Chapter 11

Massive Stars

Massive stars are low in number but make a large contribution to the properties of galaxies. They are fundamental to the production of the heavy elements and to the energy balance in the interstellar medium. They attempt to regulate the rate of star formation on large scales through feedback via intense winds, radiation and, finally, through supernova explosions.

Most stars are born in the neighbourhood of a massive star. Therefore, as viewed by the low-mass stars, massive stars are the influential or interfering relatives. The life history of a star is thus not only determined by the conditions at birth ('nature') but also the interaction with the environment in the formative years ('nurture'). Massive stars can lead to ejection from the cluster through their gravity or to a stunted growth through their feedback.

Their own origin remains a mystery. Moreover, massive stars should not even exist according to basic theory. This is because stars above 8 $M_\odot$ should 'switch on' their nuclear hydrogen burning during the accretion phase. Thus, their radiation pressure halts or even reverses the infall. This leads to the paradox that the hot O and B stars should not exist.

Studies of how massive stars form are afflicted by confusion. The problem is observationally severe because massive-star formation occurs in distant, highly obscured regions. On top of this, they are born in groups or clusters which hinders the study of the individuals. They are also theoretically difficult to analyse because of the many processes that must be acting simultaneously. The convenient well-defined stages found for low-mass star formation are missing. Despite all these obstacles, we need to explain their existence.

11.1 Basic Characteristics

A massive star is a term used for any star which will reach or has reached a mass exceeding $10\,\mathrm{M}_\odot$. They are distributed tightly within the Galactic plane, confined within a disk subtending an angle under 0.8° with the mid-plane. The properties of the emission lines used to diagnose the spectra lead to their classification as O and B stars, or as Wolf-Rayet stars (hot stars with massive obscuring winds). In addition, their intense ultraviolet radiation ionises their surroundings, thus creating classical H II regions.

Their luminosity is typically 10^4–10^6 $\mathrm{L}_\odot$. Once on the main sequence, the available hydrogen nuclear energy is supplied over a timescale $\tau_N \sim 7 \times 10^9$ yr $(M/\mathrm{M}_\odot)(\mathrm{L}_\odot/L)$. Therefore, they have short lives, spanning just $\sim$ 2–20 million years.

The time it takes to form a massive star is contentious. Arguments based on extrapolating from the mass accretion rates of low-mass star formation of $\dot{M} \sim\leq 10^{-5}$ $\mathrm{M}_\odot$ yr^{-1}, lead to formation times exceeding 10^6 yr, a significant fraction of the main-sequence lifetime of the star. However, their total pre-main sequence life must be short. Given the Kelvin-Helmholtz or thermal timescale τ_{KH} as the ratio of the thermal energy to the luminosity, and applying the virial theorem, we define a lifetime

$$t_{KH} = \mathrm{G}\ M^2/(R\ L). \tag{11.1}$$

This provides a measure of how quickly a star would collapse in the absence of a nuclear energy supply and takes the value 3×10^7 yr for the Sun but is of order of just 10^4 yr for an O star.

In the traditional scenario of star formation, a star is initiated as an isolated cloud of gas. This sphere collapses at constant mass with no accretion or outflow. The evolution timescale is then simply the Kelvin-Helmholtz timescale. There is now, however, ample evidence for high accretion which we will discuss in this chapter.

The important comparison is between the accretion and Kelvin-Helmholtz timescales. Up to some mass, t_{KH} exceeds the free-fall collapse time t_{ff}, given by Eq. 4.1. This means that the accretion will be completed before the protostar has contracted. The mass limit depends on the details but probably lies in the range 8–15 $\mathrm{M}_\odot$. Therefore, low-mass and intermediate-mass stars go through a phase where accretion has stopped but the release of gravitational energy still mediates the collapse. Accretion finishes long before hydrogen nuclear burning takes over. From then on, the protostellar evolution proceeds at constant mass.

In contrast, the high luminosity of higher mass stars means that $t_{KH} < t_{ff}$. In this case, the central protostar has finished its contraction and is burning hydrogen during the accretion itself. Hence, massive stars begin their hydrogen burning phase while still in their natal dense cores. For this reason, the application of theory relevant to low-mass star formation is highly dubious and, to proceed, we first need to get familiar with a new set of observations.

