Chapter 1

Introduction and Outline

1.1 Techniques for and Goals of Studying Young Stellar Populations

The young stellar populations in extended star-forming complexes have been studied for decades through optical photometry and spectroscopy. Most notable amongst early work is the classic series of papers by Walker in the 1950's and 1960's on the color-magnitude diagrams of extremely young, complex star forming regions (M8, M16, IC 5146, NGC 2264, and the Orion Nebula). These initial studies, and others like them, were carried out using blue-sensitive photographic plates (B,V photometry and blue spectra). The prevalent method of analysis was to obtain spectra for a few of the brightest stars, then determine a mean value for the interstellar extinction to the cluster and apply this value to all stars in the survey. More recently, optical investigations of star-forming regions have relied upon longer wavelength CCD observations (R,I photometry and red spectra) in order both to minimize the effects of sometimes significant extinction and to probe to redder, lower-mass stars. With these larger spectroscopic surveys, estimates of the reddening towards individual stars are possible. Analyses based solely on infrared data (J,H,K photometry and H- or K-band spectra) are also underway, and will enable the most complete stellar census surveys possible in regions of high molecular obscuration.

While specific photometric and spectroscopic techniques have varied from study to study, the basic goal of all of these investigations has been the same: to determine 1) the ages and masses of individual stars, and 2) the age spreads and mass spectra of composite clusters. With age and mass information we can examine issues related to star formation histories, that is, the sequence of star formation with mass or with position in a cluster. In particular, for all star formation sites, we would like to be able to relate the bulk properties of the output stellar products to the initial conditions in the clouds from which the stars formed. We are still a long way from reaching this goal of course, but are making progress by refining the level of the questions we are asking.

1.2 Re-Casting the Problem of "Initial" Mass Functions

As stellar populations studies in star-forming regions have progressed (as described above) towards longer wavelengths with time, the spatial scales over which deep unbiased imaging surveys are being carried out, have become smaller. This trend is motivated, in part, by a redefinition of our ability to address issues such as the initial mass function. Historically, photometric - plus - spectroscopic investigations of mass functions (or, more typically, luminosity functions) in star-forming regions have been carried out in populous OB associations, such as those mentioned above, comprised of stars which appear to have formed over millions of years and over tens of parsecs. From these investigations we have learned, at least at the high-mass ($M \gtrsim 10$ $M_\odot$) end, that mass spectra do appear to be universal, following a single power-law slope to within the errors (see references and discussion in Sec. 3.3 of Massey, *et al.* 1995). However, in the cases of associations, the derived mass spectra necessarily represent averages in both time and space, which encompass all star-forming "events" having occurred over the age and extent of the clusters.

In order to investigate truly *initial* mass functions, we must narrow the considered ranges in time and space. One possibility would be to examine stellar masses in large complexes *over short temporal scales* ($\lesssim 1$ Myr), for example by isolating stars along isochrones in an HR diagram. Another possibility would be to examine stellar masses in large complexes *on small spatial scales* ($\lesssim 1$ *pc*), for example by isolating stars in spatial sub-groups. Advocates of so-called universal mass functions would have us believe that, no matter how the cluster parameters of time and space are divided, a standard mass spectrum should always be recovered. We wish to test this hypothesis.

It is of course impossible in a real stellar association to parse the problem as cleanly as we have outlined above, since we can not reconstruct the spatial and temporal sequence of star formation, and thereby "resolve-out" the space- and time- integrations which are implicit when the association as it appears to us today is considered as a whole. Thus, in examinations of large cluster complexes, we are unable to determine whether, indeed, all star-forming subunits do produce identical mass spectra at all times, or whether particular epochs or regions favor the production of high- or low- mass stars. To rigorously investigate the validity of universal mass functions, we must study the mass spectra produced by *individual star formation "events."* This requires investigation of stellar populations which are *both* coeval and spatially coherent, and thus moving away from studies of large optically revealed complexes and towards analyses of the young stellar products formed within smaller, isolated molecular cores [1].

