ON THE LIKELIHOOD OF SUPERNova ENRICHMENT OF PROTOPLANETARY DISks

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ABSTRACT

We estimate the likelihood of direct injection of supernova ejecta into protoplanetary disks using a model in which the number of stars with disks decreases linearly with time, and clusters expand linearly with time such that their surface density is independent of stellar number. The similarity of disk dissipation and main-sequence lifetimes implies that the typical supernova progenitor is very massive, ~75–100 M⊙. Such massive stars are found only in clusters with ≳10⁴ members. Moreover, there is only a small region around a supernova within which disks can survive the blast yet be enriched to the level observed in the solar system. These two factors limit the overall likelihood of supernova enrichment of a protoplanetary disk to ≤1%. If the presence of short-lived radionucleides in meteorites is to be explained in this way, however, the solar system most likely formed in one of the largest clusters in the Galaxy, more than 2 orders of magnitude greater than Orion, where multiple supernovae impacted many disks in a short period of time.

Subject headings: planetary systems: formation — planetary systems: protoplanetary disks — stars: formation

1. INTRODUCTION

Meteoritic evidence for live ⁶⁰Fe, a short-lived radionuclide (SLR), in the early solar system strongly suggests that a supernova occurred shortly before the formation of the planets (Tachibana et al. 2006). Thirty years ago, and in the context of another SLR, ³⁶Al, Cameron & Truran (1977) proposed that supernova ejecta may be incorporated into planetesimals via the triggered collapse of the presolar nebula. More recently, Hester & Desch (2005) have suggested that SLRs are directly injected into newly formed protoplanetary disks.

The evolution of young stellar clusters and circumstellar disks has been well studied (Lada & Lada 2003; Haisch et al. 2001). This allows us to quantify the likelihood that a supernova will occur close enough in time and space to a planet-forming disk to provide the inferred abundances of SLRs in the solar system. In this Letter, we address two questions: what is the likelihood of SLR enrichment of a disk by a supernova, and what cluster properties maximize this likelihood?

We summarize the relevant information on cluster and disk properties that we use in our model in § 2. We find an analytic solution for the enrichment likelihood in a cluster in § 3.1 under the simplest assumption of a starburst, generalize to a finite formation period with a Monte Carlo simulation in § 3.2, and consider the effect of multiple supernovae in § 4. We calculate the overall enrichment probability and determine the cluster size that maximizes disk enrichment in § 5.

2. PARAMETERS OF THE PROBLEM

2.1. Cluster Number Distribution

We adopt a cluster number distribution, dNc/dNc ∝ Nc−1, that is consistent with both young, embedded clusters ≲3 Myr (Lada & Lada 2003), and older, optically visible open clusters (Elmegreen & Efremov 1997). The minimum cluster size is largely a matter of semantics for our calculations since small clusters are exceedingly unlikely to have supernovae within the maximum disk lifetime. The maximum cluster size, determined from the radio measurements of the ionizing luminosity of H ii regions, is Nc,max = 5 × 10⁵ (McKee & Williams 1997).

There are proportionally more chances to find a star in a larger group, so the differential probability that a star is found within a cluster with Nc members, dP/dNc ∝ 1/Nc. We plot probabilities as a function of the logarithm of the cluster size and define P0,d = dP/d ln Nc, ∆ ln Nc = Pd, ∆ ln Nc. The constant, P0, is determined by the condition that the integral of P0 over all clusters be equal to the total probability that a star is born in a cluster. Lada & Lada (2003) estimate that between 70% and 90% of all stars form in clusters and that 90% of these form in clusters with Nc ≥ Nc,min = 100. Taking an average of 80% for the former gives P0 = 0.8 × 0.9/ ln (Nc,max/Nc,min) = 0.085.

2.2. Cluster Expansion

Lada & Lada (2003) show that the number of detectable clusters declines with age and estimate that only about 10% of clusters survive as recognizable entities beyond 10 Myr. The spatial dispersion of nearby moving groups such as the TW Hya and β Pic associations show how quickly stars migrate away from their siblings. For the greater Scorpius-Centaurus region, with a spatial scale of 200 pc and age ~30 Myr (Zuckerman & Song 2004), the implied expansion speed is ~3 km s⁻¹.

