

Evolution of UV-Irradiated Protoplanetary Disks

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Abstract. Most stars are born in transient clusters within OB associations. Within the first few million years of birth, stars and their protoplanetary disks can be exposed to intense UV radiation, close-passages of sibling stars, stellar winds, and supernova explosions. Disk photo-ablation may promote the rapid formation of kilometer-scale planetesimals by preferentially removing gas and small grains, and enhancing the relative abundance of centimeter and meter-scale bodies. Disk perturbations produced by close-by passages of sibling stars or binary companions can trigger tidally induced shocks which anneal grains. Close-by supernovae can inject live radioactive species such as ^{27}Al and ^{60}Fe either before or after the formation of a low-mass star and its disk. Intense UV radiation from the pre-supernova blue-supergiant and Wolf-Rayet phases of the most massive stars can result in enhanced disk photo-ablation.

1. Introduction

A major paradigm shift has occurred in our understanding of the formation of stars during the last decade. Up until the late 1980s, it was widely believed that most stars, and our own Solar System in particular, formed in relative isolation inside dark cloud cores. In this view, most properties of stars and planetary systems should be derivable from the density, angular momentum, temperature, magnetic field, and composition of the parent cloud core. Even though it was recognized by the 1970s that most Galactic star formation occurs in Giant Molecular Clouds (GMCs - see Figure 1), the dynamical influence of clusters of sibling stars and the radiation fields of nearby massive stars were thought to be of little importance to the formation and evolution of a young star and its planetary system.

Since the early 1990s, a variety of observations have challenged this ‘isolationist’ perspective. The advent of focal plane arrays sensitive to near-infrared radiation between 1 and 5 μm led to the first exploration of the distribution of young low-mass stars within the highly obscured interiors of GMCs. These observations demonstrated that most young stars form in very dense, but short-lived, clusters (for a review, see Lada & Lada 2003). In such clusters, low-mass stars and their disks are exposed to UV radiation, dynamical encounters with sibling stars, stellar winds, and supernova explosions. These impacts occur while

planetary systems are forming - from less than 1 to over 30 million years after the formation of the star and its disk.

In this review, we first discuss the type of environment in which most stars form, summarize star formation in the Solar vicinity, and use the Orion Nebula as a detailed example. We discuss possible impacts of UV radiation, dynamical encounters, and supernovae on circumstellar disks and the formation of planetary systems. We argue that the high stellar density and UV-rich environment in which most stars form may help explain several long-standing problems in the birth of our Solar System such as the prompt formation of planetesimals, the presence of annealed materials and chondrules in meteorites, and the injection of short-lived radioactive species.

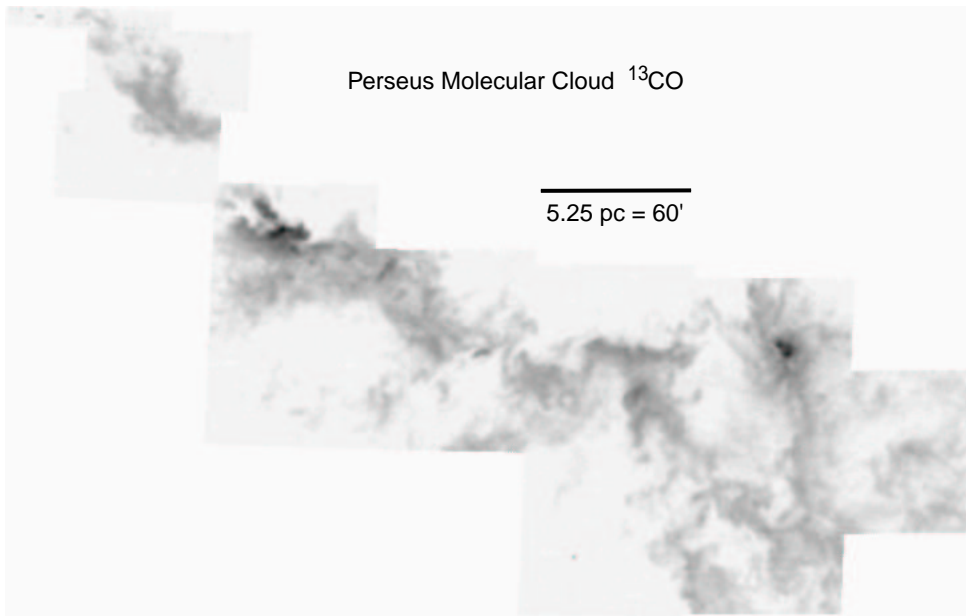


Figure 1. A 2.6 millimeter-wavelength ^{13}CO map showing the Perseus Molecular Cloud, an active site of star formation located about 300 pc from the Sun. All images in this paper are negatives: Bright emission is shown in black; faint or no emission is shown in white.

2. Two Classic Problems in Planetary System Formation

2.1. Growth from Meters to Kilometers: The Birth of Planetesimals

Models of the Solar Nebula - the disk of dust and gas from which our Solar System formed - indicate that kilometer sized planetesimals formed rapidly. As particles grow from micron-size interstellar grains to centimeter and meter-scale solids, they experience drag from gas in the circumstellar disk. Gas in a disk is supported by internal pressure and therefore orbits the protostar with a speed slightly slower than the local Kepler speed. On the other hand, large solids orbit with the Kepler speed. Thus, the pressure-supported gas disk and large solids orbit with speeds differing by $\Delta V \sim c_s^2/v_K$, where c_s is the sound speed in the

gas and v_K is the local orbital (Kepler) speed (Youdin & Shu 2002). As solids grow and decouple from the gas, they experience a ‘headwind’ which drains their orbital angular momentum. Thus, the smallest decoupled solids will tend to spiral into their central star. Gravel-sized solids must therefore accumulate into kilometer-sized planetesimals on a time-scale shorter than the inspiral time.

The transition from meter-scale solids to kilometer-scale planetesimals for which the gravitational force can assist further growth has proven problematic. The very feeble surface cohesive forces of rocks and ices implies that collisions between similar sized but small (meter-scale) solids tends to be elastic (Chokshi, Tielens, & Hollenbach 1993; Weidenschilling & Cuzzi 1993). The rate at which solids grow by sweeping-up smaller solids from their surroundings due to relative drift is too low for this to be a viable mechanism for planetesimals formation.

2.2. Chondrules and annealing

Morphological evidence indicates that millimeter-scale chondrules in primitive chondritic meteorites were heated abruptly and then cooled on a time-scale of 10^3 to 10^4 seconds. Many theories for their origins have been proposed, including electrical discharges in the disk, heating and entrainment in the ‘X-wind’ of the young Sun, and processing through shocks. Shu et al. (1996) proposed that chondrites were formed within 0.1 AU of the proto-Sun at the interface between the stellar magnetosphere and the inner-edge of the protoplanetary disk where it is disrupted by the magnetosphere. In this ‘X-wind’ model, millimeter sized droplets are lofted out of the disk, irradiated, melted, entrained in the proto-Sun’s wind, and expelled by this wind to the outer portions of the disk.

Harker & Desch (2002) proposed that shock waves in the disk were responsible for forming chondrules. Millimeter-size solids will penetrate the shock front and suffer frictional heating as they move through and decelerate in the post-shock fluid. In this model, the chondrule cooling-time is similar to the deceleration time-scale. The required mid-plane shocks could be produced by the wakes of orbiting protoplanets, or by any large perturbation to the disk.

Perhaps, these two classic problems will find their solutions not in the behavior of isolated circumstellar disks, but in the environment in which these disks evolve.

3. The Environment of Star and Planet Birth

There are several reasons why the ‘isolationist’ view of star birth has persisted for so long. First, only a very small fraction of all stars are currently observed to be in clusters. Second, the nearest and most easily studied star-forming molecular clouds are relatively low-mass objects which produce only a few stars. Third, our Solar System surrounds an isolated star. In the early 1990s, the advent of large-format focal plane arrays sensitive to near-infrared radiation changed our understanding of the typical environment of star formation. Infrared imaging allowed astronomers to study the visually obscured interiors of molecular clouds where stars form. These images demonstrate that most stars form in clusters, and not in isolation (e.g. Lada & Lada 2003).

How are these infrared observations to be reconciled with the appearance of the night sky? The disk of the Milky Way contains thousands of open star

clusters such as the Pleiades which contain anywhere from dozens to thousands of stars. Additionally, our Galaxy is surrounded by over 100 globular clusters, ancient spherical stellar systems containing from over 10^4 to nearly 10^6 stars. However, the vast majority ($\sim 99\%$) of stars are not in such clusters; they move about the Galaxy in isolation as single or multiple stars. Although most stars are observed to form in dense clusters, most stars currently exist in isolation. The solution to this apparent puzzle lies in the short life-times of the vast majority of young clusters.

The conversion of a molecular cloud core into a star requires that its linear dimension shrinks by more than 7 orders of magnitude, and that its density increases by more than 21 orders of magnitude. When a cloud core in a typical giant molecular cloud condenses under the force of its own gravity, it tends to fragment into a cluster of smaller and denser sub-cores. The observed supersonic turbulent motions in clouds tends to produce shocks which enhances its tendency to fragment.

