Bo Reipurth
Institute for Astronomy, University of Hawaii
640 N. Aohoku Place, Hilo, HI 96720, USA

Abstract. An overview is given of the astrophysical processes that govern the formation and early evolution of solar-like stars, specifically aimed at meteoriticists. After a discussion of the various types of protostars and young stars and of the collapse process, the importance of binary and multiple star formation is emphasized. The frequency and properties of young binaries as derived from observations are summarized. Theoretical work demonstrates how newborn multiple stars are unstable and decay on short time scales to stable configurations, often ejecting lower-mass members through dynamical interactions. Observations of phenomena like Herbig-Haro jets and FU Orionis eruptions find a natural explanation within a scenario involving the evolution of small multiple systems and the resulting formation of close binaries. It is emphasized that the vast majority of stars in our Galaxy are formed in clusters, but that most of these clusters dissolve soon after the remaining gas has been dispersed and the gravitational potential that held the cluster together therefore is weakened. Thus, while most stars are born in clusters, only a small fraction will remain in clusters lasting hundreds of millions of years. The likelihood that the early Sun was a member of a temporary cluster at birth and perhaps even a member of a small multiple system is stressed. Possible relic evidence that the Sun was part of a cluster of a few thousand stars includes the solar obliquity, the detection of traces of $^{60}$Fe in ordinary chondrites, the sharp edge of the Kuiper belt, and the discovery of distant large objects in eccentric orbits like Sedna. The meteoritic record must be examined with the possibility in mind that the early Sun may well have been a member of a long gone cluster and that the early solar nebula may have been affected by close passages of sibling stars.

1. Introduction

A principal goal of the workshop that has led to the present book was to bring astronomers and meteoriticists together to explore the interface between our disciplines and to continue to educate each other. The barriers created by the very different backgrounds required to understand our respective fields, the sometimes obscuring jargon, and the plain vastness of the literature are not insignificant, but on the other hand neither are they insurmountable given enough effort. The present paper is meant to give an overview, aimed at meteoriticists, of some of the astronomical background and current understanding of the processes that occurred during the formation and early evolution of our Sun.

The study of low mass star formation has been making major progress in recent years, partly due to the advent of sophisticated new instruments allowing high spatial resolution observations and of detectors sensitive at infrared and sub-millimeter wavelengths, but also through the application of increasingly powerful computers to simulate the birth processes of stars. It is, of course, impossible in a single review to cover an
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entire field as active as star formation or to give justice to all of the excellent work that is being produced by many groups. But extensive references will be given to the literature, including many review papers, so that readers who are interested in specific points can dig deeper. I will first give a broad outline of the main observational characteristics of newborn stars and their infall and outflow activity, and then focus on the binarity and multiplicity of young stars. It is increasingly evident that our understanding of the formation of stars would be seriously incomplete if we were to focus only on the birth of single stars. In fact, some would argue that we are at the beginning of a paradigm shift in star formation studies, leading to a much greater emphasis on the interaction of stellar embryos in small groups of newborn stars. Finally, I will emphasize that isolated star formation is not the norm, but that most stars are born in larger groups and clusters, leading to important stochastic events as cluster members constantly move through the potential well of a cluster. Whether our Sun has partaken in such processes is still unknown, but based on our current understanding of clustered star formation it seems very likely that the Sun had siblings, and perhaps even was born in a small multiple group that temporarily was gravitationally bound until it disintegrated. Any attempts to understand the meteoritical record must take these possibilities into account.

2. Birth and Early Evolution of Solar-like Stars

In the present context, stars are considered to be of low mass when they have masses above the brown dwarf limit of $0.08 \ M_\odot$, which is the lowest mass that can lead to nuclear hydrogen burning, but less than roughly $2 \ M_\odot$. These stars appear from their birth sites as the well known T Tauri stars (Herbig 1962). High mass stars, those with masses exceeding roughly $8 \ M_\odot$, have a much faster and very different evolution (e.g., Churchwell 2002). Stars of intermediate mass become Herbig Ae/Be stars on their way to the main sequence (Herbig 1960; Waters & Waelkens 1998). The latter two mass ranges are not considered further in this chapter.

Stars are born out of dense dark clouds, and most stars are born out of giant molecular clouds, which typically span across 100 pc or so and may contain up to $10^6 \ M_\odot$ of mostly molecular hydrogen. Isolated dark clouds with masses of just $10 - 100 \ M_\odot$ are common, as are aggregates of dark clouds with masses from a few hundred to several thousand solar masses. However, although the smaller clouds are much more common than the giant molecular clouds, these latter structures are so enormous that the bulk of the molecular gas in our Galaxy is found in giant molecular clouds (for reviews, see Blitz & Williams 1999 and Myers 1999). These large clouds have complex structures and a large range of densities, from tenuous regions with atomic hydrogen densities of about $10 \ cm^{-3}$ to dense cores with molecular hydrogen densities exceeding $10^5 \ cm^{-3}$. The cores of giant molecular clouds are the typical birth sites of stars.

Molecular clouds are highly turbulent, with random supersonic motions occurring on a range of length scales. The origin of this turbulence is unclear; however, supernova explosions are likely to play an important role in driving turbulence as a cloud forms. In turbulent clouds shocks develop, and energy is radiated away. It appears that turbulence dissipates on time-scales comparable to the free-fall time scale of collapsing cores. Clouds are typically only a few free-fall times old, suggesting that at least some turbulent energy must be continuously supplied, probably by energetic winds from young stars. As the supersonic flows interact and collide, dense sheet-like structures are formed, some of which become dense enough to be gravitationally bound.
And some of these survive long enough for the clouds to collapse to form stars. So although turbulence can support a cloud globally, it produces density enhancements that allow local collapse. A detailed discussion of star formation in turbulent clouds is given by Mac Low & Klessen (2004).

