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OB Associations: Massive Stars in Context

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ABSTRACT. Massive stars are important in a variety of contexts: individually they are examples of stars that undergo significant mass loss which is driven by line radiation pressure; as denizens of the Galaxy they play a significant role in the galactic recycling effort; as ensembles of stars they contain clues to massive star evolution in general and the question of supernova progenitors in particular. Finally, under extreme conditions of pathological star formation massive stars participate in the star burst phenomena seen in some galaxies. If we wish to understand star bursts, we must first understand locally observed variations in the mass spectrum. But all of these diverse areas of study rely on certain fundamental parameters of the stars themselves—here we include temperature, luminosity, mass, and chemical composition. And central to accurate determinations of these parameters are the distances to the stars. This review will focus on what is known about the loose clustering of massive stars termed OB associations. These associations contain many, but by no means all, of the stars with masses greater than $15M_\odot$. Most of our knowledge of the stellar content of the OB associations in our own Galaxy is surprisingly sketchy due to their large angular size, but large-field CCD detectors are changing this. Magellanic Cloud associations can now be compared with OB associations in our own Galaxy, and the initial mass function shows surprising variations. The physical cause of these variations is still unknown. Another development is the study of embedded star clusters: infrared array detectors have been probing the buried stars in molecular clouds and finding an unexpectedly large population of these objects. Both these young IR clusters, and a sprinkling of evolved red supergiants, suggest that the star-formation history of OB associations may be more complicated than we have supposed.

1. INTRODUCTION AND HISTORY

Massive stars, of spectral-type O and early B, live short violent lives but manage to create sufficient excitement to keep astronomers intrigued and busy trying to explain them. The past decade has seen remarkable developments in many areas that pertain to them. Since these stars cannot travel far from their place of formation, we can still see the ragged remains of their birthplaces, which in many cases are still apparently undergoing star formation. The ionizing radiation of these stars created H II regions that call attention to events in progress. Stellar atmosphere studies and the development of wind theory, combined with evolutionary models of these massive objects, have led to an evolutionary scenario encompassing not only normal massive stars, but also the rare and bizarre Wolf–Rayet stars and luminous blue variables—but then came SN 1987A! Concurrently, studies of starburst galaxies have fueled interest in the mass function at the upper end of the HR diagram, and in what factors, if any, might cause variations that appear to be present in distant galaxies where the individual stars cannot yet be observed.

In addition to many individual papers, a number of recent conference proceedings provide discussions of OB associations. In particular, the interested reader should refer to *Birth and Evolution of Massive Stars and Stellar Groups* (Boland and Van Woerden 1985), *The Formation and Evolution of Star Clusters* (Janes 1991), and *Massive Stars: Their Lives in the Interstellar Medium* (Cassinelli and Churchwell 1993).

An OB association is a large, gravitationally unbound clustering of stars that includes B-type and, by the definition adopted in this review, at least a few O-type stars. They are generally many tens of parcsecs in diameter, much larger than open star clusters. They are remarkable for their structure, which close examination often reveals to consist of stellar subgroups with different ages and kinematics. Many contain what will be referred to as OB clusters within them as well. These clusters are not to be confused with classical galactic clusters, but are rather denser subclusters, which are often superficially distinguished because they are identified by NGC numbers. In our Galaxy, the apparent size of galactic clusters within a few kiloparsecs are generally of the order of arcminutes in diameter; OB associations are as large as 5° to 10° across. Giant molecular clouds, wind-blown bubbles, and H II regions are some of the additional signposts of associations.

The tendency of early-type stars to cluster was noted over 80 years ago: Kapteyn (1914) presented a map of the helium stars, as they were called then, for the entire galactic plane and remarked on their distribution, as did Eddington (1914). Kapteyn (1918) also discussed the O and B stars in the region of Orion and commented that the increasing concentration with earlier spectral type suggested a local grouping which he thought very probably was part of the Orion nebula. Ambartzumian (1947) was the first to refer to them as associations and to suggest that they are young in comparison to other stars in the Galaxy; this agreed with estimates of stellar age for O and B stars based on their luminosity. The discovery of the rapid expansion of Perseus OB2 by Blaauw (1952) confirmed Ambartzumian's hypothesis that they are gravitationally unbound.

The foundation for the systematic study of associations was laid in particular by Morgan, both in his development of the MK system of spectral classification and in the calibration of MK types, *UBV* photometry, and absolute magnitudes (Morgan et al. 1953). These calibrations rely even today on the extrapolation, via well-studied clusters, from nearby stars with large parallaxes to the very distant O and early B-type stars. With the determination of distance to these stellar groups, their value as indicators of galactic structure became clear: the first evidence for Galactic spiral structure was found by Morgan et al. (1952) from the distribution of H II regions excited by OB stars. This was subsequently extended by Becker (1963) who showed that associations with spectral types of O to B2 showed more pronounced spiral structure than later clusters and associations. Becker's work relied on many studies of individual associations; typically, members were discovered from objective-prism surveys, and confirmed from photometry, radial velocities, and proper-motion work. Examples for some of the better known associations include Sharpless' (1962) work on Orion OB1, the study of Lacerta OB1 by Hardie and Seyfert (1959), and Blaauw et al. (1959) study of Cepheus OB3. These are all within 1 kpc: with increasing distance only the brightest stars in associations can be identified, so any discussion of boundaries or membership can be quite uncertain. Caution is still advised in quoting properties of OB associations beyond about 1 kpc.

In a review that is still relevant today, Blaauw (1964) provided a comprehensive discussion of the intrinsic properties of the OB associations within 1 kpc of the Sun. For most of these associations spectral classification, photometry, proper motions, and radial velocities were available for the brighter stars, but Blaauw considered the question of membership of the fainter stars to be "in a most unsatisfactory state." The situation has not changed much in the intervening years, and for exactly the reasons he gave. First, the numbers of faint members do not appear to increase rapidly with decreasing luminosity; thus even the smaller associations do not stand out with respect to the galactic background as do galactic clusters in general; second, the associations are spread over such a large area of the sky that extensive observational effort is required to identify members. The outer regions appear to merge with the general B-star distribution, making it difficult to define the boundary.

Associations cannot be thought of as monolithic structures. Proper-motion studies aimed at investigating internal motions and photometric work revealed stellar subgroups of different evolutionary ages. Blaauw (1964) reviewed the evidence: the subgroups he discussed are spatially distinct features that often show different expansion and photometric ages. Figure 1, taken from his 1964 review, shows the spatial distribution of three classical OB associations. He noted that "the proportion of earliest-type stars is always largest in the most concentrated subsystem" and "the degree of association with the interstellar matter decreases with increasing size and evolutionary stage." These subgroups studied by Blaauw and others (Crawford 1961; Warren and Hesser 1978) did not depend on the existence of highly evolved B and M supergiants, but

