Abstract. Recent analysis of the decay products of short-lived radiounlides (SLRs) in meteorites, in particular the confirmation of the presence of live $^{60}$Fe in the early Solar System, provides unambiguous evidence that the Sun and Solar System formed near a massive star. We consider the question of the formation of low-mass stars in the environments of massive stars, presenting a scenario for the evolution of a star and its disk as it is overrun by the ionization front at the edge of an expanding H$\text{\textit{II}}$ region. The stages in this scenario include: (1) compression of molecular gas around the edge of the H$\text{\textit{II}}$ region; (2) induced low-mass star formation in this compressed gas; (3) an “EGG” phase when a dense star-forming clump is overrun by the ionization front; (4) a “proplyd” phase during which the disk is truncated by photoevaporation; (5) a long-lasting phase during which a young star and its truncated disk evolve in the hot, tenuous interior of an H$\text{\textit{II}}$ region; and (6) a phase when the ejecta from one or more nearby supernova explosions overruns the disk, injecting SLRs including $^{26}$Al and $^{60}$Fe. Most of these stages can be observed directly. The exceptions are stage (2), which must be inferred from the localization of low-mass protostars in compressed molecular gas near ionization fronts, and stage (6), which is an unavoidable consequence of the presence of low-mass protostars seen near massive stars that will go supernova within a few million years. (This differs from models in which the same supernova is responsible for both triggering the formation of a star and injecting SLRs.) This mode of star formation may be more characteristic of how most low-mass stars form than is the mode of star formation seen in regions such as the Taurus-Auriga molecular cloud. We discuss the implications of this scenario for our understanding of star formation, including the possible role of photoionization in limiting the masses of stars. We also discuss the implications of the young Sun’s astrophysical environment for our understanding of the formation and evolution of the Solar System. These include the effects of intense UV radiation from nearby massive stars on the structure and chemistry of the disk, dynamical effects due to close encounters of the Solar System with other cluster members, and the role of the decay of SLRs in the evolution of the Solar System. We conclude that low-mass stars and their accompanying disks form and evolve differently near massive stars than they do in regions like Taurus-Auriga, and that these differences have profound implications for our understanding of our origins.

1. Introduction

Two of the great scientific success stories of the last several decades are our growing understanding of the way stars form, and our ability to reconstruct the history of our own Solar System. These two lines of scientific investigation meet in the Sun’s protoplanetary disk. To date we have only begun the task of
carefully merging theories of star formation with theories of the early evolution of the Solar System. That task is one of the central challenges for both fields in the years to come. Given the extraordinary amount of information and ideas that have emerged from those investigations, we should not be surprised if our theories of both Solar System formation and evolution and our theories of the formation of low-mass, Sun-like stars will each need to be modified on the basis of insights gained from the other.

Figure 1. (a) Hubble Space Telescope images of four young stellar objects and their surrounding disks located in the Taurus-Auriga molecular cloud (Padgett et al. 1999). (b) Hubble Space Telescope images of four young stellar objects (proplyds) with photoevaporating disks, located in the interior of the Orion Nebula H II region (Bally, O’Dell, & McCaughrean 2000).

Low-mass stars form in a variety of different environments. Figure 1a shows HST images of a number of young stellar objects forming in relative isolation from each other in the nearby Taurus-Auriga molecular cloud. These protostars sit in the centers of large dusty disks buried in the cold dark molecular cloud. In contrast, Figure 1b shows HST images of a number of young stars and protoplanetary disks sitting in the hot, ionized interior of the Orion Nebula. This region has formed a rich cluster of stars with a number of luminous high-mass stars at its center. The disks here are being photoevaporated by intense ultraviolet radiation from those nearby massive stars. It takes little more than a glance comparing Figures 1a and 1b to realize that the conditions under which stars form and disks evolve can be radically different, depending on their astrophysical setting.

Meteorites play a crucial role in efforts to understand the history of the Sun and Solar System. Meteorites provide detailed information about the chemical, physical, and thermodynamic properties at different locations within the disk, as well as adding constraints on the time scales and physical processes by which objects in the Solar System formed. In particular, the presence of the decay products of short-lived radionuclides (SLRs) in meteorites offers hope of establishing the type of astrophysical environment in which the Sun and Solar System formed. These radionuclides, such as $^{26}$Al, have half-lives of only a few million
years or less. While most of the chemical elements in the Solar System more massive than hydrogen and helium were synthesized in stars that lived and died over the course of the 9 billion years that transpired before the Sun formed, SLRs have such short lifetimes that they must have instead originated more locally, close to the time of the Sun’s birth. SLRs might have been formed by spallation reactions in the Sun’s protoplanetary disk due to cosmic rays from solar flares, or they might have been synthesized in nearby stars and then injected into the formation environment of the Sun by supernovae or other means. Establishing which origin is correct provides the key needed to place the birth of the Sun and Solar System in its proper astrophysical context.

In this paper we propose an answer to that question. The presence of live $^{60}\text{Fe}$ in the early Solar System can only be understood if the Sun formed in close proximity to a massive star that went supernova. Building on our earlier work (e.g., Hester et al. 1996, 2004) we consider the process of low-mass star formation in the environment around massive stars, and present a scenario for the evolution of young stars and their disks in regions of massive star formation. We also consider some of the implications of the nearby presence of massive stars on the way in which the Solar System evolved. Our hope is to formulate this discussion in a way that will help bridge the gap between the star formation and the meteoritic communities, emphasizing to each that they cannot answer the fundamental questions in their own discipline without first appreciating the perspectives of the other.

2. Environments for Low-Mass Star Formation

Studies of low-mass star formation have traditionally focused on regions such as the Taurus-Auriga molecular cloud, where low-mass Sun-like stars form in relative isolation from each other. There are good reasons for this. Located at a distance of only 140 pc, corresponding to a spatial scale of 140 AU/arcsecond, Taurus-Auriga offers our best opportunity to examine the low-mass star forming environment up close. Formation of low-mass stars in isolation is also a good place to start from a theoretical standpoint (e.g., Shu, Adams, & Lizano 1987), providing the context for various ideas such as “X-winds” (Shu et al. 2001). The convenience of Taurus-Auriga does not, however, guarantee that the mode of star formation seen there is characteristic of the way in which most low-mass stars form, or that our Sun formed in such an environment.

