Chapter 12

The Distributions

The story from conception, through birth and infancy, now approaches completion. We have formed objects with characteristics that we hope will develop into stars. They can now undergo the ultimate test – a direct comparison to the finished product: the adult star.

Population surveys yield the social groupings and associations. Although most stars are born in clusters, if they survive long enough they eventually gain their gravitational independency. These form the vast majority of the 'field stars'. While our Sun is now a field star, there are indications that it had a more interactive youth. Some others may have been raised in circumstances similar to their present relative isolation.

A population census yields the number of mature objects presently around us. In particular, we determine the fractions of massive giants and undersized dwarfs. Traditionally, we employ the star's mass as the single critical variable for the reason that this defines the main properties (luminosity, temperature and radius) once on the main sequence.

During the 1990s, we became adept at carrying out wide field surveys as well as probing into the close environment of the individuals. As a result, many promising scenarios have failed and had to be discarded. We find a high propensity of binaries and strong evidence which discriminates between their early binding and their pairing up in later life. We also find a certain propensity for segregation according to mass which helps differentiate between theories of mass migration and selective birth. Last but not least, we now detect brown dwarfs and free-floating planets.

12.1 Types and Prototypes

Any successful theory of star formation must be able to construct the following variety of objects. The ultimate fate of an object depends on its initial mass. We begin with the lowest conceived masses for gravitationally bound objects.

Planetary-sized objects (PSO). A PSO can form if a small mass $M < 0.01$ M$_\odot$ is able to fragment and collapse. With this mass, no significant nuclear reactions, including deuterium burning, are triggered. The only internal source of energy is gravitational. The most accurate estimate now available is 0.011–0.013 M$_\odot$, i.e. 12–14 Jupiter masses. The name 'free-floating planet' implies that the PSO was once orbiting a star before being liberated. Whether they are escaped planets or independent collapsed entities remains open. The number of such objects is also difficult to estimate.

Brown dwarfs (BD). A BD is a sub-stellar object with a final mass in the range 0.012 M$_\odot$ $< M <$ 0.075 M$_\odot$. The central region gets sufficiently warm to ignite deuterium but this is not a durable fuel supply. Hydrogen fusion does not occur. Therefore, the object never reaches a state of equilibrium. Lithium is also likely to be burnt but after a considerable time (§9.1.2). Therefore, the presence of lithium confirms either an extreme youth or a brown dwarf status.

Lower Main Sequence Stars. These are hydrogen-burning stars with masses in the range 0.075 M$_\odot$ $< M <$ 0.25 M$_\odot$. Their interiors are fully convective but do not get hot enough to initiate the 'triple-alpha process' which fuses helium nuclei into carbon (nuclear physicists refer to helium nuclei as 'alpha particles'). These are also called Red Dwarf stars.

Solar-like stars are similar to Lower Main Sequence Stars with masses 0.25 M$_\odot$ $< M <$ 1.2 M$_\odot$ and their convective envelopes now contain radiative cores. Those with $M >$ 0.4 M$_\odot$ will develop into giants. They also burn hydrogen through the proton-proton chain but will eventually become hot enough to fuse helium into carbon and possibly oxygen.

Upper Main Sequence stars possess mass $M >$ 1.2 M$_\odot$. They possess convective cores surrounded by radiative envelopes. Core temperatures exceed 18 million K which means that hydrogen is transmuted into helium through a chain of reactions called the carbon cycle.

Giants & supergiants with $M >$ 4.0 M$_\odot$ become hot enough to fuse carbon & oxygen into heavier elements (the central temperature reaches 600 million K) such as silicon, sulphur and iron. The iron nucleus is the end of the line as far as fusion is concerned, containing 26 protons in the most tightly bound of all nuclei.

Supergiant and Supernova progenitors possess mass $M > 8.0\ \mathrm{M}_\odot$. At these masses, iron fusion is then possible.

Wolf-Rayet stars are the short-lived descendants of O stars with $M > 20\ \mathrm{M}_\odot$. They have nearly reached the end of their stellar lives and an explosion is imminent. They are distinguished by strong obscuring winds from material being blown directly off the stars. Their spectral features are important diagnostics for estimating ages of clusters and starbursts.

The most massive stars that form within our Galaxy possess masses estimated to be of order $100\ \mathrm{M}_\odot < M < 200\ \mathrm{M}_\odot$. Even more massive single stars are not excluded.

12.2 Binarity and Multiplicity

12.2.1 *The adult population*

A major advance in our knowledge has been the discovery that binarity is the rule rather than the exception. Most stars are members of binary or multiple systems. Estimates vary according to the type of star, with percentage membership ranging from 40–60%. Optical and infrared studies find similar percentages in nearby groups of T Tauri stars. Similar ages within a system suggest that the binaries form *in situ* rather than through accidental binding or later capture. Hence, binary systems are especially important to us because they contain a fossil record of fragmentation events which occurred quite early during star formation.