Young stars are a major source of chaotic and turbulent motions in star forming regions, producing powerful jets, winds, and intense radiation fields. The resulting injection of energy and momentum into a cloud limits the fraction of a cloud's mass which can be converted into stars. The simultaneous birth of too many stars blows the parent cloud apart. Observations show that star formation is a self-limiting process. The ratio of the total mass of stars formed by a cloud, divided by the cloud's initial mass is called the *efficiency of star formation*, η_{SF} . Most clouds only convert a few percent of their mass into stars by the time they are disrupted by energy produced by the forming objects. Thus, for most clouds, $\eta_{SF} = 3$ to 30%.

As stars form from the turbulent collapse of a cloud core, they inherit the motion of each cloud fragment in the overall gravitational potential of the cloud. Thus, a cluster of forming stars will typically be born with a velocity dispersion comparable to the gravitational escape velocity from the parent cloud at the radius of the cluster, $V_{esc} = (2GM_{cloud}/R_{cluster})^{1/2}$ where G is Newton's constant, M_{cloud} is the total mass of the parent cloud core which gives rise to the clusters, and $R_{cluster}$ is the radius of the forming cluster. If η_{SF} is less than about 50%, then over half of the parent cloud's mass will be dissipated by the end of star formation and the total mass the star cluster will be too small to gravitationally bind the stars. Thus, for $\eta_{SF} < 0.5$, the resulting young cluster will dissipate and release its litter of young stars into the field on a time-scale comparable to the cluster crossing-time, $t_{cross} \sim R_{cluster}/V_{esc}$.

Observations show that the majority ($\sim 90\%$) of all stars in the sky form in dense clusters containing from tens to many thousands of stars (Lada & Lada 2003). However, most forming clusters are transient, gravitationally unbound entities. They expand and dissolve on a time-scale of several million years, comparable to the time required for planet formation. In forming clusters, the mean separation between stars can be less than 1,000 AU.

The formation of a cluster which can survive for many cluster crossing times requires $\eta_{SF} > 0.5$. Thus the formation of bound (open and globular) star clusters requires exceptional conditions. The conditions for globular cluster birth have not been satisfied in our Galaxy for over 5 billion years. The birth rate of bound open clusters such as the Pleiades is about two orders of magnitude

lower than the birth rate of unbound groups. The majority of young clusters dissolve into the field of the Milky Way's stars within a few million years of birth. Thus the high observed frequency of young, embedded infrared star clusters is reconciled with the fact that most stars move about the galaxy as isolated single or multiple stars and not as members of open and globular clusters.

As we will argue below, there is evidence that our Solar System was born in a *transient* cluster which dissolved soon after birth. The intense radiation environment of young clusters containing massive stars may have aided the first steps of planet formation. The death of these massive stars around the time of our Sun's birth may have injected the short lived radioactivities whose decay products are found in primitive meteorites. Long-range tidal perturbations by the close-by passages of sibling cluster members may be a source of shocks which can explain the sudden melting of chondrules.

3.1. Evidence for Star Birth in OB Associations

Two lines of evidence indicate that the majority of stars in the sky form in large clouds which give birth to OB associations, massive stars, and very dense but transient clusters. The first comes from counts of young stars in the Solar neighborhood. There are three OB associations younger than 15 Myr within 500 pc of the Sun: Sco-Cen, Per OB2, and Orion (Figure 2). Their parent giant molecular cloud complexes, with masses ranging from 10^4 to over $10^5 M_\odot$, have produced tens of thousands of mostly low-mass stars. The Orion Nebula, which traces a part of the most recent burst of star formation in Orion - the Orion 1d subgroup - has already spawned about 3,000 stars within the last 1 Myr. In contrast, lower mass dark clouds such as Taurus ($M < 10^3 M_\odot$) each produce at most several hundred young stars. Over a 15 Myr period, the roughly dozen low-mass dark cloud complexes within 500 pc of the Sun have produced only several thousand stars. Thus, GMCs have produced more stars near the Sun than lower-mass dark clouds which produce no massive stars.

The second line of evidence comes from the mass-spectrum of GMCs. This mass spectrum can be represented by a power-law of the form $dN/dM \propto M^{-\alpha}$; it has a shallow slope with $\alpha = 1.5$ to 1.8 , which means that most of the Galaxy's mass in molecules are found in the largest clouds. Even under the conservative assumption that the rate of star formation per unit mass is constant, most stars form from the largest clouds. Observations indicate that the efficiency of star formation actually increases with increasing cloud mass, a tendency which implies that an even larger fraction of stars form from the largest GMCs than would be indicated by the GMC mass spectrum. Observations show that within OB associations, most stars form in high density sub-groups which are not gravitationally bound, and therefore disperse within a few cluster crossing times (Lada & Lada 2003). Thus, to understand the formation environment of a typical star, we must investigate star formation in high-mass OB association sub-groups. HII regions are tracers of such groups.

3.2. Star Formation in GMCs

Observations show that isolated single star formation is extremely rare. Though there are a number of examples where an isolated cloud core has given birth to either an isolated star or a binary, most young stars are born in aggregates or

clusters containing from a few to many hundreds or even thousands of individual objects. Even in dark clouds such as Taurus, many cloud cores have produced small clusters of stars (e.g. L1551; Devine, Reipurth, & Bally 1999). Thus, fragmentation must be a common feature in the evolution of cloud cores.

Young stars have a profound effect on the structures of molecular clouds. Forming stars produce powerful outflows and jets that penetrate the surrounding medium for many parsecs (Reipurth, Bally, & Devine 1997). They sweep up and accelerate gas in their path, creating large holes in the parent molecular cloud surrounded by moving shells. The acceleration of gas by bipolar outflows from young stars is a source of internal motions that couple energy and momentum into the cloud interior efficiently. Eventually, these motions degrade into random flows that leave behind a chaotic jumble of holes, sheets, and filaments.

In addition to jets and outflows, massive stars also produce strong UV radiation fields, stellar winds, and supernova explosions. UV radiation fields illuminate cloud surfaces, and penetrate into voids created by outflows to illuminate cloud interiors. For a typical gas-to-dust ratio, the soft UV radiation ($912\text{\AA} < \lambda < 2000\text{\AA}$) penetrates the molecular cloud surface layers to a depth of order $N(\text{H}_2) \approx 10^{21} \text{ cm}^{-2}$. In these photon-dominated or photo-dissociation regions (PDRs) the radiation field destroys most molecules and raises the temperature to 50 to over 1,000 K, about an order of magnitude hotter than the shielded molecular gas (Störzer & Hollenbach 1999). As a result, wide-spread outflows moving with speeds of a few km s^{-1} normal to the local density gradient are produced and the resulting back pressure can generate motions in the cloud itself (Gorti & Hollenbach 2002). In clouds with chaotic structure, these randomly oriented photo-ablation flows can also effectively produce turbulent motions.

The expansion of HII regions create hot cavities surrounded by swept-up shells of accelerated gas that can profoundly alter cloud structure and kinematics. Large portions of a GMC can be dissociated by only a few O stars. Dense clumps can be overrun by the growing HII regions to form elephant trunks, cometary clouds, and isolated dense globules.

Collectively, OB associations can eventually destroy entire molecular clouds and inflate superbubbles in the ISM that can reach 10^3 pc dimensions (see Figures 3 and 4). Superbubble winds produced by OB associations determine the large scale shapes and velocity fields of many molecular clouds. Specific mechanisms which can sculpt and accelerate clouds include soft UV radiation, expanding HII regions powered by the Lyman continuum radiation, the stellar winds produced by massive stars, and their demise in terminal supernova explosions.

3.3. Overview of Recent Star Formation in the Solar Vicinity

The Solar vicinity, the region within about 0.5 to 1 kpc of the Sun, is the only place where we can measure the distribution and motion of young stars and associated gas in 3 dimensions. Distances, estimated using the parallax and other means, can be combined with their position on the sky to locate them in 3 dimensions. Motions on the plane of the sky, measured using multi-epoch images, can be combined with their spectroscopically determined radial velocities to obtain their velocity vectors. Clouds can be linked to specific groups of stars through reflection nebulae and common radial velocities. With the help

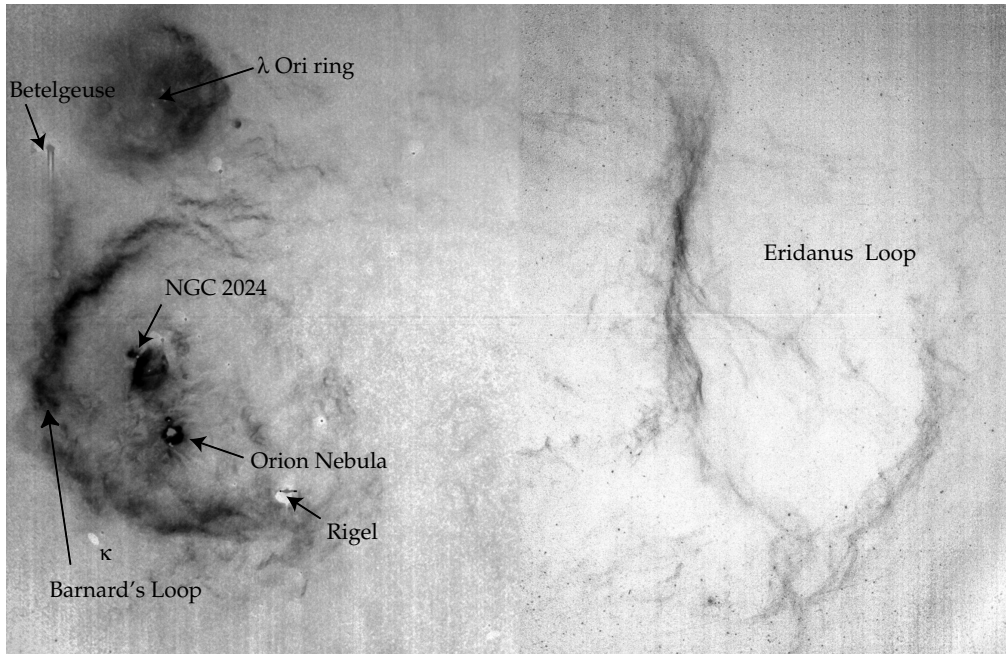


Figure 2. An $H\alpha$ image showing the Orion-Eridanus superbubble blown by the Orion OB1 association. Stars have been subtracted. Bright emission is shown in black.

of stellar ages, astronomers can reconstruct the history of nearby star formation over about the past 50 million years.