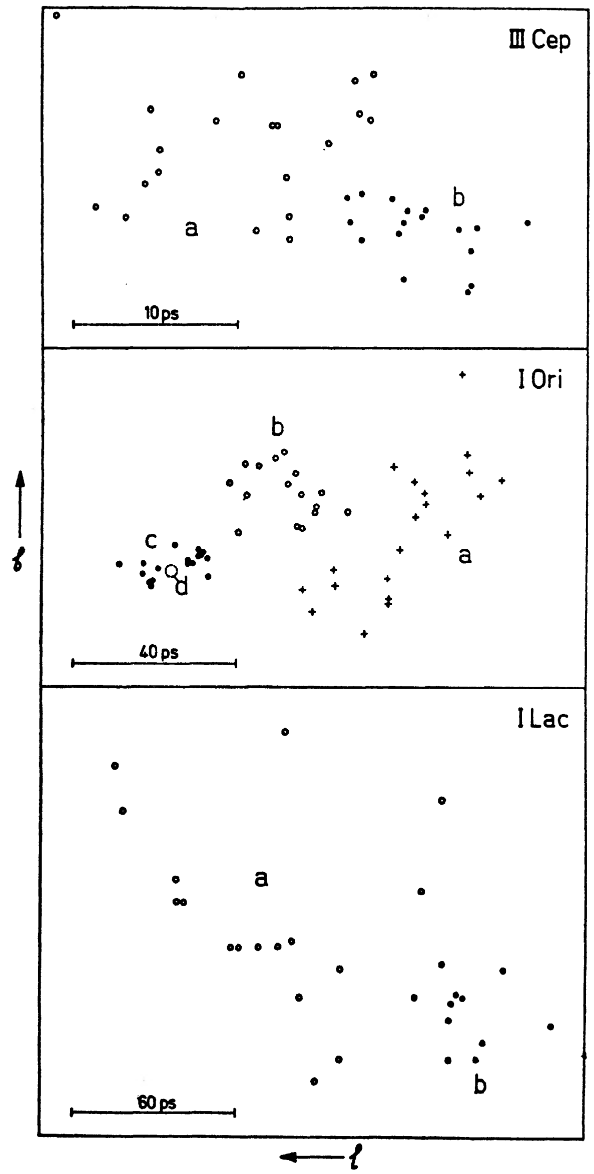

FIG. 1—Spatial distribution of stars in three nearby OB associations. Different symbols indicate subgroups a, b, c..., of increasing age. (Blaauw 1964, reprinted with permission from *Annual Review of Astronomy and Astrophysics.*)

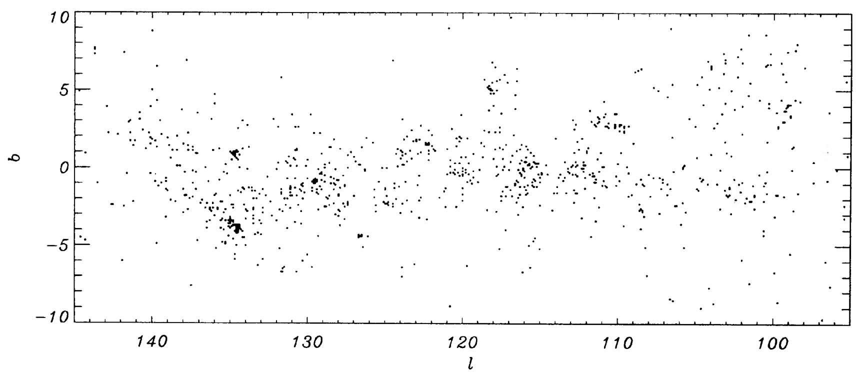

FIG. 2—The distribution over a section of the galactic plane of all O and early B-type stars for which both photometry and spectral types have been published. The sources of these data are discussed in Garmany and Stencel 1992.

rather on the position of stars along the main-sequence and the expansion ages. This distinction should be made in comparing recent discussion about association subgroups with the older work.

The studies of expansion in association based on proper motions led to a puzzle. In all cases the kinematical expansion ages are significantly less, often by a factor of 2, than the photometric ages based on theoretical evolutionary tracks. The proper-motion studies, including radial-velocity data, derived the expansion age from the ratio of the star's distance from the center and the component of proper motion along the same line. Studies by Lesh (1969) yielded ages of 1.3×10^6 yr in Per OB2 and 2.5×10^6 yr in the younger subgroup of Lac OB1; Blaauw (1964) found an age of 7.1×10^6 yr in the larger, older subgroup of Lac OB1. Lesh (1968) also examined the subgroups of Orion and derived 4.5×10^6 yr for the oldest. De Vegt (1966) found 1.6×10^6 yr for Cephei OB3. Although the resolution of this discrepancy awaits the results of the *HIPPARCOS* astrometric mission, a possible explanation has been suggested by Blaauw (1984). He suggested that the initial dimensions of the subgroups may have been cigar shaped, and not much smaller than at present. Therefore the assumption of uniform expansion from a small volume is incorrect.

Distances to associations beyond 1 kpc have been derived from the mean spectroscopic parallax of their members. Thus the distance is intimately tied to the luminosity calibration of these rare, luminous stars. As no O- and B-type stars are near enough for parallax measurements, the luminosity calibration was performed by bootstrapping from the main-sequence fit to the Hyades and the B-star association Scorpio-Centaurus (Blaauw 1963). The careful work by Walborn (1973) on the classification of O-type stars set the stage for much subsequent interest in these most massive stars.

2. GALACTIC ASSOCIATIONS: DISTRIBUTION

Figure 2 is a plot of all O and early B stars with both photometry and spectral classification in the northern sky from $l=95°$ and 145° discussed by Garmany and Stencel (1992). Garmany and Stencel examined association membership from $l=55°$ to 150°, based on a catalog by Blaha and Humphreys (1989) and supplemented with additional data culled from the literature on individual associations and clusters. Although even the untutored eye can find associations in Fig. 2, it is clear that not all stars can be grouped this way.

Not only do many OB stars lie outside associations, but the boundaries of the galactic associations are for the most part very ill defined. The only comprehensive list of boundaries were established by the IAU (*IAU Transactions*, Vol. 12b, 1966), and they are rectangular. A compilation of association members was presented by Humphreys (1978); she did not attempt to include stars farther down the main sequence than B1. Thus it is no surprise that the members, especially of the more distant associations, only weakly define a main sequence in an HR diagram. Figure 3, taken from Garmany and Stencel (1992) illustrates this for the Cep OB1 and Cep OB2 associations. If an OB cluster is part of the association, it is usually the cluster stars that determine the main sequence. Therefore, since distances to all but the closest associations are determined either by main-sequence fitting, or by the spectroscopic parallax of the brighter members, there are discouraging disagreements about individual stellar membership. There is not even agreement as to which clusters belong to any given association. An example of this can be found by comparing Leisawitz's (1988) *Catalog of Open Clusters and Associated Interstellar Matter* with Humphreys' (1978) catalog of association members.

The lack of a well-defined border for associations makes the task of assigning sizes difficult. Associations are much larger than galactic clusters. Young clusters typically have diameters of 10–35 pc (Janes et al. 1988), whereas galactic associations studied by Garmany and Stencel have a mean diameter of 137 pc. In the Large and Small Magellanic Clouds the mean diameters are 78 and 77 pc, respectively (Hodge 1985a). There is no evidence that this difference in size is not an observational artifact. Stellar associations in even more distant galaxies are larger, although Hodge has eloquently described the difficulty in identifying physical