2.1. Most Sun-like Stars Form Near Massive Stars

Several lines of evidence suggest that the majority of low-mass Sun-like stars form in rich clusters and in relatively close proximity to massive stars. The mass spectrum of molecular clouds is $dN/dM \propto M^{-\alpha}$, where measured values of $\alpha$ typically range from 1.6 to 1.8 (e.g., Elmegreen & Falgarone 1996). This distribution is weighted toward the most massive molecular clouds, which tend to form rich clusters containing massive stars. The initial mass function (IMF – the fraction of stars formed as a function of stellar mass) of stars in Taurus-Auriga is also known to be peculiar in several ways (e.g., Goodwin, Whitworth, & Ward-Thompson 2004). The IMF in Taurus peaks at a higher mass ($\sim 0.8 \, M_\odot$) than is common in the field, but is deficient in stars with masses greater than about 1 $M_\odot$. Taurus-
Auriga also produces few brown dwarfs. Similarly, Taurus-Auriga produces significantly more binary stars than are seen elsewhere. Generally speaking, field stars more closely resemble populations that formed in rich clusters than the population forming in Taurus.

The most direct way to address the question of where the majority of low-mass stars form is to take an inventory of star formation in the local neighborhood. In their recent review, Lada & Lada (2003) present a survey of star formation out to a distance of 2 kpc. They conclude that 70-90% of the young stars in the vicinity of the Sun formed in rich embedded clusters. Of the stars in embedded clusters surveyed by Lada & Lada, ~75% are in clusters that currently contain massive stars, where “massive stars” refers to stars with masses in excess of 8 M$_\odot$ that will end their lives in supernova explosions. Other clusters may have contained massive stars in the past.

On balance, we suggest that rich clusters containing massive stars may be a more common environment for low-mass star formation than are regions of isolated low-mass star formation such as Taurus-Auriga. This conclusion differs from some previous analyses of this question. For example, Adams & Myers (2001) reached the opposite conclusion that more isolated, smaller groups dominate low-mass star formation. Lada & Lada (2003) address this difference in the two studies directly. They point out that Adams & Myers underestimate the cluster birth rate in the Galaxy by almost an order of magnitude. The difficulty in the Adams & Myers calculation is that they fail to count clusters that disperse quickly. Lada & Lada find that less than 10% of clusters survive to an age of 10$^7$ years, and that less than 4% of clusters survive to an age of 10$^8$ years. Clusters are typically short-lived because when massive stars disperse much of the gas in an originally bound molecular cloud, the remains are typically unbound (see Reipurth, this volume, and Bally, Moeckel, & Throop, this volume). Most clusters therefore are not included in the catalog of classical open clusters (Battinelli & Capuzzo-Dolcetta 1991) that Adams & Myers (2001) use to estimate the cluster birth rate. Quoting from Lada & Lada (2003), “[This difference] represents an enormous discrepancy and is of fundamental significance for our understanding of cluster formation and evolution.”

2.2. The Sun Formed Near a Massive Star

Most stars may form in rich clusters near massive stars, but that does not necessarily mean that the Sun formed in such an environment. Adams & Laughlin (2001) address the specific question of the likely size of the cluster in which the Sun originated, concluding that the probability that the Sun formed in a rich cluster is ~ 0.85%. The Adams & Laughlin analysis, however, is subject to the same criticism as the analysis of Adams & Myers (2001), in that both use the same underestimate of the birth rate of clusters. Adams & Laughlin also argue against formation of the Sun in a cluster environment based on the likelihood that the Solar System would have been disrupted by close encounters with other cluster members. In making this assessment, however, Adams & Laughlin (2001) assume that clusters live for 100 times the dynamical time scale of the cluster, or ~ 10$^8$ – 10$^9$ years. This assumption leads to a substantial overestimate of the probability of disruption if, as found by Lada & Lada (2003), few clusters survive even to ages of 10$^7$ or 10$^8$ years. Potential disruption of our
planetary system does not appear to place a strong constraint on whether the Sun formed in a rich cluster.

The strongest evidence that the Sun formed near a massive star comes from analysis of the decay products of SLRs in meteorites. Studies of SLRs in meteorites date back to the discovery of evidence that live $^{26}$Al was present in the young Solar System (Lee, Papanastassiou, & Wasserburg 1976). A variety of ideas have been put forward for the origin of SLRs in meteorites. These include the idea, going back to Cameron & Truran (1977), that formation of the Sun might have been triggered by a nearby supernova which also mixed newly synthesized isotopes into the material from which the Sun formed. This idea has recently been considered in detail by Goswami & Vanhala (2000).

Another common model for the origin of SLRs in meteorites is in situ production in the young Solar System by spallation reactions involving Solar cosmic rays (Hevmann & Dziczkaniec 1976; Clayton, Dwek, & Woosley 1977; Dwek 1978; Lee 1978). In particular, Shu and collaborators develop this idea within the context of their X-wind model for low-mass star formation (Gounelle et al. 2001). A spallation model for the formation of SLRs has two distinct advantages. First, it depends on no outside source for these radioisotopes, which is a necessary condition if the Sun formed in a region of isolated low-mass star formation similar to Taurus-Auriga. Second, a spallation model can account for the presence of live $^{10}$Be in the early Solar System (McKeegan, Chaussidon, & Robert 2000). This isotope cannot be produced by supernova nucleosynthesis, but is produced in abundance by spallation. This has been called a “smoking gun” favoring an X-wind origin for SLRs (Gounelle et al. 2001).

The strength of arguments favoring spallation as the source of SLRs changed dramatically when Tachibana & Huss (2003) reported the confirmation of live $^{60}$Fe in the early Solar System. $^{60}$Fe, which has a half-life of 1.5 Myr, is a neutron-rich isotope that is not formed in abundance by spallation reactions (Lee et al. 1998), but is formed in core collapse supernovae. The presence of this neutron-rich isotope is compelling evidence for an interstellar origin for at least some SLRs. Other SLRs that are difficult to produce by spallation include $^{182}$Hf and $^{107}$Pd. Meteoritic evidence of gas-phase $^{36}$Cl ($t_{1/2} = 0.3$ Myr) in the outer parts of the young Solar System has also been interpreted as presenting a serious challenge to local irradiation models of SLRs (Lin et al. 2005).