Low-mass T-Tauri stars and dense HII regions ionized by massive stars trace sites of on-going or recent star formation with ages up to a few million years. Stars with spectral type O through B3 in OB associations mark sites of star formation active over the last 40 million years. This time-scale is set by the main-sequence lifetime of 8 Solar mass stars, the least massive that emit radiation that ionizes hydrogen and the least massive to explode as a type II supernova. Studies of the age-spread of stars in OB associations show that they require about 5 to 15 million years to form (Blaauw 1991). This is one measure of the duration of star formation in a GMC. Although we can estimate the ages of open star clusters from the masses of their most massive main-sequence stars, it is much more difficult to identify gravitationally unbound stellar groups that are older than about 40 million years. Nevertheless, some “fossil” OB associations older than 40 Myr have been identified in the Solar vicinity by the common motion of their member stars. A face-on view of the Solar vicinity is shown in Figure 5.

After correction for the effects of Galactic differential rotation, most of the cool interstellar medium (ISM) in the Solar vicinity (which consists of GMCs and atomic hydrogen clouds) is expanding with a mean velocity of 2 to 5 km s^{-1} from a point located near Galactic longitude and latitude $l=150^\circ$, $b=0^\circ$, $d=200$ pc, the approximate centroid of the 50 Myr old Cas-Tau group, a “fossil” OB association (Blaauw 1991). This systematic expansion of the local gas was first identified by Lindblad (1967, 1973) and is sometimes called ‘Lindblad’s ring’

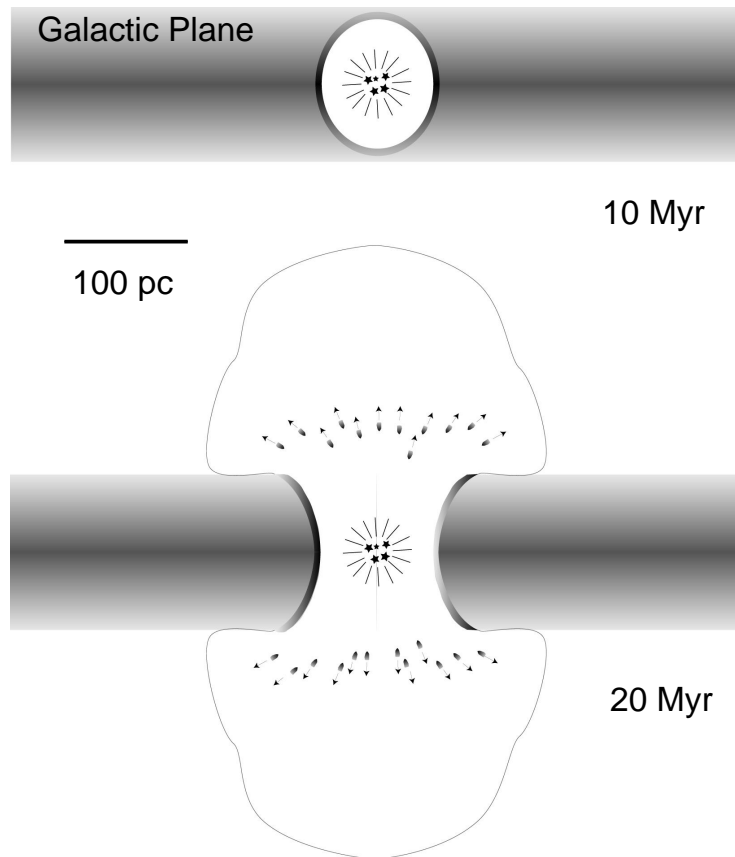


Figure 3. A cartoon showing the early evolution of a superbubble in the Galactic disk powered by the combined effects of winds and supernovae produced by massive stars in an OB association.

of HI, but it is even more apparent in the kinematics of the nearby molecular gas (Dame et al. 1987, 2001; Taylor, Dickman, & Scoville 1987; Poppel et al. 1994). The Sun appears to be well inside this expanding ring. The nearest OB associations, such as Sco-Cen ($d \approx 150$ pc), Per OB2 ($d \approx 300$ pc), Orion OB1 ($d \approx 400$ pc), and Lac OB1b ($d \approx 500$ pc), and the somewhat older B and A stars that trace the so-called ‘Gould’s Belt’ of nearby young and intermediate age stars may also be expanding from this location (Lesh 1968; De Zeeuw et al. 1999). Thus, the Lindblad ring appears to be a 30 to 60 Myr old fossil supershell driven into the local ISM by the Cas–Tau group and the associated α Persi cluster (Blaauw 1991). The nearby OB associations and star forming dark clouds may thus represent secondary star formation in clouds that condensed from the ancient Lindblad ring supershell.

McCray & Kafatos (1987) demonstrated that as supershells sweep-up the surrounding ISM and decelerate, they can fragment into clouds due to gravitational instabilities. Where the gravitational escape speed from a piece of the shell becomes larger than the local velocity dispersion, gravity can condense the

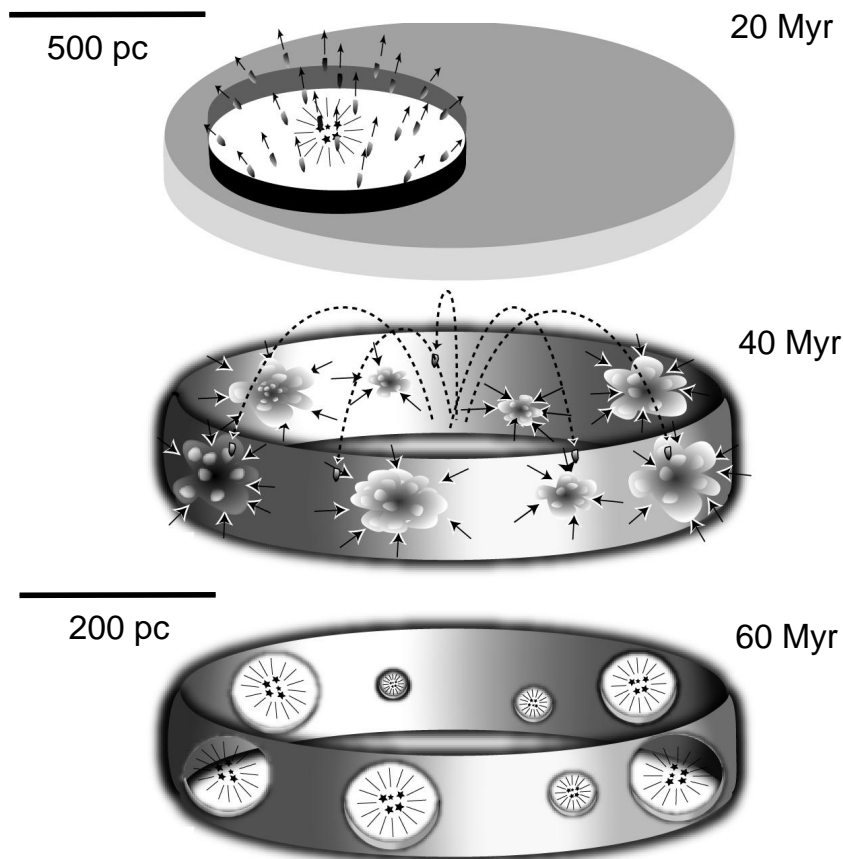


Figure 4. A cartoon showing an evolved bubble sweeping-up a super-ring from the stratified Galactic disk. The model applies to superbubbles with ages of order 25 to 50 Myr. As the dense ring sweeps-up material, it decelerates. It fragments into self-gravitating clouds with masses of order $10^5 M_{\odot}$ (McCray & Kafatos 1987). These clouds then spawn new OB associations and superbubbles.

shell into clouds having properties similar to GMCs. On small-scales, supershells are stabilized by thermal and turbulent motions. On large-scales, supershell expansion dominates. In the Solar vicinity, gravitational instabilities lead to the formation 10^5 Solar mass clouds from the decelerating shells of aging superbubbles.

Support for this view comes from the agreement between the observed radial velocity fields of the local HI emission and nearby CO clouds with models of an expanding and tidally sheared 30 to 60 Myr old superbubble (Poppel et al. 1994).