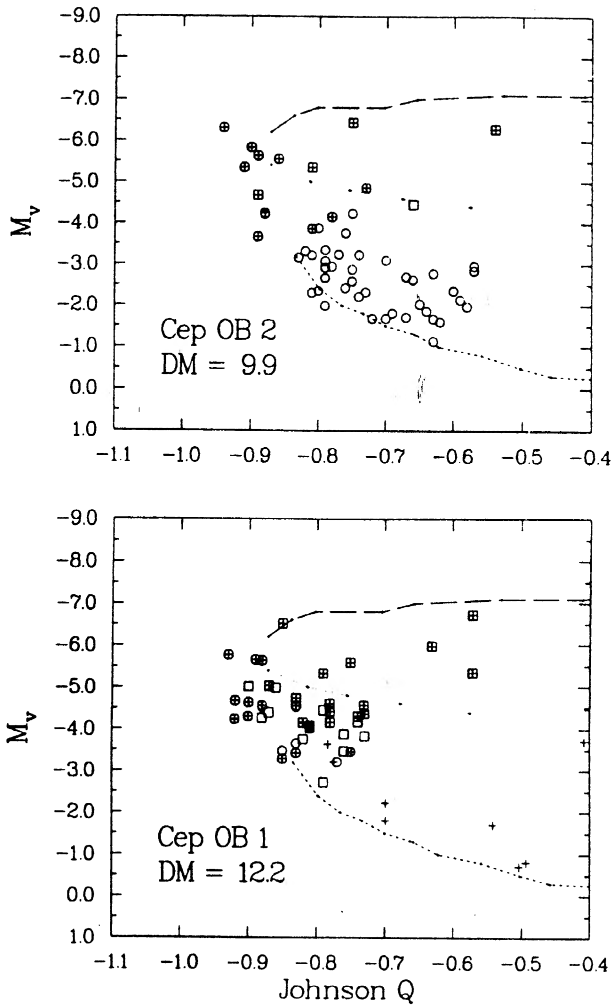

FIG. 3—Color–magnitude diagrams for two OB associations. Plotted are the stellar absolute magnitudes vs. the reddening free parameter Q, with different symbols representing different spectral types. B main-sequence stars are represented by open circles, O-type stars by crossed circles. The association Cep OB2 is relatively nearby and a number of B main-sequence stars have been identified as members, thus as is shown here, main-sequence fitting is straightforward. This is not the case for Cep OB1, a more distant association in which the membership consists mostly of O-type and B supergiant stars. The mean absolute magnitude relations for main-sequence stars from Mermilliod (1981) is shown as a dashed line; giant and supergiant relations are shown as dotted and dot-dashed lines, respectively (from Garmany and Stencel 1992).

associations from asterisms. Estimates range from 480 pc in M31 to 164 pc in IC 1613 and NGC 6822.

3. ASSOCIATIONS: THE RAW MATERIAL

It is clear that interstellar molecular clouds are the birthplace of stars, but all the interesting details still need to be worked out. A comprehensive review of star formation in molecular clouds is presented by Shu et al. (1987): here we are concerned only with the formation of massive stars in such clouds. How is the mass spectrum of these stars (IMF) related to the initial properties of the clouds such as temperature, chemical composition, velocity dispersion, and magnetic field strength? Will the answer to this explain the cause of star bursts of massive stars in distant galaxies?

Among the reasons for ascribing IMF dependence on the cloud properties are theoretical calculations indicating that the amount of fragmentation depends on the Jeans mass, which depends on the density and temperature (Larson 1982, and references therein). If molecular clouds grow by accreting smaller clouds, then, as suggested by Larson, the star formation could shift toward more massive stars with time: the maximum stellar mass should be proportional to the mass of the molecular cloud. The observational evidence offered by Larson for this comes from the study of young emission-line stars in Orion and Taurus (Cohen and Kuhi 1979). These young objects are much less massive than O and B stars, however, and as discussed later, massive molecular clouds are the birthplace of many, but by no means all, massive stars.

Kahn (1974) has theorized that the upper mass limit should be related to chemical composition, i.e., smaller at higher Z because radiation pressure from grains in the surrounding cocoon would prevent further accretion, and grain opacity is proportional to Z. Shields and Tinsley (1976) developed this further and applied it to composition gradients across spiral galaxies. They noted that their conclusions were based on uncertain assumptions, such as the slope of the IMF and the insensitivity of the grain properties to their physical environment. This latter assumption was investigated by Wolfire and Cassinelli (1987) who found that the standard dust mixture does not allow inflow to occur for massive protostars. They explored properties of grains and gas that would permit inflow to occur for a $100M_\odot$ protostar, and concluded that the total grain to gas ratio must be reduced by a factor of 4, and larger graphite grains must be missing in order for inflow to take place. The standard dust mixture could not explain accretion of stars much larger than $30M_\odot$. Since stars with masses in excess of $85M_\odot$ exist in the Milky Way then local rather than global conditions determine the upper mass limit if Wolfire and Cassinelli are correct. A shocked interstellar medium caused by supernovae or stellar winds might produce the necessary grain size distribution.

The density wave theory for spiral arms explains the formation of giant molecular clouds, which then spontaneously undergo star formation. In a classic paper, Becker and Fenkart (1970) discussed the positions of recently formed objects projected onto the Galactic plane, including OB clusters and H II regions. Within several kpc of the Sun, spiral arms are nicely delineated. However, as already illustrated in Fig. 2, many O stars are found outside of associations and clusters. Conti et al. (1983) discussed the spatial distribution of all cataloged O and WR stars within 2.5 kps of the Sun: while the distribution is certainly not homogeneous, only the most optimistic observer would say that spiral arms can clearly be seen. In recent years, evidence has accumulated for the view that massive star formation occurs just as well in the absence of density waves, and that the evidence supporting the density wave triggering hypothesis could have different interpretations. Blaauw

(1985) examined the progression of star formation in the Orion arm and could see no overall gradient in star formation attributable to spiral density waves and suggested stochastic ignition of star formation by runaway stars, based on the chance that a runaway star might explode as a supernova in the proximity of a molecular cloud. A good review is presented by Elmegreen (1986).

3.1 Molecular Clouds

While a substantial portion of interstellar molecular gas is thought to be contained in dwarf clouds that are not restricted to spiral arms, it is the giant clouds containing hot cores that appear to be the birthplace of most OB stars. Mooney and Solomon (1988) found high-mass star-formation activity to be equally likely, based on *IRAS* luminosity, in molecular clouds spanning a range in mass between 3×10^4 and $5\times10^6 M_\odot$. There are numerous individual CO surveys, but the most comprehensive survey of the Galactic plane is that of Dame et al. (1987), who have combined large-scale CO surveys to produce a panorama of the Milky Way as seen in molecular clouds. In their paper, they compare different tracers of Population I objects: dark clouds, CO, *IRAS* 100 μm, and Galactic gamma-ray emission. The best correspondence is between the dark clouds and CO, although the dark clouds represent only relatively nearby molecular clouds.

The lifetimes of giant molecular clouds are much shorter than those of smaller, colder clouds. This result was shown qualitatively by Bash et al. (1977) who found that on average, only open clusters containing main-sequence O stars are associated with molecular clouds, and not clusters with later-type stars. Leisawitz et al. (1989), in a recent CO survey of young clusters, many of which are embedded in associations, found that all of the clusters younger than about 5 Myr each contain at least one large molecular cloud greater than 40 pc in diameter and mass greater than $2\times10^4 M_\odot$, while clusters older than about 10 Myr do not have molecular clouds more massive than a few thousand solar masses associated with them. There is a caveat here: when ages of associations are based on the earliest spectral types found therein, the assumption of coeval star formation is implicit. Yet as noted by Leisawitz et al., evidence points to ongoing star formation.

In 1977, Elmegreen and Lada proposed sequential star formation by OB subgroups near the edge of molecular clouds, in which the ionizing radiation from a stellar group drives an ionization shock front into the cloud, and the material swept up in a thin layer becomes gravitationally unstable and collapses to form new massive stars. This model has many attractive features, including its ability to explain the different ages of subgroups in associations discussed by Blaauw (1964). While earlier work suggested that star-forming cores were primarily found near the edge of molecular clouds, this may have been in part an observational bias. More recent observations of substantial column densities toward protostars indicate they may form at considerable depths in clouds.

