SUPERNOVA PROPAGATION AND CLOUD ENRICHMENT: A NEW MODEL FOR THE ORIGIN OF $^{60}$Fe IN THE EARLY SOLAR SYSTEM

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ABSTRACT

The radioactive isotope $^{60}$Fe ($T_{1/2} = 1.5$ Myr) was present in the early solar system. It is unlikely that it was injected directly into the nascent solar system by a single, nearby supernova (SN). It is proposed instead that it was inherited during the molecular cloud (MC) stage from several SNe belonging to previous episodes of star formation. The expected abundance of $^{60}$Fe in star-forming regions is estimated taking into account the stochasticity of the star-forming process, and it is shown that many MCs are expected to contain $^{60}$Fe (and possibly $^{26}$Al [$T_{1/2} = 0.74$ Myr]) at a level compatible with that of the nascent solar system. Therefore, no special explanation is needed to account for our solar system’s formation.

Key words: H II regions – ISM: clouds – planetary systems: protoplanetary disks – solar system: formation – Sun: abundances – supernovae: general

1. INTRODUCTION

Short-lived radionuclides (SLRs) are radioactive isotopes with half-lives shorter than 100 Myr, which were present in the early solar system (ESS; Russell et al. 2001). Because of their relatively high abundances with respect to that of the interstellar medium (ISM), some SLRs must have been produced within, or close in space and time to the ESS rather than during continuous Galactic nucleosynthesis (e.g., Meyer & Clayton 2000).

Iron-$^{60}$ ($T_{1/2} = 1.5$ Myr) holds a special position because it is only produced efficiently by stellar nucleosynthesis unlike other SLRs, which can also be made in the protoplanetary disk via irradiation of dust/gas by accelerated energetic particles such as protons (Lee et al. 1998). As such, $^{60}$Fe provides important clues about the immediate stellar environment of the nascent solar system (Montmerle et al. 2006). Asymptotic giant branch stars are not considered a likely source of $^{60}$Fe in the solar system because of their low probability of encounter with a star-forming region (Kastner & Myers 1994).

Elaborating on the pioneering work of Cameron & Truran (1977), two different quantitative scenarios with nearby, single supernova (SN) have been proposed whereby $^{60}$Fe is injected either into the solar protoplanetary disk (e.g., Ouellette et al. 2007) or into the molecular cloud (MC) core progenitor of our solar system (e.g., Cameron et al. 1995). Some models envision both possibilities (Takigawa et al. 2008). In the SN–disk scenario, the small size of the disk requires that it lies within 0.4 pc from the injecting SN belonging to the same stellar cluster (Ouellette et al. 2007). However, when massive stars become SNe after a few Myr of evolution, remaining disks around low-mass stars are several pc away from the massive star (e.g., Sicilia-Aguilar et al. 2005), and receive only minute amounts of SLRs (Williams & Gaidos 2007; Gounelle & Meibom 2008).

In the SN–core scenario, the SN shockwave triggers the core gravitational collapse in addition to delivering SLRs only for very restricted conditions in terms of distance and shockwave velocity (Boss et al. 2008).

At present, there is therefore no satisfying model which can explain the presence of $^{60}$Fe in the ESS. Here, we quantitatively evaluate a scenario proposing that $^{60}$Fe was inherited in the progenitor MC from SNe belonging to previous episodes of star formation. This scenario differs from scenarios favoring direct injection into a disk/core from a contemporaneous, single, nearby SN mainly because the $^{60}$Fe adduction occurs at the larger MC scale. As with previous stellar models trying to account for the presence of $^{60}$Fe in the ESS (Ouellette et al. 2007; Meyer & Clayton 2000; Mostefaoui et al. 2005; Boss et al. 2008), our model cannot solve the problem of $^{53}$Mn ($T_{1/2} = 3.7$ Myr) overproduction relative to $^{60}$Fe and their relative abundances in the ESS (e.g., Wasserburg et al. 2006).