The distribution of dust in the COBE and IRAS satellite infrared data ($\lambda \approx 10$ to $240 \mu\text{m}$) and the kinematics of high Galactic latitude HI provide additional evidence for an ancient supershell centered on the Cas-Tau group. The lines of sight with the lowest column densities of HI (the Lockman Hole)

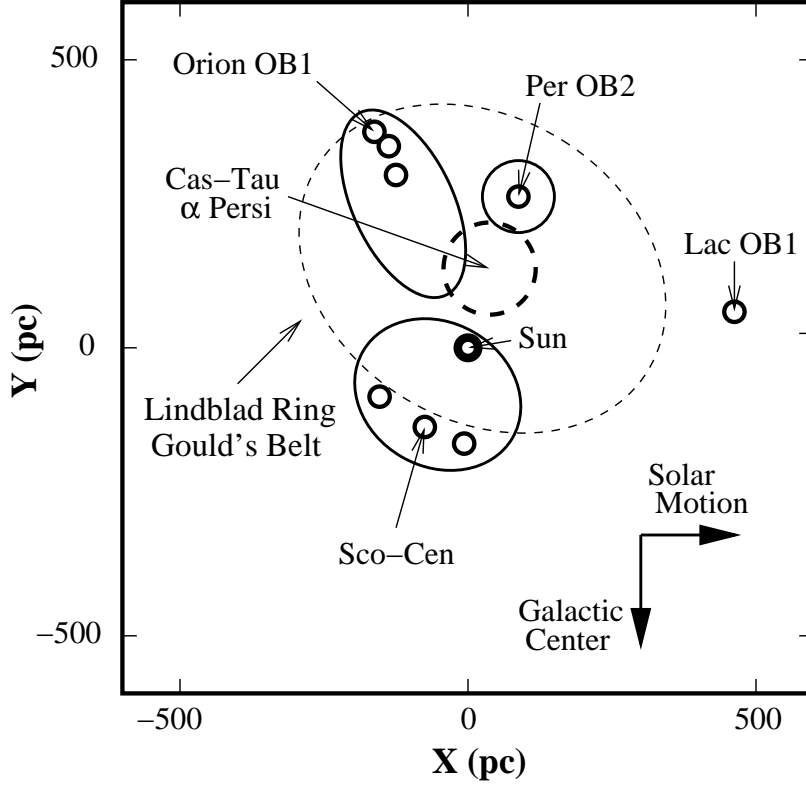


Figure 5. A cartoon showing superbubbles and OB associations within about 500 pc of the Sun (centered in the box). The major nearby OB associations younger than about 15 Myr are shown as small circles (De Zeeuw et al. 1999). Three sub-groups are shown in Orion and in Sco-Cen. Their superbubbles are shown as bold ovals. The Lindblad Ring and the Gould's Belt of young stars is shown as a large dashed oval. This ancient superbubble was created by 25 to 50 Myr old the Cas-Tau "fossil" OB association, shown by the dashed circle between the Sun and Per OB2. This core of this group is the α Persi open star cluster.

and dust (Baade's Hole) lie above and below the Cas-Tau group near $l = 150^\circ$ and $b = 35^\circ$, providing evidence that an ancient bubble burst out of the Galactic plane at about one dust scale-height above and below the Cas-Tau "fossil" OB association.

Gas gas expelled from the Galactic disk 30 to 50 Myr ago is now expected to be falling back. Indeed, the 21 cm line profiles formed by averaging all HI emission produced in both the northern and southern Galactic hemispheres show excess emission at low negative velocities in the range $v_{lsr} = -10$ to -40 km s $^{-1}$ (Stark et al. 1992), indicating an excess of infaling material at low velocities. Since the ambient pressure of the ISM orthogonal to the Galactic plane declines as an exponential, an expanding pressure driven supershell will accelerate once its radius becomes larger than the gas layer scale-height. As a supershell bursts out of the Galactic plane, it is subject to Rayleigh-Taylor fragmentation insta-

bilities (MacLow & McCray 1987). After blow-out, the resulting dense clumps will move ballistically in the gravitational potential of the Galactic disk. Up to about 500 pc above the plane, the gravitational field of the disk is reasonably well represented by a harmonic oscillator potential with a z -oscillation time of about 80 to 100 Myr (Spitzer 1978). Clumps ejected from near the Galactic plane at less than 40 km s^{-1} will stop at heights of less than 500 pc within 20 – 25 Myr of their formation. During the next 20 – 25 Myr, they fall back towards the plane. Thus, the dynamical age of the low velocity infalling HI is comparable to that of the Cas–Tau group.

The Gould’s Belt/ Lindblad Ring contains the Sco-Cen OB association, the nearest complex of massive star formation located about 150 pc from the Sun. A giant HI shell over 100° in diameter is centered on the centroid of the association and many high latitude clouds are associated with these features. The non-thermal radio emission features known as Loops 1 and 2 coincide with the outer periphery of this HI supershell. Furthermore, the outermost portions of the expanding network of clouds and hot plasma emerging from the Sco-Cen OB association have already overrun the Solar system. Evidence for this hypothesis is provided by Solar Lyman- α back-scatter and the streaming of the ISM through the Solar system which, when corrected for the Solar motion with respect to the Local Standard of Rest coordinates, has a vector velocity of about 20 km s^{-1} from the general direction of the Sco-Cen OB association (Crutcher 1982; Frisch 1996a, b; Frisch et al. 1999). In this model, the nearby ‘hot cavity’ may be an outlying portion of the Sco-Cen superbubble which is presently over-running the Solar system.

The next nearest OB association is the Perseus OB2 group located at a distance of about 300 pc. This group contains a small HI shell about 20° in diameter and has a much smaller stellar content than either Orion or Sco-Cen. In addition to Sco-Cen, Per OB2, and Orion, the Gould’s Belt/ Lindblad Ring system may also include a fourth member, the Lac OB1 association. The Ring also contains a number of giant molecular clouds and dark cloud complexes that are not at present forming high mass stars. These clouds include the Great Rift (or the Aquila Rift) extending from Ophiucus to Cygnus, the Cepheus Flare clouds, and some of the clouds in Taurus and Perseus.

These clouds and OB associations share the expanding motion of the Lindblad ring and may therefore represent fragments formed by gravitational instabilities. The OB associations may trace the first fragments to have condensed from the expanding Cass-Tau supershell and so are more evolved than the less active clouds complexes which may have formed later.

Massive stars in OB associations dominate the energy injected into the ISM. Over the 5 to 15 Myr formation time of an OB association, between 10 to 100 stars with masses in excess of $8 M_\odot$ are produced (in addition to more than 10^4 lower mass stars). Their Lyman continuum (LyC) radiation dissociates and ionizes surrounding molecular gas, their powerful winds shock and expel this plasma from the vicinity of the parent molecular cloud, and their demise in supernova (SN) explosions contribute to the 10^{52} to 10^{53} ergs of energy necessary to inflate superbubbles in the ISM. Most nearby molecular clouds may have formed by gravitational fragmentation of the Cas–Tau fossil super-ring. Gravitational

instabilities in a swept up ring lead to a fragment mass of order $10^5 M_\odot$ and to a global velocity structure similar to what is observed in the local ISM.

The above model and data can be used to reconstruct the 30 to 60 Myr history of the Solar vicinity. A large OB association formed between 40 to 60 Myr ago at the present location of the Cas–Tau group and centered on the α Per cluster, possibly triggered by the previous passage of the local ISM through a major spiral arm. The resulting superbubble overran pre-existing clouds, swept-up the low density ISM into a $10^6 M_\odot$ super-ring, and blew out of the Galactic disk to produce the Baade and Lockman Holes. About 15 to 25 Myr ago, the first GMC sized condensations formed near the Orion, Sco-Cen, Lac OB1b, and Per OB2 associations. Orion may have formed first at the collision point between the Cas–Tau and GSH238 superbubbles (Heiles 1998). These GMCs started forming OB associations about 15 Myr ago and are presently driving their own superbubbles into the remnants of the ancient Cas–Tau fossil supershell. The expansion velocity of the Cas–Tau fossil shell is imprinted on the currently forming OB groups, the Great Rift clouds, the Lindblad ring, and most other clouds lying within 500 pc of the Sun. The model is self-sustaining. The nearby younger supershells will in turn produce super-rings by sweeping up ambient HI produced by the destruction of old molecular clouds into new GMCs that will produce future generations of OB associations.

3.4. An Example: The Orion Nebula

The Orion star forming region (distance $D \approx 380$ to 460 pc - See Figures 2 and 6) contains the nearest GMCs, bright HII regions, and some of the closest young clusters in the sky. The Orion Nebula marks the site of its most spectacular stellar nursery. In a region only a few parsecs in diameter, about 3,000 mostly low-mass stars formed here within the last few million years. This young cluster (known as the Orion Nebula Cluster; ONC) also contains about a half-dozen massive (spectral type earlier than B3) stars. The most massive of these stars, θ^1 Ori C (spectral type O7), is most responsible for ionizing the Orion Nebula.

Near-infrared excess emission from these stars provided evidence that most low-mass members of the ONC are surrounded by hot dust disks with radii of at least 0.1 to 1 AU. The detection of radio frequency radiation from thermal plasmas surrounding many of the low-mass young stars in the OMC (Churchwell et al. 1987), combined with the low extinction towards most of the associated stars, provided indirect evidence that these disks were large and massive, similar in size and mass to the hypothesized primordial Solar Nebula. The sub-arcsecond images produced by the nearly diffraction limited 2.4 meter diameter Hubble Space Telescope (HST) produced the first direct images of 100 to 500 AU radius disks surrounding many of these stars (Figures 7 and 8).