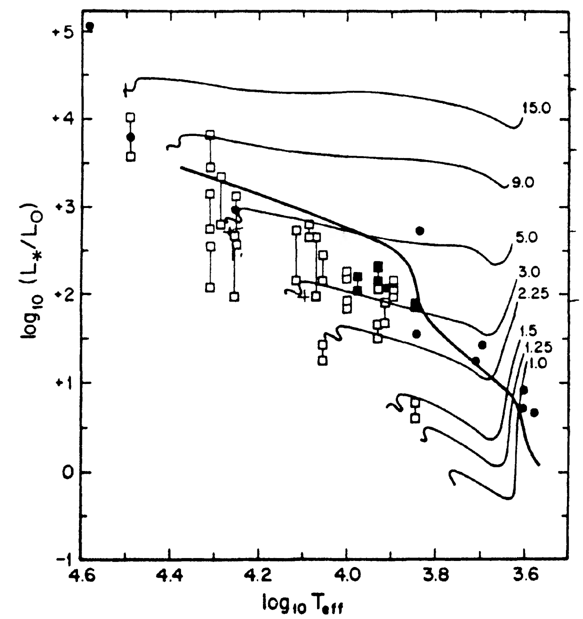

FIG. 4—The stellar birthline, or locus in the HR diagram along which young stars first appear as optically visible objects. This figure, taken from Palla and Stahler (1990), shows the birthline as the heavy line cutting across the lighter pre-main-sequence tracks. The symbols are observed Herbig Ae/Be stars and outflow sources. (Reprinted with permission from the *Astrophysical Journal.*)

3.2 Protostar Formation and Pre-Main-Sequence Stars

The theory of protostar formation is a vigorous and exciting field (see Stahler 1988) and is now reaching the point where results are applicable to OB associations. If the initial cloud is close to a state of hydrostatic balance, then it undergoes nonhomologous or inside out collapse, with the highest density central region collapsing first. This core grows via accretion from its surrounding envelope which is still collapsing. The Kelvin–Helmholtz time scale will be shorter than the infall time scale and the core will reach the main sequence before accretion stops. The luminosity of the protostar is derived both from its accretion shock and from thermonuclear reactions: however, it is invisible at optical wavelengths because of dust in the envelope. Not until accretion has halted does the star appear optically as a pre-main-sequence star. Stahler (1983) has predicted an upper envelope in the HR diagram for optical pre-main-sequence stars, which he terms the birthline, and which agrees well with observed positions of T Tauri stars and Herbig Be and Ae stars. Herbig Ae/Be stars were identified by Herbig (1960) as possible high-mass counterparts to the T Tauri stars. Stahler's birthline intersects the main sequence at about $9M_\odot$, which indicates that for massive stars there will be no observable pre-main-sequence phase (Palla and Stahler 1990). See Fig. 4.

The pre-main-sequence contraction time is essentially Kelvin–Helmholtz collapse; values for massive stare are given by Iben (1965) and are roughly equal to about 1% of the main-sequence life of the star. Thus the reader should keep in mind when examining the HR diagram that the

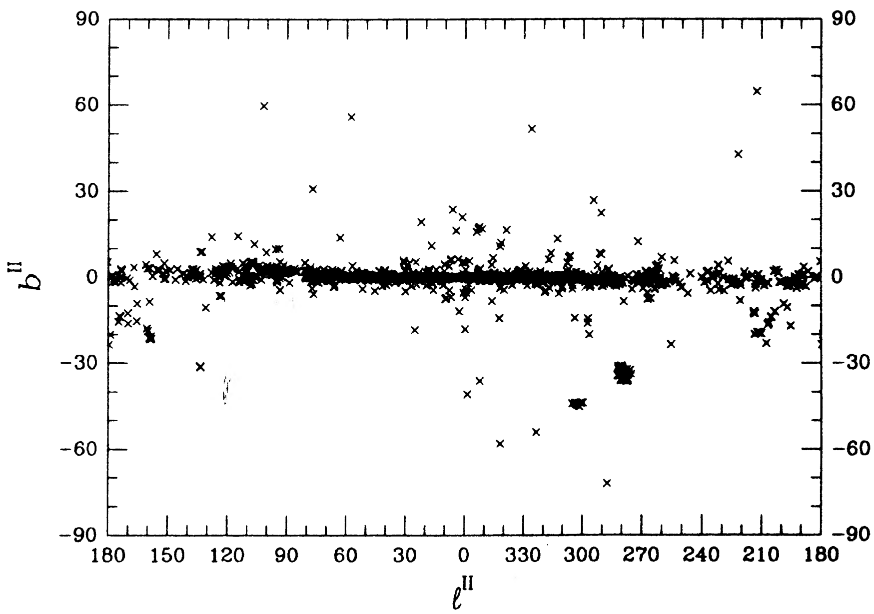

FIG. 5—Distribution in the galactic plane of the candidate ultracompact H II regions (Wood and Churchwell 1989, reprinted with permission from the *Astrophysical Journal*).

pre-main-sequence time for a $3M_{\odot}$ star is 2.5×10^{6} yr, approximately the main-sequence lifetime of a $60M_{\odot}$ star (Maeder and Meynet 1988).

Thus as accretion ceases (a process not yet well understood), stars more massive than about $10M_{\odot}$ are able to produce sufficient UV photons to form detectable H II regions in the surrounding cocoon. The appearance of massive stars in molecular clouds is heralded by compact H II regions or IR sources, temperature peaks in the molecular gas, the presence of water or OH masers, and CO self-absorption. Mezger et al. (1967) were the first to suggest that compact H II regions are the signatures of recently formed O stars. Compact H II regions are some of the most luminous objects in the Galaxy, and some of the strongest *IRAS* point sources; linking these objects to the subsequent appearance of massive luminous stars is extremely interesting. Separated by almost two decades in wavelength, there are no simultaneous observations to date of an embedded O star in both the visible and IR. Workers observing compact H II regions have generally based their derived luminosities on kinematic distances to the stars taken, for example, from the Schmidt rotation model. Their derived spectral types are based on the total luminosity of the source: for example, M17 (NGC 6618) is a strong H II region excited by a cluster containing several highly reddened early O stars. Multicolor photometry by Chini et al. (1980) and others yields a photometric distance of 2.2 kpc. Within the cluster lies a compact H II region, G15.04 −0.68 (Chini et al. 1987).

Prior to the *IRAS* mission, very few compact H II regions had been observed from the infrared to radio. Wood and Churchwell (1989) observed a sample of over 50 ultracompact H II regions (UCH II) with the VLA, and compared them with data from the *IRAS* point source catalog. The shapes of the spectral energy distribution of the UCH II are remarkably similar: they peak at about 100 μm, 3–4 orders of magnitude above that expected from the free–free emission extrapolated from longer wavelengths. The computed Lyman continuum photon flux required to maintain the ionization source implies that these objects are all O and early B stars. When combined with the computed electron densities, emission measure, and diameters, this is consistent with their being small nebulae produced by O and B stars embedded in their placental clouds and radiating most of their energy in the far IR region.

Wood and Churchwell then proceed to show that since the shape of the FIR flux density spectrum of their known sample of embedded O stars is similar for each source, this type of object should be isolated in the *IRAS* color–color plot. Based on the FIR flux distribution which peaks near 100 μm, corresponding to a blackbody of about 30 K, and the *IRAS* bandwidths, they calculate that all embedded O stars in the galaxy as well as some nearby early B stars should be detected by *IRAS*. Their final catalog of *IRAS* candidate UCH II regions strongly supports the assumption that these are young massive stars: the projected distribution on the sky hugs the galactic plane, with less than 4% of the objects at galactic latitude greater than 15°, and they occur primarily in the first and fourth quadrant (Fig. 5). Their distribution matches the CO cloud galactic survey by Dame et al. (1987) very well.

