ISOLATED HERBIG AE/BE STARS: RARE EXAMPLES OF INDIVIDUAL HIGH-MASS STAR-FORMING EVENTS

LYNNE A. HILLENBRAND
Five College Astronomy Dept., LGRC 517G,
University of Massachusetts, Amherst, MA 01003

ABSTRACT As *the youngest* optically visible high-mass stars, the Herbig Ae/Be population can be used to probe the conditions under which massive stars are born. Preliminary results from a study of star-forming regions containing Ae/Be stars (consisting of molecular gas maps, optical/infrared images, and spectra) reveal that the most massive of these objects appear not to have formed alone! The partially embedded stellar groups accompanying even those Ae/Be stars which are isolated from extended complexes of star formation, provide a rare opportunity to quantify the properties of stellar populations produced within *single* high-mass star-forming molecular cores. Determining the distribution of masses and ages within these groups allows us to address issues such as the true initial mass function, the length of time over which star formation takes place, and the time sequence of star formation as a function of stellar mass (if such a sequence exists) – at the level of individual high-mass star-forming "events." This contribution summarizes recent progress towards this end.

INTRODUCTION

The youthfulness of Ae/Be stars is supported by their surroundings (association with molecular clouds; illumination of reflection nebulosities), stellar parameters (locations above the zero-age main sequence; low surface gravities), remnant protostellar disk/envelope signatures (millimeter continuum fluxes indicating large masses of circumstellar dust; near-infrared spectral energy distributions consistent with those expected for disks/envelopes), and activity (strong variable permitted and forbidden emission lines; centimeter continuum emission; molecular outflows). Large-scale unbiased surveys of young ($0.1 < \tau < 10$ Myr) star-forming complexes with significant high-mass stellar populations, regions in which *many* examples of extremely young high-mass stars might be expected, have surprisingly revealed only a small number of Ae/Be candidates. This suggests that if the Ae/Be phenomenon represents a phase through which all young high-mass stars pass, they must do so rather quickly.

Assuming a near-infrared excess to indicate the presence of a remnant disk/envelope associated with the star formation process, we find that the fraction of such objects is low in extremely young ($\tau << 1$Myr) "high-mass" star-forming complexes, consistent with short disk/envelope survival times. Thus the optically visible, massive Ae/Be stars which *do* have large infrared excesses, represent a rare and unique group which can be used to investigate the physical conditions conducive to high-mass star formation. The ages inferred for these young Ae/Be objects (a few hundred thousand years) imply that the stars are likely to be found within a few tenths of a parsec of their birthplaces. Thus multiwavelength survey techniques, as described below, enable us to isolate and then quantify the environmental conditions at or near the time and place of "birth" of these high-mass stars.

THE ENVIRONMENTS IN WHICH AE/BE STARS FORM

A first step towards probing the origin of intermediate- and high-mass stars is to place observational constraints on the environments in which these stars are born. Young Ae/Be stars are found:

- in extended star-forming complexes containing large populations (10's - 100's) of young high-mass stars as well as many young low-mass stars, *e.g.* M17, M8, NGC 6611, NGC 2264, Orion
- in small groups containing a few (2-5) young high-mass stars plus a mix of young lower-mass stars, *e.g.* NGC 7129, the BD+40 4124 / V1686 Cyg Group, the LkHa 198 / V376 Cas Group
- in relatively isolated molecular cores containing a single (1) young high-mass star plus a partially embedded aggregate of young lower mass stars, *e.g.* MWC 1080, BD+46 3471, HD 200775, VV Ser, MWC 297, V921 Sco, HD 259431, LkHα 215, MWC 137, HD250550, BD+61 154.

THE CASE OF ISOLATED AE/BE STARS

Although extremely young open clusters (case (1) above) provide perhaps the best arenas in which to search for and study candidate Ae/Be stars, these environments are complicated by the spatial and temporal mixing of multiple star formation events occurring in different places and at different times. Thus the conditions under which an *individual* high-mass star forms, are hopelessly confused and impossible to isolate. However, that some Ae/Be stars are located in molecular cores which are distinctly isolated from larger-scale star-forming complexes and in which only a single generation of stars has formed, allows us to use these regions (cases (2) and (3) above) to investigate the local environmental conditions under which just one or a few high-mass stars are produced. Once the local environments in which stars of different mass form are understood, we can then probe how the conditions *necessary* for high-mass star formation differ from those which lead to the more commonplace production of low-mass stars.

The suggestion that innate differences do exist between individual high- and low-mass star-forming events, is based upon observational trends with mass of molecular core and stellar environmental properties. Molecular studies of protostellar cores and cores which have recently produced stars, suggest that low-mass stars form in cores whose internal structure is thermally controlled while high-mass stars form in cores in which nonthermal gas motions dominate thermal gas motions. Optical and infrared studies of young clusters, suggest that low-mass stars form in a variety of environments, *including in total isolation*, while high-mass stars seem preferentially to form in clustered environments. With this evidence, one must thus ask whether the mechanism which determines the final mass of a star is *either* 1) set by the initial conditions (mass, angular momentum, effective sound speed) in the protostellar core, or 2) environmentally controlled?

We can begin to address this question by investigating first whether high-mass stars *ever* form alone – in isolated regions like those in which young low-mass stars can be found – or whether high-mass stars are *always* formed in association with other young stars. If truly isolated examples of young high-mass stars are found, then high- and low- mass stars can in fact form in similarly isolated local environments; we must then study the molecular cores in regions of isolated high- and isolated low-mass star formation to determine how the physical conditions in the cores differ. Alternatively, if no truly isolated examples of young high-mass stars are found, we must then identify the important environmental parameters (*e.g.* high local stellar density) unique to areas of individual high-mass star formation.

