Chapter 1

Introduction

1.1 Our Perception

Fifty years ago, the suspicion was raised that star birth was a thing of the past. The presence of young stars in an old galaxy seemed impossible. Even recently, little was known about how stars presently form and the birth itself remained an absolute mystery. There was a mute gap left exclusively to hand-waving gestures. Even in the best circumstances, we were restricted to weak evidence which often led to indecisive or contradictory conclusions. Today, we find ourselves immersed in facts as the nature of the birth emerges. The revolution was instigated by technological advances which have enabled us to make the necessary observations. Centuries of error-prone and conflicting thoughts can now be laid aside. Stars are indeed being born profusely even in our own back yard.

Stars have a dramatic life history. They are conceived within obscuring maternal clouds and are born through rapid contractions and violent ejections. They grow with others with whom they interact. And they often die in isolation having lived a life unique in some way. Yet, stars are inanimate objects, worthy of scientific endeavour and, apart from the Sun, of no direct bearing on the human condition.

The human condition, however, improves through revelation. Insight and discovery evoke profound feelings of excitement and inspiration which help raise the quality of our lives. Although we live in awe of the stars and we depend upon them for our existence, the mystery of their origin has been maintained. This has been in spite of our deep understanding of the intricacies of how they subsequently evolve and die. Yet the death of stars proves to be important to the conception of life, both stellar and human. This provokes the Genesis question: what made the first star in the Universe?

The quest for the 'holy grail' of star formation was the quest to detect the moment of birth. The decisive journey was along an evolutionary track which connects a cloud to a star. The challenge was to complete the journey by finding the connection between the collapsing cloud and the emergent young star. To do so, we developed telescopes, cameras and receivers which could probe deep into the clouds. In optical light, the clouds are opaque. In light with longer wavelengths – infrared and millimetre radiation – the clouds become transparent. For the first time, our view penetrates the clouds and we can discuss how stars form.

The tremendous advances in our knowledge make this book almost unrecognisable from previous books on the subject. There have been five other major upheavals in the subject in the last few years. They also make for a vast quantity of fascinating material, none of which should be excluded. The story has reached epic proportions.

1.2 The Story of Star Formation

The significance of the six upheavals can be realised by placing them into the story of formation. The chapters are thus ordered to follow the storyline which leads to a star like our Sun, as sketched in Fig. 1.1.

We first introduce the rudimentary materials from which stars are made. Stars are seen to be forming in giant clouds of molecules within the tenuous interstellar medium (Stage 1 of Fig. 1.1). It has long been intriguing that the interstellar gas has not been exhausted and that star formation continues despite the advanced age of our Galaxy.

The basic tools that we possess to work the materials are a range of interacting physical, chemical and radiation processes (§1.5). This provides an essential background that permits observations of the interstellar medium and molecular clouds to be placed into perspective (§2.5).

This leads to the classical theory of star formation in which the opposing forces of gravity and pressure provide a precarious equilibrium. The gradual collapse through states of hydrostatic equilibrium is laboured but was consistent with the fact that star formation continues in our Galaxy (§3.7).

However, the slow evolution and delicate balance contradict almost all other observational evidence as well as our computer simulations. We find that individual clouds are simply too young and too turbulent. We ob-