2. THE SUPERNOVA PROPAGATION AND CLOUD ENRICHMENT MODEL

2.1. Model Sketch

Recently, a new paradigm concerning the formation mechanisms and lifetimes of MCs emerged (see Hennebelle et al. 2007 and references therein). In this new paradigm, referred to as the turbulent convergent flow model, MCs result from the collision of coherent flows and large-scale shocks in the ISM driven by winds from massive stars and SN explosions. Such collisions compress the interstellar atomic gas and after 10–20 Myr of evolution, the gas is dense enough to be shielded from the UV radiation and to become molecular (e.g., Glover & Mac Low 2007). Star formation follows immediately after the formation of the dense molecular gas. The turbulent convergent flow model provides a natural explanation for the wind-swept appearance of MCs (Vázquez-Semadeni et al. 2005), but is also consistent with the short lifetime of MCs (Hartmann et al. 2001) and the formation of stars in MCs within a crossing time (Elmegreen 2000). In addition, the turbulent convergent flow model elegantly accounts for the division of OB associations in subgroups of different ages (Lada & Lada 2003). A famous example is the Scorpio–Centaurus region made of the Lower Centaurus Crux (LCC, ∼16 Myr), the Upper Centaurus Lupus (UCL, ∼17 Myr), and the Upper Scorpius (Upper Sco, ∼5 Myr) subregions (Preibisch & Zinnecker 2007).

If the turbulent convergent flow model is correct, relatively high concentrations of $^{60}$Fe and other radioactivities with half-
lives $\gtrsim 1$ Myr are expected in MCs. This is because SN ejecta, whose compression effects build MCs, also carry large amounts of radioactive elements such as $^{60}$Fe. Although it can take as long as 20 Myr to build an MC depending on the starting density of the atomic gas, live $^{60}$Fe is continuously replenished in the second-generation MC by SNe originating from the first episode of star formation, which explode every few Myr. We therefore suggest that $^{60}$Fe in the ESS was inherited from multiple SNe belonging to previous episodes of star formation and name our model SPACE for Supernova Propagation And Cloud Enrichment.

### 2.2. Quantitative Estimate

We consider a first generation of stars formed in MC1 and a second generation of stars formed in MC2. After dissipation of the gas, the first (second) generation of stars become the OB1 (OB2) association. In our model, a number of SNe from MC1 deliver $^{60}$Fe into the second-generation MC2 (Figure 1).

The mass of $^{60}$Fe in MC2 as a function of time $t$ (time zero being the onset of star formation in MC1) reads

$$M_{MC2}^{(60\text{Fe})}[t] = f \eta \sum_{i=1}^{i=N_{SN}} Y_{SN}^{(60\text{Fe})} e^{-[(t-t_i)/\tau]}$$  \hspace{1cm} (1)

where $f$ is a geometrical dilution factor, $\eta$ is the mixing efficiency, $N_{SN}$ is the number of SNe which have exploded in OB1 before time $t$, $\tau$ is the mean life of $^{60}$Fe, $Y_{SN}^{(60\text{Fe})}$ is the $^{60}$Fe yield of the $i^{\text{th}}$ SN in MC1, and $t_i$ is the time of the $i^{\text{th}}$ SN explosion in MC1.

The stellar masses ($M$) in MC1 are calculated following the stellar initial mass function (IMF), using the generating function of Kroupa et al. (1993),

$$M = 0.01 + (0.19\xi^{1.55} + 0.05\xi^{0.6})/(1 - \xi^{0.58}),$$

where $\xi$ is a random number to be chosen between 0 and 1 (Brasser et al. 2006). We consider only the distributions whose most massive star is less massive than $150 M_\odot$, a likely upper limit for stellar masses (Weidner & Kroupa 2006). Importantly, we find that $f_{SN}$, the fraction of stars more massive than $8 M_\odot$ which will go SN, is $2.3 \times 10^{-3}$.

The yields of $^{60}$Fe have been determined for a diversity of SNe, corresponding to progenitor massive stars with masses ranging from 11 to 120 $M_\odot$ (Woosley & Weaver 1995; Rauscher et al. 2002; Limongi & Chiffi 2006; www.nucleosynthesis.org). Though in relatively good agreement, the yields somehow vary because of differences in the stellar and nuclear physics used by the different groups. For a given mass, when different yields are available, we use the average of the different yields. For stellar masses for which the yields are unknown, we take the yield of the star closest in mass. The explosion time $t_i$ of each massive star depends on the mass of the progenitor and is given by the evolutionary tracks of Schaller et al. (1992). The model input parameters are summarized in Table 1.