11.2 Compact H II Regions

We cannot directly observe the optical and ultraviolet radiation from recently-formed stars. However, a massive young star emits ultraviolet photons in the 'extreme UV' (EUV), also termed the Lyman continuum (§2.4.2). These photons are not observed since they are spent ionising their immediate surroundings. However, the resulting H II region generates strong electron free-free emission at radio wavelengths. This radiation escapes and so produces a bright radio beacon, signalling the location of a hot star.

If we can estimate the age of the various beacons, we can learn how massive stars evolve. Normal H II regions around established massive stars are of size in the range 1–30 pc. The compact regions are of size between 0.005 pc and 0.5 pc and the electron density is in the range 2×10^3–3×10^5 cm^{-3}. Ultracompact H II regions (UC H II regions) are those regions with size near or under 0.01 pc and the electron density above 10^5 cm^{-3}. Their morphologies have attracted much speculation: about 20% are cometary (compact head plus diffuse tail), 16% core-halo, 4% shell-like, 43% spherical or unresolved, and 17% irregular or multiple-peaked structures. We first investigate if these UC H II regions belong to the youngest massive stars.

The classical theory of H II regions assumes a uniform ambient medium and a sudden turn-on of the ionising flux. The first stage is very short-lived: the gas is ionised from the centre outwards, being led by an ionisation front. This expansion is halted when the ionised region is so large that the number of recombinations within that volume is equal to the number of photo-ionisations. This yields a volume of $4/3\,\pi\, R_S^3$ where R_S is called the Strömgren radius. The total number of recombinations in unit volume is proportional, of course, to the number of close encounters, $\alpha_B n_e^2$, where n_e is the electron density (roughly equal to the ion density) and $\alpha_B = 2.6 \times$

10^{-13} cm^3 s^{-1} is the appropriate recombination coefficient. This coefficient excludes captures directly to the ground level since they re-emit an ionising photon whereas recombinations into excited levels produce photons which can escape from the region or are absorbed by dust. Equating the ionisation and recombination rates results in a sphere of size

$$R_S = 0.032\left(\frac{N_{UV}}{10^{49}\ \mathrm{s}^{-1}}\right)^{1/3}\left(\frac{n_e}{10^5\ \mathrm{cm}^{-3}}\right)^{-2/3}\ \mathrm{pc}. \qquad (11.2)$$

The number of UV photons covers a wide range. For main sequence stars classified as B2 ($\sim$ 20,000 K), $N_{UV} \sim 4 \times 10^{44}$; an O8.5 star ($\sim$ 35,500 K), $N_{UV} \sim 2 \times 10^{48}$; and for an O4 star ($\sim$ 50,000 K), $N_{UV} \sim 9 \times 10^{49}$.

The duration of this first stage is equal to the time required for the star to increase its output in the EUV since the region response time to the changing flux is very short, just $1/(n_e\alpha_B)$. After this, the internal pressure of the heated gas will drive a shock wave through the neutral surroundings. The expansion speed will be of order of the sound speed in the ionised region. The expansion finally stalls when the internal pressure has fallen so that pressure equilibrium is reached. This should occur at a radius estimated to be $(2\,T_e/T_o)^{2/3}\,R_S$ where T_e/T_o is the internal-external temperature ratio.

The quantity that radio astronomers derive from the measured radiation is called the emission measure, EM, $n_e^2 \times L$, where L is the length through the region of electron density n_e, since this is proportional to the observed flux. From this, they find that, for a wide range of UC and compact H II regions, there is a relationship of the form $n_e = 7.8 \times 10^2 L_o^{-1.2}$ where L_o is the size. This would appear to agree with Eq. 11.2 only if the more compact regions are, in general, excited by less luminous sources. Another trend is derived from radio recombination lines of hydrogen: whereas line widths in typical regions are 20–30 km s^{-1}, with large thermal contributions, the compacter regions display dominant systematic or turbulent motions of between 25–60 km s^{-1}.