High resolution techniques used to explore stellar systems include speckle interferometry and adaptive optics. Both are based on the same idea: very short exposures contain much more fine detail of the sources than long exposures do because atmospheric turbulence cannot smear out the information. The trick is to process a large number of these short exposure frames using special algorithms. The term speckle interferometry was coined since stars really look speckled on the short exposures. Each speckle can be considered as an image of the source limited by diffraction.

We begin with the important details for adult stars. Our most reliable source of statistics is derived from the local population of low-mass main-sequence stars. The results are clear and unbiased.

1. Family membership. The frequency of occurrence for low mass or dwarf stellar systems can be expressed as single:binary:triple:quadruple sys-

tem ratios of 57:38:4:1, for mass ratios exceeding 0.1. For M dwarfs, ratios of 58:33:7:1 were found. However, there are hints for smaller companions and the estimate for the average number of companions that each primary star has is ~ 0.5–0.55.

2. Orbital periods. The periods are drawn from a wide distribution from less than a day to over 1 Myr. The distribution is single peaked and roughly log-normal i.e. log(P) rather than P is distributed like a Gaussian (§3.1). The median period, P, is 180 yr.

3. Separation. Multiple systems display a hierarchical structure (e.g. a distant companion orbiting a close binary) corresponding to long and short period sub-systems. The periods correspond to separations from a few $R_\odot$ to 10,000 AU with a broad peak at ~ 30 AU.

4. Mass ratio. We define $q = M_2/M_1 \leq 1$ as the mass ratio. Here, the data are not conclusive as yet. There may well be a peak in the distribution at $q \sim 0.23$ but the distribution below this value is not well determined. Brown dwarf companions may be relatively rare.

5. Eccentricity of orbits. Close binaries with periods of order days are in circular orbits. This could be expected from our knowledge of how tidal dissipation influences orbits during the main-sequence lifetimes of these stars and so does not provide clues as to the star formation processes. Wide binaries take on a range of eccentricities from ~ 0.1–0.9.

6. Age. Similar frequencies and statistics have been found in young clusters, Hyades (500 Myr old) and Pleiades (70 Myr old).

12.2.2 *The pre-main sequence population*

At the distances of the nearest regions of star formation, the lowest mass stars and brown dwarfs are very faint. We still have only hints about such properties as their mass accretion rates, rotational velocities and spectroscopic binarity (i.e radial velocity information). Binarity has been explored through diverse means: near-infrared speckle interferometry, lunar occultation and radio continuum observations.

1. Family Membership. Most stars form in multiple systems. For separations between 15 AU and 1800 AU, the binary frequency in T associations, such as Taurus and ρ Ophiuchus, appears to be about double that of the field. On the other hand, within the Orion Trapezium cluster the binary frequency is similar to that of the main-sequence.

2. The orbital parameters, periods and eccentricities, are quite similar

to those of main-sequence stars. The distribution of mass ratios of T Tauri stars in Taurus is comparatively flat for $M_2/M_1 \geq 0.2$, but the result is sensitive to the assumed evolutionary tracks. The mass ratio is neither correlated with the primary's mass or the components' separation.

3. Age. Binary formation has finished by the time young stars are a few million years old. The pairs in a binary appear to have the same age. Binary protostars have also been discovered but detailed information is still lacking.

12.3 Binarity: Theory

12.3.1 *Mechanisms*

We are not certain of the mechanism which produces binaries. We do know that the observations require that binary pairing and star formation proceed together. Potential explanations depend on the chosen combination of initial conditions and physical processes. We raise the following five possibilities here and show that the arguments narrow the field down to just one or two:

(i) Capture: joining together of two unbound stars.
(ii) Fission: bisection of one bound object.
(iii) Prompt Initial Fragmentation: early, during core formation.
(iv) Fragmentation during collapse.
(v) Fragmentation within a disk.

Gravitational capture of point-like stars is extremely unlikely. Therefore, to enhance the direct capture argument, we search for processes which raise the probability of a close encounter which might lead to a capture. Removal of excess energy during an encounter can be caused by dissipation through the raising of tides on the two participating stars ('Tidal Capture') or by the transmission of energy to a third participating body ('Dynamical Capture'). However, both processes are found to be ineffective. Capture can be enhanced in dense clusters, or tighter sub-cluster locations, provided massive circumstellar disks are present to interact with ('Star-Disk Capture'). This favours small tight clusters where massive extended disks are more likely to survive the first encounter. This mechanism would naturally favour the formation of wide long-period binaries.