Magnetic fields thread molecular clouds and form another obstacle to star formation. Where magnetic fields resist compression, gas must diffuse past the field-lines to fall to the self-gravitating center of a cloud core. This process – known as ambipolar diffusion – can delay cloud core collapse, but gravity can ultimately overwhelm magnetic cloud support. Once it starts, inside-out collapse proceeds only slightly slower than in the non-magnetic case. This is discussed further in Section 3.

The moment of birth of a star can be defined in a variety of ways. Some say that it is when a static core has formed at the center of an infalling envelope. Others set \( t = 0 \) at the time when a stellar embryo has gained half of its ultimate mass. Because evolution is extremely rapid in this early dynamic phase, the difference is slight.

The common classification scheme of young stars is based on the energy distribution of the objects (Lada 1999). Objects are called Class 0, I, II, or III depending on the amount and the emission of their circumstellar material (see Fig. 1).

Class 0 objects are so deeply enshrouded by large infalling envelopes that they are predominantly detected at sub-millimeter wavelengths as extremely cold objects. These objects were only recognized a decade ago when sub-millimeter array detectors became available (André et al. 1993; Chini et al. 1993). The masses of the infalling envelopes of the youngest Class 0 objects can be larger than the masses of their stellar embryos, and the radiation we receive from such objects is dominated by the accretion luminosity \( L_{\text{acc}} \sim GM_\star \dot{M}_{\text{acc}}/R_\star \).

Class I objects are still embedded in massive circumstellar material, but are more evolved and can be studied at infrared wavelengths. From statistical studies of star forming regions, it appears that the Class 0 phase lasts a few times \( 10^4 \) yr, and the Class I phase ends after a few times \( 10^5 \) yr. The properties of these early evolutionary stages have recently been reviewed by André (2002).

Once young stars emerge from their placental material, they become the well known, optically visible, classical T Tauri stars or, in continuation of the above scheme, Class II sources. These objects are still surrounded by large circumstellar disks, so they remain bright at infrared wavelengths.

As young stars evolve, the infalling envelopes that fed the stars and their disks disappear. At this stage a disk can no longer be replenished as it processes material and feeds the central star. Disks are therefore expected to diminish in mass as the stars age and mature. Since most characteristics of Class II sources are due to their disks, it follows that we should be able to find a population of more evolved young low mass stars with few or no signatures of disks. These are the weak-line T Tauri stars or Class III objects. As the name suggests, these stars are characterized by very weak H\( \alpha \) emission. They also have virtually no infrared emission in excess of that expected from a star of the same spectral type. This does not mean that these objects are completely devoid of circumstellar matter, rather the material that is left over in their circumstellar disks may have begun to coagulate into larger bodies, which are building blocks for the construction of planets. If much of a disk’s mass is incorporated into such large bodies, it becomes invisible at most wavelengths. It is likely that Class III stars represent the active phase of planet building. Figure 2 shows the disappearance of infrared signatures of disks with time (see the chapter by Hartmann in this volume). The
Figure 1. Evolution of newborn stars. Five different stages are indicated, from a pre-stellar core, over the epoch of dynamical infall of an envelope to the formation of a disk and eventually the possible formation of planets. The different stages are characterized by different bolometric temperatures $T_{\text{bol}}$, which is the temperature of a blackbody having the same mean frequency as the observed continuum spectrum of an object (see Myers & Ladd 1993). From André (2002).
The Early Sun

3. The Collapse Process

Observations show that star formation occurs in dense cloud cores. Assuming that such pre-stellar cores are initially magnetically supported, they will contract only gradually through ambipolar diffusion until the point when dynamical collapse commences. Such collapse is always non-uniform and starts in the densest part of the centrally condensed core. From there the free-fall collapse spreads outward through the core in an inside-out fashion (Shu 1977). The hydrostatic core is born with a small mass of about 1/100 of a solar mass, but it is large compared to most stars, with a diameter of several AU.

A key roadblock to star formation comes in the form of rotation. Slow rotation is commonly observed in the cores of molecular clouds. When rotating cores collapse, a central hydrostatic stellar embryo is still formed, but most of the mass ends up in a centrifugally supported disk around the central object. The angular momentum of a rotating cloud core is a thousand times greater than what can be contained in a star even if rotating at break-up speed. This is called the classical “angular momentum problem” of star formation.

There are several ways a star forming cloud core can shed its spin. First, it can fragment into a binary or multiple star system whose orbital motion contains most of the core’s angular momentum. Second, as noted above, higher angular momentum material from the core will rain onto a spinning disk surrounding the stellar embryo. However, to grow into a star the embryo must accrete additional mass from the surrounding disk. This requires the further dissipation of orbital angular momentum within the disk. Magnetic fields trapped in the disk and torques exerted by self-gravitating clumps can transfer disk orbital angular momentum from the center of the disk to its outer parts.

Figure 2. Infrared disk signatures as a function of time. The plot shows the fraction of cluster members with near-infrared excess emission, an indicator of the presence of circumstellar disks. From Haisch et al. (2001).
As matter in the disk spirals towards its center, the outer radius of the disk must expand to conserve angular momentum. But the accretion of matter from the inner edge of the disk onto the equator of the protostar would still make the star spin too fast. The forming star’s own magnetic field, perhaps generated by an internal dynamo, may be responsible for additional removal of angular momentum from matter accreting from the disk’s inner edge onto the young star. This stellar magnetic field may expel a fraction of the matter spiraling in from the disk’s inner edge as powerful bipolar jets which carry away excess angular momentum, allowing low angular momentum material to settle onto the star. The interplay between angular momentum and accretion in a circumstellar disk is an essential driver for the evolution of the youngest stars.