The ultracompact H II regions have been the centre of attention for another reason: there are far too many of them to be consistent with the classical Strömgren theory. Their number in the Galaxy indicates an average age of 100,000 yr, a hundred times longer than that given by expansion at the sound speed of 10 km s^{-1} to 0.05 pc. This is the *lifetime paradox* which models must try to address. In other terms, we estimate from observations that about 0.04 O stars are born per year, whereas the rate implied by fast expansion would be 0.3 O stars per year. Hence, the simple expansion of an ionised region is not a viable interpretation.

11.3 Models for Massive Star Environments

The lifetime paradox has found several interesting solutions. The range of solutions allows us to simultaneously explain the variety of compact H II region morphologies. We find that we cannot isolate a simple mechanism which can cope with all the facts and this leads us to understand the underlying complexity of massive star formation.

Bow shock models are ideal for explaining the cometary shaped regions. Where an ionising star moves supersonically through a cloud, ram pressure replaces thermal pressure as the limiting factor in the direction of motion. This model can be distinguished by obvious velocity structure in the high-pressure head region. Seen approaching or receding, the bow may appear circular.

A *champagne flow* is established if the massive star forms while near the edge of a molecular cloud. This is illustrated in panel (b) of Fig. 11.1. A cavity forms until the ionising front breaks out of the cloud. The ionising gas then streams away down the direction of least resistance. This forms a blister-type H II region, with a strong ionisation front on the cloud interior and a fan-shaped ionised region towards the exterior. This model is distinguished by high outward speeds in the fan or tail of the structure.

Strong stellar winds are also expected early in the formation. It is not clear exactly when the wind is bipolar. The wind produces a limb-brightened morphology from a very early stage as deposited momentum drives an expanding shell which is exposed to the ionising radiation.

The *mass-loaded wind* model invokes a clumpy environment, which can be expected through turbulence and fragmentation in the original cloud. The wind becomes mass-loaded as it ablates material from the surfaces of the clumps. The ionising radiation photo-ionises the clumps, reducing the size and extending the life of the H II region. Recent observations have yielded some awesome examples of such regions, with structures being eroded away to leave pillars and nests where the clumps may be triggered into collapse and further star formation, as shown in Fig. 2.2 and illustrated in Fig. 11.1.

Other models apply to more compact regions. Denser or more turbulent cores than have been considered as typical would provide the material to delay the expansion of the ionisation front and the pressure to resist the