All clusters at a given age, regardless of stellar number, have a similar average stellar surface density, Σ∗ = Nc/πr², where r is the cluster radius (Adams et al. 2006). For the list of small clusters, Nc ∼ 30–1000, in Lada & Lada (2003) the average surface density is Σ∗ = 100 stars pc⁻² at an average age t ∼ 3 Myr. The clusters in Carpenter (2000) defined from Two Micron All Sky Survey data have lower surface densities, Σ∗ = 30 stars pc⁻². For massive star-forming regions, McKee & Tan (2003) find a much higher characteristic surface density, 1 g cm⁻², corresponding to Σ∗ ∼ 10⁴ stars pc⁻² but in much younger objects, t ≪ 1 Myr. We assume a constant expansion speed such that r = exp t and Σ ∝ r⁻², so the equivalent stellar surface density at 3 Myr is at least 1, and possibly as many as 2, orders of magnitude less. To bracket the possibilities, we consider the values Σ₃ Myr = 30, 100, and 300 stars pc⁻².

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2.3. Stellar Mass Function

The stellar initial mass function (IMF) appears remarkably uniform over a range of cluster sizes (Kroupa 2001). We use the Scalo mass function for which the number of stars with masses $M > 8 M_\odot$ that will become core-collapse supernovae are a fraction $f_{SN} = 3 \times 10^{-3}$ of all stars and follow a power-law distribution, $dN_{\star} dM_{\star} \propto M_{\star}^{-\alpha}$, with index $\alpha = 1.5$ (Scalo 1986). The cumulative distribution of supernova progenitors in a cluster containing $N_\star$ stars is therefore

$$N_\star(>M_\star) = f_{SN} N_\star \left( \frac{M_\star / M_{\odot}}{M_{\odot}/M_{\odot}} \right)^{-\alpha - 1},$$

where the lower and upper limits of the progenitor distribution are taken to be $M_1 = 8 M_\odot \leq M_\star \leq M_\star = 150 M_\odot$. The existence of an upper limit is clear, although its actual value can only be statistically estimated (Figer 2005).

2.4. Disk Lifetimes and Supernova Timescales

Mid-infrared surveys of stellar clusters, for which an average age can be determined, show that the fraction of stars with disks, $f_d$, is observed to decrease from unity at $<1$ Myr to zero at $t_d = 6$ Myr (Haisch et al. 2001). The decrease in disk fraction to zero is approximately linear with time,

$$f_d(t) = \left\{ \begin{array}{ll} 1 - \alpha t / t_d, & t \leq t_d, \\ 0, & t > t_d. \end{array} \right.$$

UV radiation from O stars can rapidly photoevaporate the outer radii of protoplanetary disks (e.g., Störzer & Hollenbach 1999), but sufficient mass to form planetary systems may remain bound to the star (Williams et al. 2005; Eisner & Carpenter 2006). Several of the clusters in the Haisch et al. survey and other similar studies (e.g., Mamajek et al. 2004) contain O stars, and the average disk fraction does not appear to be adversely affected, at least for luminosities comparable to Orion. Note also that whatever the star formation scenario, whether instantaneous, gradual, or induced, it is effectively incorporated into this empirical formalism.

For supernova timescales, we use an empirical fit to the Schaller et al. (1992) stellar evolution models, $\log t_{SN} = 1.4/(\log M_{SN})^{1.5}$, where $t_{SN}$ is in megayears and $M_{SN}$ is in solar masses.

If all stars in a cluster are coeval, the similarity of circumstellar disks and massive star lifetimes implies that no more than about half the disks remain when the first supernova occurs, even for the most massive progenitors. The least massive star that could explode within 6 Myr is $M_{\odot} = 30 M_\odot$ and is only likely to be found in clusters with $N_\star \geq 2600$. If clusters are formed more gradually, some disks may exist at later times and slightly lower mass progenitors may play a role (§ 3.2).

2.5. Proximity to Supernova Blast

Disk enrichment places tight constraints on spatial scales too. A minimum mass solar nebula disk with radius 100 AU around a solar mass star will be stripped by supernova ejecta within 0.2 pc (Chevalier 2000). Matching the abundances of the ejecta with the meteoritic record, however, requires that disks lie within $0.22 \text{ pc}$ for a $25 M_\odot$ progenitor (Looney et al. 2006) and $0.3 \text{ pc}$ for a $40 M_\odot$ progenitor (Ouellette et al. 2005). We find that even larger masses are more likely sources of enrichment due to their shorter main-sequence lifetimes. These can enrich a larger volume, out to $\sim 0.4 \text{ pc}$ for a $100 M_\odot$ progenitor. We therefore consider a radial range, $r_p < r < r_p + r_c$, where $r_p = r_c = 0.2 \text{ pc}$ within which disks can survive the supernova and be enriched to the level observed in the solar system. The number of stars in this "enrichment zone" depends on the cluster density profile and size.