In Orion-like environments, young stars are subjected to intense UV radiation fields, and occasional dynamical encounters with sibling stars. These environmental factors may play important roles in the early evolution of planetary systems during their formative years. A high probability of dynamical perturbations by passing sibling stars intense UV irradiation, and the effects of nearby supernovae can persist for between 10^5 to a few times 10^7 years, the time-scale on which early planetary system evolution occurs.

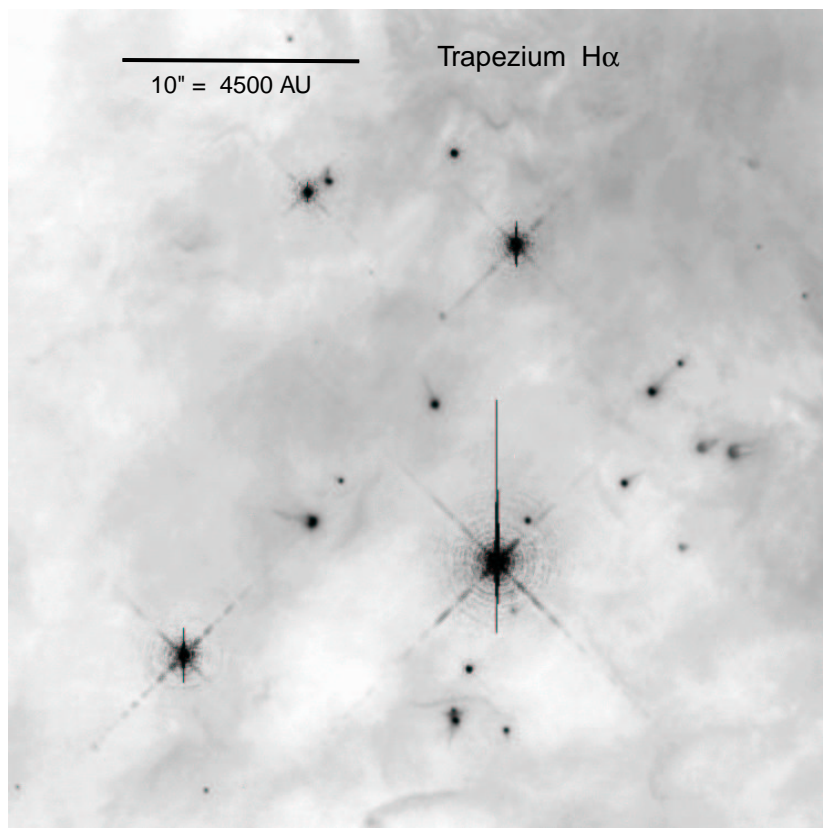


Figure 6. A Hubble Space Telescope showing the massive stars in the core of the Orion Nebula along with more than a dozen low-mass star which have cometary tails pointing away from the brightest members. Stars are black.

4. Irradiated Protoplanetary Disks

Young clusters frequently contain massive stars which produce powerful stellar winds and intense UV radiation, and explode as supernovae soon after birth. These massive stars carve bubbles of hydrogen plasma (HII regions) in their surroundings by ionizing their parent molecular clouds. HII regions such as the Orion Nebula, one of the nearest and best studied celestial objects, are signposts of on-going star and planet formation. These clustered star forming environments and their massive stars can pose potential hazards to nascent protoplanetary disks because UV radiation and close-encounters with sibling stars can rapidly strip away their outer parts. Observations of young disks surrounding low-mass stars in the Orion Nebula show that many disks lose the equivalent of Jupiter's mass every 10,000 years to UV-induced photo-ablation (Henney & O'Dell 1999).

O, B, and even A stars rapidly dissociate the low-density portions of their parent molecular clouds. Mass loss from irradiated cloud cores, globules, or circumstellar disks can occur by two distinct UV induced mass-loss mechanisms: The soft-UV radiation ($912 < \lambda < 2000\text{\AA}$) dissociates molecules and heats cloud surfaces (to a column depth of order $\sim 10^{21} \text{ cm}^{-2}$) to temperatures of 100 to

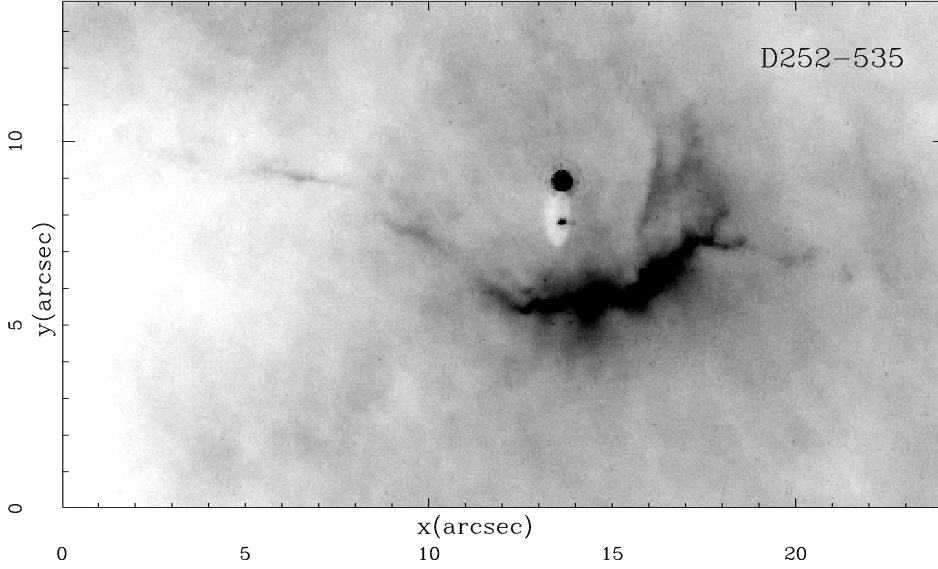


Figure 7. A protoplanetary disk in a binary system embedded in an externally ionized globule in Messier 43 (from Smith et al. 2005). Stars are black and the disk seen in silhouette is white.

more than 10^3 K, and raises the sound speed in the optically thin layer to $1 - 5 \text{ km s}^{-1}$. If the corresponding increase in sound speed exceeds the local gravitational escape speed, then heating results in mass loss. O and early B stars produce Lyman continuum radiation fields ($\lambda < 912\text{\AA}$) which ionizes this material, raises its temperature to nearly 10^4 K and sound speed to about 10 to 15 km s^{-1} (Johnstone, Hollenbach, & Bally 1998).

As UV radiation strips away the lower density gas, it wraps around denser cloud cores and circumstellar disks, and drives mass flows until either the objects are completely evaporated or ionized, or until a radius is reached where gravitational escape speed is larger than the sound speed. These processes sculpt the pillars and elephant trunks in HII regions and are responsible for the proplyds in the Orion Nebula (O’Dell, Wen, & Hu 1993; Bally et al. 1998; Bally, O’Dell, & McCaughrean 2000; O’Dell 2001).

The UV-induced mass-loss-rates can be estimated by considering a highly idealized spherical cloud which is losing mass. For a spherical cloud of radius r_c , and a soft-UV absorbing layer thickness $N_{21} = 10^{21} \text{ cm}^{-2}$, and a sound speed (in the soft-UV heated layer) v_I ,

$$\frac{dM_{\text{soft}}}{dt} \approx 2\pi\mu m_H v_I r_c N_{21} = 6.7 \times 10^{-5} v_3 r_{18} N_{21} \quad (M_\odot \text{ yr}^{-1}) \quad (1)$$

where v_3 is in units of 3 km s^{-1} and r_{18} is in units of 10^{18} cm .

Consider a cloud core, disk, or globule whose UV-induced “wind” is in photoionization equilibrium with the ionizing (Lyman continuum) radiation field of a nearby massive star located at a distance d . If the Lyman continuum

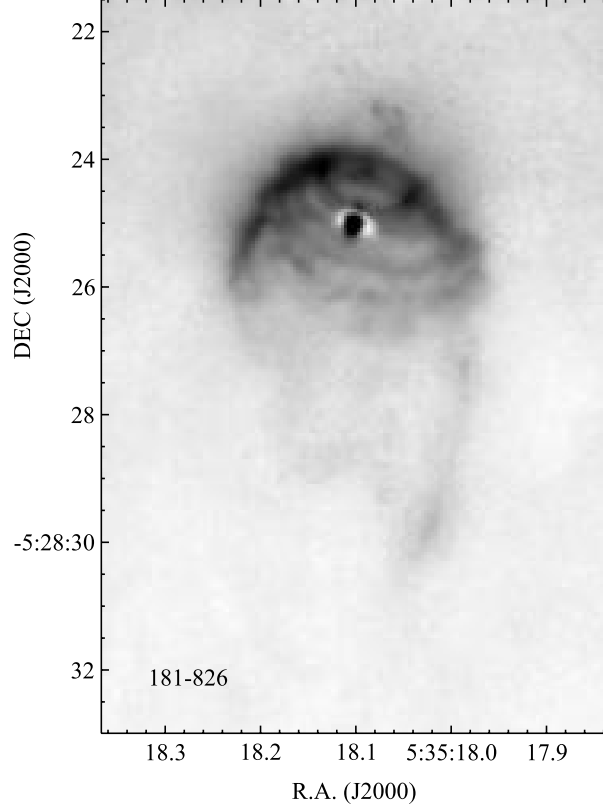


Figure 8. A protoplanetary disk embedded in a cometary proplyd in the southern portion of the Orion Nebula. The jet emerging from the disk drives the HH 540 outflow (from Bally et al. 2005).

luminosity is given by $L(LyC)$, the mass loss rate is given by

$$\frac{dM_{hard}}{dt} \approx \mu m_H c_{II} (3\pi L(LyC)/\alpha_B)^{1/2} r^{3/2}/d \quad (2)$$

$$= 2.2 \times 10^{-5} c_{10} L(LyC)_{49}^{1/2} r_{18}^{3/2} d_{10}^{-1} (M_{\odot} \text{ yr}^{-1}) \quad (3)$$

where c_{10} is the sound speed in ionized gas in units of 10 km s^{-1} , $L(LyC)_{49}$ is the Lyman continuum luminosity in units of $10^{49} \text{ photons s}^{-1}$, $\alpha_B = 2.6 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ is the recombination coefficient for hydrogen, and d_{10} is the distance of the cloud from the ionizing star in units of 10 pc .