The value of $\eta$ depends on the efficiency of mixing of ejecta material into cold compressed gas that eventually becomes molecular material. The interface of the ejecta and the shocked ambient medium is expected to be turbulent due to various instabilities. Especially, when the elapsed time of SN expansion becomes comparable to the cooling timescale of postshock gas, thermal instability makes the interface highly turbulent. This process is clearly shown in hydrodynamical simulations of the propagation of a shock wave or of a shocked layer into warm neutral medium, which results in the creation of cold turbulent clumps embedded in warm neutral medium via thermal instability (Koyama & Inutsuka 2002; Audit & Hennebelle 2005). The spatial scale of the smallest turbulent eddy is probably comparable to the characteristic size ($\lambda_C$) of the smallest cold clump that is on the order of the critical length scale (less than 0.01 pc) of thermal instability. The characteristic mass ($M_C$) of the smallest cold clumps is much smaller than the solar mass and can be given by the following equation:

$$M_C \equiv \frac{\rho_c \lambda_C^3}{5.6 \times 10^{-5} M_\odot \left(\frac{\rho_c}{10^{-21} \text{g/cm}^3}\right) \left(\frac{\lambda_C}{0.01 \text{pc}}\right)^3},$$ \hspace{1cm} (2)

where $\rho_c$ is the gas density of cold clumps. Thus, the mixing of the metal-rich ejecta and the ambient medium should be very
efficient on this small mass scale. Therefore, we expect the efficiency of mixing to be very high, and use $\eta = 1$ hereafter, in line with the value of $\eta$ adopted by Looney et al. (2006) in the case of a disk and a starless core. Given that in our model, the SNe from OB1 by definition face MC2 (see Figure 1), we expect $f$ to be close to 0.5. We conservatively assume that only one-tenth of the SN ejecta contributes to the sweeping-up of atomic gas and the adduction of $^{60}$Fe into the new MC, and therefore adopt $f = 0.1$.

The evolution of $^{60}$Fe in MC2 is calculated for different sizes of MC1, i.e. for different values of its number of stars, $N_1$. For each $N_1$, the calculation is realized about 100 times to account for the stochastic nature of star formation. A typical example, with $N_1 = 5000$ stars, is given in Figure 2 where each thin line represents one realization of the simulation, while the thick red line is the average of 102 realizations.

| $M$ ($M_\odot$) | $t_{SN}$ (Myr) | $Y_{SN}^{(60)Fe}$ ($M_\odot$) |
|-----------------|----------------|------------------|
| 11              | 20.8           | 5.25E-6           |
| 12              | 17.8           | 3.62E-6           |
| 13              | 15.5           | 9.03E-5           |
| 14              | 13.8           | 5.72E-6           |
| 15              | 12.5           | 3.31E-5           |
| 16              | 11.4           | 4.39E-6           |
| 17              | 10.6           | 7.96E-6           |
| 18              | 9.9            | 2.54E-5           |
| 19              | 9.2            | 7.83E-5           |
| 20              | 8.8            | 2.09E-5           |
| 21              | 8.3            | 2.45E-5           |
| 22              | 7.9            | 5.19E-5           |
| 25              | 7.0            | 6.96E-5           |
| 30              | 6.0            | 3.75E-5           |
| 35              | 5.3            | 7.37E-5           |
| 40              | 4.9            | 5.93E-5           |
| 60              | 3.9            | 2.27E-4           |
| 80              | 3.4            | 7.55E-4           |
| 120             | 2.9            | 9.93E-4           |

Notes. $M$ is the stellar mass, $t_{SN}$ is the stellar lifetime, and $Y_{SN}^{(60)Fe}$ is the $^{60}$Fe yield. The stellar lifetime is calculated using the formula $\log(t_{SN}) = 1.4/\log(MF)^{1.5}$ (Schaller et al. 1992; Williams & Gaidos 2007). Iron-60 yields are the average of the yields modeled by Woosley & Weaver (1995), Rauscher et al. (2002), and Limongi & Chiffi (2006).