Observations of Orion (Hillenbrand & Hartmann 1998) and other clusters (e.g., Muench et al. 2003) show that the number of stars per unit area declines approximately inversely with angular distance from the center (albeit with some significant substructure in some cases). The inferred stellar volume density profiles are therefore approximately inverse square, $n_\star \propto 1/r^2$, and the number of stars increases linearly with radius, $N_\star(<r) = n_\star(r/r_\star)$, where $r_\star$ is the cluster radius. The most massive stars in a cluster are generally found near its center (Lada & Lada 2003). Assuming that this is the case for the supernova progenitor, the fraction of stars in the enrichment zone is

$$f_e(t) = \frac{N_\star(<r + r_p) - N_\star(<r_p)}{N_\star} = \frac{r_p}{r}. \quad (3)$$

The stellar motions in a cluster have characteristic value, $v_{\text{exp}} = r_p/t = (N_\star/\pi^2 \Sigma_{1\text{Myr}})^{1/2}$. For example, a typical cluster in Lada & Lada (2003) with $N_\star = 10^4$, $\Sigma_{1\text{Myr}} = 100 \text{ pc}^{-2}$, has $v_{\text{exp}} = 0.6 \text{ km s}^{-1}$, but the velocities are higher in larger clusters with similar surface densities. To estimate the fraction of stars within the enrichment zone, we assume that the cluster maintains its inverse square density profile and, when considering the effect of multiple supernovae (§ 4), that stars move independently through this zone.

3. CALCULATION OF THE ENRICHMENT LIKELIHOOD

3.1. Cluster Formation in a Starburst

Under the assumption that all the stars in a cluster form at the same time, i.e., in a starburst, the first supernova will be the most massive star and the enrichment likelihood can be calculated analytically.

The conditional probability that the most massive star in a cluster has mass $M_{\text{SN}}$ is the expected number of stars of this mass times the probability that there are none more massive (see Williams & McKee 1997).

$$P_{\text{SN}|N_\star} = \frac{\alpha f_{SN} N_\star}{(M_{\odot}/M_{\text{SN}})^{1+\alpha}} \left( \frac{M_{\text{SN}}}{M_{\odot}} \right)^{1+\alpha} e^{-N_\star(>M_{\text{SN}})}. \quad (4)$$

If we further assume that the disk lifetime is independent of cluster location, then the fraction of disks that exist within the enrichment zone can be separately factored as $f_d f_e$. Evaluating this at the time of the supernova and integrating over all possible progenitors gives the likelihood that a disk in a cluster of a given size is enriched with SLRs at the level observed in our solar system.

$$P_{\text{SLR}|N_\star} = \int_{M_{\odot}}^{M_{\odot}} f_d(t_{SN}) f_e(t_{SN}) P_{\text{SN}|N_\star} dM_{\text{SN}}. \quad (5)$$

Figure 1 shows that $P_{\text{SLR}|N_\star}$ has a similar form independent of $\Sigma_{1\text{Myr}}$ with a broad maximum centered on $N_\star \sim 8000$. Small clusters are unlikely to have supernovae within the disk lifetime and large clusters expand more rapidly, so relatively few stars lie within the enrichment zone. The absolute likelihood increases for higher surface densities since the expansion speed
will be lower, and the enrichment fraction higher, for a given cluster number.

3.2. Cluster Formation over a Finite Duration

The starburst assumption is a simplification: young clusters contain protostars in a range of evolutionary states, suggesting that they are built up over a period $t_d \sim 1$ Myr (Lada & Lada 2003).

For a prescribed star formation rate (SFR), $\dot{N}_v(t)$, the average disk fraction in the cluster is $f_d(t) = \int_0^t \dot{f}_d(t') N_v(t') dt' / N_v$. The time dependence of the SFR in clusters is unknown. The simplest assumption is that it is constant, $N_v = N_v t_d$. In this case, for $t > t_d$,

$$\tilde{f}_d(t) = \begin{cases} 
1 - (t - t_d/2)/t_d, & t \leq t_d, \\
(t_d + t - t_d)/2t_d, & t_d < t \leq t_d + t_d, \\
0, & t > t_d + t_d. 
\end{cases}$$ (6)

We proceed by randomly sampling a star from the IMF at each time interval $\Delta t = 1/N_v$. The birth time is added to the main-sequence lifetime for each star with $M_* > 8 M_\odot$ to determine when the first supernova occurs. At this time, $t_1$, $P_{\text{SLR}}(N_v)$ is calculated as the product of the disk fraction above the enrichment fraction, which is determined by integrating the enrichment likelihood, or conversion probability, $P_{\text{SLR}}$. We average over $10^5$ simulations for each cluster number.