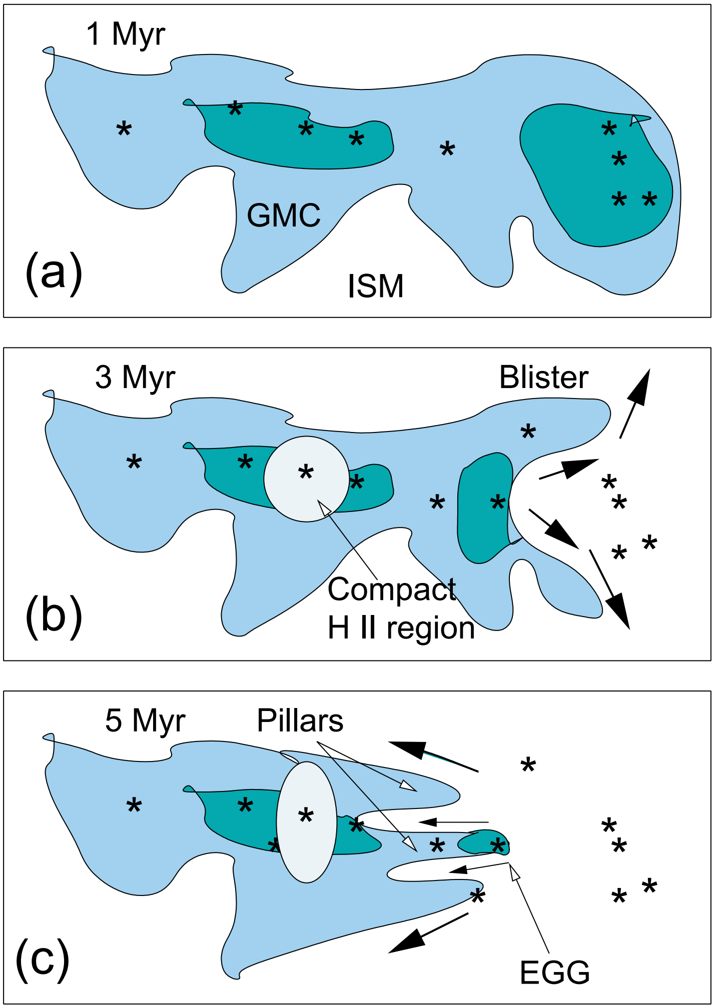

Fig. 11.1 A schematic diagram of the evolution of a high mass star formation region, illustrating a champagne flow, compact H II region, pillars and EGGs.

H II region. *Infall of gas* would prolong the compact state by providing more material and increased pressure. This may find application to some ultracompact and unresolved regions.

Photo-evaporation is expected to yield a dense wind from a disk. Moreover, massive disks are thought to surround massive stars although they have proven difficult to detect. The wind replenishes the gas in the H II region which is thus sustained for as long as the disk persists.

We conclude that massive stars are born in environments with a range of density, non-uniformity and disk masses and also with a range of dynamical states. Each star may develop along its own evolutionary path.

11.4 Hot Cores and Masers

A 'hot core' is a title bestowed upon a compact dense molecular core which is hot and dynamic. In the past few years, these cores have been shown to be the sites of massive star formation. Although most hot cores are intimately associated with compact and ultracompact H II regions, they are also found as their precursors. Hence, they are truly the 'cradles' of massive stars.

The hot cores possess temperatures in the range 100–200 K, density 10^6 to 10^8 cm^{-3}, masses from $100\,M_\odot$ to a few $\times\,1000\,M_\odot$ and size 0.3–1 pc. The densest cores are traced in NH_3 and possess densities of 10^8 cm^{-3}, sizes down to 0.05 pc and temperatures of up to 250 K. These ammonia cores are often associated with very compact H II regions. The high temperatures lead to the evaporation of the icy mantles of grains, enriching the gas phase chemistry.

Hot cores are not isolated entities but are contained within Giant Molecular Clouds, within a hierarchical structure. Internally, the temperature and density decrease with distance from the heating star. Density gradients fall in the range $n \propto R^{-\alpha_n}$ with $\alpha_n \sim 1.5$–1.7 and $T \propto R^{-\alpha_T}$ with $\alpha_T \sim 0.4$–0.6. Line widths are high, 4–10 km s^{-1}, which provides evidence for a high accretion rate. There is also evidence for collapse, rotation and expansion in different cores.

The above properties suggest an early evolutionary sequence, beginning with a dense ammonia core. The core is under-luminous in the infrared and shows signs of collapse yet no UC H II region. An increasing luminosity is generated by an increasing mass accretion rate. A high accretion rate quenches the formation of an H II region. This situation is short-lived with radiation pressure onto dust grains reversing the infall. Then, an expansion phase begins which ends in the destruction of the core.

Masers appear in dense, active regions and so offer an opportunity to explore the changing conditions in the environments (see §2.3.1). They are proving useful for spotting regions of massive star formation. Water masers appear in small clusters of features which outline either disks or outflows. It is thought they appear during the earliest stages. Next, methanol masers are also signposts of disks and early protostars but often with detectable radio sources. Finally, OH masers appear to be associated with UC H II regions, possibly located in a shell of gas adjacent to a Strömgren sphere. Despite these assertions, our interpretations remain rather speculative. Nevertheless, masers sometimes provide indisputable evidence for jets and rotating disks on scales as small as 10 AU.

11.5 Outflows from Massive Stars

Molecular bipolar outflows are a basic component of all young massive protostars. Compared to their low mass counterparts, outflows from young massive protostar are much more energetic. Furthermore, massive molecular outflows are observed on large spatial scales (in the parsec range). Therefore, they are often easy to resolve spatially despite their typical distance of kiloparsecs.