Fission scenarios require a contracting protostar to be unstable. If spinning rapidly, then a rotational instability could come into play as the contraction proceeds. Conserving angular momentum, the protostar will spin up and become unstable to axisymmetric perturbations when the ratio of rotational to gravitational energies surpasses a critical value calculated to be 0.27. The protostar deforms into a bar-shape and then the bar splits into two distinct bodies, forming a close binary. In this manner, spin angular momentum is converted into orbital angular momentum. This mechanism would clearly produce just close binaries. However, computer simulations have led us to abandon this attractive idea. The problem with it is that we are dealing with a compressible gas which will readily form spiral arms. The arms remove angular momentum, leading to a single central body surrounded by a spinning disk

12.3.2 *Fragmentation*

Gravitational fragmentation is one of the most popular themes for computer analysis. The complex physics, the extremes in scale and the variety of possible initial states make the numerical simulations challenging but the results often dubious. Nevertheless, the methods described in §5.5 have now reached some sophistication.

In the Prompt Initial Fragmentation scenario, we invoke an external agency such as a clump-clump collision. Clump collisions produce shock waves which help build up unstable dense layers capable of fragmenting into multiple protostars. For example, an initial mass of one Jeans mass, on a a scale of 10,000 AU, is disturbed and transformed into a compressed and distorted entity of several Jeans masses. The collapse then takes place simultaneously onto several gravitational centres. The gravitational centres are protostar-disk systems, which then evolve through dynamical interaction and energy dissipation to produce close binaries.

Fragmentation during collapse is the most versatile in theory. This can produce wide binaries, eccentric orbits, hierarchical clustering, disk and bar fragmentation. However, single stars are still predicted to result from the collapse of cores in which the density is centrally peaked. Cores in which the density peaks with $\rho \propto R^{-2}$ are quite resistant to fragmentation since each collapsing shell of gas has little influence on other shells. However, this now appears to be consistent with the latest findings as discussed in §8.3: pre-stellar cores are less compact and usually possess flatter density profiles.

Furthermore, pre-stellar cores are non-spherical (§6.5) and contain only a small fraction of their energy in their rotational motions (§6.2.2). This has prompted simulations of prolate and oblate clouds which are more prone to collapse into bars and rings, which subsequently fragment.

A second problem is raised by the standard scenario in which an inside-out collapse occurs. Here, one might expect that when about one Jeans mass of material has accumulated, it will promptly collapse directly to a single star. The scenario does not predict the formation of an object with at least two Jeans masses – the required mass in order to produce two separately bound fragments within a common envelope.

A third problem is to produce a sufficient number of close binaries with separations under 1 AU. Orbital decay is again invoked although other possibilities, such as very low angular momentum cores, remain to be explored. On the other hand, to see how to directly produce a binary on this scale, we use the formula for the Jeans length (Eq. 4.16) and $\lambda_J = 1$ AU to predict the required density: $\sim 10^{-10}$ g cm^{-3} or $n \sim 10^{14}$ cm^{-3}. This corresponds to a Jeans mass of < 0.01 M$_\odot$, on substituting into Eq. 4.19. In this case, fragmentation is only the beginning – it must be followed by massive accretion to build up the component masses.

Accretion of residual matter is expected to occur through a disk which will also influence binary. A companion will prevent a disk from forming in its vicinity, opening up gaps on either side of its orbit. It will also inhibit the expansion of a disk as it evolves on to larger scales, as calculated in §9.5. When the disk can no longer expand, the mass will empty out on quite a short timescale and the angular momentum can be transferred into the binary orbit through tides. Given the high percentage of binaries and the median separation of just 30 AU, it is feasible that half of the young stars will have their disks drained quite quickly, becoming relatively young (1 Myr) Weak-line T Tauri stars.

Interaction with a circumbinary disk would drive the system towards a tighter orbit. One can also argue that the accretion of gas with low angular momentum will lead to the merging of the components, whereas high angular momentum leads to a binary of near equal mass

Finally, disk fragmentation can be initiated by encounters or through disk instability as discussed in §9.4.2. In simulations, objects as massive as 0.01–0.1 M$_\odot$ have been found to form. Furthermore, early encounters may explain anomalous structure in our own solar system such as high eccentricities and inclinations.

These fragmentation models can be linked to the pattern emerging from observations of cores. First, we note that fragmentation is responsible for clustering as well as binarity and multiplicity. In principle, the distance between stars in binaries can take any value. There is, however, a pronounced 'knee' in the observed distribution at about a separation of 0.04 pc (8,250 AU). Apparently, this is the scale which divides clusters from binaries. This scale was found by Larson in 1995 and suggested to be correlated with the Jeans length. Larger systems form by fragmentation and independent collapse to form the independent envelope systems as mentioned in §8.3. A cloud containing many Jeans masses, often envisioned as prolate or filamentary, may thus form several independent cores akin to that expected through Prompt Initial Fragmentation.