Various ideas have been put forward as possible interstellar sources for $^{60}$Fe and other SLRs. Busso, Gallino, & Wasserburg (2003), for example, suggest that an Asymptotic Giant Branch (AGB) star may have been the source. AGB stars, however, are old objects and are not observed to be correlated with sites of low-mass star formation. Even using very optimistic assumptions, Kastner & Myers (1994) compute a probability of $< 3 \times 10^{-6}$ that the material from which the Sun formed had recently been contaminated by mass loss from an AGB star. Similar statistics should apply to most other sources involving long-lived objects in the late stages of their evolution (e.g., novae or Type Ia supernovae).

In contrast to AGB stars, formation of massive stars is correlated both spatially and temporally with the formation of low-mass stars. Massive stars typically have lifetimes of $\sim 3$–30 million years. For realistic IMFs, Shull & Saken (1993) find that the rate of supernovae in a cluster will be roughly constant over
the 30 million years between the first explosion and the time that the 8 $M_\odot$ stars die. Low-mass star formation in surrounding regions is common throughout the lives of massive stars, so many low-mass stars will experience a nearby supernova within a few million years of their formation. Even in a relatively meager cluster containing only 5 massive stars, the median time between formation of a low-mass star and a local supernova is only about 3 million years. In the richer Scorpius-Centaurus OB association, 95% of the low-mass stars formed within the last 8 to 12 Myr (Preibisch & Zinnecker 1999; Mamajek, Meyer, & Liebert 2002). During that time there have been $\sim$ 20 supernovae in the association (Maíz-Appellániz 2001), or roughly one every 500,000 years.

Supernova models are capable of producing most of the observed SLRs in reasonable abundance (Meyer & Clayton 2000; Meyer et al. 2003), and it is unavoidable that many young low-mass stars experience nearby supernovae. We conclude that one or more core-collapse supernovae provide by far the most astrophysically plausible source for $^{56}$Fe (and by association most other SLRs) in the young Solar System. The only well-established SLR that a nearby supernova cannot account for is $^{10}$Be. If no other source of $^{10}$Be were known, it might require spallation in an X-wind as a significant source of SLRs in addition to supernovae. An alternative source for $^{10}$Be has been proposed, however. Desch, Connolly, & Srinivasan (2004) found that the amount of $^{10}$Be in the early Solar System can be accounted for quantitatively by direct capture of Galactic cosmic rays by the protosolar cloud, and that this may rule out significant production of $^{10}$Be by spallation. Evidence of $^{10}$Be is found in all meteorites in which it has been sought, while other SLRs are absent in a small fraction of grains, suggesting that indeed $^{10}$Be has a unique origin from other SLRs. With $^{10}$Be due to captured cosmic rays and other SLRs consistent with or requiring a supernova origin, it is unclear that any evidence remains requiring spallation as a source for SLRs in the early Solar System.

We conclude that $^{56}$Fe has replaced $^{10}$Be as a new and unambiguous “smoking gun” that places the Sun’s formation in a rich cluster environment near at least one massive star.

3. Massive Stars Dominate the Structure of Their Environments

The birth of a massive star is a violent event. Massive stars have extremely high luminosities, often in excess of $10^5 L_\odot$. These stars produce intense extreme ultraviolet (EUV) radiation that ionizes a star’s surroundings, and intense far ultraviolet (FUV) radiation that can penetrate into regions of neutral gas. (The volume of ionized gas surrounding a massive star is referred to as an “H II region,” because the principal constituent of the region is ionized hydrogen.) When a massive star turns on, a volume of gas around the star is rapidly ionized and heated to $\sim 10^4 K$. The resulting high pressure region then expands into surrounding molecular gas at roughly the speed of sound in the hot gas. This pressure-driven expansion typically continues until the H II region breaks free of the confining molecular cloud, at which point the gas in the interior of the region rapidly vents into the intercloud ISM (e.g., Tenorio-Tagle 1982). The cavity that is left behind in the wall of the molecular cloud is referred to as a “blister H II region” (Zuckerman 1973). Figure 2 shows an image of one such
Figure 2. The structure of a blister H II region. This is a ground-based image of the Eagle Nebula, M16, obtained with the 1.5-m telescope at Palomar Observatory.

region, M16, otherwise known as the Eagle Nebula. The interior of the cavity of a blister H II region is filled with relatively tenuous \((n \lesssim 100 \, \text{cm}^{-3})\), hot \((T \sim 10^4 \, \text{K})\), ionized gas. This gas typically presents very little opacity to the UV radiation from the massive stars. Of the ionizing radiation that does not escape the cavity altogether, most reaches the wall of the cavity where it is absorbed in a very thin zone called an ionization front. Gas at the ionization front has yet to expand much, so has a density like that of the molecular cloud, but has a temperature like that of the interior of the H II region. The resulting high pressure drives a photoevaporative flow of photoionized material away from the surface of the molecular cloud into the H II region interior. At the same time, the pressure at the ionization front drives a shock into the surrounding molecular cloud, compressing that gas and driving up the pressure (e.g., Kahn 1958). The ionization front and its shock typically move into the molecular cloud.
at velocities of order a few km/sec. Ionization fronts are apparent in Figure 2 as the bright rims seen at the edge of the H\textsc{ii} region.

Shocks driven in advance of ionization fronts compress dense molecular gas surrounding H\textsc{ii} regions. Regions in Figure 2 that have been compressed by such shocks include several prominent columns, as well as the dense layer of material seen immediately beyond the ionization fronts around much of the periphery of the nebula. Massive stars are also the source of powerful winds, and at the ends of their lives undergo supernova explosions that inject significant energy and momentum in addition to newly synthesized nuclei into their surroundings. Winds and supernovae contribute additional momentum and energy into their environment, adding to the compression of nearby dense molecular gas. Once a single massive star forms, the combined energy and momentum input from that star quickly reshapes its environment, dominating all that goes on in its surroundings, including the process of low-mass star formation. Low-mass star formation around massive stars cannot be assumed to be the mode of star formation seen in Taurus-Auriga, only writ large. As illustrated in Figure 1, YSOs in H\textsc{ii} region environments demonstrably are not “just like” YSOs in Taurus-Auriga.