From Figures 2 and 3, it is clear that second-generation MCs are expected to contain a significant amount of $^{60}$Fe due to contamination by SNe of a first generation of stars. It remains to compare that amount of $^{60}$Fe contained in MC2 to its abundance in the ESS. Note that because the observed collapse timescales of cores (a few 10$^5$ yr; Onishi et al. 2002) are far shorter than the $^{60}$Fe half-life, there is no need for an extra decay term between the MC stage (assumed to start 10–20 Myr after the onset of star formation in MC1) and the disk stage, implying that the abundance in protoplanetary disks is identical to that of MC2 from which they form.

2.3. Comparison with the Solar System

The initial abundance of $^{60}$Fe in the solar system is not precisely known (Mostefaoui et al. 2005; Gounelle & Meibom...
The most recent and precise studies failed to detect an isochron and placed upper limits of 6 × 10⁻⁷ and 1 × 10⁻⁷, respectively, for the initial \(^{60}\text{Fe}/^{56}\text{Fe}\) ratio (Dauphas et al. 2008; Regelous et al. 2008). Adopting a conservative initial ratio \(^{60}\text{Fe}/^{56}\text{Fe} = 3 \times 10^{-7}\), it is estimated that the MC progenitor of our solar system had an \(^{60}\text{Fe}\) concentration of \([^{60}\text{Fe}]_{\text{ESS}} = 4 \times 10^{-10} M_\odot\) per unit of solar mass, assuming an \(^{56}\text{Fe}/\text{H}\) ratio of 3.2 × 10⁻⁷, and a metallicity of 0.7 (Lodders 2003).

Our model can account for the \(^{60}\text{Fe}\) abundance in the ESS provided it formed in an MC with a mass \(M_{\text{MC2}} = \dot{M}_{\text{MC2}}(^{60}\text{Fe})/[^{56}\text{Fe}]_{\text{ESS}} = (0.80 \pm 0.50) \times 10^4 M_\odot\). Our typical case, \(N_1 = 5000\) stars, corresponds to the estimated number of stars in the UCL–LCC association which formed \(\sim 12\) Myr before the Upper Sco association (de Geus 1992), within the 10–20 Myr interval defined above. If we take \(2350\) \(M_\odot\) as the stellar content of Upper Sco (de Geus 1992) and a molecular gas mass of \((0.8 \pm 0.5) \times 10^4 M_\odot\), we obtain a star formation efficiency of 29–31%. This star formation efficiency is in line with the observed star formation efficiencies (5%–30%) of nearby star-forming regions (Lada & Lada 2003), implying that if Upper Sco molecular gas was swept-up by the explosions of SNe from the UCL–LCC association (Preibisch & Zinnecker 2007), it is expected to contain \(^{60}\text{Fe}\) at a concentration similar to that of the ESS. This indicates that our model is self-consistent and offers a plausible astrophysical setting for the presence of \(^{60}\text{Fe}\) within the nascent solar system.

3. DISCUSSION

It is obvious that given the stochastic nature of star formation and the variable formation timescales of MCs, a range of \(^{60}\text{Fe}\) abundance is expected in MCs (Figures 2 and 3), and therefore in protoplanetary disks. Some of the input parameters such as \(f\) or \(\eta\) could be a factor of a few smaller than the adopted values, lowering accordingly \(\dot{M}_{\text{MC2}}(^{60}\text{Fe})\). The \(^{60}\text{Fe}\) content of the ESS might however be a factor of 3 smaller than the one we adopted (Regelous et al. 2008). In addition, \(f_{\text{SN}}\) could be significantly higher \((f_{\text{SN}} = 3 \times 10^{-3};\) Adams & Laughlin 2001) than the value we adopted \((f_{\text{SN}} = 2.1 \times 10^{-3}\) resulting in a higher value of \(^{60}\text{Fe}\) in MC2 due to a larger number of SNe in MC1. Finally, any increase of the half-life of \(^{60}\text{Fe}\) (G. Korschinek 2008, personal communication) would increase (exponentially) \(\dot{M}_{\text{MC2}}(^{60}\text{Fe})\).

The point of the calculations above is to show that for typical numbers \(^{60}\text{Fe}\) yields, MC masses and formation timescales, star formation efficiency, etc.) the estimated ESS abundance of \(^{60}\text{Fe}\) can be reproduced in the context of a reasonable astrophysical model.