Probing the stellar populations which may be embedded in cores of significant molecular column density requires infrared technology. Deep infrared imaging surveys over the past several years have revealed that many isolated molecular cloud cores are 1) forming stars which are not yet optically visible and 2) forming not just single stars, but aggregates and small clusters of stars (*cf.* Lada,

[1]

A "core" is canonically defined as a ~ 10 $M_\odot$, ~ 0.2 pc, $\sim 10^4$ cm^{-3} molecular enhancement expected to collapse under self-gravity and produce a single star (Benson & Myers 1989, Myers, Linke, & Benson 1983).

et al. 1991). These young clusters, together with the remnant molecular material, are likely to be still bound systems. They thus appear to be pristine groups, in the sense that no stars are likely to have escaped from the core/cluster system, and so the local stellar populations "seen" today represent the total output by the cores to the current epoch. If we can accurately determine the masses and ages of individual stars located in these types of isolated aggregates, we can then address the questions of interest on the spectrum of initial stellar masses and the time sequencing of star formation among stars of different mass.

1.3 Sample Selection for this Investigation

Having justified our interest in stellar populations found in isolated molecular cores (as opposed to characteristically older, larger complexes), we now make one further refinement to our questions regarding the initial mass function. Investigations of isolated star-formation sites which have already produced high-mass stars are uniquely advantageous for probing the universality of initial mass spectra, as it is in these types of regions that we are most likely to uncover deviations from standard mass functions, if such deviations exist. By this we mean that given samples of stars with large enough dynamic ranges in stellar mass, it is easier to test whether one or a few high-mass stars are accompanied by their expected complement of low-mass stars, than it is to test whether a group of predominantly low-mass stars is replete with an only rarely expected high-mass star. [2]

In this thesis we report the results of a detailed study of stellar populations in isolated, core-sized regions containing young ($\tau \lesssim 1$ Myr), intermediate / high-mass ($M \gtrsim 3$ M$_\odot$) stars. Our survey sample is drawn from the set of

[2] However, given a rich enough sample of clusters, we do recognize that the latter technique would be the more statistically robust approach.

pre-main sequence Herbig Ae/Be stars. This selection is motivated by our interest in capturing recently born stellar populations associated with the youngest, most massive stars. Because they are optically revealed stars, we have enough information available to us about individual Ae/Be stars (see general description of the population in Appendix A) so that we know their masses to reasonable accuracy, about 10% in most cases. Their ages, although anecdotally extremely young, are uncertain at the Myr level or by more than 100%. We will now discuss the accuracy of, in turn, Ae/Be masses and ages.

To determine stellar masses for this study, we use an unpublished analysis (Ghandour, Hillenbrand, & Strom 1995) of classification - resolution blue Ae/Be spectra. As described in Appendix A, spectral types are translated into effective temperatures while Balmer wing depths are translated into surface gravities. Stars can then be placed onto a theoretical grid of surface gravity as a function of effective temperature in the HR diagram. The resulting luminosity value provides us with a radius, from $R = \sqrt{L/4\pi\sigma T_{eff}^4}$, and finally, the mass is computed from $g = GM/R^2$. For stars without measured surface gravities, the masses are derived from the main sequence mass-luminosity relationship (which is adequate given the proximity of most Ae/Be stars to the main sequence) applied to luminosities calculated from reddening-corrected V-magnitudes. Comparison of the masses derived from surface gravities with those derived from a mass-luminosity relationship, in cases where both are available, shows good agreement in most cases.