The major question is: are these bipolar outflows driven by the same mechanism as those from low-mass stars? For example, the magneto-centrifugal wind scenarios predicts outflows which are morphologically similar to low-mass outflows and which show a high degree of collimation due to the star-disk interaction (§10.6). On the contrary, colliding protostars are expected to be extremely eruptive phenomena during which accretion disks should not be able to survive and, therefore, any resulting outflows are likely to be less collimated and rather appear more like explosions.

Many well-studied massive outflows have complex structures. A wide distribution of bow shocks, filaments and clumps are found. For example, the OMC-1 outflow in the Orion KL region consists of many bow shocks moving at hundreds of km s^{-1}. These bows may have formed as a dense shell of gas decelerated and fragmented. No evidence for a molecular jet is found although many show radio jets.

The studies agree on the basic facts that bipolar outflows from massive stars are ubiquitous and that they are very massive and energetic. However, there is disagreement on the typical collimation of the observed outflows. The average collimation of the classical massive outflows is lower than observed for their low-mass counterparts. However, in larger surveys and taking properly into account the poor spatial resolution, it is argued that the data are consistent with highly collimated outflows in high-mass star-forming regions. Single-dish millimetre observations are not sufficient to understand the complex bipolar outflows in massive star formation and proof will require interferometer observations.

The outflows are difficult to study because multiple outflows often emanate from the same large scale core. Clusters of stars form simultaneously in a core and the outflows originate from different protostars. For example, at least three molecular outflows are resolved in the core containing IRAS 05358+3543. This core contains an outflow with a collimation factor q_{coll} of 10, the highest so far associated with the formation of massive stars, and approaching the highest values recorded in low-mass star formation (§10.2).

The observations indicate that bipolar outflows in high-mass regions are made complex due to the strong UV radiation and stellar winds, in addition to the strong clustered mode of formation. Nevertheless, outflows of high collimation are produced by a physical mechanism comparable to that of their low mass counterparts. The protostars and outflows propagate within a crowded protostellar environment, which imprints very different structure onto the envelope and protostar. Thus, no other physical process has to be invoked, and high-mass star formation can proceed as in the classical low-mass scenario, with significantly enhanced accretion rates.

Much of the uncertainty and disparity in the results has been caused by attempts to unify all types of bipolar outlow. The wide outflows, classed by their low collimations and fragmented morphologies, may well be the result of the complex environment, combined outflows and stellar winds, and a poor hydrodynamic collimation mechanism, such as discussed in §10.6. It has been proposed that the models with accretion disks might not be appropriate for high-mass objects. Instead, massive stars may form through coalescence of stars rather than accretion. However, either scenario might lead to such wide outflows.

11.6 Accretion Theory

The physical processes controlling the birth of massive stars are still the subject of controversy. An accretion process is favoured for essentially two reasons: we observe disks and we observe massive bipolar outflows, both thought to be intimately linked to infall.

The following classical counter-argument shows that massive stars cannot form through direct radial infall. Radiation pressure on the gas and dust is able to reverse the infall, preventing the formation of stars with masses larger than 10 $M_\odot$. Explicitly, we require the gravitational acceleration to exceed the radiative acceleration of the dusty material i.e.

$$\frac{GM_*}{R^2} > \kappa \frac{L}{4\pi R^2 c} \tag{11.3}$$

where c is the speed of light and κ is the opacity. This equation yields a straightforward maximum opacity condition:

$$\kappa < 130 \left(\frac{M_*}{10\ \mathrm{M}_\odot} \right) \left(\frac{L_*}{1000\ \mathrm{L}_\odot} \right)^{-1} \mathrm{cm}^2\ \mathrm{g}^{-1} \tag{11.4}$$

for inflow. Since the stellar luminosity increases as a high power of the stellar mass, this condition gets more difficult to satisfy for higher mass stars. Furthermore, dusty interstellar material has a very high opacity to the EUV radiation from hot stars, with $\kappa > 200$ cm^2 g^{-1}. In theory, we could overcome this problem by assuming that the dust opacity is significantly reduced, that the inflow is non-steady or that it takes place via optically thick blobs (such blobs could also be low-mass stars).

