities and the masses of the defining Ae/Be stars.

- We have found the fraction of aggregate members with infrared continuum and optical spectroscopic evidence for circumstellar disk / envelope signatures to be high (50-80%), and comparable to the fraction discernible by the same techniques in well-studied stellar populations found in nearby dark clouds. We have also argued that these numbers are lower limits to the true fractions of stars with circumstellar material, due to the imperfectness of the activity diagnostics available to us from our imaging and spectroscopic surveys.

- We have constructed infrared color-magnitude diagrams from which we deduced that the companions to the Ae/Be stars are typically young stars ($\tau < 3$ Myr) of lower-mass ($M < 1$ $M_{\odot}$).

- We have attempted to investigate quantitatively, by locating several of these groups in the HR diagram, what we presume from simple examination of our images and from the evidence on circumstellar activity described above – that the young aggregates accompanying young high-mass Ae/Be stars are comprised primarily of young, low-mass stars.

- We have found, instead of a straightfoward conversion from log $(L_*/L_{\odot})$ and log T_{eff} to stellar mass and age, that mass estimates derived from different pre-main sequence evolutionary codes are uncertain at the 50% level and that age estimates are uncertain at the several Myr level. From this exercise we have concluded for pre-main sequence stars that most mass and *all* age information must be interpreted with caution.

- We have found, treating the mass and age information with appropriate reserve, that the high- and low-mass populations in the Ae/Be groups do appear to be coeval at the 1-3 Myr level, and that there is no (discernable) time sequence of star formation as a function of stellar mass.

- We have developed a statistical test, which accounts for the uncertainties in derived stellar masses, to investigate the compatibility of the observed mass distributions with those predicted by the Miller-Scalo mass function. At the level of our ability to address the problem, given our small number statistics, we have found at least one aggregate, the BD +40° 4124 region, to be apparently biased towards forming intermediate- and high-mass stars. Based on the relative source brightness distributions derived from a qualtitative

inspection of our infrared images, however, we suspect this region to be the only one in our sample with such an unusual bias.

- We have summarized the information available from our and others' sensitive near-infrared images on close (< 10 arcsec) companions to the Ae/Be stars (see Appendix B). This information is important for two reasons. First, we can assess the possible influence of nearby infrared-luminous stars on spectral energy distributions constructed for Ae/Be stars, which are typically interpreted in the context of star / disk /envelope structures. Second, we can investigate the range of separation distances for any candidate wide-binary systems. Perhaps important for both of these issues, we find that the brightest companions ($\Delta K < 3$ mag) are also the closest ($\Delta r < 1000$ AU).

11.2 Remaining Questions

This document has been a first-order summary of the local molecular cloud and stellar populations parameters in the vicinity of extremely young, ($\tau < 1$ Myr), intermediate- and high-mass ($M > 3 M_{\odot}$) stars found in relative isolation from other sites of ongoing star formation. In our discussion we have tried to place this work into the context of what is anecdotally known from the literature about massive star formation. Given the apparent differences in the local molecular and stellar clustering environments in which stars of high- and low-mass form, in the future we would like to explore whether either 1) initial core conditions, or 2) local stellar environmental conditions, might be the primary driver in determining the final mass of a star.

To investigate the influence of initial core conditions, we must understand whether and how the molecular cloud cores in which high-mass stars are produced differ from those in which only low-mass stars are produced. We must also

understand the importance of large-scale dynamics / energetics to the formation of high-mass stars, given the likely complexity of fragmentation processes in situations where turbulence is generated by cloud compresssion.

To address the influence of local stellar environment, we offer the following provocative thoughts. For the young stellar aggregates defined by Ae/Be stars investigated in this work, we found an apparent correlation of local stellar density with the mass of the most massive star in the group. Furthermore, we showed that the stellar densities in the aggregates are high ($n \approx 1000\ stars\ \ \mathrm{pc}^{-3}$), and that the fraction of stars apparently surrounded by disks / envelopes is also high ($f \gtrsim 50 - 80\%$). This scenario introduces a potentially interesting dynamical situation. If, indeed, a significant fraction of the stars in these dense groups are still undergoing remnant infall and accretion, they must have done so at higher rates in the past in order to form the stars we see today. Extrapolating backwards in time, one can envision a situation during the main stellar accretion phase when many "seed" protostars were essentially competing for the same ambient molecular core material. In this "competitive accretion" scenario, one star, the Ae/Be star, somehow managed to accumulate many times more mass (up to several hundred times more) than its cloud core siblings. Understanding this situation from a theoretical point of view seems crucial to our picture of star formation in groups.