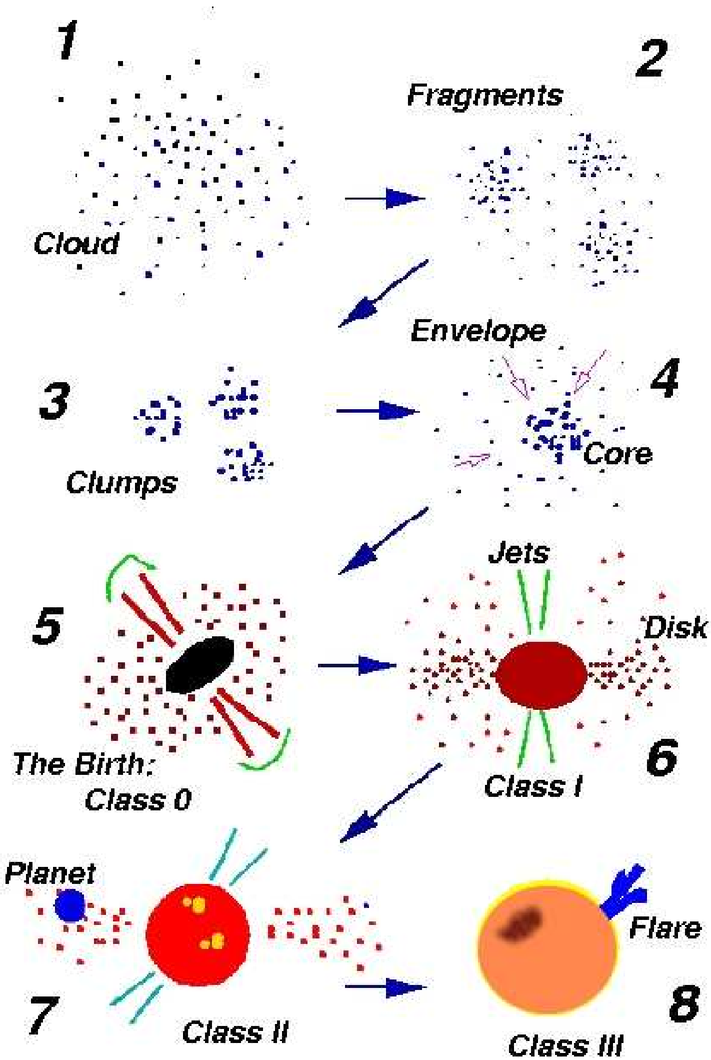

Fig. 1.1 A sketched guide to the stages in the formation of a low mass star like our Sun from conception through early development.

viously need a hydrodynamic approach to describe the fragmentation into clumps (Stages 2 & 3 of Fig. 1.1). After 50 years of stagnation, the concepts of turbulence are no longer in chaos and in §4.4 we see how a turbulent revolution is solving long-standing problems. We now interpret the sustained star formation as one of the effects of turbulence: stirring the gas generates some stars but recycles most of the gas to the interstellar medium.

Out of the turbulence, eggs are laid (Stage 4). We have now uncovered the sites of star conception: compact molecular cores within tenuous surroundings. We attempt to follow the collapse and contraction of cores as a pure gas or fluid flow and find the way blocked: the spinning gas will be held up by its own centrifugal force.

To permit the collapse to progress, we invoke a magnetic field. Magnetic flux threads the clouds which, when combined with the core dynamics, leads to fascinating magnetohydrodynamic concepts (§6.6). The gas thermal pressure interacts with magnetic pressure and tension. In addition, magnetic lines of force are twisted by the rotating fluid and, perhaps later or elsewhere, uncoil to rotate the fluid. The collapse problems are then solvable.

We now believe we have detected the young star in the nest (Stage 5). Not only pre-stellar cores, but protostellar cores have been discovered. The mammoth effort required to detect these cold contracting cores is the second of the six major advances (§7.8).

The formative period of a young star is millions of years (Stages 6 & 7). The baby stars are tiny centres of attraction, being fed from a disk supplied from an envelope. The disk continues to feed the star from birth through to infancy. Questions remain as to what makes the disk such a reliable source. Finally, the young star starts to resemble the adult (main sequence) star but with exaggerated behaviour (Stage 8). It is no longer nurtured but still liable to close encounters which can be traumatic (§8.10).

Since the birth, a protostar has been ejecting remarkable slender jets of gas which drive spectacular outflows to highly supersonic speeds. This yields the inflow-outflow enigma: when searching for evidence for inflow, we often find just outflow. Many outflows turn out to be gigantic twin structures, which have only been detected after developing innovative technology to explore wider areas of sky. This has been the third great advance, the consequences of which are still being deliberated (§9.8).