Inflow should, however, occur through an accretion disk. Therefore, radiation pressure is largely employed in blowing away the more tenuous spherical envelope, allowing material to sneak in through the massive disk. This is not clear cut, however, since the disk material must have originated from an extended but unprotected envelope. The radiation may also escape anisotropically, producing a 'flashlight' effect, occurring whenever a circumstellar disk is present. This permits material to approach the central source. However, at this point the material would again be rejected unless the dust has been largely destroyed.

Large and massive interstellar disks have been detected around massive stars. Rotation is suggested by the presence of smooth velocity gradients. However, circumstellar disks on scales under 10,000 AU have been difficult to detect although there is now plenty of good evidence mainly derived through maser detections. The EUV should photo-evaporate such disks on a timescale of 10^5 yr, forming an UC H II region.

However accretion proceeds, the standard star-forming theory predicts low accretion rates independent of mass (10^{-6}–10^{-5} M$_\odot$ yr^{-1}), just dependent on the sound speed (Eq. 8.5). At such rates, we would require over 10 Myr for a 100 M$_\odot$ star to form. Moreover, the inflowing momentum is not sufficient to overcome the radiation pressure of a star $\geq 8\ M_\odot$. According to this scenario, more massive stars should not form although they are, of course, observed to exist.

The answer appears to emerge on assuming a much higher mass accretion rate. We now have envisaged the rate to exceed 10^{-3} $M_{\odot}$ yr^{-1}. In this case, the thrust of the infalling gas overcomes the outgoing radiation pressure. The cause of the high accretion rate follows from applying the fact that hot cores are supersonically turbulent. High turbulent velocities are indeed found in the hot cores (see §11.4) and, along with them, very high densities and pressures, conspiring to raise the expected accretion rate. The star formation time in this turbulent core model is several times the mean free-fall time of the core out of which the star forms but is about equal to that of the region in which the core is embedded. Thus, the high densities in regions of massive-star formation result in timescales for the formation of a massive star of about 10^5 yr.

In support, observations indicate that massive stars in the Galaxy form in regions of very high surface density corresponding to 1 g cm^{-2}. Clusters containing massive stars and globular clusters have a mean column density comparable to this i.e 10^3 stars pc^{-2}. The total pressure in clouds with such a column density is $P \sim 10^{-7}$–10^{-8} dyne cm^{-2}, far greater than that in the diffuse interstellar medium or the average in clumps and Giant Molecular Clouds given by Eq. 4.9.

The birthline concept introduced in §8.1 has been used as the basis to construct model evolutionary tracks on Hertzsprung-Russell diagrams. A single birthline is taken as the path followed by all protostars as their luminosity increases according to some fixed accretion rate formula (Fig. 9.2). For the typical case we consider, in which the cores have a density structure of the form $n \propto R^{-1.5}$, the mass accretion rate increases with time. The tracks do not divert from this line until the moment accretion halts, thus largely determining the final stellar mass. Therefore, in this theory, the birthline represents obscured objects while those off the line should be exposed, consistent with the observational definition of the birthline. If the accretion rate is low, then the birthline intercepts the main sequence once the accumulated stellar mass has reached ~ 8 $M_{\odot}$, implying there is no pre-main sequence stage for higher mass stars. Instead, they then proceed to move up the main sequence from the intercept. Therefore, massive stars may evolve along the main sequence provided they are still accreting.

Evolutionary models are fraught with uncertainty. We must still pin down how the infall of mass will develop and how much of this is ejected into the outflow. The infall rate also influences the deuterium available for burning. This, in turn, alters the protostar's radius, which is critical to the location on the Hertzsprung-Russell diagram.

11.7 Formation within Clusters

Complex patterns of radio continuum emission indicate that massive young stars are gregarious. They are born in associations and clusters. In addition, infrared surveys show that there are many more objects in the young clusters. Low mass stars to the tune of 10^3–10^4 stars per cubic parsec are found spread over regions of size 0.2–0.4 pc.