In this picture, the common envelope systems (see §8.3) may be related to the fragmentation of cores more spherical and centrally condensed. In this case, fragmentation mechanisms work within the central region, especially when the density is not centrally peaked but quite flat, and proceeds according to the 'Fragmentation during Collapse' scenario.

Common disk systems, on the other hand, would appear to originate in clouds containing relatively high angular momentum. The disk forms early before splitting; tight stellar systems would result.

In summary, while a few plausible and some feasible binary mechanisms have been studied, direct observations of forming binaries may be necessary to really establish our knowledge. The wide range in periods and mass ratios, the number of close orbits, the range of eccentricities, the production of single stars are all in need of convincing explanations. Nevertheless, fragmentation (or the lack of it) at different stages during infall probably lies at the heart of the matter while dynamical events, rather than quasi-static collapse, greatly enhances the probability of fragmentation.

12.4 Nearby Clusters: Observations

Soon after their first exploration, Ambartsumian concluded that T Tauri stars were objects which had recently formed. The loose congregations of these youthful stars were termed *T associations.* They are unbound groups in dusty regions such as Taurus-Auriga, ρ Ophiuchus and Chamaeleon I. They typically produce a few thousand stars over a lifetime of 10 Myr. Because they are nearby, they provided most of our knowledge on the production of low-mass stars. It was assumed that low-mass stars were born almost exclusively in these groups.

It was also thought that high-mass stars were born in distinct clouds. Groups of these young stars were called *OB associations*, striking concentrations of short-lived brilliant stars. This has now proven false. The truth is that most T Tauri stars are also born in the environments of OB associations such as those found in Orion. Counting local stars, it is estimated that over 90% of the low mass stars younger than 10 Myr are born with OB association status. In addition, it has been proposed that our Sun probably formed in an OB association since that would automatically locate it close to a supernova, a possible origin of the chondrules found in the solar system (see §8.5).

It was infrared surveys which changed our view, enabling us to carry out a census of the stars still embedded in clouds. Infrared array cameras with large formats allow us to cover wide areas of molecular clouds. We now distinguish embedded clusters from exposed clusters. Rich clusters of stars (i.e. those containing over 100 stars) were identified within the clouds. We have discovered that star formation is not spread out evenly in a Giant Molecular Clouds but is strongly clustered. An example is the L 1630 cloud in Orion, where three clusters which cover 18% of the cloud contain over 96% of the stars. The three clusters are NGC 2071, NGC 2068 and NGC 2024. Ongoing star formation exterior to these regions is negligible.

Most stars form in clusters and so most stars interact while forming and should not be treated as isolated entities. Note that ρ Ophiuchus is also an example of the clustered mode with $\sim$ 100 young stars within an area of $2\,\mathrm{pc}^2$. Clusters are, however, ubiquitous around young stars more massive than ~ 5 M$_\odot$. In contrast, the low-mass stars in Taurus are formed in an isolated mode with $\sim$ 100 stars spread out over $300\,\mathrm{pc}^2$.

Stars clusters are centrally condensed. In young clusters we find that the surface density falls off as $\propto 1/R$ with distance R from the location where the number density peaks. Superimposed on this distribution are significant sub-clustering and structure. Cluster densities can reach several thousands per square parsec (e.g. Trapezium and NGC 2024) within small circular areas of radius 0.1 pc. Starless cores are of similar size (§6.2) and their mass density reaches values of $\sim 5 \times 10^3$ M$_\odot$ pc^{-3}. This is two orders of magnitude greater than presently found in optically-visible open clusters such as the Pleiades.

The spatial spread of young stars in such T associations yields information about past star formation. The typical dispersion in velocities of the stars is $v_{disp} \sim 1$–2 km s^{-1}. The lack of older stars gives rise to the so-called post T Tauri problem. This problem is that the older stars, which should have dispersed out of the cloud, are not found there. The velocity dispersion implies that these stars of age 10 Myr should be found in a halo of size 10–20 pc. Two types of solution have been offered: (1) Star formation in a cloud accelerates so that few of the older stars are to be expected in regions now industriously making protostars; (2) Star formation throughout a cloud is rapid. It begins and ends quite abruptly, lasting for not much longer than a crossing time of a shock wave, sound wave or magnetosonic wave. In other words, the dynamic timescale of an association and the free-fall timescale of an individual core are comparable.

The spatial spread of stars in OB associations is not always spherical. The youngest clusters, at least, maintain a record of the shape of the cloud from which they condensed. The Orion Nebular Cluster is apparently elongated with an aspect ratio (the ratio of major to minor axes) of 2. This probably stems from an even more elongated original cloud, estimated to have had an aspect ratio of 5. We explain this in terms of the process of 'violent relaxation', discussed below.