Massive stars provide their own evolutionary problems. They live short and intense lives during which they have a disproportionate influence on events around them. Their positive feedback is the triggering of new generations of stars through compression; the negative feedback is the disruption of potential cores in their vicinity. As a result, we suspect that much of star formation is *self-regulated* (§10.10).

Stars are not isolated. They tend to form as members of binaries or small systems. The systems form and evolve almost exclusively in clusters.

The gas supply to the individual depends on their location in the cluster and the competition within the cluster and within the system. Observation and theory then demonstrate principles of mass segregation. These studies of the dynamical evolution, with remarkable spatial resolution provided by the latest generation of telescopes and supercomputer simulations, comprise the fourth great advance (§11.9).

The amazing discovery of very low-mass objects in these same regions of star formation is the fifth advance. The objects which will never become stars are brown dwarfs and free-floating objects with the sizes of planets. Their origins and relationship to the wide range of initial masses are crucial tests for all our ideas. Are they failed stars, ejected members or independent characters? In addition, planet formation can only be studied as part of the star formation process. The planet Earth was constructed during the formation of the Sun, probably during the late Class II phase when the disk was still quite active (§11.9).

Where and when appeared the very first star? In the early Universe, only basic commodities were present. The first star in the Universe preceded the first supernova. This is obvious but, in the absence of supernova enrichment, primordial stars must have formed in *warm atomic* gas. What this means and how this has determined the character of our present day Universe is just coming to light. The latest satellite observations and highly sophisticated simulations indicate that the primordial stars appeared first and extremely early. This, the sixth great advance, heads our final chapter which investigates the galactic scale, the super star cluster and the starburst galaxies (§12.8).

In terms of physics and chemistry, the story is too complex. However, scientists and mathematicians are developing tools to describe the *dynamics* of complex systems. In the future, we can combine principles of turbulence, self-regulation, self-propagation and self-destruction to construct working models.

1.3 The Early History

There is little early history surrounding the general subject of Star Formation. All the attention has been focused upon the origin of a single stellar system. As outlined below, some renowned individuals have contemplated the origin and early development of the solar system. Many of the ideas will resurface in modern theories.

René Descartes proposed a Theory of Vortices in 1644. He postulated that space was entirely filled with swirling gas in various states. The friction between the vortices 'filed' matter down and funnelled it towards the eye of the vortex where it collected to form the Sun. Fine material formed the heavens on being expelled from the vortex while heavy material was trapped in the vortex. Secondary vortices around the planets formed the systems of satellites.

Emanuel Swedenborg put forward a Nebula Hypothesis in 1734. The Sun was formed out of a rapidly rotating nebula. The planets were the result of condensations from a gauze ejected out of the Sun. The germinal idea for his nebular hypothesis came from a seance with inhabitants of Jupiter.

Georges Buffon suggested an Impact Theory in 1745. He proposed that a passing comet grazed the Sun and tore some material out of it. This cooled and formed the Earth. Apparently, Buffon had in mind a comet as massive as the Sun and an encounter corresponding to a modern tidal theory.

Immanuel Kant (1755) and Pierre Simon de Laplace (1796) independently proposed Nebular Hypotheses, amongst the oldest surviving scientific hypotheses. They involved a rotating cloud of matter cooling and contracting under its own gravitation. This cloud then flattens into a revolving disk which, in order to conserve angular momentum, spins up until it sheds its outer edge leaving successive rings of matter as it contracts. Kant tried to start from matter at rest whereas Laplace started with an extended mass already rotating.

Charles Messier (1771) recorded the shapes of astrophysical nebulae which were suggestive of disks around stars in which new planets might be forming. Even though these nebulae turned out to be galaxies, the Kant-Laplace hypothesis still survives.

George Darwin, son of Charles Darwin, conjured up a Tidal Hypothesis in 1898. Extrapolating back in time, to four million years ago, the moon was pressed nearly against the Earth. Then, one day, a heavy tide occurred in the oceans which lifted the moon out.