Large amounts of theoretical work increasingly suggest that the normal outcome of the collapse of a rotating cloud is fragmentation leading to a binary or multiple system, and that the formation of single stars is the exception (e.g., Hoyle 1953; Larson 1972, 1978; Burkert et al. 1997; Boss 2000). For reviews, see Bonnell (1999) and Bodenheimer et al. (2000).

4. Young Binaries and Multiple Stars: Observations

Over the last decade, searches for binaries among young stars have been conducted at both optical and infrared wavelengths, and numerous young binaries with ages less than 10 million years have been found (e.g., Reipurth & Zinnecker 1993; Ghez et al. 1993; Köhler & Leinert 1998). Surprisingly, there appear to be more binaries and multiples among young stars in some regions than among older stars. In the solar neighborhood, about 55% of solar-type main-sequence stars are binaries or multiples (Duquennoy & Mayor 1991). In relatively isolated star forming regions such as Taurus, some studies suggest that, after incompleteness has been corrected for, as many as 90% of the young stars may be binaries or multiples. On the other hand, in the rich young clusters such as Orion’s Trapezium cluster, the percentage of multiples appears to be similar to that found in the solar vicinity (Köhler 2004).

One possible explanation for the excess numbers of multiples in some star forming regions is that they could have wider separations while young, and are therefore easier to detect. But when we compare young systems with older binaries in the same separation ranges, we again find more young binaries, suggesting that the higher binarity among young stars could be real. Variations in binarity among different star forming regions have also been noted (e.g., Duchêne 1999) and could be explained by interactions between the stars. In crowded regions like Orion, young stars have a greater probability of passing close to each other as they move through the potential well of the cluster. Mutual interactions can lead to the destruction of some binaries, or a faster shrinkage of their orbital separation. But it is also conceivable that some star forming regions produce more binaries than others, and that the fraction of binaries among field stars represents an average over different formation environments.

How do circumstellar disks behave in young binary systems? T Tauri disks typically have radii of the order of 100 AU. In binaries with much larger separations, disks around the individual stars may remain unperturbed by the distant companion. Similarly, if the binary components are very close, the system may be surrounded by a circumbinary disk which would behave as if orbiting a single star. But when the binary components have separations of the order of 10 to 100 AU, there is little room for disks. Disks around the individual stars are then constrained to be only a few AU in diameter,
and circumbinary disks would have inner radii of order a 1000 AU. Intermediate sized disks would suffer strong tidal deformations, warping, and collisions that would lead to their rapid destruction. Observations show that binaries of all separations have at least some disk material. But observations also confirm that disks associated with binaries having separations between 10 and 100 AU turn out to contain much less material than those around isolated stars (Jensen et al. 1996; Jensen & Akeson 2003).

If young binaries have eccentric orbits, a number of interesting phenomena may occur as the components approach and move away from each other. A well studied case is the DQ Tau binary, a classical T Tauri star which consists of two identical components in a close spectroscopic binary with a high eccentricity of \( e = 0.56 \) and a period of 15.8 days (Mathieu et al. 1997; Basri et al. 1997). At periastron, the components are extremely close, \( \sim 8 \, R_\odot \), and during such close passages DQ Tau often brightens and shows increasing line emission, indicative of increased accretion. It appears that gas is flowing from a circumbinary disk (observed at millimeter wavelengths) across the binary orbit and accretes onto the stars modulated by the orbital motion of the stars.

Young stars are members not only of binary systems, but also of higher-order multiples (Fig. 3). Statistics on multiple systems suffer from serious incompleteness, not only among young stars, but even among main-sequence stars (Tokovinin 2000). Because the volume of space increases as distance to the third power, the number of multiples should grow as \( d^3 \) if all multiples within a certain distance \( d \) had been found. The observed growth with distance is much slower, even for stars very close to the Sun (Tokovinin 2000). This is because most multiple systems are structured hierarchically, and so different techniques, each optimized to a particular range of resolution, are required to discover all members of a multiple. The situation is even worse for young stars, where studies of multiplicity are still in their infancy. In a study of 14 Herbig-Haro energy sources, Reipurth (2000) found that about 80% are binary systems, of which half are higher-order multiples. Detailed optical and infrared studies of young stars to find multiple systems have begun to appear (e.g., Brandeker et al. 2003; Haisch...
et al. 2004; Tokunaga et al. 2004), and will eventually provide observational tests of theoretical work on the evolution and stability of newborn multiple systems, as outlined in the following section.

5. Tidal Interactions and the Break-up of Multiple Stars

While the motion of two bodies around their common center of mass is very simple and can be precisely expressed in analytical form, the motion of three or more bodies is entirely unpredictable and can be followed only numerically and treated only in a statistical manner. Such systems are inherently unstable and, depending on the configuration, may break up.