Making the assumption that their *IRAS* sample is mostly O stars uniformly distributed over the galactic disk, Wood and Churchwell have compared the fraction of candidate embedded O stars expected in the volume of the disk surveyed by Conti et al. (1983) for optical O stars. From

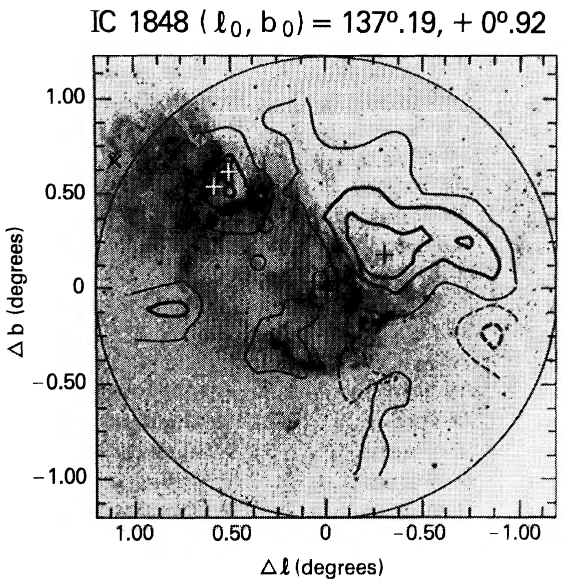

FIG. 6—Contours of CO intensity superimposed on the POSS red plate in IC 1848 within the association Cas OB6 (Leisawitz et al. 1989, reprinted with permission from the *Astrophysical Journal*). I have added multiple circles to indicate the optical position of IC 1848, and single circles to mark the location of additional O-type stars. Pluses mark the location of embedded IR sources 1, 2, and 3 from Wilking et al. (1984) and the location of an ultracompact H II candidate is marked by an x.

this comparison they conclude that about 10% of all O stars in the solar neighborhood within 2.5 kpc of the Sun are currently embedded in molecular clouds. Now, how closely do these embedded star candidates match the boundaries of known associations? Using the study of northern galactic OB associations by Garmany and Stencel (1992) and a list of objects in the *IRAS* point source catalog I examined the positional coincidences in detail. This list satisfies the Wood and Churchwell color criteria but also somewhat arbitrarily requires a 100 μm flux of 500 Jy or greater. There are 72 PSC sources between l=55–141°, and 62 are within or just outside the association boundaries, confirming the supposition that ultracompact H II regions could be embedded O stars.

A composite view of the stages of star formation taking place within an association is illustrated in Fig. 6. This shows IC 1848 in the association Cassiopeiae OB6, taken from Leisawitz et al. (1989) with contours of CO intensity from their molecular survey superimposed on the POSS red print. I have added symbols representing infrared sources from work by Wilking et al. (1984) and an embedded O-star candidate from the list of Wood and Churchwell as well as the location of the rich cluster IC 1848 and some outlying O-type stars. This picture of multiple stages of star formation is repeated in many associations: often the connection between association subgroups or OB clusters is only evident when the molecular clouds and infrared sources are examined. Another interesting case is presented by Sargent (1979) for Cep OB3 which shows the molecular clouds mapped by CO and the two stellar subgroups in this association.

The recent development of large-format near-infrared cameras has allowed imaging in *J*, *H*, and *K* and has revealed clusters of intermediate- and high-mass stars invisible at optical wavelengths. For example, Lada et al. (1991) imaged 9′×9′ of M17 and found evidence for more than 100 stars they classify as OB. They argue that they have completely sampled the cluster down to a spectral type of late B, and from the *K* luminosity function they transform their data to a mass function, which agrees with the Salpeter (1955) slope. Assignments of spectral types derived from infrared luminosities are difficult to compare with high signal to noise slit spectra taken in the visible. A possible breakthrough is described by Conti et al. (1993) who have detected ionized helium absorption lines in the infrared K band spectra of O-type stars. It remains to be seen if these lines will show up in infrared sources and ultracompact H II regions.

An important step toward a quantitative understanding of the pre-main-sequence phase that the Herbig Ae/Be stars represent has been made by Hillenbrand et al. (1993). They have systematically searched for a complete sample of candidate Herbig Ae/Be stars in a number of extremely young OB clusters, something that has not previously been done. Hillenbrand et al. looked at five open clusters, M8, M16, M17, M42, and NGC 2264, and showed that the *JHK* infrared colors can be modeled by a central star surrounded by a dusty optically thick accretion disk.

4. STAR FORMATION: COEVAL, SEQUENTIAL, OR CONTEMPORANEOUS?

To understand star formation in a particular region one needs to know at least two basic parameters: the length of time over which star formation was active in the region and the initial mass function. The presence of subgroups with different ages within an association rules out strict coevality. We now consider the age spread within subgroups and OB clusters. Age-dating clusters from the turn-off point is well established for intermediate-age and globular clusters, but its significance in the case of young OB clusters is problematical, even if the cluster appears to have the necessary evolved supergiants. Herbig (1962) first pointed out the conflict between the upper turn-off age and the age inferred from faint members if the assumption was made that all members were coeval. He proposed that star formation can take place over a long time and is halted only when a high-luminosity star forms and sweeps away the surrounding gas. His examples included Orion and NGC 2264 where K-type emission-line stars assumed to be pre-main-sequence are present, as well as G and K giants assumed to represent evolved B- or A-type stars because they show no sign of associated nebulosity, variability, or abnormal lithium abundance.

If stars form with a continuous probability distribution given by any accepted form of the IMF (referred to as stochastic star formation), the low-mass stars are statistically more likely to form before high-mass stars. High-mass stars are highly disruptive of the interstellar medium, both through their radiation fields and strong stellar winds and by virtue of their short lives and ultimate demise in supernovae explosions. It is therefore generally assumed that the formation of a significant number of massive stars in a region will signal the end of all future star formation by blowing away the gas and dust. This scenario does not imply that the time of star birth is strictly a function of stellar mass, sometimes referred to as sequential star formation.

Additional studies of age spread in young clusters followed Herbig's (1962) paper (for example, Iben and Talbot 1966; Herbst and Miller 1982), which presented the process as one in which the average stellar mass produced increases smoothly with time: while low-mass cluster stars are produced over a long period of time, high-mass stars are produced during a relatively short interval at the end of the star-formation history of the cluster. Stahler (1985) argued that while continuous star formation over a period of time, which he terms contemporaneous, is observationally supported, the picture of sequential or bottom-up star formation is not. He made the point that pre-main-sequence isochrones cannot be used to accurately date stars with no other evidence of their youth, such as variability or Hα emission. Work on pre-main-sequence stars has generally focused on associations closer than about 500 pc, such as Orion OB1 and Scorpius OB2 (Walter and Boyd 1991). The T Tauri phase, and related objects such as Herbig–Haro objects are usually associated with lower-mass stars of $3M_\odot$ or less, not identified with OB associations. While NGC 2264 contains well-documented T Tauri stars, as discussed by Adams et al. (1983), the more massive stars cannot simply be assigned ages from theoretical pre-main-sequence isochrones without more data on the individual stars. This is now being done by Hillenbrand et al. (1993) for NGC 2264 and other clusters.