4. An Evolutionary Scenario for Low-mass Stars in H\textsc{ii} Regions

Stars form in dense cores buried in the interiors of molecular clouds. Stars do not form in the hot, tenuous interiors of H\textsc{ii} regions. The young stellar objects seen in the interiors of H\textsc{ii} regions, such as the young stars, protostars, and “proplyds” seen in the Orion Nebula, did not form in the environments in which they reside today. Rather, these stars necessarily formed in the dense molecular gas that once surrounded the massive stars and were later uncovered by the advancing ionization front. As a young star and its natal environment are overrun by an ionization front and emerge into the interior of an H\textsc{ii} region they go through a well-ordered evolutionary sequence. This evolutionary sequence is illustrated in Figures 3 and 4. Figure 3 shows an HST WFPC2 image of the G353.2+0.9 H\textsc{ii} region in NGC 6357 (Healy et al. 2004) with a strip indicated cutting from the massive stars across the ionization front and into the molecular gas beyond. Figure 4 shows schematically the sequence of events that are experienced by young stellar objects as the ionization front pushes into the molecular cloud. We suggest that this sequence provides the correct astrophysical context for understanding the early evolution of the Solar System.

4.1. Gas is Compressed Around H\textsc{ii} Region Peripheries

In Figure 4 panel 1, radiation from a massive star drives an ionization front and its leading shock into surrounding molecular gas. (Momentum input from winds and supernovae contribute to the momentum input into the cloud as well, but this does not change the basic picture of energy input from a massive star compressing the molecular gas beyond the edge of the H\textsc{ii} region. Nor does it change the basic nature of the ionization front that defines that interface.) Compression around the periphery of H\textsc{ii} regions is observed in many ways. Observations of the molecular gas itself often shows compression just outside the ionization front, together with the kinetic signature of expansion (e.g. White et al. 1999). Observations of photodissociation regions (regions imme-
Figure 3. An HST WFPC2 image of the G353.2+0.9 H II region in NGC 6357. This figure illustrates the astrophysical context for the sequence of events described in Figure 4.

Immediately beyond the ionization front where H$_2$ is dissociated by FUV radiation) show these regions to be at significantly higher pressure and the ambient molecular cloud (Hollenbach & Tielens 1997, and references therein). Observations of magnetic fields around H II regions show that the fields generally line up with the edge of an H II region, which is a clear signature of compression perpendicular to the field (e.g., Gaensler et al. 2001). Compressed molecular gas around H II regions can often also be seen in extinction against the background of the nebula, as described above.

4.2. Star Formation Can be Triggered by Compression

It is reasonable that significant compression of the gas around the periphery of an H II region might play a role in initiating the collapse of clumps and the formation of stars in this region (e.g., Elmegreen & Lada 1977; Bertoldi 1989; Bertoldi & McKee 1990), as shown schematically in Figure 4 panel 2. It is
Hester, J. J., & Desch, S. J.

Figure 4. The proposed sequence of events that characterizes the formation and evolution of low-mass stars around the periphery of H II regions. Each panel represents a section through the nebula, as indicated in Figure 3.

possible that, left to themselves, some of these clumps eventually might have collapsed on their own. These clumps are not left to themselves, however. They are located in gas that will soon be dispersed by the advancing ionization front. Without the added push from the high post-shock pressure, it is likely that these clumps would have been destroyed before collapsing to form stars. The clump mass required for collapse also decreases with increasing pressure. The mass required for the collapse of a virialized sphere, for example, is $\propto P^{-1/2}$, where $P$ is the pressure of the surrounding medium (e.g., Larson 2003). There should therefore be a population of low-mass clumps that would not have collapsed at all were it not for compression in advance of the ionization front.

Numerous authors have argued in favor of triggered star formation around H II regions on the basis of protostars located in gas that has been compressed...
Star Formation in H II Regions

by the expansion of the H II region. For example, Lefloch & Cernicharo (2000) find that star formation around the periphery of M20 is concentrated in cores undergoing radiatively driven implosion, while star formation in W5 lies just beyond the boundaries of the H II region in gas that shows the kinematic signature of ionization shocks (Karr & Martin 2003). Healy, Hester, & Claussen (2004) recently found that water masers in M16, which trace the presence of Class 0 protostars, are concentrated in compressed molecular gas located just beyond ionization fronts. Similarly, Reach et al. (2004) found that protostars in the cometary globule IC 1396 seen in Spitzer IRAC and MIPS 24 μm images are concentrated within 0.02 pc of the ionization front on the leading edge of the globule. Preibisch & Zinnecker (1999) argue that low-mass star formation throughout the Upper Scorpius OB association was triggered. While Dolan & Mathieu (2001) stop short of claiming that star formation is triggered, the sequence of ages and properties of stellar populations they report in their study of λ Orionis is in very good agreement with what one would expect if star formation throughout the region was triggered by the expansion of the H II region. The list of specific regions in which various authors have argued for triggering of low-mass star formation by massive stars could go on at length. This issue is discussed further below in Section 5.1.

In this paper we stress the role of massive stars in triggering low-mass star formation, as is appropriate to the focus of this volume. However, energy input from massive stars plays a key role in triggering the formation of additional massive stars as well (e.g., Blaauw 1991). Oey et al. (2003), for example, find that two subsequent generations of massive stars in W3/W4 were triggered by an original generation. Each of these generations of massive stars in turn gave rise to large populations of triggered low-mass star formation.