To estimate stellar ages we can not rely upon HR diagram analysis, as we have done to estimate stellar masses, since there is considerable uncertainty in the theoretical isochrones near the zero-age main sequence for high-mass stars. There are two reasons for this. First, the "zero-point" of pre-main sequence evolution is not well-established for high-mass stars, for reasons having to do with our currently poor understanding of the physics of the initial accretion episode (see discussion in Chapter 8). Second, the rapidity of pre-main sequence evolution for high-mass stars (less than 1 Myr for stars more massive than 5 $M_{\odot}$) means that small uncertainties in theoretical evolutionary timescales translate into large differences in predicted locations in the log $(L_*/L_{\odot})$ - log T_{eff} plane. In addition, for these same reasons, observational errors in locating stars in the HR diagram imply extremely large uncertainties in stellar ages – even if the theory is assumed to be entirely correct. Thus, as we can not accurately or reliably age date high-mass pre-main sequence stars, we must rely upon circumstantial evidence of stellar youth. The general youthfulness of the Ae/Be population is supported by their surroundings (association with molecular clouds; illumination of reflection nebulosities), stellar parameters (photometrically determined locations in the pre-main sequence domain of the HR diagram; low surface gravities; presence of Li I λ6707 in a few cases [3], significant continuum flux excesses (diagnosed via infrared, submillimeter, and millimeter measurements), and activity (strong variable permitted and forbidden emission lines; rapid photometric and in some cases polarimetric variability; centimeter continuum emission; molecular outflows).

To ensure the youth of our sample, we have selected from among the several tens of candidate Ae/Be stars (*cf.* the compilation by Thé, de Winter, & Perez, 1994), a set which exhibit near infrared spectral energy distributions consistent with those expected from stars surrounded by remant protostellar disk / envelope structures. We justify this restriction as follows. Large-scale unbiased imaging

[3] The presence of Li I , a line usually thought of as an accurate chronometer for young low-mass stars but as quickly destroyed in higher-mass stars, interestingly occurs in at least two Ae/Be stars which are known to have nearby low-mass companions (HK Ori and V380 Ori – see Appendix B); this might indicate spectroscopic confusion as a simple explanation for the presence of Li I . Alternatively, the presence of Li I might indicate some of the purported Ae/Be stars in fact to be low-mass stars undergoing phases of rapid accretion and masquerading in luminosity as higher-mass stars.

surveys of young ($0.1 < \tau/Myr < 3$) star-forming complexes with significant high-mass stellar populations, regions in which *many* analogs of Ae/Be stars might be expected, have surprisingly revealed only a small number of Ae/Be candidates (see preliminary results in Hillenbrand *et al.* , 1993b and a completed study of NGC 6611 in Hillenbrand *et al.* , 1993a). This conclusion is based upon searches for objects showing infrared photometric properties similar to Ae/Be stars, namely, the existence of circumstellar excess emission in the $(J-H)-(H-K)$ color-color diagram. If observation of a near-infrared excess can indeed be used reliably to indicate the presence of a remnant disk/envelope associated with the star formation process, that the fraction of such objects is low in extremely young high-mass star-forming complexes, implies that the typical disk / envelope lifetimes for massive stars must be short ($\lesssim 1$ Myr). Thus, although direct confirmation from HR diagrams of the suspected short duration of the Ae/Be phase is difficult, under the assumption that high-mass star / disk / envelope structures do not survive for very long, we assert the following: identifying a rare sample of massive stars with disk / envelope signatures ensures us that they are among the youngest stars in their mass range.

In Table 1.1 we present spectral classifications, extinction values, photometric data, stellar parameters (masses, radii, luminosities, and surface gravities), coordinates, and distances for all star / disk / envelope (Group I and Group II) systems accessible from the northern hemisphere in the study of Hillenbrand *et al.* (1992). It is from this initial list that we draw our sample for investigation of stellar populations associated with cores identified by the presence of an Ae/Be star.