The combined energy deposition from stellar winds and supernovae can create a hot cavity with radius greater than 100 pc surrounded by a dense expanding shell of cool interstellar gas. Such a supershell can persist for periods longer than 10^6 yr (McCray and Kafatos 1987), and among other things, could possibly trigger further star formation. Saken et al. (1992) discuss such a supershell surrounding Cygnus OB1 with dimensions 26 by 65 pc. Assuming that the cavity was produced by stellar winds and supernovae, the maximum bubble age is only 10^6 yr, significantly less than the ages of the most massive stars. It is interesting to compare this age dilemma with the one referred to in Sec. 1 between kinematic and evolutionary ages.

Unbound, expanding OB associations are fundamentally different from bound galactic clusters. An explanation for the difference has been offered by Elmegreen (1983) who argued that bound clusters are the result of star formation in low-mass cloud cores, and OB associations the result of star formation in high-mass cloud cores. He further proposed that a correlation is expected between cloud mass and maximum stellar mass. Most studies find that galactic clusters are gravitationally bound, which implies either that the clouds from which they form are dispersed very slowly after cluster formation, or that the efficiency of star formation is very high. For example, Elmegreen and Clemens (1985) showed that a bound cluster will be formed if the star forming efficiency, the ratio of total mass to stellar mass is between 0.1 and 0.5, depending on the ratio of magnetic to turbulent pressure. It is not clear why we observe bound OB clusters within many OB associations. One possibility relates to the binary frequency. For example, Trumpler 14, a cluster within Carina OB1 contains three O3 stars and from its compact appearance is still bound. Penny et al. (1993) have studied the binary frequency of this cluster, which they find to be anomalously low. As expansion of subgroups and clusters can be powered by dynamical exchanges involving binaries (Leonard and Duncan 1990), Penny et al. proposed that the lack of binaries in this cluster has negated the importance of this expansion mechanism, and predicted that dense clusters containing slightly evolved OB stars will have a low binary frequency.

A very recent study of NGC 6611 by Hillenbrand et al. (1993), combining optical CCD photometry and spectroscopy with infrared imaging photometry reveals the best evidence yet for a young OB cluster that is presently forming intermediate mass ($3–8M_\odot$) stars. NGC 6611 is in the association Serpens OB1, embedded in the nebula M16. The earliest star is classified O4 V((f)) by Walborn (1973), O5 V((f*)) by Hillenbrand et al.: the implied age of this star is about 1.5 million years from isochrones. The presence of pre-main-sequence stars is inferred both from their position above the zero-age main sequence and spectroscopic and infrared evidence of circumstellar material. Previous studies proposing that pre-main-sequence stars had been discovered in clusters have often relied only on the position of stars in the HR diagram, a very uncertain technique. Indeed, Walker (1961) suggested this to be true in NGC 6611 but his conclusion was not generally accepted.

The combination of short stellar lifetimes and gravitational unbound systems suggests that we might observe OB associations in the process of disintegration. An example of an old, disintegrating association has been nicely discussed by Sahu (1992) in a study of the Puppis–Vela region. Vela OB2, consisting of B stars and also the WR binary γ^2 Vel (WC 8+O9 I) is surrounded by a structure she names the *IRAS* Vela shell, in which low-mass star formation is taking place. Vela OB2 can be described as an extension of the Sco-Cen association, with an age of 20×10^6 yr. This age then raises questions about the WR star, whose age can be only about one-quarter that of the association. It could be yet another example of noncoeval star formation within a subgroup.

4.1 Association Membership: The Mass Function

Eventually massive stars manage to disperse their surrounding cocoon and begin to emit copious UV radiation, some of which tails off into the visible. It is at this point that classical membership studies in the optical are possible. A complete stellar census of the members, both main sequence and evolved, provides the statistical basis for testing theoretical evolutionary models, as well as understanding the origin of the stellar mass function. Ideally, we would like to know the temperature and bolometric luminosity for every physical member of an association from the most massive O star down to the least massive stars on the main sequence. There is at present no way to accurately include possible massive stars embedded in ultracompact H II regions, or even to estimate how their contribution might affect the slope of the mass function. If these objects are single very massive stars, their inclusion will flatten the derived IMF's, but if they are multiple star groups, they may not change the results much. Section 1 of this paper mentioned some of the uncertainties in defining galactic associations: in most of these it is only the OB clusters that are sufficiently well studied to permit quantitative discussion of the mass function, as the large angular size of associations themselves makes their study difficult. The study of entire associations is actually easier in the Magellanic Clouds.

In Scalo's (1986) notation, which we will use here, the slope of the IMF, Γ, is given by

$$\Gamma = d \log \xi(\log M)/d \log M,$$

where $\log \xi$ $(\log M)$ is the number of stars formed per logarithmic mass interval per unit area. The often quoted Salpeter (1955) IMF has $\Gamma = -1.35$. Most of the recent work on massive star IMFs has derived stellar masses from some variation on the principle that from photometry complete to some limiting magnitude and spectroscopy of the brighter stars, a prescription for converting these data to temperatures and luminosities, and a set of evolutionary tracks, one can bin the data by mass interval and derive the IMF. An increase in the ratio of massive to less massive stars leads to a smaller absolute value of Γ which is commonly referred to as a flattening of the IMF. This is essentially the method used by Lequeux (1979) who used all stars brighter than $V=7.5$, independent of their membership in associations to derive the IMF between 2.5 and $100 M_\odot$. Garmany et al. (1982) chose to concentrate just on the O-type stars and rejected Lequeux's assumption that almost half of the O stars are old disk population objects. They found an IMF with $\Gamma = -1.6$ that flattened toward the galactic center. This conclusion was disputed by Humphreys and McElroy (1984) who included less luminous B stars, and argued that incompleteness is a serious problem and derived $\Gamma = -2.4$ with no variation with galactocentric distance. As all of these studies are time-averaged determinations they should not be directly compared with work on individual associations.

In an important series of papers on Galactic and Magellanic Cloud OB associations, Massey and his collaborators, using deep CCD images to derive UBV photometry and spectroscopy of the brighter members, have systematically studied the massive stellar component, and the results to date indicate flatter IMFs for galactic associations than in the Magellanic Clouds (Massey 1993). The following example points out the importance of deriving IMFs from very complete, deep photometric CCD studies. Let us consider derivations of the IMF for NGC 6611. This cluster is one of several studied by Sagar et al. (1986) to determine the mass spectrum and age distribution of stars. Based on photoelectric UBV data, they derived a DM $=12.5$. They converted the colors to luminosity and temperature, and used evolutionary models by Maeder and Mermilliod (1981) to derive masses. They concluded that the data were complete over the mass range 9 to $70 M_\odot$, and derived a slope for the mass function of $\Gamma = -0.87$ making use of a total of 26 stars. Their formal error on this slope is ± 0.19, but an examination of their plot of the mass function suggests somewhat more uncertainty.

NGC 6611 has been revisited by Massey (1993) and by Hillenbrand et al. (1993), who obtained CCD photometry of 900 stars and spectra suitable for the classification of 73 stars, and noted that there is strong differential reddening and derived a slope for the IMF of $\Gamma = -1.3 \pm 0.3$, or -1.1 ± 0.3 for only the best data, based on the mass interval 9 to $85 M_\odot$. There are about 34 stars with masses greater than 9 in Massey's HR diagram, only 8 more than in Sagar's data, but Massey's data extend to much lower masses. Additionally, Massey's plot of the mass function shows a beautiful fit to a straight line.