4.3. Emerging Clumps are Seen as EGGs

The next stage in the evolution of a young star’s environment comes when the ionization front overruns a clump and the young star within, as illustrated in Figure 4, panel 3. The ionization front typically moves into the cloud at ~1-2 km/sec, while the typical separation between the shock and the ionization front is ~0.1 pc, so the ionization front will overtake young stars and dense clumps within ~10^5 years after passage of the shock. As the ionization front sweeps past a dense clump and the young star within (if one has formed), the evaporating clump appears as a small protrusion extending from the molecular cloud into the interior of the H II region. The clump may even become detached altogether from the wall of the molecular cloud. This is the “EGG” or “evaporating gaseous globule” phase of evolution of the object. The EGG phase of evolution was first seen in HST WFPC2 images of M16 (Hester et al. 1996). Several EGGs in this field have visible stars at their tips. Figure 5 shows that image together with enlargements of a number of EGGs that are known to have associated stars. Also included are HST NICMOS near infrared images of young stellar objects at the heads of Columns 1 and 2 (Thompson, Smith, & Hester 2002).

In the previous section we argue that concentration of young stars in gas that has been compressed by passage of the ionization front is evidence of triggering of star formation by an expanding H II region. The ~10^5 years between passage of the shock and passage of the ionization front is compa-
rable to the timescale over which low-mass stars accrete their mass. This means that arrival of the ionization front and photoevaporation of a protostar’s surroundings may cut the protostar off from its accretion reservoir prematurely, and may be an important factor in limiting the final mass of the star. This idea was discussed in the context of HST images of M16 (Hester et al. 1996), and was later proposed independently in the context of the Orion Nebula (Robberto et al. 2004). Among the predictions made on the basis of this idea is that the number of brown dwarfs would be found to be higher in regions of massive star formation than in regions of isolated star formation (Hester 1997; Whitworth & Zinnecker 2004). Observations subsequently confirmed this prediction (e.g., Goodwin, Whitworth, & Ward-Thompson 2004). Limiting the masses of protostars by photoevaporation of accretion reservoirs might also push

Figure 5. HST WFPC2 image of the three central columns in M16 (Hester et al. 1996), along with enlargements of several EGGs and HST NICMOS images of two prominent YSOs (Thompson, Smith, & Hester 2002).
the peak of the IMF toward lower mass, which is qualitatively in the right direction to explain the observed differences between the IMF in Taurus and the IMF in field stars and in rich clusters.

Observations of accreting protostars that are about to be over run by ionization fronts support a role for photoevaporation in limiting the masses of stars. Examples include the Class 0 protostars associated with water masers discussed by Healy, Hester, & Claussen (2004), and the very young YSOs in IC 1396 observed by Reach et al. (2004). In each case, very young objects likely to still be experiencing infall are seen in regions that will be overrun by ionization fronts within a few $\times 10^4$ years. The statistics of EGGs are consistent with truncation of infall by photoevaporation as well. If all or almost all EGGs contained visible stars, it might indicate that the ionization front was uncovering a region in which star formation was a fait accompli. McCaughrean & Andersen (2002) find instead that $\sim 15\%$ of EGGs in M16 contain young stars that can be seen at 2 $\mu$m from the ground, as might be expected if the ionization front is overrunning a region in which star formation is still ongoing.

4.4. Photoevaporating Disks are Seen as Proplyds

An EGG is photoevaporated within $\sim 10^4$ years of the passage of the ionization front. If there is a young star inside the EGG, the star and its disk are then exposed to the intense UV radiation from the nearby massive stars, as shown in Figure 4, panel 4. Gas that is photoevaporated from the surface of the disk by FUV radiation is ionized by EUV radiation a short distance above the disk, and pushed back into a characteristic teardrop shape (e.g., Johnstone, Hollenbach, & Bally 1998). The EGG has become a “proplyd.”

The best-known examples of the evaporating disk or proplyd phase of evolution are seen in the Orion Nebula (see Figure 11). Orion provides the best opportunity to see these objects, simply because is the nearest prominent H II region. Proplyds have now been seen in a number of other H II regions, including the Carina Nebula (Smith, Bally, & Morse 2003), and NGC 6357 (Figure 3). Not all proplyds are easily resolved, even with HST, but Hα excesses in stellar spectra can indicate the presence of unresolved photoionized gas associated with evaporating disks. Studies of the properties of young stars in H II region environments (e.g., Dolan & Mathieu 2001; Sugitani, et al. 2002) typically find that young stellar objects with Hα excesses are most common near ionization fronts, while weak line YSOs are located deeper in the interiors of H II regions. This trend is at least in part due to destruction of circumstellar disks.

We propose in our scenario that EGGs and proplyds are two evolutionary phases objects pass through as they are uncovered and left behind by the passage of ionization fronts. If this is the case then we would expect to see objects that are undergoing the transition from EGG to proplyd. HST images show a number of such objects. A good example can be seen in the inset in Figure 6 (Hester et al. 2004). The tip of this finger-like EGG in the Trifid Nebula shows a number of features that are characteristic of proplyds. These include reflection nebulosity from the star at the tip of the EGG, an ionized evaporative flow standing off from the star by $\sim 10^{16}$ cm, and a small stellar jet. The lower part of this object is a classical EGG of the sort seen in M16, but the upper portion of this object has all of the characteristics of an Orion proplyd (Bally, O’Dell, & McCaughrean)
Figure 6. *Hubble Space Telescope* WFPC2 image of a field in the Trifid Nebula ([Hester et al. 2004](#)).

A similar object can be seen in the original *HST* image of M16 as well, where a small [S II] jet protrudes from the region around a visible star sitting at the tip of a long finger-like EGG (bottom inset in Figure 5).

### 4.5. Proplyds Leave Behind Young Stars with Truncated Disks

Proplyds are also short-lived objects. Within $10^4 - 10^5$ years disks are eroded down to a radius of 30 AU or so. Photoevaporation of the rest of the disk takes several million years ([Johnstone, Hollenbach, & Bally 1998](#); [Störzer & Hollenbach 1999](#)). As shown in Figure 4, panel 5, after the outer parts of the disk are evaporated, the protostar and its now-truncated disk are left sitting in the hot, tenuous interior of the H II region, where the disk remains subject to intense ultraviolet radiation.