THE STUDY

To assess the local environments of individual high-mass star formation, I have focussed my study on the youngest ($\tau < 1$Myr), most massive ($M/M_{\odot} > 4$), most isolated members of the Ae/Be population. To quantify the environments which have produced these Ae/Be stars, the following types of data are needed: 1) submillimeter and millimeter maps of molecular gas, in order to trace the spatial extent, column density, degree of clumpiness, sound speed, rotation, and energetics of the cloud; 2) optical images, in order to gauge the large scale environment and obtain photometry for the surface stellar population; 3) infrared images, in order to obtain photometry for the embedded stellar population and to search for evidence of remnant protostellar disks/envelopes; 4) optical *and infrared* classification spectra, in order to locate the stars in the HR diagram and thereby determine their masses and ages. We can then investigate:

- the stellar densities in recently formed groups containing high-mass stars

  how do they compare with groups forming exclusively low-mass stars?

- the true *initial* mass function

  is the mass function "normal," or are "excessive" numbers of high-mass stars found in the isolated cores containing Ae/Be stars?

- the time sequence of star formation as a function of stellar mass

  did the stars accompanying the high-mass star form
  – before the massive star?
  – contemporaneously with the massive star?
  – after the massive star?
  – some combination of the above?

- the physical conditions within the molecular cores

  how do they differ from cores forming only low-mass stars?

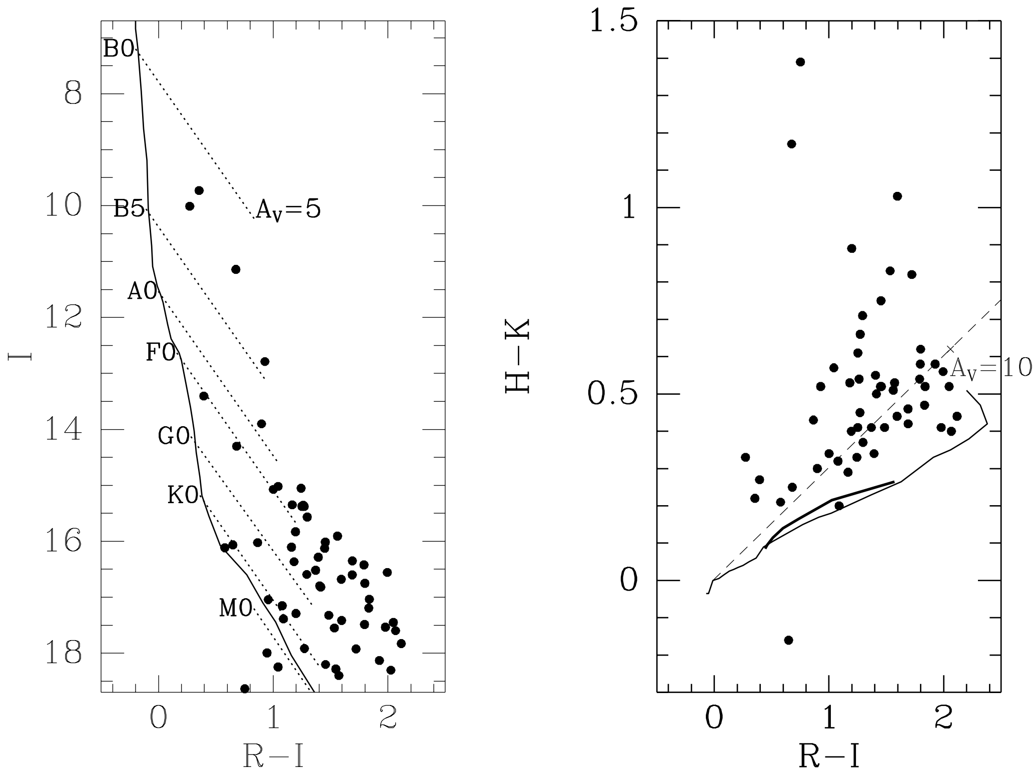

FIGURE: Color-Magnitude and Color-Color Diagrams of the Lk Hα 234 Group. Although spectroscopy is needed for certain placement of stars in the HRD, an I-(R-I) diagram of the central 0.8 pc^2 of NGC 7129 indicates the stellar population to occupy a wide range of masses and ages. An (H-K) - (R-I) diagram, in which the (H-K) index measures heated dust while the (R-I) index measures stellar photosphere, indicates a high fraction of star + disk/envelope candidates.

PROGRESS-TO-DATE

1) *Ae/Be stars often define the centers of small, partially-embedded aggregates of 10-50 stars formed within a single molecular core.* In contrast to their lower mass counterparts, we find that even apparently isolated, young high-mass stars do not seem to have formed alone.

2) *The accompanying stellar aggregates are compact and dense.* We find that molecular condensations traditionally defined as "cores" ($\rho \sim 10^4$ g cm^{-3}; d $\sim$ 0.2 pc) and expected to collapse and produce single stars, are instead capable of producing dense clusters of 10's of stars. The stellar volume densities derived from star counts within sub-pc regions containing Ae/Be stars are typically a few $\times 10^3$ pc^{-3}.

3) *The aggregate members are young.* Based on their locations in the HR diagram, ages range from just several hundred thousand to a few million years. Furthermore, many of the stars found to accompany the massive Ae/Be objects display significant infrared excesses and Balmer emission features, signifying that they, too, are young stars with large amounts of remnant circumstellar material.