12.5 Cluster Formation: Theory

The mechanism by which a molecular cloud fragments to form several hundred to thousands of individual stars has remained elusive. The evolution from cloud to cluster involves three major steps: from gas to stars, dynamical relaxation, and cluster dissolution.

12.5.1 *From gas to stars*

The primary insight from large-scale computer simulations is that a stellar cluster forms through the hierarchical fragmentation of a turbulent molecular cloud. The supersonic turbulence manoeuvres the gas into sheets and filaments which occupy only a small fraction of the cloud volume. Fragmentation into many bodies also occurs most readily when the cloud contains filamentary structures.

The two observed modes of star formation are also reproduced in the simulated world. Isolated or distributed star formation occurs if the turbulence is driven. This inhibits wholesale collapse of a cloud. The driving scale and driving energy then determine the typical size of the star forming regions. Despite the turbulent cascade, the energy remains predominantly on the injected scales. Therefore, turbulent support breaks down on some smaller scales provided sufficient matter can be accumulated within a shock-compressed layer for gravitational forces to dominate locally.

The clustered mode occurs if the turbulence decays or is sufficiently intermittent so that large regions find no support over a dynamical timescale. A problem is to establish the initial state in which fragments are not forming on the small scale, yet turbulence is only driven on a large scale. In principle, one requires a high energy input on the small scales to prevent immediate collapse of isolated regions.

However, in a turbulent interstellar medium, an initial state with some form of quasi-static equilibrium rarely arises. When it does, the cloud is likely to be long-lived. Therefore, our observations of clouds, clumps and cores are all strongly biased towards these rare objects. Such a selection effect has almost certainly diverted our attention from dynamical models even though the turbulence was measured.

The most sophisticated SPH simulations are now able to follow the hydrodynamical evolution of quite rich clusters. First to develop are many small sub-clusters, which interact and merge to form the final stellar cluster. As opposed to a more uniform distribution arising from a monolithic formation, the hierarchical nature of the clustering implies that a protostar has a higher number of close neighbours and more frequent dynamical interactions. Such close encounters can truncate circumstellar discs, harden existing binaries and potentially liberate a population of planets. It is estimated that at least one-third of all stars, and most massive stars, suffer through such disruptive events.

12.5.2 *Cluster relaxation*

Groups of young stars can be rich or poor in number, bound or unbound gravitationally, and clustered or isolated in mode. They also tend to be segregated in mass, with the massive stars forming in the cluster centres (see §11.7).

Young clusters of stars are subject to two types of dynamical evolution. The first is a contradiction in terms: violent relaxation. This involves the global change of the cluster's gravitational potential due to collapse. The timescale is given by an average crossing time, $t_{cross} = 2\ R_c/v_{disp}$ where R_c is the radius of the cluster within which half the mass resides. The effect is independent of stellar mass since the gravitational potential of the entire cluster determines the dynamical evolution. It generates a centrally condensed configuration which slowly removes the record of the original state. However, the removal is slow and the imprint of an initial non-spherical configuration may be recognised.

The second type of evolution is called two-body relaxation (again, an apparent contradiction in terms). Two-body interactions transfer kinetic energy to the lower mass body, which has two major effects: a tendency towards equipartition of object energies and the sinking of more massive bodies towards the cluster centre. This requires the much longer time $t_{relax} \sim t_{cross}(N/8\ lnN)$, where N is the number of cluster members, but does lead to a complete loss of memory of the initial state. This process, while always in operation, is too slow to explain the observed segregation of massive stars in young clusters (see §11.7).

Numerical simulations demonstrate that the gas accretion and the dynamical interactions are simultaneous processes. Observations also show that young stellar clusters are still gas rich. At the outset, material not bound to a particular core provides frictional drag while the individual cores compete to attract the gas. Therefore, the final mass of the stars depends on the outcome of the *competitive accretion.* Gas falls preferentially into the deepest part of the core potential. Protostars which loiter in the centre thus accumulate most mass and so become massive central stars. Protostars in binary systems will also grow fast due to their location near the centre (where dynamical capture is more likely) and due to their extra attraction. As a result of the competition, inequalities in mass are promoted and a runaway might ensue. As a result of the dissipation, the cluster becomes tighter and binaries closer.

12.5.3 *Cluster dissolution*

The vast majority of stars are field stars: free to move within the Galactic potential. So, how do clusters dissolve? There are two strong possibilities: feedback from protostars and binary-controlled ejection.

All clusters develop out of massive and dense molecular cores. Their rapid dynamical evolution is the cause of their high gas content: most of the gas has not had time to accrete or disperse. If this gas is removed abruptly in the star formation process, blown away by winds, H II regions or outflows, then the cluster becomes unbound. Hence, exposed open clusters will be quite rare, explaining why the visible clusters that we do see cannot account for all field stars. Alternatively, if the gas is removed less dramatically over several crossing times, the cluster may adapt and survive with reduced numbers.