This is the longest-lived phase in our scenario, and should therefore be the most common stage in which to find young stellar objects in H II region
environments. Observations bear this out. For example, there are around 4,000 young low-mass stars in the volume of the H II region ionized by the Trapezium cluster in Orion \cite{Hillenbrand&Hartmann1998}. Of these, \cite{Hillenbrandetal1998} find that 55–90\% have infrared excesses indicating that they are still surrounded by disks. In contrast, only about 150 objects are seen in Orion in the EGG or proplyd phases \cite{ODell2001}. This is easily understood if truncated disks live for $\gtrsim 20$ times as long as do proplyds, in reasonable agreement with the lifetimes estimated above. These statistics should be viewed with caution because of the different selection criteria used in different studies. Even so, they make the point that as expected, proplyds are relatively rare as compared with low-mass YSOs surrounded by truncated disks.

In our scenario, progress of the ionization front should leave behind small groups of young stars that formed in large cores that were compressed by radiatively driven implosion and then disrupted by photoevaporation. A number of such small groups of stars can be seen in the HST image of the Trifid Nebula in Figure 6. Of particular interest is the group of stars on the left side of the image that surround the tadpole-shaped remains of the molecular column from which the stars formed. There are many indicators of ongoing star formation in the TC2 molecular column in the central part of the image \cite{Leflochetal2002}, including a prominent stellar jet (HH 399) emerging from an unseen young stellar object located near the head of TC2, and a water maser indicating the presence of a young protostar \cite{Healyetal2004}. It seems likely that in $10^5$ years or so TC2 will look much like the tadpole and its surrounding group of young stars on the left edge of the field of view.

Figure 4 panel 5 shows the environment where a Sun-like star and its protoplanetary disk spend most of their youth, immersed in the hot, low-density interior of an H II region, subject to intense ultraviolet radiation and possibly fast winds and other effects due to nearby massive stars. This is where formation of our own Solar System is likely to have begun.

### 4.6. Protoplanetary Disks May Be Overrun by Supernova Ejecta

A final entry in the sequence of events befalling a young low-mass star in an H II region environment is shown in Figure 4 panel 6. Massive stars live short lives, typically $\sim 3 - 30$ million years, then die in supernova explosions. When a supernova goes off in an H II region the ejecta will expand freely through the low-density cavity, sweeping over any low-mass stars and their disks present at that time. When the gaseous ejecta from a supernova hits a protoplanetary disk, a bow shock is established that directs most of the ejecta around the disk. \cite{Chevalier2000} discussed this possibility, and showed that a protoplanetary disk around a young star should survive passage of the supernova ejecta relatively unscathed. Some turbulent mixing may occur as the ejecta sweeps past the disk, and some capture of ejecta by the gravitational potential of the young star is possible. However, even if very little of the gaseous supernova ejecta winds up in the disk, dust in the ejecta will continue to travel on ballistic trajectories, passing through the bow shock then being vaporized as it encounters the much greater column of gas in the disk itself. This “aerogel” model for the injection of short lived radionuclides into protoplanetary disks, illustrated in Figure 7, is discussed by Ouellette, Desch, & Hester (this volume). Dust is known to form
in supernova remnants. Its presence is inferred from infrared emission from supernovae themselves (e.g., Lucy et al. 1989, and subsequent work on SN1987A), and can even be seen directly in absorption against the background of the synchrotron emission in the Crab Nebula (e.g., Pesen & Blair 1990, Sankrit et al. 1998). Many of the SLRs found in meteorites are refractory elements that might be expected to be found in the solid phase in supernova ejecta.

Figure 7. Illustration of the “aerogel” model for injection of SLRs from Ouellette, Desch, & Hester (this volume).

The interaction of supernova ejecta with a low-mass star and protoplanetary disk has not been observed directly, which is not surprising as these are fleeting events. Even so, the occurrence of such events should not be considered controversial. Most low-mass stars seen in H ii regions are found in close proximity to stars that will go supernovae in the relatively near future, with very little intervening material to stand in the way of the expanding ejecta. As Ouellette, Desch, & Hester (this volume) show, this provides a natural way to inject SLRs into the protosolar disk in reasonable abundances to explain the meteorite data.

There are several caveats worth mentioning at this point. The first is that most clusters disperse on time scales that are comparable to the lifetimes of massive stars (Lada & Lada 2003). While we have not addressed the effects of migration of either the high- or low-mass stars quantitatively, this will not change the basic conclusion that many low-mass stars will be close proximity to a supernova explosion within an a few million years of their formation. Proximity to a supernova explosion is an unavoidably common aspect of the evolution of low-mass stars. Even so, there is need for much more detailed work on cluster dynamics and related topics if we are to understand the overall statistics of SLR injection into protoplanetary disks.

A second caveat is that there may be alternative paths by which SLRs can find their way from massive stars into protoplanetary disks in and around H ii regions. Supernova injection of SLR-bearing dust into the molecular cloud is likely when ejecta hits the wall of a cavity. This newly synthesized material could find its way into forming planetary systems located very near to the ionization front. These are much less common, however, than young stars and disks located in the interiors of H ii regions. The Wolf-Rayet phase of massive star evolution is also characterized by significant mass loss, and may provide another source for newly synthesized material if a way can be found to mix that material into
protoplanetary disks. Neither of these issues change the idea underlying our basic scenario for late injection of SLRs, but rather allow for the possibility of additional avenues whereby material from an evolved massive star might find its way into a protoplanetary disk.

5. A Closer Look at Triggered Star Formation

The scenario above outlines the sequence of events that takes place as an ionization front overruns a region of low-mass star formation. For the most part, this sequence of events does not depend on whether low-mass star formation is triggered or not. Any young object that finds itself in the interior of an H II region must have experienced the basic sequence of events illustrated in Figure 4. While perhaps of secondary importance to the meteorite community, however, the question of how low-mass star formation is initiated is of vital importance to astrophysics.

As discussed by Bally, Moeckel, & Throop (this volume) and Reipurth (this volume), there has been much recent progress on the process of star formation in a hierarchy of nested density fluctuations resulting from turbulence in molecular clouds (Vázquez-Semadeni 2004, and references therein). We do not rule out the possibility of hierarchical collapse in turbulent gas that has been compressed around H II regions. Nor do we rule out the possibility that ongoing hierarchical collapse might have shaped the spectrum of clumps that are overrun by ionization fronts and their leading shocks. From our perspective the crucial issue is not the detailed mechanism by which compression triggers star formation around H II regions, but rather the timing of that star formation and the likelihood that forming stars will soon be overrun by an ionization front. The key question, then, is how to assess the relative importance of triggered star formation as opposed to star formation that occurs near to but independently of massive stars, and is subsequently uncovered by the passage of an ionization front.