Stars listed in Table 1.1 include those found in giant molecular clouds as parts of extended star-forming complexes containing tens to hundreds of high-mass stars, as well as those found in smaller molecular clouds and cloud cores containing just

Table 1.1. Initial Sample of Group I and Group II Ae/Be Stars

Name	Gr.	Sp.T.	A_V mag	V mag	K mag	M $M_\odot$	log L $L_\odot$	R $R_\odot$	log g cm^2/s	RA 1950.	DEC 1950.	Assoc. Name	dist pc	θ/pc min	VLSR km/s
LkHα 198	II	A5	2.5	14.32	6.30	9.6	3.4	25.4	2.7	00 08 47.78	+58 32 48.6	L1265	600	5.5	+0.3
V376 Cas	II	F0	2.9	15.50	6.10	1.3	0.5	1.2	–	00 08 47.56	+58 33 22.5	L1265	600	5.5	+0.3
BD+61 154	I	B8	2.1	10.38	5.70	5.1	2.8	6.7	3.5	00 40 21.94	+61 38 15.1	N225	650	6.0	+3.2
Elias I	II	A6	4.1	15.30	5.64	0.9	-0.1	0.5	–	04 15 34.51	+28 12 01.8		160	21.	
AB Aur	I	A0	0.4	7.07	4.40	2.5	1.4	1.7	4.4	04 52 34.24	+30 28 21.9	L1517	160	21.	+6.0
UX Ori	I	A3	1.2	10.73	7.40	3.2	1.8	3.5	–	05 02 00.62	–03 51 19.5		460	7.2	
HK Ori	I	A3	1.4	11.66	7.29	2.2	1.2	1.8	–	05 28 40.08	+12 07 00.2		460	7.2	+10.6
HD 245185	II	A1	0.1	9.90	8.26	2.1	1.2	1.6	4.4	05 32 24.08	+09 59 57.2		400	8.3	
T Ori	I	A2	1.3	10.35	6.22	3.5	1.9	3.7	3.8	05 33 23.05	–05 30 25.9		460	7.2	
V380 Ori	I	B9	1.7	10.37	6.09	3.6	1.9	2.4	–	05 33 59.50	–06 44 46.4	N1999	460	7.2	+8.9
BF Ori	I	A7	0.5	11.92	8.03	1.6	0.7	1.2	–	05 34 47.24	–06 36 45.3		460	7.2	
RR Tau	I	A3	1.1	11.07	7.10	8.4	3.2	17.8	2.9	05 36 23.84	+26 20 49.2		800	4.2	–5.4
HD 250550	I	B9	0.3	9.54	6.63	3.9	2.1	3.1	–	05 59 06.43	+16 30 59.4		700	4.8	+2.4
LkHα 208	I	A2	1.7	11.62	8.88	4.1	2.3	5.4	3.6	06 04 53.17	+18 39 55.0		1000	3.3	+0.2
MWC 137	I	B0	4.5	11.84	6.41	18.9	4.5	6.2	–	06 15 53.51	+15 18 09.1		1300	2.6	–30.
LkHα 215	I	B7	2.0	10.36	6.90	9.5	3.5	13.1	3.2	06 29 56.10	+10 11 24.0	N2245	800	4.2	+2.9
HD 259431	I	B5	1.3	8.70	5.68	8.9	3.5	9.5	3.4	06 30 19.40	+10 21 38.0	N2247	800	4.2	+4.8
R Mon	II	B0	4.3	12.80	5.83	10.4	3.6	2.2	–	06 36 26.05	+08 46 54.5	N2261	800	4.2	+9.4
LkHα 25	II	B7	0.9	12.75	9.42	3.8	2.2	3.0	4.1	06 37 59.49	+09 50 53.4	N2264	800	4.2	
LkHα 218	I	A0	1.3	11.87	8.50	3.8	2.1	4.0	3.8	07 00 21.90	–11 21 46.0		1150	2.9	
HD 150193	I	A2	1.5	8.80	5.51	2.5	1.4	2.0	4.2	16 37 16.44	–23 47 56.4	ρ Oph	160	21.	
KK Oph	I	A3	1.9	10.57	5.64	7.4	3.0	13.8	3.0	17 07 00.73	–27 11 36.2		160	21.	
HD 163296	I	A0	0.3	6.83	4.72	3.3	1.8	2.8	–	17 53 20.65	–21 56 57.0		160	21.	
MWC 297	I	O9	8.3	12.17	3.08	26.5	5.0	8.5	–	18 25 00.9	–03 51 39		450	7.4	+5.7
VV Ser	I	B9	3.0	11.87	5.61	7.5	3.1	9.8	3.3	18 26 14.33	+00 06 39.6		440	7.6	+8
Par 21	II	F8	2.2	13.93	9.90	1.3	0.4	1.6	–	19 26 37.50	+09 32 24.0		400	8.3	
V1686 Cyg	I	B5	4.8	12.90	6.17	8.5	3.3	7.5	–	20 18 43.62	+41 11 54.3	N6910	1000	3.3	+7.8
BD+40 4124	I	B2	3.0	10.54	5.78	12.6	3.9	8.3	–	20 18 42.50	+41 12 20.0	N6910	1000	3.3	+7.8
HD 200775	I	B3	1.9	7.36	4.70	7.2	3.3	4.5	4.0	21 00 59.70	+67 57 55.5	N7023	600	5.5	+1.0
LkHα 234	I	B3	3.4	11.90	6.84	8.5	3.2	4.6	–	21 41 57.60	+65 53 07.1	N7129	1000	3.3	-10.0
BD+46 3471	I	A0	1.0	8.21	6.58	7.3	3.0	12.8	–	21 50 38.55	+46 59 35.4	IC5146	900	3.7	+6.5
LkHα 233	II	A5	2.6	13.56	8.30	2.6	1.5	2.6	–	22 32 28.26	+40 24 32.2	Lac OBI	880	3.8	+0.1
MWC 1080	I	B0	5.3	11.68	4.70	20.6	4.6	7.2	–	23 15 14.84	+60 34 19.2		1000	3.3	–29.3