Figure 1 shows that $P_{\text{SLR}}(N_v)$ is relatively insensitive to $t_d$ and much more dependent on $\Sigma_3$ Myr. Peak probabilities are slightly lower for a finite formation time as the higher disk fraction at the time of the supernova is offset by the larger cluster size and lower enrichment fraction. The extended period over which a supernova can impact circumstellar disks allows for lower mass progenitors, however. The average supernova mass is $74 M_\odot$ for $t_d = 1$ Myr compared to $98 M_\odot$ for the starburst.

In each case, such high masses are favored because of the short disk lifetimes and are only likely to be found in very large clusters, $N_v \sim 10^4$.

4. MULTIPLE SUPERNOVAE

Large clusters, $N_v \sim 5000$, should have more than one supernova within the maximum disk lifetime, $t_d + t_d$. We model the effect of additional supernovae by summing enrichment probabilities using the same Monte Carlo formulation as in § 3.2. The assumption here is that cluster dynamics move new star-disk systems into the enrichment zone by the time of the next supernova. Two relatively small corrections are made: first, the fraction of possible disks that may be enriched is decreased by the fraction that are stripped by the previous supernova, $r_{\text{dd}}/t_d$; second, the fraction of disks in the enrichment zone, $f_{\text{dd}}$, is decreased by $v_{\text{grav}} \Delta t_{\text{sup}} / r_{\text{dd}}$ if this is less than 1, where $\Delta t_{\text{sup}}$ is the interval between supernovae, to allow for migration of new disks into this region. In practice, only at most a few percent of disks are close enough to a supernova to be destroyed and, except for the very largest clusters, the interval between supernovae is large enough that the enrichment zone is continually refreshed.

The results are shown in Figure 2 both for starburst and extended SFR scenarios, $t_d = 0$, 3 Myr. The enrichment likelihood continually increases to the largest clusters where many tens of supernovae can contribute. The inset shows the total number of supernovae within $t_d + t_d$ and the number that enrich half of the overall total for a fiducial $t_d = 1$ Myr.

5. IMPLICATIONS

The overall probability of supernova enrichment for any star is determined by integrating the enrichment likelihood, or conditional probability of enrichment given cluster size, over the cluster number distribution, $P_{\text{SLR}} = \int_{N_v} P_{\text{SLR}}(N_v) f(N_v) dN_v$. This “Galactic enrichment likelihood” is plotted versus a wider range of average surface densities in Figure 3. The incorporation of the cluster number distribution adds some uncertainty to the absolute numbers, but the general form, in particular the strong dependency on $\Sigma_3$ Myr and near independence on $t_d$, is inherited from $P_{\text{SLR}}(N_v)$ and is robust. As the surface density decreases with time, the cluster will become harder to identify. A rough estimate of the cluster lifetime, $t_c$, for which $\Sigma(t_c) = 3$ stars pc$^{-2}$, comparable to the field star density, is shown on the upper axis. Given that $\sim 90\%$ of all clusters do not survive beyond 10 Myr, and that planetary systems are disrupted in longer lived systems (Adams & Laughlin 2001), we conclude that supernova enrichment of protostellar disks is a highly unlikely event, affecting $\sim 1\%$ of all stars in the Galaxy.
How, then, to explain the presence of $^{60}$Fe in the early solar system? If, however unlikely, it was injected into the protoplanetary disk from a nearby supernova, then a Bayesian estimate of the most likely cluster size is $P_{N_i|\text{SLR}} = P_{\text{SLR}|N} R_i/R_{\text{SLR}}$. Because $R_i$ is independent of $N$, and $P_{\text{SLR}}$ is a normalization factor, the conditional probability of stellar number given enrichment is directly proportional to the enrichment likelihood plotted in Figures 1 and 2. This strongly favors our solar system’s origin in the largest clusters in the Galaxy, exemplified by NGC 3603 (Moffat et al. 1994), more than 2 orders of magnitude more luminous than Orion, where multiple supernovae can potentially enrich many disks.

A key assumption in this conclusion is that the disk fraction is independent of cluster location. Recent work by Balog et al. (2007), however, shows that $f_d$ is a factor of 2–3 lower than equation (2) in the central 0.5 pc of NGC 2244, a cluster intermediate in luminosity between Orion and NGC 3603. This would decrease $P_{\text{SLR}|N}$ by the same amount, lessen or even nullify the increase toward large $N_i$ in Figure 2, and only strengthen the conclusion that the direct injection of supernova ejecta into a protoplanetary disk is a very unlikely event.

Finally, we note that if one or more massive stars is the source of other SLRs, particularly $^{26}$Al, in the early solar system, then their implied scarcity in other planetary systems may have important implications for the thermal history of planetesimals in those systems (Ghosh & McSween 1998).

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