The crucial issue is how to accumulate sufficient material into a single star of mass 10–100 $M_\odot$. The gas accretion picture necessitates the presence of a massive turbulent core. However, we don't expect such cores to arise according to gravitational fragmentation. We have already calculated that the Jeans mass is typically just 1 solar mass in molecular clouds and will be only reduced within the dense environments within which massive stars form (§4.3.4).

One potential remedy is to delay the formation of massive stars until after the production of a large number of lower mass stars. This leaves warmer diffuser residual gas. The Jeans mass is then increased in the hotter cloud. Against this idea is that there is no observational evidence that the massive stars form later. Alternatively, we now understand how supersonic turbulence dominates the cloud dynamics. Consequently, we can envisage massive stars as forming directly out of massive cores generated by chance within a highly turbulent gas.

Segregation must also be explained: the most massive stars lie preferentially near the cluster centre. They cannot have dynamically evolved to the centre since the collisional relaxation timescale is longer than their ages. This has been explicitly shown for the Orion Nebula Cluster where the Trapezium stars are centrally located within a cluster of age ~ 1 Myr, too young to have dynamically relaxed. Furthermore, their distribution is not spherically symmetric, as would be expected if the 'swarm' of stars had relaxed. Therefore their location is a 'primordial' feature. That is, massive stars do not migrate to but are born in cluster cores. Note that, according to the Jeans criterion, the contrary should occur since high densities and high pressures favour the production of low mass fragments (see §4.3.4).

The merging of stars will produce higher mass stars and the higher collision probability in the crowded cluster core would naturally lead to the correct sense of segregation. The frequency of collisions depends on the effective cross-sectional area of the stars. While the actual cross-sections, πR_*^2 are tiny, the effective cross-sections will be given by the gravitational capture radius:

$$A_c = \pi R_c^2 = \pi R_*^2 \left(1 + \frac{GM_*}{2v_{disp}^2 R_*}\right) \tag{11.5}$$

where v_{disp} is the velocity dispersion of the stars. Adapting the molecular collision rate, Eq. 2.4, to stars, yields a collision timescale of roughly $t_C = 10^9/(n_s/10^4 \text{ pc}^{-3})$ yr on substituting typical parameters (e.g. $v_{disp} = 2$ km s^{-1}), which means that even with the high stellar density of $n_s = 10^4$ pc^{-3}, stellar collisions are far too infrequent.

There are theoretical possibilities to increase the collision rate. First, one can imagine that residual gas lying in the outskirts will move into the cluster core with the aid of tidal forces which disrupt incipient condensations. This has at least two positive effects. The residual gas can supply existing protostars, preferentially supplying the more massive stars as members of the population compete for the available gas. As well as this 'competitive accretion' (see §12.5.2), the increased core mass forces a contraction, enhancing the stellar density and the stellar collision rate.

Secondly, there is also a high density of cores and one can consider core coalescence to produce massive cores. If the cores contain low-mass stars, these stars would then merge. The outcome of a close encounter is uncertain although it is clear that the two stars form a binary with a decaying orbit. Simulations show, however, that such tight binaries disperse the remaining stars. Thirdly, and as a counter-argument, one can consider the protostars to be extended objects, possibly with massive disks. This increases their effective cross-sections and the massive disks can soak up the excess energy, alleviating the dispersal problem.

These ideas could be combined into a three stage scenario for the collisional evolution of a large cluster. In the first, the cores coalesce. In stage 2, the remaining gas settles towards the centre. In stage 3, star–star collisions occur in the core. There are, however, too many uncertainties and we save further discussion for our presentation of multiple star systems in general (§12.5).

Massive stars are not exclusively members of rich stellar clusters. Recently, isolated examples of massive stars have been discovered in nearby galaxies. Massive stars have been found in association with only very small groups of lower mass stars in the bulge of the M51 galaxy. There are also reports of apparently isolated, massive field stars in both the Large and Small Magellanic Clouds. Therefore, we need quite versatile theories, encompassing wide concepts if we are to reach a consistent understanding.