one or a few high-mass stars. We target for our study those young massive Ae/Be stars which are found in isolated cores, which we define to mean not associated with any large complex of star formation, such as Orion or NGC 2264. Finally, we prioritize the surviving sample by mass. In reality we have obtained some form of imaging data (optical or infrared or both) for most of the stars in Table 1.1, but will include the entire set only when we discuss the effects of nearby companions on the Ae/Be spectral energy distributions (Appendix B). Otherwise, our "sample" is strictly comprised of 17 intermediate / high-mass ($M \gtrsim 3\ M_{\odot}$) Ae/Be stars which are presumably young ($\tau \lesssim 1$ Myr) and apparently isolated on the sky. These stars are denoted explicitly in Table 2.1 in the following Chapter, and in Table 5.1 in which we present our summary of the local clustering properties.

1.4 Procedures and Aims

With assumed ages of only a few hundred thousand years, our sample of Ae/Be stars is likely to be comprised of objects found within a few tenths of a parsec of their birthplaces. According to radial velocity studies comparing photospheric with cloud LSR velocities (Finkenzeller & Jankovics, 1983), and conclusions reached from the two-dimensional molecular gas distributions (see below and Loren, 1975), the Ae/Be stars do appear to be still associated with the molecular material from which they formed. Multiwavelength survey techniques, as described below, therefore enable us to do two things. First, we can isolate and then quantify the environmental conditions at or near the time and place of "birth" of these high-mass stars. Second, we can carry out a complete census of the objects formed relatively contemporaneously with young high-mass stars. As long as the timescale for star formation is shorter than the dynamical cluster dispersal time and/or the gas removal time, any accompanying young stars are likely to be physically associated with the cloud core, the other members of the aggregate, and the Ae/Be star.

Our plan, therefore, was to conduct a deep optical and infrared imaging survey to the same physical completeness level in stellar mass, age, and extinction for each Ae/Be site. However, because of unavoidable variety in source distance, image quality, and instrumental sensitivity, the data we obtained permitted a survey which was uniformly complete between different Ae/Be regions only over a fixed linear size scale, which we established from examination of our infrared images. With these imaging observations alone, we could: 1) assess the degree to which Ae/Be stars are found amidst local condensations of lower mass stars; 2) compute statistics regarding the number and number density of companion stars; 3) estimate the fraction of accompanying stars surrounded by circumstellar material; and 4) roughly gauge the mass and age composition of the stellar population based on color-magnitude diagrams.