The second mechanism relies upon a central massive binary which prevails over the cluster, interacting and ejecting lesser bodies. The ruling binary takes up the total potential energy. The timescale depends strongly on the number of stars with a dissolution time of $t_{diss} \sim t_{cross}(N^2/100)$. Therefore, small clusters are depopulated rapidly, making them difficult to find before they have dissolved. In rich clusters, however, this mechanism is very inefficient. One then requires the above feedback mechanism, enhanced by the presence of highly interactive massive stars.

12.6 Brown Dwarves and Planets

Arguments have been made against the formation of sub-stellar objects. Therefore, the successful search for brown dwarfs represents considerable progress. The formation of sub-stellar objects is now an intimate part of the star formation story. Theories of star and planet formation predict that stars ($M > 0.075\,\mathrm{M}_\odot$) form during the dynamical collapse of a cloud core, while planets ($M < 0.012\,\mathrm{M}_\odot$) form via the accretional coagulation of material in a circumstellar disk. The intermediate mass at which the dominant formation mechanism switches from collapse to disk coagulation, however, is not known. Since brown dwarfs are objects with masses intermediate between those of stars and planets, they offer an important link between star and planet formation.

The formation of brown dwarfs and even of the lowest mass stars remains obscure because of the difficulty in determining their basic properties (e.g. mass accretion rates, rotational velocities, and spectroscopic binarity) at young ages. Accurately determining these properties generally requires high-resolution spectroscopy. At the distances of the nearest regions of star formation, however, the lowest mass stars and brown dwarfs are too faint to have been included in all but the most recent high spectral resolution surveys.

A brown dwarf forms when sufficient mass is not accreted to raise the central temperature high enough to spark hydrogen burning. This is a result of the Pauli exclusion principle of quantum mechanics which forbids electrons to occupy the same state. Therefore, the density reaches the level where the electrons in the core become degenerate and degeneracy pressure provides stiff resistance to collapse and heating. The result is that the cloud compression is inhibited and the core stops getting hotter. Such a cloud fails to become a star and is called a brown dwarf (since the term 'red dwarf' was already allotted to the class of lower main sequence stars).

A principle reason for examining brown dwarfs here is to complete a census of all objects formed during star formation. They are often identified as objects excluded from being stars: stars possess luminosities and temperatures of at least 10^{-4} $L_\odot$ and 1,800 K. The 'lithium test' is based on the prediction that low mass stars burn their lithium within their first 50 Myr of life, whereas those brown dwarfs with masses below 0.064 $M_\odot$ maintain their lithium abundance forever. Since these stars are fully convective, the surface lithium reflects the value throughout the star. Another method to detect brown dwarfs involves the search for methane (present if $T < 1{,}500$ K), and, to distinguish brown dwarfs from planets, the detection of deuterium signatures.

Planets begin to take shape at the end of the Class II stage (0.001 $M_\odot$ necessary). About 60% of T Tauri stars younger than 3 million years possess dust disks, compared with only 10% of stars that are 10 million years old. The implication is that the disappearance of disks in older stars is linked to the appearance of (unseen) planets. In our solar system, the comets in the Kuiper belt (100–200 AU) and the Oort Cloud (0.1 pc) are the residuals of the disk.

Therefore, planet formation is a by-product of star formation. In detail, we can envisage the following sequence. During the infall, material that does not fall onto the star forms a disk. During the Class 0 protostellar stage, the dust sinks to the midplane of the disk, forming a dense opaque sheet. Within this sheet, the dust clumps together and agglomerates into larger objects, called planetismals. During the Class I protostellar stage, the planetismals collide and build up to Earth-size planets and the cores of giant planets like Jupiter and Saturn. During this stage, proto-Jovian cores rapidly form beyond ~ 5 AU (the 'snow line' beyond which water freezes, making much more mass available in the solid phase). Within this radius, the solids available to make the terrestrial planets are metal oxides and silicates. Therefore, the inner solar system slowly forms rocky planetesimals. However, the early planetismals and any other objects are swept into the protostar, producing some of the accretion variability we observe.

During the Class II stage, surviving bodies can accrete atmospheres. Proto-Jovian cores (10–20 Earth masses) gravitationally accumulate huge amounts of hydrogen and helium gas from the disk. Planetary embryos of terrestrial and ice giants form 1000–10,000 km diameter bodies. Considerable orbital migration occurs in the disk because the disk actively accretes. In the Class III stage, Jovian planet formation has ceased but the terrestrials and ice giants are still forming through accretion. Finally, the residual gas and dust in the disk dissipate by being either blown away by stellar winds or accreted onto the planets.