Why did Sagar find such a different slope from Massey? The answer lies in his very limited sampling of the upper IMF. Although Sagar does not give sufficient detail to permit me to reconstruct a plot of the mass function to compare with Massey's, another study by The et al. (1990) lists 33 stars with masses greater than 9 in NGC 6611, so I have used the temperatures and luminosities derived by The et al. to compute masses. With the same mass bins as Massey used, the data for a total of 33 stars leads to a $\Gamma = -0.95$. Figure 7 shows both HR diagrams: Massey's and the one I construct from The's much more limited data set (essentially the same data as that used by Sagar). The importance of deriving IMFs from magnitude limited CCD frames, rather than older methods which relied on individual photoelectric photometry of stars in the field, is clear.

With the same techniques as used for NGC 6611, Massey and Johnson (1993) have investigated Tr 14 and Tr 16, two OB clusters near the star η Carinae in the association Car OB1. This region contains six O3 stars, more than any other association in the Galaxy, and as the authors point out, presents a good test of the hypothesis that very massive stars are indicative of a flatter than normal IMF. Their derived IMF for this region is $\Gamma = -1.3 \pm 0.2$. In another similar study, Massey and Thompson (1991) have also investigated Cyg OB2 using CCD photometry and spectroscopy. This a small, highly reddened association containing one of the few known O3 If stars. Cyg OB2 has the smallest angular size of any galactic OB association, which allowed Massey and Thompson to obtain CCD frames of the entire association. The high reddening allowed them to eliminate foreground stars. They list UBV colors for 799 stars in the region. Of these, 108 are isolated as very blue and bright, and they obtained spectra for 76. The slope for the IMF is $\Gamma = -1.0 \pm 0.3$ for stars more massive than $9 M_\odot$.

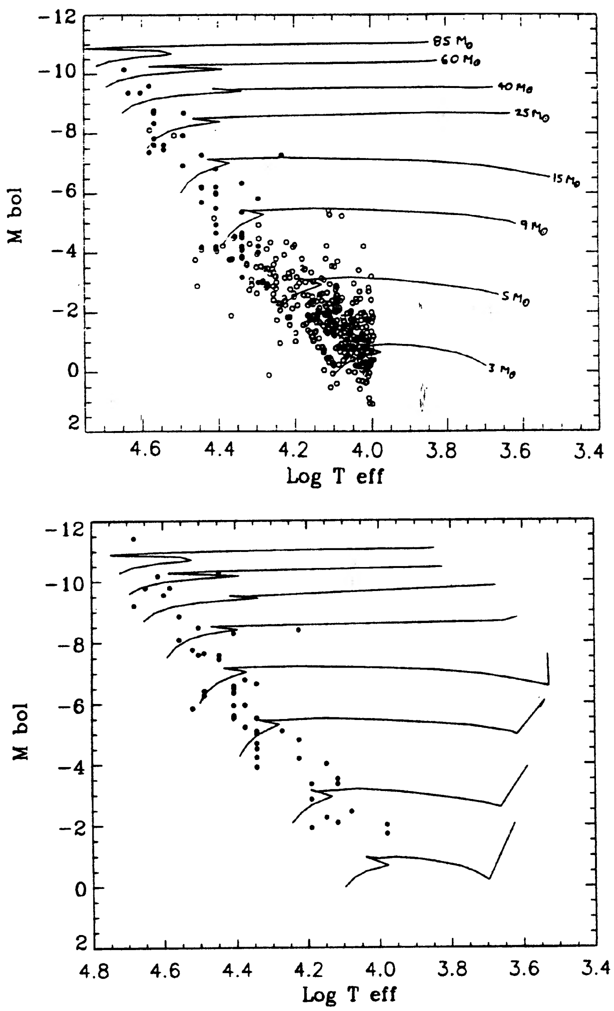

FIG. 7—Two separate presentations of the HR diagram for NGC 6611. The top panel is by Massey (1993) (reprinted with permission from PASP) and showed CCD photometry to a much fainter limit than the study by Sagar et al. (1986), shown in the bottom panel. It is clear that the reason the IMF derived from the data in the bottom panel was much flatter (indicating a larger proportion of massive stars) than the top panel was due to incompleteness in the older data.

Theory has led to the expectation that the upper mass cutoff and the slope of the IMF should be a function of metallicity, so it is especially interesting to compare these galactic data with the Magellanic Clouds. The SMC in particular is lower in dust and metals (Dufour 1984). However, studies of Magellanic Cloud associations done in essentially the same manner as Massey's work on galactic associations do not find an upper mass limit significantly different from stars in the Galaxy. Associations in the Clouds have been identified and cataloged by Lucke and Hodge (1970) and by Hodge (1985b). LH 117 and LH 118 are adjacent associations in the LMC in which Conti et al. (1986) classified several O3 and O4 stars. Massey et al. (1989), from both UBV CCD photometry and spectroscopy of stars selected from the photometry, found approximately 50 stars greater than $10M_\odot$ and derived a slope of the IMF, $\Gamma=-1.8\pm0.1$ for the combined associations.

A subsequent study of NGC 346 in the SMC (Massey et al. 1989) found $\Gamma=-1.9$ and stars as massive as $85M_\odot$. However, the next paper in this series (Parker et al. 1992), treated LH 9 and LH 10 (N11), two adjacent associations in the northwest corner of the LMC. The Hα flux measured by Kennicutt and Hodge (1986) for the entire region is second only to 30 Doradus. The IMFs for the two associations differ substantially: LH 9 has $\Gamma=-1.6\pm0.1$ and LH 10 has $\Gamma=-1.1\pm0.1$. All seven stars earlier than O6 are in LH 10, which also has much more nebulosity associated with it and a higher color excess than LH 9. LH 9 does contain the WR multiple system HD 32228; this partially resolved cluster has not been included in the IMF because crowding prevents accurate photometry and spectroscopy of its members.

And the final conundrum: one of the richest regions of massive stars is the 30 Doradus nebulae in the LMC. This association, often considered an example of the star burst phenomenon, has recently been studied by Parker (1993) and Parker and Garmany (1993). Parker presents UBV photometry for 2400 stars; his catalog is complete to about 18 mag although nebulosity seriously hampers results at the faintest limit. Spectra, obtained by Walborn and by Parker are used to assign temperatures to the bluest stars. Contrary to expectations that this association, so rich in very massive stars, should have a flatter than normal IMF (i.e., with relatively more very massive stars), Parker and Garmany found instead that they could not characterize the slope by a single power law slope: rather the slope became steeper with increasing mass. There are several explanations: unlike most other associations discussed here there are a significant number of WR stars present, and adding them to the mass bins would flatten the slope to -1.5. There are also still a number of heavily reddened stars without spectra, and their addition might further flatten the IMF. However, it seems unlikely that these effects could lead to a slope as flat as $\Gamma=-1.0$.