The motions of the three bodies while they are bound together can basically be divided into three classes, which interchange at random until the system decays through escape of a member (Fig. 4). One class is the interplay, during which the three members perform completely random motions with no periodicity. During interplay two members, often the two most massive, can form a temporary binary, which have frequent two-body encounters, while continuously being perturbed by approaches by the third member, sometimes in the form of a flyby, but occasionally resulting in exchange of binary membership. A second class is the close triple approach, in which all three bodies briefly and more or less simultaneously are brought close together. It is during such events that energy is exchanged between the components. Statistical studies show that close triple approaches are necessary but not sufficient conditions for escape. The third class of motion is the ejection, which may occur following a close triple approach during which a binary is formed that absorbs the potential energy of the third member, thereby loosening its ties to the system. At this point the triple transforms into two two-body systems, namely a close binary and an ejected member moving on an approximately elliptic orbit, which eventually brings it back to the close binary. If instead the ejected member moves on a hyperbolic orbit, the ejection becomes an escape. Statistical studies show that it is usually, but not always, the lightest member that is ejected; the escape probability scales approximately as the inverse third power of the mass. Numerous dynamical studies of small N-body systems have been performed, and important papers include Anosova (1986), Sterzik & Durisen (1995, 1998, 2003), Bate, Bonnell, & Bromm (2003), and Delgado-Donate, Clarke, & Bate (2003). Sometimes the decay can occur so early in the collapse phase that the ejected member has not reached the hydrogen burning limit, and it will thus become a free-floating brown dwarf (Reipurth & Clarke 2001; Bate, Bonnell, & Bromm 2002; Clarke, Reipurth, & Delgado-Donate 2004). Although eventually most non-hierarchical triple systems disintegrate in an escape, this is clearly not always the case, as the presence of stable hierarchical triple systems among main sequence stars demonstrates (e.g., Tokovinin 1997). Finally, it is important to note that numerous studies have shown that the close binaries which form as a result of the escape of a third member usually are highly eccentric, with eccentricities exceeding 0.9 not being unusual (e.g., Valtonen & Mikkola 1991).

It is not possible to define the precise lifetime of a triple system, because numerical studies of large numbers of triple systems show that the decay of a triple system occurs randomly. However, approximately within a hundred crossing times about 95% of the triple systems have decayed (Sterzik & Durisen 1995, 1998; Armitage & Clarke 1997). For parameters which are likely to hold among newly born multiple stars, decay times are of the order of several times $10^4$ yr.
Figure 4. A schematic presentation of the three stages of motion of a young triple system. The evolution is stochastic, but eventually the triple system transforms from a non-hierarchical to a hierarchical configuration. Sometimes the ejection leads to an escape, so that the triple disintegrates, but for incomplete ejections the third member remains attached, albeit in a distant eccentric orbit. From Reipurth (2000).
A number of studies have recently appeared, which explore the formation of single, binary, and multiple stars in turbulent clouds (e.g., Klessen 2001; Bonnell et al. 2003; Bate et al. 2003). In a detailed numerical study, Delgado-Donate et al. (2004) followed the formation and early evolution of newborn stars, binaries and multiples and their disks inside their gas-rich environment for 500,000 years, and later in a gas-free environment they followed the dynamical evolution of the small N-body groups for another 10 million years. These simulations show that most stars form in multiple systems, but that after 10 million years half of the systems have broken up, releasing into the field mostly weakly bound distant components. The systems that are most likely to survive are those where the two most massive objects form a central binary, with additional low mass members distributed hierarchically at larger distances. In Figure 5, two examples of the resulting geometries of multiple systems are shown, one with five stars, and another with eight stars.

In a recent study, Reipurth (2000) postulated that the dynamical decay of triple or multiple systems leads to strong outflow activity, which we will discuss in the following section.

6. Outflow Activity from Newborn Stars

Outflow activity is found in association with all stages of early stellar evolution, from deeply embedded protostellar objects to visible young stars. Herbig-Haro (HH) objects are the optical manifestations of this powerful mass loss (Fig. 6). Other outflow signatures can be observed at infrared, millimeter, and centimeter wavelengths (e.g., Bachiller 1996; Anglada 1996). Analysis of HH flows, and in particular of the subset of highly collimated HH jets, provide indirect but important insights into the nature of the accretion and mass loss processes which govern the formation of stars (e.g., Shu et al. 1994). It is now known that HH flows may attain enormous dimensions, stretching across many parsecs, which opens the possibility to partially reconstruct the mass ejection history of the newly born driving sources and therefore their mass accretion history. Furthermore, HH flows are astrophysical laboratories for the analysis of shock structures, of hydrodynamics in collimated flows, and of their interaction with the surrounding environment. HH flows may be an important source of turbulence in molecular clouds. Recent technological developments have enabled detailed observations of outflows from young stars at near-infrared, mid-infrared, sub-mm, mm and cm wavelengths, providing a comprehensive picture of the outflow phenomenon from young stars. For a review, see Reipurth & Bally (2001).

It is clear that outflows are ultimately powered by the release of gravitational potential energy liberated by matter accreting onto a forming star. At least 90% of the energy released by accretion is in the form of radiation, and only about 10% is carried away by mass loss. In low luminosity protostars the outflow momenta are typically one to two orders of magnitude larger than the momentum available in the radiation field, so magnetohydrodynamical or magnetocentrifugal processes are generally assumed to be responsible for the launch of jets. There are several theories of jet formation. One focuses on the ‘X-wind’ launched a few to tens of stellar radii from the star, where the stellar magnetosphere interacts with the inner edge of a magnetized accretion disk (for a review, see Shu et al. 2000). Another suggests that a magnetocentrifugal ‘disk wind’ is launched from the accretion disk at distances of 0.1 AU or more from the young star (for a review, see Königl & Pudritz 2000). A variety of dynamic models produce short
Figure 5. Examples of multiple systems formed in a numerical simulation. Separations between the components are listed (in AU) next to the dashed lines (note that the separations vary over three orders of magnitude, and so cannot be shown to scale). In the 8-body system two low-mass objects are found in very distant eccentric orbits. The most distant components will be lost first. Courtesy E.J. Delgado-Donate.
duration outbursts (e.g., Goodson et al. 1999). In all cases, these engines need to be fed by accretion through a circumstellar disk. This is commonly assumed to occur through disk instabilities, but can also happen through perturbations from a companion star.