12.7 The Masses of Stars

The birth rate for stars of each mass can be determined from the number of star of each mass that we find around us, given their age. In turn, their masses can be determined from their luminosities, given a few basic assumptions contained in the theory of stellar evolution. In this manner, 'the rate of star creation as a function of stellar mass' was derived from the luminosity function by Edwin Salpeter in 1955. This distribution is now described by the Initial Mass Function (IMF). Salpeter found that the number of stars, N_s, in a complete volume in the solar neighbourhood could be approximately represented by a declining power-law when divided into bins of equal $\log \mathcal{M}$:

$$\frac{dN_s}{d \log_{10} \mathcal{M}} \propto \mathcal{M}^{-1.35} \tag{12.1}$$

for stars in the mass range $0.4 < \mathcal{M} < 10$ where $\mathcal{M}$ is the mass in solar units. (It is sometimes easier to distribute the stars into bins of equal mass, in which case the function is one steeper: $dN_s/d\mathcal{M} \propto \mathcal{M}^{-2.35}$.) We are now able to calculate the IMF more accurately. However, considerable uncertainties remain, as illustrated in Fig. 12.1. Systematic variations of the IMF with star-forming conditions, the 'Rosetta Stone' for theorists, have yet to be confirmed.

For young contracting stars, there is also considerable uncertainty in the mass-luminosity relation. Alternatively, one can determine the spectroscopic class of the stars and use models to predict the masses. This is not so error prone as it might seem since model masses for pre-main-sequence evolution can be justified by calibrating against the masses of specific stars where dynamical measurements of mass are available (e.g. from the rotation of a disk). For young clusters, near-infrared surveys detect very low mass objects below $0.01\,\mathrm{M}_\odot$.

An analytical fit based on a log-normal distribution, which is a normal (Gaussian) distribution with $\log \mathcal{M}$ as the variable, is often discussed. Such a distribution is favoured in circumstances where many independent processes are contributing in a multiplicative manner. However, it is now excluded since it does not predict a sufficient number of high-mass stars.

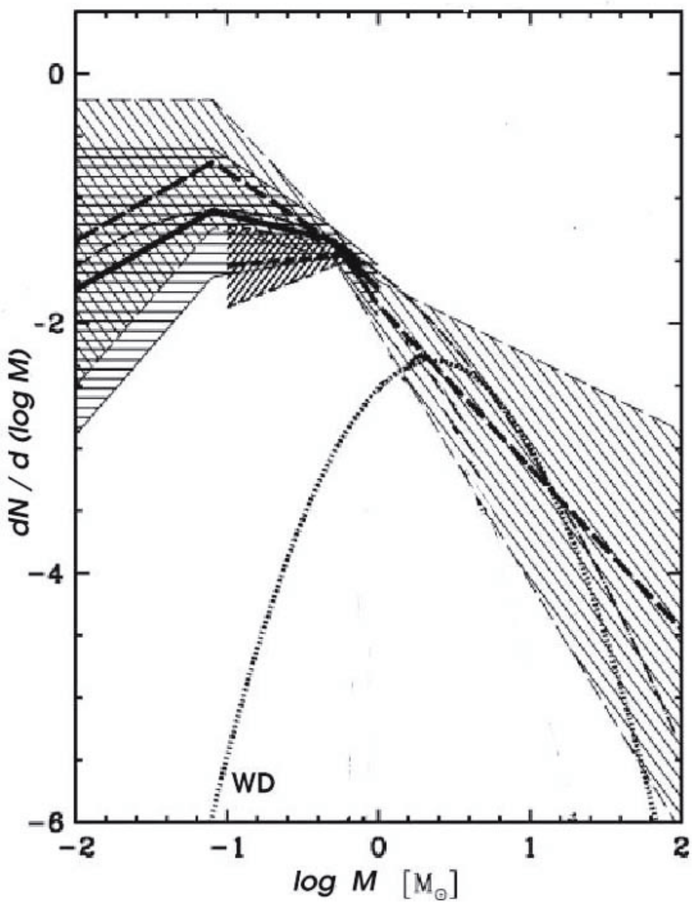

Fig. 12.1 The present-day IMF (thick-dashed) and Galactic-field IMF (thick solid line). The errors are large: the shaded areas represent the approximate 95-99 per cent confidence region. A possible IMF for Galactic-halo white-dwarf progenitors is also shown (labelled WD) and might indicate a variable IMF (Credit: from data originally presented by P. Kroupa in MNRAS, 322, 231).