5.1. Triggering of Star Formation is a Testable Hypothesis

Evidence cited for triggered star formation in specific regions often amounts to finding so many young stars in compressed gas around an H II region that their presence there cannot be attributed to chance. If applied systematically, this same criterion could be used to investigate the extent of triggered low-mass star formation around H II regions as compared with star formation in clouds that collapse in the absence of external triggers. If most low-mass star formation takes place independently of the effects of massive stars, then low-mass star formation should be uncorrelated with compressed gas around H II regions. Instead, rich regions of low-mass star formation should then be seen in the extended regions around H II regions, especially young and compact H II regions, in gas that is unaffected by H II region expansion. In this case, which is illustrated in Figure 4, we also expect to find regions of low-mass star formation that are comparably intense to those found in H II region environments, but in regions that have yet to form any massive stars. Finally, we would expect that the ages of many low-mass stars found in H II regions would be greater than the ages of the massive ionizing stars. Conversely, if most low-mass star formation
in regions around massive stars is triggered, then young stellar objects should be found concentrated in gas that has been compressed by H II region expansion, as illustrated in Figure 9. We would also expect low-mass stars in H II regions to typically have a spread of ages up to the age of the massive stars.

It is clear that some star formation is triggered by massive stars, while other star formation is not. Figures 8 and 9 suggest a means by which the relative contributions of these two modes of star formation might be assessed. A number of new data sets such as the Spitzer GLIMPSE survey of the inner portion of the Galactic plane may allow this test to be carried out for a statistically meaningful number of objects.

5.2. This is Not Classical “Supernova Triggered Star Formation”

The mode of induced star formation discussed here differs from “classical” supernova triggered star formation as understood by either the star formation or meteorite communities. To star formation researchers, supernova triggered star formation
formation refers to the idea that a massive star mostly triggers star formation in its surroundings with the sudden burst of energy of a supernova explosion. While supernovae contribute to the compression of gas around massive stars, they are not necessarily the dominant means by which star formation is induced.

As discussed above, the radiation and winds from a massive star carve a large cavity in the interstellar medium, compressing the surrounding gas into a dense shell. Even when a supernova does occur, the energy released is unlikely to dominate the cumulative effects of radiation and winds. Figure 10 shows what happens when a supernova explodes in a blister H II region. (This is the type of astrophysical environment in which many massive stars are found and in which intense low-mass star formation is seen, so it is the appropriate environment in which to consider the effects of supernovae.) When a blister H II region forms, the high pressure interior breaks out of the molecular cloud and vents into the surrounding lower density ISM, as shown in Figure 10a. When the supernova goes off, the ejecta expands freely through the low density cavity (Figure 10b). This is the phase during which SLRs may be injected into protoplanetary disks (Figure 7). Some of the ejecta leaves the H II region directly, but some hits the wall of the cavity. Where this happens, a reverse shock is driven back into

Figure 9. The evolution of an H II region environment, assuming that most low-mass star formation in the region is triggered by expansion of the H II region. Compare with Figure 8.
the ejecta, thermalizing its kinetic energy (Figure 10b). The sound speed in the gas between the molecular cloud and the reflected shock is comparable to the velocity of the ejecta, or a few thousand km/sec. This high pressure region expands, venting out of the cavity in a time comparable to the sound crossing time for the cavity at the temperature of the shocked ejecta (Figure 10c). For $R_{HI} \sim 5$ pc and $c_s \sim 2000$ km/sec, this corresponds to about 5,000 years.
between the time of the supernova and the time at which the pressure in the interior of the region has dropped significantly. Once the overpressure associated with the supernova has vented, any remaining massive stars will reestablish a photoevaporative flow away from the walls of the cavity, and the region will soon look much like the H II region it was prior to the explosion of the supernova (Figure 10).

In an event like that illustrated in Figure 10 little of the kinetic energy or ejecta mass from the supernova are trapped within an H II region or transferred to the surrounding molecular gas. Many well-studied supernova remnants have been inferred to be such “cavity explosions,” and extended regions of hot gas are observed to be associated with regions of massive star formation. The Eridanus bubble, for example, is filled with hot gas that has vented from star forming regions in Orion. Observations of $\gamma$-ray line emission from $^{26}$Al in the direction of Eridanus offer direct evidence that this bubble contains recently synthesized supernova ejecta (Diehl 2002). Similarly, it has been proposed that the Local Bubble is filled with hot gas originating in the Sco-Cen OB association, and that ejecta from supernovae in Sco-Cen are responsible for $^{26}$Al found in ocean floor sediments on Earth.

Calculations of classical supernova triggered star formation typically assume that the pressure of the thermalized ejecta is confined within a small volume around the site of the supernova, and that this confined high pressure gas has a long time to do work on its surroundings. This assumption leads to a significant overestimate of the amount of compression caused by the supernova. If the explosion takes place within a blister, as described above, the momentum deposited at the wall of the cavity is close to that required to reverse the motion of the ejecta, or $\Delta p_{SN} \sim 2M_{\text{ejecta}}\langle v_{\text{ejecta}} \rangle/4\pi R_{\text{HII}}^2$, where $M_{\text{ejecta}}$ is the mass of the supernova ejecta, $\langle v_{\text{ejecta}} \rangle$ is the average speed of the ejecta, and $R_{\text{HII}}$ is the radius of the H II region. The momentum deposited by the ionization front is given by the pressure at the ionization front times the lifetime of the H II region, or $\Delta p_{IF} \sim 2n_{e,IF}kT_{IF}t_{\text{HII}}$, where $n_{e,IF}$ is the electron density in the ionization front, $T_{IF}$ is the temperature in the ionization front, and $t_{\text{HII}}$ is the lifetime of the H II region. For characteristic values ($n_{e,IF} \sim 5,000$ cm$^{-3}$, $T_{IF} \sim 8000$ K, $M_{\text{ejecta}} \sim 10M_\odot$, and $\langle v_{\text{ejecta}} \rangle \sim 3,000$ km/sec), we find

$$\frac{\Delta p_{IF}}{\Delta p_{SN}} \sim 3.5 \left( \frac{R_{\text{HII}}}{1 \text{ pc}} \right)^2 \left( \frac{t_{\text{HII}}}{1 \text{ Myr}} \right).$$