Figure 6. The image shows the collimated Herbig-Haro jet HH 47 as seen with the Hubble Space Telescope with a [SII] filter. The jet emanates from a dense Bok globule, which harbors an embedded newborn binary star (at the base of the jet in the lower right corner). From Heathcote et al. (1996).

It is possible to understand the long-term evolution of outflows from young stars in terms of the break-up of a small multiple system and the subsequent evolution of the resulting close binary (Reipurth 2000), as discussed in the following.

The process of close triple approach will cause serious perturbations and probably direct collisions among the circumstellar disks. Massive disk truncations result, accompanied by large-scale accretion onto the stars, with a consequent burst of outflow activity. This may be one mechanism that produces giant HH bow shocks. Much of the material culled from the individual circumstellar disks may settle into a circumbinary disk around the newly bound stellar pair. The truncated circumstellar disks can be fed from the circumbinary disk through gas streams and this as well as other dynamical effects cause the binary orbit to shrink (Artymowicz & Lubow 1994, 1996). Gas streams together with disk interactions at periastron will drive cyclic accretion modulated on an orbital time scale. As the stellar components gradually spiral towards each other, the increasingly frequent mass loss events form chains of HH objects until eventually the binary has a semi-major axis of roughly 10 AU or so, at which point the closely spaced
shocked ejecta appear as a finely collimated jet. In this stellar dynamics jet hypothesis, a jet originates from at least one (probably the more massive) of the stellar components, and the binary serves to modulate the accretion and thus the outflow on an orbital time scale. The circumstellar and circumbinary disks play different roles: The circumstellar disk is likely to interact with the stellar magnetosphere and provides the jet launch platform despite being truncated to a few AU. The circumbinary disk provides the reservoir of gas for fueling the jet activity. Thus, HH flows formed in this way can be read as a fossil record of the evolution of orbital motions of a binary, newly formed in a triple disintegration event, as it shrinks from a typical separation of 100 AU or more to 10 AU or less. Orbital decay appears to be a very efficient process for such very young binaries, and may be completed within a period of the order of $10^4$ yr. Altogether, this stellar dynamics jet hypothesis suggests that giant HH bow shocks are linked to close triple approaches in a triple or multiple system just prior to breakup, and that a highly collimated jet is the result of orbital shrinkage in the resulting binary after the third member has been ejected. Thus, jets witness the brief final phase of dynamical interaction as a close binary is formed, and therefore major jets should appear only during one epoch from any given binary.

Since orbital shrinkage in a newly formed binary is driven by interaction with circumstellar gas, it follows that once most of the gas has been accreted or expelled, the shrinkage slows and eventually ceases, thus leaving the binary with whatever orbital parameters it happened to have at that time.

It is worth noting that there are many ways in which a disk can be disturbed, thus leading to accretion with ensuing mass loss. While the major HH jets are likely caused by the evolution in close binaries, single stars may produce small stubby jets due to other disturbances of their disks. Such microjets are commonly found in association with young low-mass stars (e.g., Bally et al. 2000).

As discussed in the next section, it is possible that the phase following the production of major jets, as the components of a binary spiral towards each other, may be the so-called FU Orionis eruptions.

7. The FU Orionis Accretion Events

The FU Orionis eruptive variables are young stars associated with dark clouds and reflection nebulae. The two best studied members of the class, FU Ori and V1057 Cyg, both exhibited increases in optical brightness by 5–6 magnitudes on time scales of about a year, followed by a much slower fading (Herbig 1966, 1977). Post-eruption optical spectra show peculiar supergiant F-G type spectra, with blueshifted shell components, and P Cygni profiles in H$_\alpha$ and the Na I resonance lines. The spectral type becomes gradually later with increasing wavelength. A model in which accretion through the circumstellar disk is greatly increased can explain many observed peculiarities of FU Ori objects, including the broad spectral energy distributions, the variation of spectral type and rotational velocity with wavelength of observation, and many “double-peaked” spectral lines in the optical and the near-infrared (Hartmann & Kenyon 1985; for a review see Hartmann & Kenyon 1996). The onset of increased mass transfer through the disk may be triggered by a thermal instability (Bell & Lin 1994), or by the close passage of a companion star (Bonnell & Bastien 1992). While the accretion disk model is successful in explaining many of the observed properties of FUors, some discrepancies remain. It has been suggested by Herbig (1989) and Herbig, Petrov & Duemmler
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Figure 7. A schematic presentation of how a non-hierarchical quadruple system can dynamically evolve into two pairs of increasingly close binaries. When the members of the close binaries have spiraled sufficiently together for their circumstellar disks to interact vigorously, FUor eruptions may occur at about the same time in the two pairs.

(2003) that a number of observations are better accounted for by a rapidly rotating star near the edge of stability, a concept that has been discussed by Larson (1980). Up to now only about a dozen objects have been generally accepted as members of the FU Ori class, including some for which no eruption has been observed, but which are spectroscopically very similar to the “classical” FUors.

It is unclear whether the Sun has undergone one or more FUor eruptions (or any at all) in its early years. Herbig (1977) and Hartmann & Kenyon (1996) argued, based on the limited statistics of known FUors, that FUor eruptions must be repetitive. But whether this implies a few eruptions in all young low-mass stars or more eruptions in a smaller subset of low-mass stars is currently a matter of debate. In the following I describe a scenario in which FUor eruptions are the result of the orbital evolution of a close binary. If this interpretation is correct, then our Sun has not suffered FUor eruptions (although its circumstellar disk may have been subjected to powerful perturbations if the Sun was once part of a triple system partaking in close triple approaches).