Instead, we fit a multi-component power-law which describes the flattened distribution at low stellar masses and a further restriction or dearth in the number of brown dwarfs. There is evidence that two breaks in the power law are required:

$$\frac{dN_s}{d\log_{10}\mathcal{M}} = \begin{cases} 0.26 \ \ \mathcal{M}^{+0.7} & \text{for } 0.01 \le \mathcal{M} < 0.08 \\ 0.035\mathcal{M}^{-0.3} & \text{for } 0.08 \le \mathcal{M} < 0.5 \\ 0.019\mathcal{M}^{-1.3} & \text{for } 0.5 \quad \le \mathcal{M} \ . \end{cases} \tag{12.2}$$

The indices are only indicative. There also appears to be considerable variation according to the precise population chosen. Nevertheless, a 'Universal IMF' can still be roughly adopted which has a characteristic mass of about one solar mass and a power-law tail at the high-mass end. Note that we can also trace where most of the mass is channelled: the mass function possesses indices one greater than the number function. This implies what we have already guessed: to order of magnitude, star-forming gas produces stars of one solar mass. In addition, very little mass goes into brown dwarfs and low-mass stars.

Important variations are beginning to emerge from cluster to cluster. The mass function in the Taurus star-forming region is quite narrow and sharply peaked. The young cluster IC 348 possesses more low-mass stars, giving a wider distribution. However, both IC 348 and Taurus are deficient in brown dwarfs (about 8% of the samples). In contrast, the Trapezium cluster and σ Orionis show no such deficit (over 20% are brown dwarfs). In fact, isolated planetary-mass objects may be as common as brown dwarfs, which together may be as numerous as the total number of stars.

To summarise, we emphasize that a reliable mass-age-luminosity relation is needed to derive an IMF. Assuming this, the galactic IMF is described by a power-law function for $M > 1 \ \ \mathrm{M}_\odot$ and a log-normal form below. Star formation in the Galactic disk and in young clusters extends well below the hydrogen-burning limit and very likely below the deuterium-burning limit. The number of brown dwarfs is roughly equal to the number of stars, with a space density of order 0.1 pc^{-3}.

How do these facts tie in with the models? The near-uniformity of the IMF points toward a dominant self-similar, scale-free process. There have been a variety of explanations, some outdated, some updated and some still with merit. We list the following:

(i) A variety of mechanisms, involving many parameters, determine the mass of a star. Statistics then go according to the so-called central limit theorem (as if we combine values from a bank of random numbers).

This means that the number distribution should approach a log-normal distribution.

(ii) Mass regulation by protostellar feedback. The stellar mass might be determined when the outflow strength exceeds the inflow strength. Even here, the number of physical variables involved suggest that the number distribution might approach a log-normal distribution.

(iii) Accretion or competitive coagulation. The distribution is determined by collisions and mergers. A collisional hypothesis would seem less likely for the T associations.

(iv) An inherent property of supersonic turbulence. To verify, this requires numerical simulations involving a high number of Jeans masses and a wide range in scales.

(v) A reflection of the core mass function. The environment determines the distribution of gravitationally unstable cores which go on to form the protostars. The clump mass distribution is described by a substantially shallower power-law function than the IMF but the core mass function is perfectly consistent (§6.2.3). This was then interpreted to mean that the more massive *clumps* are less efficient in forming stars. They are indeed weakly bound or unbound and particularly prone to dispersal by their own protostars.

Given the many constraints on the speed of the star formation process, the turbulent production of cores, and the close resemblance of the IMF to the core mass function, it appears most straightforward to account for the distribution of stellar masses by supersonic turbulence in molecular clouds, preservation of the mass function during collapse followed by cluster evolution. However, this remains to be proven. According to the turbulence hypothesis, the higher frequency of brown dwarfs in richer clusters could be a result of their ejection from multiple systems before they have accreted up to stellar proportions. According to the fragmentation hypothesis, the higher frequency of brown dwarfs could result from the higher gas density in the star-forming environment, leading to a smaller minimum Jeans mass. Furthermore, a wider range in gas temperature would also broaden the mass distribution as inferred from the strong temperature dependence of the Jeans mass.

12.8 Summary

The ultimate data to test our concepts of star birth are the population census. Distributions in space and in mass can be measured for young populations as well as mature ones. Facts to highlight are the high number of binaries, mass segregation, a dearth of brown dwarfs in the low density environments so far explored, power-law high-mass tails and a characteristic mass (in the Galaxy field and Galaxy clusters) close to one solar mass.

A combination of hydrodynamics and stellar dynamics adequately explains most of these characteristics. However, the next few years of observations will certainly decide if other factors are essential.

Stars of each mass feature in a unique manner. The chemical enrichment of our Galaxy depends primarily on stars with mass exceeding $10\,M_\odot$ for their heavy-element content and the energy feedback produced by supernovae. The luminosity results mostly from stars with masses between 1 to a few $M_\odot$, and most of the mass is contained in objects with mass less than $1\ M_\odot$. Such mass distributions are found for galaxies in general as well as the components in the present day intergalactic medium (IGM). However, as we will now discover, it may not always have followed this pattern.