Sir James Jeans investigated Gravitational Instability in the early 20th century. He demonstrated that there was a minimum amount of gas that will collapse under its own self-gravity. Jeans calculated that above this critical value, gravity would overcome the thermal motion of the particles which would otherwise disperse the cloud. The critical mass of gas is called the Jeans Mass.

Thomas Chamberlin (1901) and Forest Moulton (1905) proposed a planetesimal hypothesis. They postulated that the materials now composing the Sun, planets, and satellites, at one time existed as a spiral nebula, or as a great spiral swarm of discrete particles. Each particle was in elliptic motion about the central nucleus. James Jeans (1916) and Harold Jeffreys proposed a new Tidal Hypothesis in 1917 while World War I was in progress. A passing or grazing star is supposed to have pulled out a long cigar-shaped strand of material from the Sun. The cigar would fragment to form the planets with the larger planets at intermediate distances.

1.4 Modern History

In the 1930s, it was realised that stars are powered through most of their lives by thermonuclear reactions which convert hydrogen to helium. With the lack of observations, however, the suggested models could only be tested against physical principles. For example, Lyman Spitzer's 1939 refutation of tidal theory brought down the Jeans-Jeffreys' hypothesis. He showed that the material torn out of the Sun by near-collisions would be hot and so would then rapidly expand and never contract into planets. Nevertheless, ideas were plentiful.

Henry Russell's Binary and Triple Star Theories (1941) resemble Buffon's passing star theory. The Sun was originally part of a binary system and the second star of this system then underwent a very close encounter with a third star. The encounter ejected a gaseous filament in which the planets formed.

Raymond Lyttleton proposed the Triple Star Theory in 1941 in which the Sun was originally part of a triple star system. The Sun's companions accreted gas and grew closer and closer together until they fragmented because of rotational instabilities. After merging, the stars form planets.

Fred Hoyle put forward a Supernova Hypothesis in 1944. Hoyle, inspired by Lyttleton's system, set up a system in which the Sun's companion star was a supernova. The outburst would have to be sufficient to break up the binary system yet leave sufficient remains to form the planets.

Fred Whipple promoted the Dust Cloud Hypothesis in 1946, applicable to the origin of all stars. The pressure of light rays from stars pushed dust into clouds, and chance concentrations condensed into stars. A smaller dust cloud was then captured with a much greater angular momentum, enough to form the planets. Whipple had thus proposed a mechanism to trigger stars.

Carl von Weizsäcker revived the Nebula Hypothesis in 1944. An extended envelope surrounds the forming Sun. Large regular turbulent eddies form in a disk containing one tenth of a solar mass. He realised the significance of supersonic motion and magnetic coupling of the dust to the gas.

Dirk ter Haar (1950) discarded the large regular vortices and found that gravitational instabilities would also be ineffective in the thick solar nebula. He thus proposed collisional accretion into condensations. The problem he raised, however, was that the turbulence would decay before sufficient collisions would build up the condensations. The turbulence would have to be driven but there was no apparent driver. This problem was to return again in the 1990s but on a much larger scale.

Von Weizšacker then put forward a Rejuvenation Hypothesis in 1951. The existence of young stars within an aged Galaxy is a contradiction. Turbulence and gravity imply a formation time of 5 million years, a thousand times shorter than the age of the Galaxy. Therefore, all the gas should have been consumed. It would take over forty years to solve this dilemma. In the meantime, von Weizsäcker was led to the 'suspicion' that star formation was impossible! Instead, supposedly young stars were old stars, being rejuvenated by accumulating gas which lay in their paths.

1.5 Summary

The star formation history serves as a warning to ignore speculation in this book. The theories have flourished on being qualitative and floundered when subject to quantitative analysis. To try to avoid repeating history, we will not shy away from a quantitative approach where appropriate. To the credit of their founders, however, we will meet again many of the above concepts in revamped forms.