Two pre-main sequence binaries are known in which both components have FUor characteristics, namely RNO 1B/1C (Kenyon et al. 1993) and AR 6A/6B (Aspin & Reipurth 2003). Given the rarity of FUors, finding two FUor-like objects within a few arcseconds of each other in any star forming region is exceedingly improbable. In other words, whatever has triggered the FUor outburst in one component of such a binary FUor seems likely to be somehow connected to whatever triggered the FUor outburst in the other component.
One way this could happen is if the FUor components in such a binary are themselves close binaries. Bonnell & Bastien (1992) suggested that binary companions could trigger FUor outbursts. Reipurth & Aspin (2004) employed this mechanism in an evolutionary scenario, in which they suggested that the progenitor of a binary FUor is a non-hierarchical quadruple system (Fig. 7 stage 1), which evolves dynamically to become a hierarchical quadruple (Fig. 7 stage 2). As the two pairs of binaries slowly drift apart, their components evolve through viscous interactions and gradually spiral towards each other as discussed in Section 6. Eventually, after passing through the stage of major jet-formation, the members of the two close binaries become so close that they erupt in a series of FUor eruptions (Fig. 7 stage 3). Since the time scale of dynamical evolution will be comparable for the two binary systems, they will in many cases be observed in elevated FUor stages at about the same time. In this interpretation, FUors represent one more phenomenon in early stellar evolution that depends on the multiplicity of newborn stars. Figure 8 shows a numerical simulation of a companion star that violently perturbs the circumstellar disk of a star during a periastron passage.

8. Clustering of Young Stars

Scattered across the sky one can see concentrations of stars that are gravitationally bound together. These stellar clusters divide into two categories, open clusters and globular clusters. Of the order of 100 globular clusters are known in our Galaxy. They are extremely rich and each may contain up to a million stars. The stars in globular clusters are all very old, and in fact the exceedingly violent star forming events that gave rise to the globular clusters appear not to occur at the present epoch of our Galaxy’s
evolution. Open clusters, on the other hand, are found with ages from newborn to several hundred million years.

Few of the stars in our Galaxy are observed to belong to open clusters. At first glance this seems to suggest that it is unlikely for any given star to have formed in a cluster. However, open clusters are generally transient structures and most are destroyed at a young age. In fact, as we shall see, the vast majority of stars are formed in stellar clusters.

Giant molecular clouds, discussed in Section 2, are very non-uniform, with most of the mass in huge volumes of diffuse gas. But of the order of 10% of the gas is found in dense cores up to 2 pc in diameter. The densest and most massive of these cores are observed to be the sites of cluster formation (Fig. 9).

A cluster is defined as a stellar group with a sufficient stellar volume density to survive tidal disruption and early dissolution. The main cause of tidal disruption is encounters with interstellar clouds as a cluster orbits the Galactic center, but for densities exceeding a tidal stability limit of $1 M_\odot \text{pc}^{-3}$, a cluster will survive such encounters (Spitzer 1958). Dissolution occurs as cluster members are gradually ejected through mutual dynamical interactions. One can estimate that for a cluster to survive of the order of $10^8$ yr, it must contain at least 35 members. Groups of stars that meet this number limit and the above tidal stability limit are considered a stellar cluster (e.g., Lada & Lada 2003). Such clusters can be either bound (kinetic plus potential energy is negative) or unbound (total energy is positive).

Newborn clusters are embedded in the gas and dust of their parental clouds. Such clusters are often optically invisible and are detected only through infrared or radio continuum observations. On time scales of less than 5 million years such embedded clusters produce enough winds and outflows, as well as UV radiation from the most massive members, to disrupt the surrounding cloud material and render the cluster visible (e.g., Leisawitz et al. 1989). In the process of losing this considerable mass, the total energy of a cluster often goes from negative to positive, that is, a cluster that was initially bound at birth becomes unbound, and the cluster members start to disperse. Only about 5% of clusters survive the emergence from the embedded stage to remain a bound cluster for several hundred million years.

A very well studied example of an embedded cluster in the process of emerging from its surrounding molecular material is the Orion Nebula Cluster, which contains of the order of 3500 stars, including the famous Trapezium of massive OB stars (e.g., Herbig & Terndrup 1986; Hillenbrand 1997; Hillenbrand & Hartmann 1998; Hillenbrand & Carpenter 2000; Muench et al. 2002). Detailed studies of such clusters can produce information on the Initial Mass Function (IMF), that is, the relative frequency of stars of different masses. Since mass is not a directly observable quantity, the derivation of a cluster IMF is not entirely straightforward, but requires the transformation of stellar luminosities into stellar masses, a process that involves a number of assumptions. Despite such uncertainties, evidence is building that the IMF’s of embedded clusters, of more evolved open clusters, and of field stars are very similar, suggesting that star formation results in a universal IMF (a possible exception being the most violent star forming bursts). For a review, see Kroupa (2002).