11.8 Intermediate Mass Stars

In 1960, George Herbig suggested that Ae and Be stars associated with nebulosity are pre-main-sequence stars of intermediate mass. They are either the analogues of T Tauri stars in the mass range between 2 and 8 $M_\odot$ or in their radiative phase of contraction onto the main sequence. Specifically, the selection criteria of these 'Herbig Ae/Be stars' were (1) the spectral type is A or earlier, (2) the spectra display emission lines, (3) they are located in an obscured region and (4) they illuminate a bright reflection nebula in the immediate vicinity.

The first criterion ensures that the stars lie in the desired mass range. The second and third ensure that the stars are young. The fourth excludes stars that are projected by chance onto dark clouds. The third and fourth together exclude extended objects which have detached envelopes produced by violent ejections (e.g. planetary nebulae and Wolf-Rayet stars). Applying these criteria, Herbig proposed a list of 26 stars.

Nowadays, the criteria are not so stringently applied. More relevant is the fact that all known Herbig Ae/Be stars possess an infrared excess due to thermal re-radiation indicating the presence of dust in the form of a circumstellar envelope or disk. In addressing the question as to whether accretion disks around high mass stars are present, the Herbig Ae/Be stars play a crucial role, since these objects are the only higher mass pre-main-sequence stars that are visible at optical and infrared wavelengths. Additional characteristics of Herbig Ae/Be objects include an anomalous extinction law and photometric variability. Furthermore, the spectral range has now been widened to include cooler stars up to F8, to bridge the gap between Herbig Ae/Be stars and the boundary for classical T Tauri stars.

Whether or not Herbig Ae/Be stars are embedded in accretion disks has not been fully established. It is now clear that there are large differences between the most massive stars in this group (with spectral types B5-B0, Be), and the less massive Ae ones. In Ae stars, we have strong evidence for the presence of circumstellar disks from millimetre interferometry and from direct images in the visual. This is not the case for Herbig Be stars. However, even for Herbig Ae stars there is great uncertainty surrounding the structure of the disks, with arguments for the existence of a dust component which is roughly spherically distributed. As a consequence, the spectral energy distributions of Ae stars have been interpreted as originating from extended spherical envelopes of low optical depth.

The excess emission of Herbig Ae stars has been a long-standing puzzle.

A large fraction of the stellar luminosity is re-radiated between $\sim 1.25\,\mu$m and $7\,\mu$m, with a peak at about $3\,\mu$m. The solution is now thought to involve the nature of the inner walls of the disk. For these stars, dust evaporation in the inner disk, where the gas component is optically thin to the stellar radiation, is expected if the mass accretion rate is low. The result ids the creation of a puffed-up inner wall of optically thick dust at the dust sublimation radius. This can account for the near-infrared characteristics of the SEDs and suggests that, by interpreting the details, we are approaching a more comprehensive understanding of star formation.

11.9 Summary

How long do massive stars take to form? Observations of hot molecular cores suggest a formation time of 10^5 yr. An analysis based on observations of protostellar outflows suggests a similar timescale: 3×10^5 yr. The small spread in ages of stars in the Orion Nebula Cluster, where there is no evidence that the higher mass stars have formed systematically later compared to the lower mass population, provides an upper limit of 1 Myr.

Do massive stars form from rapid gas accretion or coalescence? Discriminating between these possibilities is a challenging observational task for one main reason: massive stars form in rich clusters emitting copious amounts of ionising photons that profoundly alter the surrounding environment. This makes it very difficult to deduce the primordial configuration of the molecular cloud which represents the initial conditions for massive star formation.

The search for high-mass protostars in the act of collapsing has been another major quest during the last decade. Studies are hindered: representative statistics are not available, with surveys for massive protostars suffering from severe bias toward the brightest infrared sources in the Galaxy. Moreover, massive stars form in a clustered mode: it is nearly impossible to resolve the forming cluster with current telescopes. However, dust millimetre emission is optically thin and, therefore, scales with the masses of the protostellar envelopes. Large-scale dust continuum imaging of rich molecular complexes may prove crucial to constructing representative samples.

In conclusion, the formation, birth and early development of high mass stars are not distinct phases. Since high mass stars are never isolated, their formation is ultimately tied to that of star cluster formation. Hence, the next step is to investigate star formation in the cluster context.