All of the above analyses have been made with the tacit assumption that star formation within the region is coeval to first approximation and no correction need be made for ages of the stars, as would be the case in deriving the IMF of a field population. In each association, however, there are one or more 15–$20M_\odot$ supergiants that must have formed long before the $40M_\odot$ and greater main-sequence stars. While the majority of stars fall on the main sequence, these few blue and red supergiants have ages, based on their evolutionary tracks, of at least 7–12 ± 10^6 yr. Figure 8 is a heuristic demonstration of this age spread: the relative pre-main-sequence and main-sequence lifetimes of stars between 3 and $85M_\odot$ are compared using Iben (1965) and Maeder and Meynet (1988) evolutionary tracks. According to these model calculations, it is just possible for the main sequence to be populated with stars ranging from 85 to $3M_\odot$ that all formed at the same time, but a 15 to $25M_\odot$ supergiant cannot have formed coevally with a $40M_\odot$ or larger star still on the main sequence. For example, NGC 346 contains five probable red supergiants and two B supergiants that are at least 10 million years old, while the

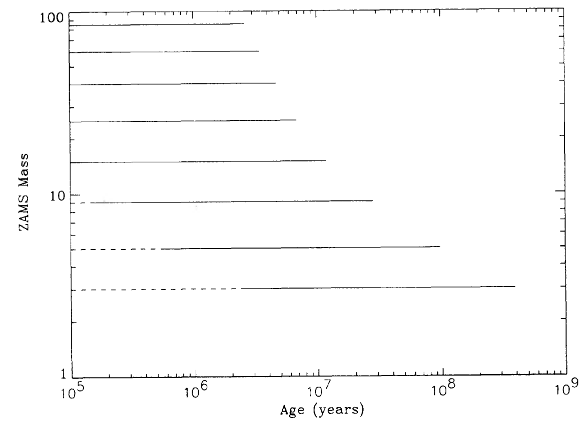

FIG. 8—The evolutionary lifetimes of stars with masses between 3 and $85M_\odot$. The dashed line represents pre-main-sequence lifetimes (Iben 1965) and the solid portion of the lines are main-sequence lifetimes calculated by Maeder and Meynet (1988) up to the point when the star attains its coolest main-sequence temperature. This occurs shortly before central hydrogen exhaustion.

earliest O star is less than 2 million years old. The spread is at least 8 million years. This figure also demonstrates that the presence of low-mass (3–$5M_\odot$) stars on or very close to the main sequence is not a particularly interesting constraint on star-formation history, as these stars could have ages anywhere between a few million to many tens of million years. Additional spectroscopic evidence that such low-mass stars are really pre-main-sequence objects such as Herbig Be stars would further support contemporaneous star formation over a longer interval. And finally, indirect evidence for a spread in star formation is provided by supernova remnants: Chu and Kennicutt (1988) have shown that of 32 known remnants in the LMC, 18 lie within the boundaries of OB associations or H II regions. Depending upon the assumed mass of the supernova progenitor star, the age spread is defined by the youngest and most massive star presently observed in the association.

There is another assumption in these analyses concerning the temperature calibration. At present there is no available temperature calibration as a function of stellar metallicity. Maeder (1990) has computed evolutionary models for initial masses between $120M_\odot$ and $15M_\odot$, and metallicities Z=0.002, 0.005, 0.020, and 0.040. From the point of view of the observational data, there is no difference between models with Z=0.04 and 0.02, or 0.005 and 0.002. Between Z=0.005 and Z=0.020, the ZAMS slides to higher temperatures by about 0.03 in log temperature although the main-sequence tracks stay essentially unchanged in luminosity. If the models are correct, the Magellanic Cloud association stars should have systematically higher temperatures and bolometric corrections which would imply higher masses and a flatter IMF.

5. MASSIVE STARS OUTSIDE OB ASSOCIATIONS

There are, as can be seen from Fig. 2, a significant number of OB stars that do not appear to be members of associations. The catalog from which Fig. 2 is plotted lists a total of some 1650 stars earlier than about B2: about 960 of these are members of associations and the rest are referred to as field stars. The fraction of field stars decreases with earlier spectral type. Of the 1650 stars, about 200 are of type O and some 150 of these are association members (75%). As this catalog makes no claim to be complete at later spectral types, it is likely that the relative fraction of O to B stars in the field is even smaller than suggested by these numbers. However, these early stars, apparently unassociated with any massive stellar group, raise important questions. They are not confined only to our Galaxy: many are found in the Magellanic Clouds, and even farther afield; Wilson (1991) found that one-third of the Wolf–Rayet stars in M33 lie more than 75 pc from any OB association. What is the origin of these stars?

Runaways, described by Blaauw (1964), are O stars with space velocities derived from radial velocities and proper motions well in excess of 30 km s^{-1}. Blaauw's original hypothesis, amplified by van den Heuvel (1985) was that they are formed by the ejection of the secondary in a binary supernova explosion. An alternative explanation, advanced by Gies and Bolton (1986) is that ejection takes place through close gravitational interaction during the early evolution of a cluster. A careful study of the kinematics and binary properties of O runaways by Gies (1987) concluded that 70% were in clusters and associations, 21% were field, and 9% were runaway stars. Gies notes that the field stars in his sample show a larger dispersion in peculiar radial velocity, a wider Z distribution, a factor of 2 lower incidence of visual binaries, and a deficiency of spectroscopic binaries compared to the cluster and association members. None of these can account for all the field stars, and other explanations must be sought, such as formation in individual low-mass clouds.

The runaway stars suggest some form of ejection, but there are a number of isolated cases of trapezium-like systems, often in regions containing an H II region. An early discussion of these by Sharpless (1959) pointed out that these systems are dynamically unstable. Some of the stars discussed in his paper are actually the brighter members of OB clusters, such as IC 1805, IC 1848, and NGC 6823, but others, e.g., the multiple system containing HD 5005 are nice examples of isolated H II regions in a small molecular cloud. This particular system is discussed by Abt (1986). The brightest component is spectral type O4; Abt classifies two O9 V components. A recent CO survey of the region has been made by Leisawitz et al. (1989); they derive a cloud mass of $16\times10^3M_\odot$.

Thus while massive associations contain many of the cataloged OB stars, small star-forming regions also produce high-mass stars. Hunter et al. (1990) note regions of massive star formation in clouds with masses ranging from 1 to $60\times10^3M_\odot$. In a related spectroscopic study of small galactic H II regions less than 7 in. in size, Hunter and Massey (1990) found stars as early as O6 in gas clouds only a few parsecs in diameter. They compared the expected Lyman continuum radiation with the observed flux from Hα, far IR, and radio to confirm that all massive stars had been identified, and constructed mass functions which lie statistically between a Salpeter (1955) and a Scalo (1986) mass function. This offers additional evidence that formation of massive stars is not a simple function of global parameters.

6. SUMMARY

OB associations, first described over 80 years ago, are unbound, expanding stellar groups that today are recognized as containing infrared sources, ultracompact H II regions, and molecular clouds. Membership in many OB associations is still only based on the brightest O and B supergiant stars. In these cases, the distance is usually based only on spectroscopic parallax of a limited number of stars, so the distance can be quite uncertain and the boundaries even less well known. The combination of modern CCD photometry covering large areas to very faint limiting magnitudes, and recent infrared technology have added enormously to our ability to probe the many stages of star formation and development. This is particularly important for OB associations, which show increasing evidence for star formation over significant time intervals and for variations in the mass function produced during star formation.

It appears that a few stars with masses between 15 and $30M_\odot$ appear several million years before the bulk of the O stars form. But even after this, low (3–$8M_\odot$) stars may continue to form. All this means that the concept of a turn-off age from the most massive evolved stars is meaningless in OB associations. Modern determinations of the slope of the IMF in galactic OB clusters yield values similar to, or slightly flatter than, the Salpeter IMF. Studies of OB associations in the Magellanic Clouds so far suggest somewhat steeper IMFs. In all cases the most massive stars, as determined from evolutionary tracks, are about $80M_\odot$.

Unlike the classical picture of star formation in clusters in which all stars form at the same time (the high school class photo) current evidence points to a much more complicated scene with stars forming over an extended period and in different regions (the photograph of an extended family).

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