Two parameters determine whether a cluster emerging from its parental cloud will remain bound or quickly disperse, namely the star formation efficiency and the time scale of gas dispersal. The star formation efficiency ($SFE = M_{\text{stars}}/(M_{\text{gas}} + M_{\text{stars}})$) of an entire giant molecular cloud is generally low, around a few percent, but for a dense
cluster-forming core it is substantially higher, typically around 10 to 30%. The higher the $SFE$, the greater is the probability that enough stars have formed to remain bound after the gas has been removed (Mathieu 1983). However, the fate of the cluster also depends to some degree on how fast the gas is dispersed. Clusters which form O stars will suddenly be flooded with UV radiation, which ionizes and heats the gas, leading to a sudden rise in pressure and consequent rapid expansion of the gas. The members of a cluster which suddenly sees all of its gas removed will remain bound only if the SFE has reached about 50% (Wilking & Lada 1983). In contrast, clusters which have lost gas more gradually may have time to slowly expand through a series of equilibrium states, leaving at least part of their members bound together. The more rapid the gas removal, the more stars are likely to be lost in the process (e.g., Kroupa & Boily 2002). Although many details remain to be studied, a key result is that the large majority of stars in our Galaxy are formed in embedded clusters, but only a small fraction remain in long-lived open clusters, and even those clusters will eventually dissolve given enough time.

The specific processes involved in the formation of a stellar cluster can be explored using advanced numerical simulations. One important insight resulting from such simulations is that accretion onto nascent stars in a newborn cluster is very non-uniform.
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and that different stars can accrete at significantly different rates depending on their location in the cluster potential well. Stars nearer the cluster center, where gas densities are higher, accrete more than stars further away. Cluster members thus share the available gas unequally, and this competitive accretion plays a role in the creation of a stellar mass spectrum (Bonnell et al. 2001). Numerical simulations also make it possible to follow the fragmentation of a turbulent cloud and to follow the various stages in the formation of a cluster. It has been recognized that fragmentation is hierarchical, leading to the formation of small subclusters, which eventually merge to form the final cluster. The higher stellar density of the subclusters compared to cluster formation without subclusters implies that dynamical interactions among stars are more common, with ensuing effects on the circumstellar disks of the cluster members (Bonnell et al. 2003).

For reviews on the formation and evolution of star clusters see e.g., Bonnell (1999), Clarke, Bonnell, & Hillenbrand (2000), Elmegreen et al. (2000), and Lada & Lada (2003). The impact of massive stars on their surroundings and on nearby young low-mass stars is discussed in detail in the chapters in this book by Hester & Desch and by Bally, Moeckel, & Throop.

9. **Was the Early Sun formed in a Cluster?**

A fundamental result of the research outlined in the preceding pages is that stars are seldom if ever born in isolation, but rather in binary and multiple systems, which themselves often form in clusters of varying sizes. As stated by Larson (2003): "The available evidence is consistent with the possibility that all stars form in multiple systems of some kind, and that the minority of stars that now appear single have originated as escapers from such systems." See also van Albada (1968), Larson (1972), Reipurth (2000), and Larson (2002). New observational and numerical studies increasingly support this view, indicating that we are at the threshold of a paradigm shift, away from the single star formation scenario and towards a dynamic view in which interactions and stochastic events play indispensable roles.

Since our Sun is a single star it is an obvious question whether there is any evidence that the early Sun had siblings, in a small-N group from which it was ejected and/or as a member of an evaporating cluster. Various studies related to this question are discussed in the following.

**The Solar Obliquity.** It is a well-known fact that our planetary system has a total angular momentum vector which is inclined by 7° with respect to the rotational axis of the Sun. This non-zero solar obliquity may be a memory of events unfolding at the time when the Sun was born. One possibility is that the collapse leading to the formation of the Sun and its circumstellar disk was not axisymmetric, but perhaps clumpy, causing a twisting of the disk out of which the planets formed (Tremaine 1991). Alternatively, the random close passage of a star or a molecular cloud within the last 4.5 billion years could have produced the necessary torque. However, such encounters are very rare (e.g., Garcia-Sanchez et al. 1999), and furthermore encounters have to occur on unrealistically long time scales to preserve the observed small eccentricities and inclinations of the planetary orbits, suggesting the likelihood that the encounter occurred before the planets had formed (Tremaine 1991). It was emphasized already by Mottmann (1977) and Herbig (1983) that the situation is very different in newborn
clusters, and they noted that because the epoch of planet formation is approximately the same as the period when most young stars are still members of newborn clusters, the disk around the early Sun may have been significantly affected by close encounters. Heller (1993) carried out numerical simulations of encounters in young clusters and found that during a one million year period, 39% of the stars in a cluster like the Trapezium cluster in Orion will experience an encounter that is capable of producing a disk tilt of 7° or greater. The non-zero solar obliquity may therefore well be evidence that the early Sun was a member of a transient and long gone cluster.

**Enrichment of the Early Solar Nebula by Radioactive Species.** As extensively discussed elsewhere in this book (see the chapters in section IV), the meteoritic record indicates that the early solar nebula was enriched by short-lived radioactive nuclei. This could be due to self-enrichment through energetic spallation processes within the solar disk (e.g., Lee et al. 1998). Alternatively, a common explanation for these abundance anomalies is that a supernova detonated in the close vicinity of the newborn Sun (e.g., Cameron et al. 1995; Goswami & Vanhala 2000). The *in situ* irradiation mechanism has gained support by indications of decay of short-lived $^{10}$Be in the early solar nebula (McKeegan, Chaussidon, & Robert 2000), since this isotope is not produced by nucleosynthetic processes in supernova eruptions. Recent detailed calculations, however, show that $^{10}$Be can be produced by cosmic rays, and the presence of $^{10}$Be therefore does not uniquely point to an origin by spallation (Desch, Connolly, & Srinivasan 2004). The detection of excess $^{60}$Ni as decay product of $^{60}$Fe in ordinary chondrite chondrules by Tachibana & Huss (2003) has provided further support for the nearby presence of a supernova to the early Sun, since $^{60}$Fe is not produced in significant amounts by spallation processes, whereas the detected levels can be accounted for by a supernova source. The distance to a supernova should be about 2 pc or less, indicating that the Sun and the supernova progenitor would be members of the same cluster. Adams & Laughlin (2001) show that, for a normal IMF, a cluster of about 2000 stars or more is required for at least a 50% probability that a 25 $M_\odot$ star is formed in the cluster.