Thus, large cloud envelopes and disks lose mass at large rates and shrink rapidly in the presence of either soft UV or ionizing radiation. Solar mass cloud cores can be evaporated in 10^5 years. However, as the object shrinks, the mass loss rate declines.

Inside HII regions such as the Orion Nebula, the more penetrating soft-UV tends to drive mass loss in regions with a large enough density to exclude the

harder ionizing radiation field. Thus, for disks with radii ranging from about 40 to over 500 AU and distances from the UV source ranging from $d = 0.03$ pc to several parsecs, the soft UV dominates mass loss and pushes the ionization front (where hard UV can ionize the flow) to radii several times larger than the disk radius. A minimum mass Solar Nebula ($0.01 M_{\odot}$) disk can survive for about 10^5 years if the mass-loss rate is of order $\dot{M} = 10^{-7} M_{\odot} \text{ yr}^{-1}$. However, as disks shrink to Solar system dimensions (~ 10 AU), mass loss rates decline and survival times increase to longer than the main sequence life-times of the massive stars that generate Lyman continuum radiation (Adams et al 2004).

This simple, highly idealized model of photo-evaporation has several important consequences:

- UV-producing O, B, and A stars can rapidly evaporate cloud cores. Where the sound speed exceeds the local gravitational escape speed, gas is removed from the object.

- Photo-evaporation can limit the amount of mass available for accretion onto forming stars, thereby limiting stellar masses. Stars just starting to form when a nearby O or B star is born are likely to lose their envelopes and cores and may on average be less massive than stars formed in the absence of massive stars. Thus, radiation fields can play a major role in determining the initial mass function (IMF) in OB associations.

- Photo-ablation of cloud cores or molecular clouds can produce large-scale mass-flows. Soft-UV can drive complex mass motions in photon-dominated-regions (PDRs) with speeds of $1 - 6 \text{ km s}^{-1}$ (e.g. Gorti & Hollenbach 2002). Chaotic structure leads to chaotic motions. The back-reaction on the GMCs can generate cloud turbulence. Ionizing UV can generate flows with velocities several times the sound speed in ionized gas ($10 - 30 \text{ km s}^{-1}$). These flows can deflect stellar jets to produce the commonly observed outward facing C-symmetric stellar outflows and parabolic inward facing shock fronts typified by stars such as LL Orionis (e.g. Bally et al. 2000).

- The survival time increases with decreasing source size. The photo-destruction time-scale (time it takes to shrink by about a factor of two in radius) for typical proplyds in the Orion Nebula with 100 AU or larger disks is around 10^5 years. But, as these disks shrink, mass-loss rates decrease and their photo-destruction time-scales increase. Minimum Solar Nebula mass disks with 10 AU disks can survive for several million years. *Thus, proto-planetary systems in Orion-like environments may retain sufficient material in the inner disk to eventually form planets.*

In addition to the external UV radiation, the forming and young stars embedded within disks also produce their own UV radiation fields. Some of this radiation is produced by magnetic activity near the surface of the star. UV radiation can also be generated by the shocks where matter accreting from the inner edge of a disks crashes onto the star. Current models of low-mass young stars indicate that they possess very strong (few kilo-gauss) magnetic fields. It is thought that magnetic pressure disrupts circumstellar disks within 5 to 10 stellar radii. As gas approaches the inner edge of the disk where the magnetic pressure dominates the thermal and turbulent pressures in the disk, the field can lift the gas and funnel it along the field lines. A roughly dipolar magnetic field geometry would guide plasma lofted from the disk inner-edge to the footprint

of these field lines at high stellar latitudes. As this matter crashes onto the stellar surface, it is decelerated and greatly heated by accretion shocks which contribute to the UV luminosity of star.

Magnetic fields may regulate the spin-rates of stars because they tend to rotate with the star as a rigid body. These fields are also anchored to the disk inner-edge, so the rotation rate of the star tends to be locked to the Kepler speed at the disk inner-radius. If the magnetic field at the disk inner-edge were to move faster than the disk orbital speed, the stretching of field lines would apply a braking torque to the star. The torque on the disk would tend to disrupt this portion of the disk, pushing its inner edge outward. On the other hand, if the field were to move slower, the interaction tends to spin-up the star.

If the magnetic field is generated by a dynamo process in which the field strength is proportional to the stellar spin rate, the interaction between the disk inner boundary, the magnetic field, and the stellar rotation rate may be self-regulated. Consider an accreting star with no spin and no magnetic field. The accretion disk could then spiral right down to the stellar equator, and accreting matter would spin-up the star by adding the maximum amount of angular momentum of a Keplerian orbit at the stellar surface. Thus, the star would spin-up. Under the above hypothesis, dynamo action would start to generate a magnetic field. As the field strengthens, it will start to interact with and disrupt the disk inner-edge, forcing it to recede from the star. But, the resulting decline in orbital speed will tend to slow the stellar spin, which diminishes the dynamo action and the resulting further growth of the field. Apparently, a quasi-steady-state is established for stellar spins of about 1 rotations every 2 to 10 days, which corresponds to a Keplerian orbit radius of about 5 to 10 stellar radii. The stellar and disk magnetic fields are thought to launch and accelerate the ubiquitous outflows powered by young stars.

The outer parts of an accretion disk can be illuminated by stellar UV directly along the line of sight, and by light which has been scattered by plasma launched by the disk and stellar magnetic fields. This UV radiation generates a disk corona which will be gravitationally bound to the star and disk inside the gravitational radius, $r_G \approx GM/c_s^2$ where M is the mass of the star and c_s is the sound speed in the photo-heated gas. UV irradiated gas at larger radii will leave the system. In general, there are two gravitational radii: A smaller radius r_{II} determined by the sound speed, $c_{II} \approx 11 \text{ km s}^{-1}$, in gas irradiated by Lyman continuum radiation, and a more diffuse radius, r_I determined by the sound speed $c_I \sim 1 \text{ to } 5 \text{ km s}^{-1}$, in gas irradiated by soft-UV radiation.

Thus, there are two regions in a protostellar envelope where mass loss is powered by UV radiation. The first, outer region is at $r \gg r_G$, where mass-loss is powered by the external radiation of massive stars in the parent cluster. Mass-loss is first driven by soft UV and, as the envelope shrinks, it becomes powered by the Lyman continuum which ionizes hydrogen. In the second, inner region at $r \approx r_G$, mass-loss is powered by the young star's own radiation field. In a disk in which there is no radial transport, a gap will be created near $r = r_G$ as 'self-irradiation' removes material from this region. However, viscous diffusion within a disk pumps fresh material from both smaller and larger radii into this zone (Matsuyama, Johnstone, & Murray 2003; Matsuyama, Johnstone, & Hartmann 2003). This process has two consequences for disks: First, in sufficiently viscous

disks, gaps may not form. Second, viscosity enables mass loss to continue until all available gas in the inner disk is either removed at r_G , or accreted onto the central star.

4.1. UV Triggered Planetesimal Formation

At first sight, it would appear that the UV-rich environment of HII regions would be hostile to the formation for planetary systems. However, the mass-loss rate due to photo-ablation decreases as the disk shrinks. Direct mass-loss rate measurements are available for some giant disks in the Orion Nebula from high resolution spectroscopy of the H α emission line in proplyd ionization fronts. These measurements indicate that Orion's largest disks are losing mass at rates of about 10^{-7} Solar masses per year (Henney and O'Dell 1999). At this rate, a 10^{-2} Solar mass disk could only survive for about 10^5 years. However, as a disk shrinks, its mass-loss rate declines, and as discussed above, the disk survival times increases. Analytic and numerical models of photo-evaporation indicate that inner disks can survive for millions of years (e.g. Adams et al. 2004) even in the presence of viscous transport which transports material to beyond the gravitational radii where UV (soft or ionizing) can remove it.

Recent modeling indicates that contrary to being hostile, HII regions may be ideal sites for planetary system birth. The central parts of most disks (to radii of tens of AU from the central star) can survive photo-erosion for many millions of years, longer than the survival time of unbound clusters and their most massive stars. Additionally, recent models show that in disks where grain growth and sedimentation have started by the time the disk is irradiated from the outside, the removal of light gases and small grains increases the concentration of heavy elements, rocks, and ices. Large (millimeter to meter scale) particles will tend to sediment to the disk mid-plane, and have lower velocity dispersion than the remaining gas. As sedimentation occurs, the gas to dust ratio in the upper layers of the disk will become increasingly depleted of heavy elements and solids. Photo-ablation of the disk surface will therefore selectively remove dust and metal depleted material.

