Chapter 10

Discussion

Our analysis of the Ae/Be clusters has provided the most comprehensive description to date of the bulk molecular and stellar clustering properties in the immediate environments of Ae/Be stars, the youngest known examples of massive optically visible stars. We have taken the last several Chapters of this work to present our detailed analysis of the makeup of the stellar populations accompanying the Ae/Be "signposts." We would like to return in this Chapter to our interest in developing a quantitative understanding of the overall characteristics of these and other star-forming environments, which might be conducive to their production of high-mass stars.

We begin by describing the general differences between star-forming sites in which young high- and young low-mass young stars are found. We then place our results on clustering properties in the vicinity of Ae/Be stars into this environmental context. Finally, we speculate on the possible influence of environment in the star formation process for, in particular, higher-mass stars.

10.1 The Issue of Environment in the Star Formation Process

If one surveys the literature on young regions of star formation, different trends emerge for the low-mass ($M/M_{\odot} < 1$) stellar populations than for the intermediate-mass ($1 < M/M_{\odot} < 10$) and high-mass ($M/M_{\odot} > 10$) stellar populations.

Low mass stars appear to form in a variety of environments: 1) locally isolated; 2) as members of small (T) associations and somewhat larger groups which contain only low-mass stars (*e. g.* Lupus, Chameleon); and 3) within cluster complexes which contain both low- and intermediate-mass / high-mass stars (*e. g.* Taurus-Auriga, Ophiucus). This lack of any specific environment is true amongst low-mass main sequence stars as well as amongst their progenitors. Furthermore, the molecular cores which produce roughly solar mass stars appear to contain no more than a few solar masses of material. Core thermal motions dominate nonthermal motions in these low-mass cores, and protostellar mass infall proceeds in a nonhomologous manner over a timescale $M_*/\dot{M}_{acc} = M_* \cdot G/c_s^3$, where M_* is the final mass of the star, G the gravitational constant, and c_s the local sound speed.

Regions of high-mass star formation, on the other hand, do not display such a clear relationship between the output stellar products and the properties of their parent cores. It appears that more massive cores do yield more massive stars, and that particular values of cloud radius and cloud pressure seem able to support the formation of stars in particular mass ranges. However, there is increasing evidence that core nonthermal motions (*e. g.* turbulence, magnetically controlled processes, *etc.*) dominate over thermal motions in the denser cores which tend to produce more massive stars. Thus gravitational collapse may not proceed in the same way during high-mass star formation as it does in low-mass star formation, and simple scaling of the $1/c_s^3$ law may not be applicable. This suggests that the role of local environment may be relatively more important to the production of high-mass stars. Indeed, observationally, high-mass stars seem to form preferentially in small unbound (OB) associations (*e. g.* individual complexes in Sco-Cen) or in larger clusters (*e. g.* M42, NGC 2264). High-mass stars are found in association with stars of all masses, and it is generally true that the highest mass stars are agglomerated near the densest parts of the immediately surrounding clusters (for further discussion, see Larson, 1982; Zinnecker, McCaughrean, & Wilking, 1993).

Our survey of apparently isolated molecular cores which contain young high-mass stars has shown that even young Ae/Be stars are not without companions.

Based upon the trends apparent in the literature on differences in the local molecular and stellar clustering properties between regions forming high- and low-mass stars, we speculate that either 1) initial conditions in the molecular cloud or 2) local stellar density must be the primary driver in determining the final mass of a forming star. We would like to know whether and how the conditions necessary for the formation of low-mass stars differ from those which seem to only rarely produce high-mass stars. If we can understand the influence of core properties and of local clustering properties in the star formation process, we may be able to constrain the mechanisms by which and conditions under which high-mass stars are built.

10.2 The Ubiquity of High-Mass Star Formation in Groups?

Certainly one of the major conclusions of this thesis is the typical association of young, massive Ae/Be stars with small, dense aggregates of young, lower-mass stars. Is this local clustering phenomenon to be expected in *all* high-mass star-forming cores? The answer is unclear at the present time, and depends critically on knowing whether the population of well-studied Ae/Be stars is representative of high-mass star formation in general. As noted in Chapter 1, the statistics derived from unbiased imaging surveys in young OB associations suggest that Ae/Be stars are rare amongst young A and B stars. This could mean either that the Ae/Be population represents a quite rapid stellar evolutionary phase through which all young high-mass stars do indeed pass, or that Ae/Be stars are an intrinsically rare group of peculiar stars without any context at all in standard stellar evolution. We prefer the first of these possibilities.

If it is true that all young high-mass stars form as the centrally dominant members of small aggregates, then it would seem likely that the existence of the cluster must have played a role in the formation of the high-mass star. If, on the other hand, it is found that some young high-mass can in fact form in truly isolated environments, then only the initial conditions in the molecular cloud core were responsible for the formation of the high-mass star. Observational assessment of the ubiquity of high-mass star formation in groups remains limited at the present time. Future investigations are warranted, but will likeley be complicated by unknown effects with cloud / cluster age and mass.

10.3 Theoretical Implications

Most theoretical work on the formation of stars has concentrated on the production of individual objects. Our current paradigm of a single star forming out of a collapsing molecular cloud core evolved from studies of primarily low-mass star-forming regions, in which star formation appears to be proceeding in relative isolation over scales of many parsecs.

In theoretical collapse calculations for single high-mass stars, however, the inward flow of a collapsing envelope is halted and frequently even reversed by heat flow from the interior. Beyond a maximum time (corresponding to a maximum mass), further spherical accretion of material is not possible. This raises important questions as to how high-mass stars are built. It appears that some mechanism other than simple spherical infall must be in effect, perhaps accretion through a disk. Larson (1990, 1982) suggests that protostellar interactions in a clustered environment may stimulate the accretion of material through disks onto forming stars. In his scenario, the standard fragmentation of molecular clouds leads to widespread low-mass star formation, while high-mass star formation remains a secondary process and is the result of continued and enhanced disk accretion onto the low-mass protostellar seed. The redistribution of angular momentum in the disk is caused by some combination of gravitational perturbations, tidal effects, and disk turbulence. In the case that negative angular momentum is imparted to the disk, one result of the encounter is an increase in the rate of accretion through the disk, and possibly onto the central star. Accretion-enhancing effects may be induced by the local presence of either substantial numbers of point masses, or a single star of comparable mass passing within about 5 disk radii. Such close encounters may be quite frequent for number densities exceeding a few 10^3 pc^{-3}, as in the Trapezium region, M17, and many of the Ae/Be clusters.

The question, then, is the following: is the final mass of a star "set" once the core has produced a star / disk / envelope system, or are subsequent environmental interactions important in determining the final stellar mass? If the Ae/Be stars and their associated dense aggregates of stars can be considered as young stellar *systems* (instead of as isolated core collapse events), they may provide important clues to the physical processes which produce massive objects. We therefore urge the theoretical consideration of star formation in dense groups (≈ 1000 $stars\ pc^{-3}$) as an expansion to the developing theory of protostellar collapse for individual high-mass stars.