**Orbits of Kuiper Belt Objects.** Since the time scale for close encounters with stars in a young cluster may be comparable to the time it takes an open cluster to dissolve, which is of the order of a hundred million years, it follows that planets that have formed from the early solar nebula may see their orbits severely affected. Laughlin & Adams (1999) have found that 13% of stars with a giant planet in a Jupiter-like orbit will suffer significant orbital disruption, in many cases leading to highly eccentric planetary orbits. Up to 5% of planets in a typical cluster may be ejected from their planetary system.

There are no traces of such effects in our planetary system, but in recent years interest has focused on the effect of stellar encounters on the Kuiper belt (Luu & Jewitt 2002). Ida, Larwood, & Burkert (2000) have used numerical simulations to explore how an encounter with a cluster member approaching to within 100-200 AU can pump up the velocity dispersion of more distant Kuiper belt objects, leading objects outside of about 40 AU to have a steep increase in eccentricity and inclination with semimajor axis. Such a dynamical signature may remain for very long after the dissolution of the original cluster, and is consistent with observations of a sharp outer edge to the Kuiper belt at around 50 AU (Jewitt, Luu, & Trujillo 1998; Allen, Bernstein, & Malhotra 2001; Gladman 2005). The radial gradients of eccentricity and inclination are so steep that they essentially form a boundary between an inner region where planet formation
was still possible, and an outer region where the planetesimals were so perturbed as to inhibit planet formation (Kobayashi & Ida 2001).

Two objects, 2000CR105 and Sedna, have perihelia so large that they cannot have been scattered by Neptune, nor are they likely to have formed with such orbital characteristics. However, numerical simulations demonstrate that a fly-by within about 500–1,000 AU with another cluster member is a likely mechanism to scatter them from a Neptune-crossing orbit to their present orbits (e.g., Morbidelli & Levison 2004). In a detailed study, Kenyon & Bromley (2004) derive an initial orbital distribution of planetesimals from a planet-formation calculation, followed by N-body simulations of the orbits of objects scattered by fly-by’s of different geometries. Kenyon and Bromley not only can reproduce the observed edge of the Kuiper belt (Fig. 10), but also produce objects in Sedna-like orbits. Moreover, they find that when the path of the Sun and disk of the passing star co-rotate, then the Sun can capture up to one third of the outermost extrasolar planetesimals orbiting the passing star, again depending on the fly-by geometry. The majority of such captures should have orbits with very high inclinations to the plane of the Solar System, and if objects with such orbits should one day be discovered, they are likely of extrasolar origin.
The Early Evolution of the Sun In Isolation vs. in a Dense Cluster. The very earliest evolution of the Sun also depends on whether it is formed in isolation or whether it is part of a cluster. As pointed out by Bonnell et al. (2001), accretion in clusters is a dynamic phenomenon, with mass accretion rates depending on where a stellar embryo is as it moves through the gravitational potential of the gas and the forming stars. The highest accretion rates are found near the center of the cluster. Wuchterl & Klessen (2001) have carried out a detailed study starting at the cloud fragmentation phase, through the collapse phase and the first million years of early evolution of the Sun. They find that formation in a cluster environment leads to violent accretion that produces a considerably higher luminosity in the young Sun than if it had formed in isolation. The luminosity oscillates while the rates of accretion vary as the newborn Sun moves through the dynamic environment of the protocluster. When heavy accretion gradually ceases and the cluster stars approach their final masses, the evolutionary track of a solar-like star approaches and eventually, after about a million years, converges with that of a similar star born in isolation. The difference in evolution occurs on a time scale that is shorter than even the formation of CAIs and chondrules, so it is unclear whether the different evolutionary paths would lead to any measurable impact on the meteoritic record.

Did the Early Sun have Companions? So far we have discussed the impact of perturbations from the close passage of stars within a cluster. But as discussed in Sections 4 and 5, a large fraction, and probably a majority, of stars are born in small multiple systems, either in isolation or more commonly as part of a cluster. The presence of such solar companions bound gravitationally from birth and until the eventual dissolution of the multiple system or cluster would be, at least temporarily, a source of dynamical perturbations of the early solar nebula that would produce shocks, which may have led to the formation of chondrules and CAI’s (Larson 2002; see also the chapter by Bally, Moeckel, & Throop in this volume). With our increased appreciation that star formation is a highly chaotic process often leading to binary or multiple systems, we need to examine the meteoritic record with the possibility in mind that the early Sun could have had siblings and/or been a member of a long gone cluster.

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Further Reading. Several excellent books have recently appeared dealing with different aspects of star formation and molecular clouds. 


The Origin of Stars by Michael D. Smith (Imperial College Press, 2004) provides an easily accessible overview of the basic processes involved in star birth, particularly suitable for scientists approaching the topic from other fields.
The Formation of Stars by Steven W. Stahler and Francesco Palla (Wiley-VCH, 2004) is a major monograph that provides an in-depth discussion of the detailed processes of star formation.


Protostars and Planets V edited by Bo Reipurth, David Jewitt, and Klaus Keil (University of Arizona Press) will appear during 2006, and will offer a wide-ranging and up-to-date overview of our current understanding of star and planet formation.

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