Regions with significant numbers of optically visible companions were then targeted for spectroscopic follow-up. With spectra and photometry we could construct HR diagrams of the stellar populations, from which the relative masses and ages of individual stars could be more accurately determined. Thus, we could answer questions on: 1) the spread in age of stars found within the same cluster or association as a high mass pre-main sequence star; 2) the formation time of the central high-mass star relative to the formation times of the accompanying lower mass stars; 3) the range in mass of stars found within the same cluster or association as a high mass pre-main sequence star; 4) details of the stellar mass spectrum, including whether differences exist between the coherent *initial* mass spectra found in extremely young, isolated regions and the "universal" mass functions inferred a) in slightly older and larger high-mass clusters, b) in regions of primarily low-mass star formation, or c) in the well-mixed field.

Finally, a molecular survey of the regions containing Ae/Be stars was carried out as a complement to our imaging work. By observing both low- and high-density molecular gas, we could: 1) ascertain the morphology and physical structure of the cloud cores; 2) construct visual extinction maps based on derived gas opacities; 3) calculate the sizes and masses of remnant ambient molecular material; and 4) identify candidate molecular outflow sources. We acknowledge that one risk of attempting to trace the gas properties in cores which have already produced stars, of course, is that the star formation process itself may have altered the initial core properties; we find evidence of this in a few cases. In most cases, however, the detection of molecular gas implies not only that the stars found near the cores are extremely young, but also that star formation may be ongoing.

1.5 Outline of Presentation

This ideal plan of obtaining uniformly complete molecular, photometric, and spectroscopic data on *all* priority regions (those containing the youngest, most massive, most isolated Herbig Ae/Be stars) was of course mediated due to observational constraints. Thus the approach we take in presenting each type of data set, is to describe our survey technique and our analysis, and to summarize (using examples) the global properties of the Ae/Be star-forming sites. There are three regions (BD +40° 4124, LK Hα 215, and NGC 7129) for which we in fact have obtained fully sampled molecular, photometric, and spectroscopic data sets, and can rigorously address the questions outlined above. Although we do not base our analysis solely on these three regions, or explicitly carry each of them though every step of the presentation, we do feature them throughout.

We begin with a presentation of our molecular dataset (Chapter 2) followed by description of our optical and infrared imaging programs (Chapter 3) and our ongoing spectroscopic program (Chapter 4). From the large-field molecular and optical surveys we can characterize the general attributes of the isolated clouds within which massive Ae/Be stars are forming. Focussing on the infrared survey, in Chapter 5 we define an appropriate size scale over which to characterize the clustering properties of the companions found in physical association with Ae/Be stars, and investigate the distribution of stellar surface densities with Ae/Be mass. We then turn towards deciphering the nature of the members of these newly discovered aggregates, and present evidence in Chapters 6, 7, and 8 that these stars are also young pre-main sequence stars, of lower mass. With this evidence, in Chapter 9 we explore techniques for investigating the distribution of stellar masses and ages in our sample of small, partially embedded stellar aggregrates, as well as the limits of these techniques. In Chapter 10 we discuss the potential role of local environment (molecular and stellar clustering) in the star formation process. A summary of our presentation and conclusions can be found in Chapter 11.

There are three Appendicies to this work. They contain information on the general properites of the Herbig Ae/Be population, the sample of young high-mass stars upon which this study is based (Appendix A); nearby companions uncovered in our imaging survey, which are projected close enough to the Ae/Be stars possibly to influence their near-infrared spectral energy distributions (Appendix B); and a description of the unpublished data set on the Trapezium region used in Chapter 8 in discussing pre-main sequence evolutionary tracks (Appendix C).