Johnstone et al. (1998) used the observed radius of the ionization front of a proplyd in Orion, 182-413 - HST10, to calibrate a free parameter in the photo-ablation models which depends on the column density of gas in which the UV incident UV flux is absorbed. The calibration indicates a dust and metal depleted photo-ablation flow. A subsequent analysis of 10 proplyds by Störzer and Hollenbach (1999) indicates that the best-fit soft-UV dust cross-section per H nucleus in these flows is approximately $\sigma_{soft-UV} = 8 \times 10^{-22}$ cm² per H nucleus, which is about 1/3 the value for standard interstellar dust. This provides evidence that proplyd photo-ablation flows are dust and metal poor and that most solids are likely to have grown and sedimented in the disk mid-plane. Thus, the observations indicate that as photo-ablation proceeds, a significant fraction of the metals and large particles are left in the disk.

As photoablation proceeds, the surviving disk becomes enriched in heavy particles. Youdin & Shu (2002) argue that as the solid particle-to-gas mass ratio approaches a value of order 10 (about 10 times lower than an interstellar gas/dust mixture), gravitational instabilities start to occur in the settled dust subdisk. (The instability criterion depends on radial location and disk mass.)

Thus, gravitational instabilities in the mid-plane of a gas-depleted disk can start to clump the solids into planetesimals. Radiation may facilitate the first steps toward planet formation.

Throop & Bally (2005) have modeled the evolution of the properties of circumstellar disks undergoing grains growth and sedimentation in the presence of external UV-photoablation (Figure 9). These models show that as grains grow and sediment towards the disk mid-plane, the photo-ablation flow from the disk surface becomes dust depleted. Particles larger than a critical grain size (which depends on gas density) are left in the disk; only smaller particles are entrained in the photo-ablation flow. As the outer-radius of the gas disk shrinks due to mass-loss, large solid particles can be left behind in the disk mid-plane. Eventually, the outer disk becomes completely gas depleted. In the absence of viscous transport, gas photo-ablation stops when the radius r_G is reached.

The increasing dust-to-gas ratio drives the effected portions of disks towards gravitational instability. Throop & Bally (2005) propose that kilometer-scale planetesimals can form from photo-ablated disks on a time-scale short compared to the time in which the orbits of centimeter-scale particles decay. Thus, contrary to being hazardous, external UV radiation may stimulate the prompt growth of planetesimals in the outer portions of protoplanetary disks.

In the presence of viscous transport, gas from the inner disk can be continuously fed to radii where it can be removed by photo-ablation at the gravitational radius, r_G . Thus, even the inner disk where the Kepler speed is much greater than the sound speed in photo-heated gas can eventually become gas depleted. Thus, radiation may also promote gravitational instabilities and prompt planetesimals formation in the inner disk.

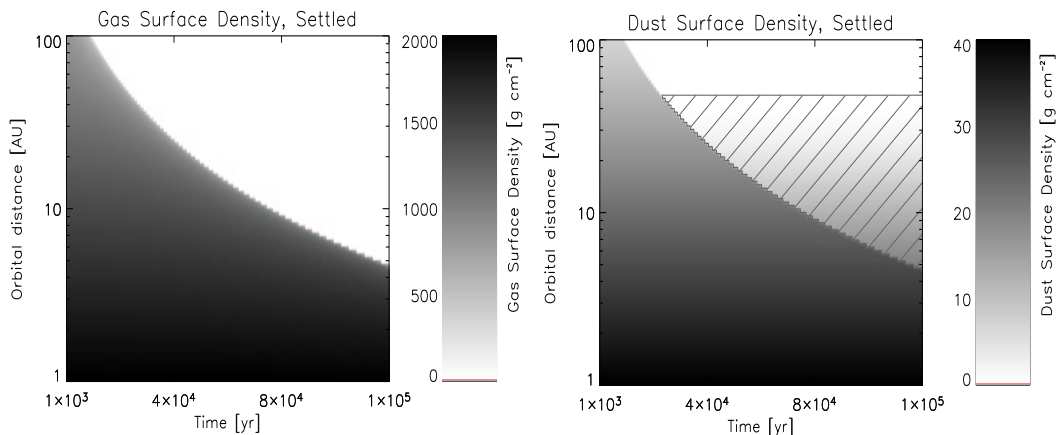


Figure 9. A model showing evolution of gas and dust surface density in an externally irradiated disk in the presence of grain growth and sedimentation. (Throop & Bally 2005).

5. Dynamical Interactions and Disk Shocks in Clusters

Most young stars are born in non-hierarchical multiple systems (e.g. Reipurth 2000) or in dense clusters such as the ONC. Individual objects in such systems can pass close to other sibling stars. Such stellar interactions can dynamically eject the outer parts of cloud cores and disks, and in case of three body interactions, eject one of the stars. By altering their trajectories, stars can be ejected from their accretion zones. Thus, dynamical interactions can terminate mass accretion. Dynamical interactions in clusters and non-hierarchical multiple systems are stochastic. If a young star is ejected early in its formation, it may be not have sufficient mass to become a star – such objects may be one source of brown dwarfs (Reipurth & Clarke 2001). If the star is ejected much later, it can accrete longer and grow to be more massive. Thus, stellar dynamics can also play a major role in determining the IMF in clusters.

Interactions with sibling stars can re-orient circumstellar disks and hence the jets and flows produced by such disks. Gradual torques can lead to S-shaped outflow symmetries while abrupt re-orientations are expected to produce point-symmetric (about the source) bends that lead to Z-shaped flows.

Stellar interactions in very dense clusters of protostars surrounded by dense circumstellar disks can lead to the formation of captured binaries (Clarke & Pringle 1991) and even to stellar mergers (Bonnell, Bate, & Zinnecker 1998), which may be an important method for the formation of the most massive stars. But, near misses in such clusters will also truncate disks. The outer radii of such disks will be truncated to to a radius of about 1/2 of the closest periastron distance of a passing sibling star during the first few million years of a cluster's life. The current mean separation between stars in the ONC is only a few thousand AU. During the birth of this cluster, the mean interstellar separation may have been one to two orders of magnitude smaller. Thus, stellar dynamics may limit the sizes and longevity of disks both multiple star systems and in clusters.

In dense clusters of stars, or in multiple star systems in which companions are moving along eccentric orbits, the close-passage of sibling stars can generate tidally induces spiral density waves and shocks which can re-process gas and solids in a protoplanetary disk. Figure 10 shows a snapshot in the time-evolution of a numerical SPH model of a sibling-star encounter with a $1 M_{\odot}$ star surrounded by a $0.05 M_{\odot}$ disk. The intruder star has a mass of $1.0 M_{\odot}$ and the periastron separation (distance of closest approach between the two stars) is 50 AU. In this simulation, the post-shock temperature exceeds 1,000 K.

Harker & Desch (2002) proposed that amorphous silicate droplets can be melted and partially crystalized when passing through shocks with speeds in excess of about 6 km s^{-1} . Millimeter-sized dust aggregates and stones are expected to move with the disk gas. As the gas passes through a hydrodynamic shock in the disk mid-plane, it is suddenly decelerated by nearly the shock velocity. But, the millimeter-scale solids move ballistically through the post-shock medium and experience heating by frictional drag. Such particles decelerate after traversing a distance containing roughly their own mass in gas. Thus, the deceleration time-scale of a solid with density ρ_s , radius r_s , moving through a