For very small, short-lived H II regions, a supernova may come to dominate the momentum input due to radiation, but in such regions stellar winds would likely dominate both. On the other hand, for an H II region with a radius of 5 pc around a star with a lifetime of 2 Myr, the momentum deposition in the surrounding molecular material due to radiation will be two orders of magnitude greater than that due to a supernova explosion. While it is true that the injection of momentum from a supernova is very abrupt and will lead to a temporary spike in the pressure, supernovae seem unlikely to be the principle way in which massive stars trigger low-mass star formation in their surroundings.

“Supernova triggered star formation” takes on a more specialized meaning when discussed in the context of meteorites. A possible explanation for the injection of SLRs into the Solar disk, dating back to (Cameron & Truran 1977),
is that a single supernova event both triggered the collapse of the Sun and injected SLRs into the material from which the Sun formed. We stress that our proposal is fundamentally different from this picture. While models of this process suggest a single supernova could both trigger collapse and seed a clump (e.g., Vanhala & Boss 2000), the astrophysical setting required (a slow shock with all of the supernova ejecta trailing it) is unlikely to be as common as the astrophysical setting in which supernova ejecta directly impacts protoplanetary disks in H II region interiors.

6. Implications of the Birth Environment of the Sun

Most low-mass stars form near massive stars. Analysis of SLRs in meteorites shows that the only habitable system of which we know – ours – was among them. Star formation in these environments is demonstrably not just a scaled-up version of the same processes seen in nearby regions of isolated low-mass star formation. Our hope is that by providing a specific testable scenario for low-mass star formation around massive stars, that we might encourage redirection of some of the research effort that has for so long been focussed on regions like Taurus-Auriga. At the same time, we hope to encourage the meteorite and planetary science communities to consider the ways in which nearby massive stars might have affected the young Solar System.

Studies of low-mass star formation in H II regions hold the promise of new insights into a number of fundamental astrophysical questions including, for example, the origin of the IMF. These insights may apply on the much larger scales of the giant H II regions that dominate star formation in many other galaxies. Scowen et al (1998), for example, found that the physical conditions (radiation field, pressure, temperature, ionization stratification, and morphology) at ionization boundaries in 30 Doradus are quite similar to those found in smaller, nearby H II regions. It is reasonable to assume that the same processes forming low-mass stars in our neighborhood are at work in regions such as 30 Doradus as well.

The question of low-mass star formation near massive stars is of even greater importance to the planetary science community. EUV and FUV radiation from nearby massive stars incident on the Sun’s protoplanetary disk is likely to dominate that from the Sun itself. This radiation may have played an important role in the chemistry of the disk. For example, UV radiation may have been a driver of the complex chemistry required to explain the properties of organic compounds in carbonaceous chondrites (Bernstein et al 1993). Massive stars would also provide a convenient source of the FUV radiation that Young & Lyons (2003) invoke to account for observed anomalies in the relative abundances of $^{16}$O, $^{17}$O, and $^{18}$O (Clayton 2003).

Turning to the overall structure of the Solar System, truncation of the Sun’s protoplanetary disk to a size of a few tens of AU provides a natural explanation for the observed 50 AU outer edge of the Kuiper Belt (Chiang & Brown 1993). This has also been invoked as a potential explanation for the relatively low masses of Uranus and Neptune (Shu, Johnstone, & Hollenbach 1993). Short disk lifetimes near massive stars may provide support for unstable collapse rather than core accretion as the origin for giant planets (e.g., Boss 2001).
Dynamical effects of a cluster environment on the young Solar System might also have been important. The orbit of Sedna, for example, is most easily understood if it was disturbed by an encounter with another cluster member (Brown, Trujillo, & Rabinowitz 2004).

Finally we return to the question of SLRs, which provide the strongest single line of evidence linking formation of the Sun and Solar System to the environment around a massive star. While most Calcium-Aluminum-rich Inclusions (CAIs) require a fairly uniform abundance of $^{26}\text{Al}/^{27}\text{Al}$ of $\sim 5 \times 10^{-5}$ (MacPherson, Davis, & Zinner 1995) at the time they formed, others (the so-called “FUN inclusions,” for “Fractionated Unusual Nuclear effects”) contain no $^{26}\text{Al}$. FUN inclusions appear to be among the most primitive of the CAIs. The data are easiest to understand if there were a single injection of freshly synthesized material after the disk had formed, during the few $\times 10^5$ year period over which CAIs were produced (Sahijpal & Goswami 1998). Such events are a natural consequence of our scenario. But SLRs are more than just tracers of the astrophysical environment in which the Sun formed. Decay of $^{26}\text{Al}$ was an important source of energy responsible for differentiation of planetesimals (Grimm & McSween 1993), which in turn are believed to be the source of much of Earth’s water (Morbidelli et al. 2000). The habitability of Earth may be directly tied to the larger interstellar environment in which the Sun formed, and in particular to its location in proximity to a massive star at the time it went supernova.

It is clear that the astrophysical, meteoritic, and planetary science communities have a great deal to learn from each other. Like the proverb of the Blind Men and the Elephant, we will not have a complete picture of the formation and evolution of our Sun and Solar System until we have more completely integrated the insights from all three fields. While we are fortunate to have a region of low-mass star formation like Taurus-Auriga so close at hand, it is important to keep in mind another proverb about a man who chose to look for his keys under a street lamp because the light there was better. In the introduction to their paper on modes of star formation, Adams & Myers (2001) note that, “If most star formation takes place within sufficiently dense environments, then the current theory of star formation could require substantial modification, or perhaps even a new paradigm.” It is time for each of our communities to face more directly the implications of that prescient statement.

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