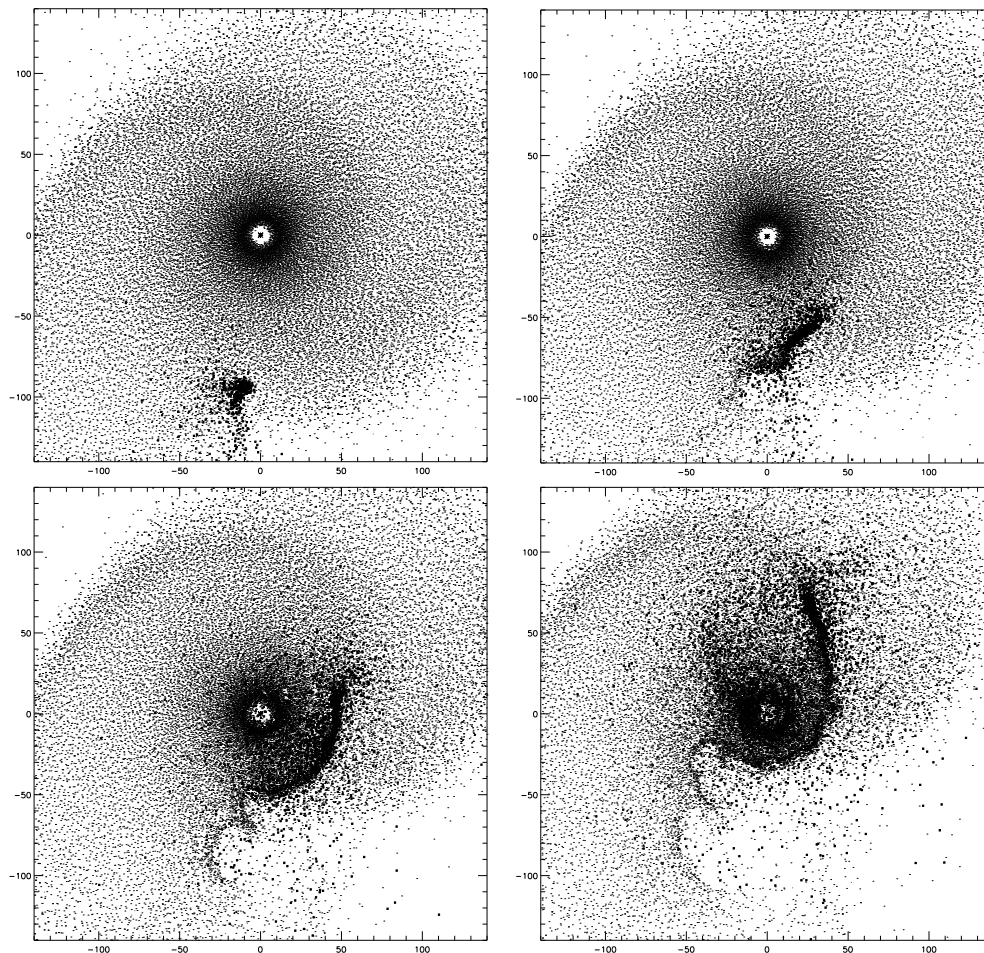


Figure 10. Four frames from an SPH simulation showing the evolution of the shocks produced by the passage of a 1 Solar mass star through a 0.05 Solar mass protoplanetary disk orbiting a 1 Solar mass star. Disk particles orbit clockwise. The intruder is on a counterclockwise trajectory. The axes are labels are in AU. Heavy symbols show the regions where the post-shock temperature exceeds 1400 K (Nickolas Moeckel).

medium with a gas density ρ_g at velocity V is

$$t_{stop} \sim \frac{\rho_s r_s}{\rho_g V}.$$

For $\rho_s = 1 \text{ g cm}^{-3}$, $r_s = 1 \text{ mm}$, $\rho_g = 10^{-10} \text{ g cm}^{-3}$, and $V = 10 \text{ km s}^{-1}$, $t_{stop} \sim 10^4$ seconds.

Harker & Desch (2002) proposed that shocks in a protoplanetary disk can be produced by forming giant protoplanets. Here, we propose that close encounters with sibling stars in the birth cluster provide an alternate source of large-scale shocks which can re-process much of the volume of a protoplanetary disk and flash heat small solids.

Assuming that the Sun formed in a transient cluster which dissipated within a cluster crossing time, the density of sibling stars and therefore the probability

of a close encounter with an other star would decline rapidly on a time-scale of about 10^5 to 10^6 years. Thus, the greatest probability of a close encounter would occur right when the Sun and its disk formed. Meteoric evidence, however, indicates that most chondrules were re-melted several million years after the calcium-aluminum rich inclusions (CAIs) formed.

A number of processes may result in close-stellar encounters several million years after the birth of the Sun and its disk. First, it is easily possible that the Sun was one of the first stars formed in the parent OB association. If so, the proto-Sun and its disk may have fallen into the gravitational potential of the cloud core just as it was starting to form a dense cluster. Stellar encounters with cluster members would have become more probable as additional members of the cluster were born. Second, several million years after its birth, the Sun and its disk may have wandered into the an adjacent sub-group of the parent OB association. Third, it is possible that the Sun formed in a non-hierarchical multiple star system with several other member stars. Such groups are dynamically unstable (e.g. Reipurth 2000). Such systems tend to rearrange into a hierarchical configuration in which two stars become tightly bound into a short-period binary while the least massive member is ejected. Such re-configurations typically occur in about 100 orbital time-scales. Thus, if the Sun formed in a loosely bound system of stars on elliptical 10^4 year or longer orbital periods, the final disintegration of the system may have occurred one or more million years after the birth of the Sun and its disk. Finally, it is possible that the Sun formed in one of the rare clusters which were gravitationally bound at birth - an open cluster. Such clusters can survive for tens of millions of years or longer, but most decay in a billion years, leaving their stars isolated. Thus, shocks created by ~ 50 AU encounters with sibling stars provide a viable alternative to shocks produced in the disk by internal processes.

In summary:

- Dynamical interactions can re-orient the outflow axes of stellar jets to produce the S- and Z-symmetric flows observed in some star forming regions (e.g. HH 200 in L1228 – Bally et al. 1995; IRAS20126 – Shepherd et al. 2000; and RNO 43 – Bence, Richer, & Padman 1996).
- Ejection of low mass stars from clusters or non-hierarchical multiple star systems can explain the C-symmetric bends of stellar jets that face towards the center of mass of a star cluster (e.g. HH 498 and 499 in NGC 1333 – Bally & Reipurth 2001).
- Stellar dynamics may shape the IMF in clusters and limit the masses and sizes of protoplanetary disks.
- Penetrating encounters of sibling stars can generate large-scale shocks in a disk which can heat the gas and melt solids. Such encounters are most likely during the earliest evolutionary times in the life of a cluster. Penetrating encounters are possible in non-hierarchical multiple star systems several hundred dynamical times-scales after formation of the system. In wide-separation multiple star systems, penetrating encounters can occur up to several million years after formation.

6. The Effects of Supernovae

Massive stars die and explode as supernovae on time-scales ranging from about 3 Myr (for the most massive stars) to about 40 Myr (for $\sim 8 M_{\odot}$ stars, which are the least massive to explode as in a supernova explosion). The shortest lived, and most luminous of the massive stars usually go through a brief (few hundred-thousand year) blue-supergiant phase during which their luminosity can be between 10^6 and 10^7 times the luminosity of the Sun. Most of their luminosity emerges in the UV portion of the spectrum. Thus, a few million years following the birth of the most massive stars in a OB association sub-group, they go through a phase of enhanced UV luminosity. The blue-supergiant phases of massive stars can increase the soft-UV induced photo-ablation of surrounding interstellar gas and disks of close-by low-mass stars.

The supernova explosions of massive stars produce a several month-long pulse of UV and visual luminosity, producing a radiation dose which can be a substantial fraction of the total amount of radiation emitted during the entire main-sequence life of the star. Thus, radiation emitted by the post-main-sequence and pre-supernova stages in the evolution of massive stars can produce enhanced rates of photo-ablation of close-by circumstellar disks.

The supernova blast-wave tends not to disrupt surviving portions of circumstellar disks located more than a fraction of a parsec from the explosion. The blast-wave will be rapidly decelerated by interactions with the surrounding ISM, and the amount of mechanical energy delivered to a disk will in general be much less than the gravitational binding energy of a disk to its parent star.

However, atoms, ions, and grains formed in the supernova ejecta, which consist of or contain short-lived radio-isotopes produced in the supernova explosion, can embed themselves in the disk. Thus, SN exploding in the parent OB association may provide a natural source of short-lived species whose decay products are found in abundance in primitive meteorites. SNe may be the only viable source for r-process species such as ^{60}Fe (Hester et al. 2004; Tachibana & Huss 2003).

7. Summary

Studies of star forming regions have shown that most stars form in high density star clusters which are not gravitationally bound by their own mass. Such clusters form from the gravitational fragmentation of dense, turbulent cloud cores in giant molecular clouds (GMCs). Typical GMCs produce OB associations consisting of from several to dozens of individual subgroups and short-lived clusters over the course of about 10 Myr. The combined energy released by protostellar jets, outflows, massive star radiation fields, winds, and supernovae tends to disrupt GMCs by the time 3 to 30% of their mass has been converted into stars. The OB association subgroups and clusters become unbound as the bulk of the gas is dispersed.

The collective effects of UV radiation, stellar winds, and supernovae inflate superbubbles whose shells can become larger than the scale-height of the Galactic gas layer. As these shells sweep-up the densest gas in the Galactic-plane, they decelerate. As the shells and super-rings reach radii of several hundred

parsecs, their swept-up masses grow to more than $10^6 M_{\odot}$. In the Solar vicinity, gravitational instabilities form $10^5 M_{\odot}$ self-gravitating clouds which may evolve into new GMCs. This cycle occurs on a 30 to 60 Myr time-scale. It is probably amplified by the high-pressure spiral arms of the Galaxy, and inhibited in the low-pressure inter-arm regions.

These OB association processes occur on the time-scales of planetary system formation and early evolution. Low-mass stars formed in OB associations and in HII regions are exposed to intense UV radiation fields during their first few million years of existence. In disks undergoing grain-growth and sedimentation, photo-ablation selectively removes gas and small grains, and leaves behind large solids. Thus, UV radiation tends to increase the dust-to-gas ratio in disks, to the point where gravitational instabilities in the disk mid-plane can produce kilometer-sized planetesimals on a time-scale short compared to the orbital decay. Thus, the OB association environments may promote the early phases of planetary system formation.

Disks surrounding stars in dense clusters are subject to close encounters with sibling stars. The spiral density waves and shocks induced by encounters which come within about 50 AU of a Solar mass star can produce the conditions required to melt solids and produce chondrules. However, such encounters are most probable within the first 1 Myr of a star's life. Late phase encounters are possible in some circumstances such as formation of the star in a bound cluster which survives for many crossing times, in a non-hierarchical multiple star system, or in the unlikely event that star wanders into an adjacent sub-group or cluster forming from the same GMC.

The OB association environment is rocked by supernova explosions for about 40 Myr following its formation. Enhanced UV radiation by the pre-supernova stages of massive stars may produce late-phase photo-ablation of disks. As disks are over-run by supernova ejecta, they will be pelted with freshly synthesized species. This may explain the presence of the daughter products of short-lived r-process elements which can only be synthesized in massive stars such as ^{60}Fe .

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