Our model differs from previous models on several important points. First, \(^{60}\text{Fe}\) is delivered to an MC by a diversity of SNe rather than by a single SN. Second, the mass of the receiving phase \((\sim 10^4 M_\odot)\) is orders of magnitude larger than for the disk and the core model (0.013 and 1 \(M_\odot\), respectively; e.g., Looney et al. 2006). Third, \(^{60}\text{Fe}\) is not injected into a dense phase \((n_H \sim 10^5 \text{ cm}^{-3} \text{ and } \sim 10^{14} \text{ cm}^{-3}\) for the core and disk, respectively) isolated from the rest of the ISM, but is delivered into a relatively diffuse ISM phase interacting with other ISM components leading to high mixing efficiency (see Section 2.2).

Fourth, the \(^{60}\text{Fe}\)-producing SNe belong to previous generations of massive stars rather than to the same generation of stars. Fifth, the SNe shock waves do not trigger the collapse of a pre-existing MC core, but rather contribute to build on a timescale of 10–20 Myr a new, second-generation MC. Finally, this new model takes quantitatively into account the stochasticity of the star-forming process (though this approach has been used in a different context; Cerviño et al. 2000).

The paradigm for MC formation described in Section 2.1 is however not universally accepted. An alternative or complementary view is that gravitational instabilities represent the main driver for MC formation rather than large-scale convergent flows (e.g., Hennebelle et al. 2008). However, independently of the main driver for MC formation, it remains observationally true that most stars form in giant molecular clouds (GMCs). In such a context, MC1 and MC2 would represent two different regions of the same GMC which have evolved at different paces (e.g., Fellhauer & Kroupa 2005). The aforementioned observation that OB associations are made of subgroups of different ages can indeed be interpreted as an evidence for sequential star formation in GMCs (Elmegreen & Lada 1977), preserving the essence of our model.

The strength of our model is that the \(^{60}\text{Fe}\) content in the ESS is easily reproduced within a plausible, if not common, astrophysical setting, unlike the disk or core models (Section 1), and that all solar systems (within MC2 or the younger region of a GMC) will receive \(^{60}\text{Fe}\) instead of a few disks or cores. Therefore, even if a significant fraction of stars (50%) form in MC1, the overall probability for \(^{60}\text{Fe}\) MC inheritance is far higher than that of injection into a disk or a core. In that respect, though there is not one typical solar system, there is no need to call for an unlikely astrophysical setting for our solar system formation.

An important and so far unresolved problem associated with all models based on SN ejecta is the overproduction of \(^{53}\text{Mn}\) relatively to \(^{60}\text{Fe}\) and their inferred ratio in the ESS (Wasserburg et al. 2006). In the current SN one-dimensional models, \(^{53}\text{Mn}\) and \(^{60}\text{Fe}\) are produced deep in the SN interior, together with \(^{56}\text{Ni}\) \((T_{1/2} = 6\) days\). Nickel-56 is known to make it to the surface (Arnett et al. 1989), ruling out fallback as a solution to the \(^{53}\text{Mn}\) overproduction problem (e.g., Meyer & Clayton 2000).

Our model does not offer a solution to this general problem, but it is not inconceivable that a solution might come from new developments in SNe nucleosynthetic models, many aspects of which are not fully understood (Woosley & Heger 2007; Magkotsios et al. 2008).

Though \(^{26}\text{Al}\) can be produced by energetic particles irradiation (Lee et al. 1998), it might be difficult for irradiation to account for the entire ESS inventory (Duprat & Tatischeff 2007; Fitoussi et al. 2008). The ESS \(^{26}\text{Al}/^{60}\text{Fe}\) mass ratio was \(\sim 8\), adopting \(^{60}\text{Fe}/^{56}\text{Fe} = 3 \times 10^{-7}\), \(^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}\), and an \(^{27}\text{Al}/^{56}\text{Fe}\) ratio of 0.11 (Lodders 2003). Given the strong homogeneity in the \(^{26}\text{Al}\) distribution (Dielh et al. 2006), this compares relatively well with the observed ISM \(^{26}\text{Al}/^{60}\text{Fe}\) mass ratio of \(\sim 3\) (Wang et al. 2007). This suggests that together with \(^{60}\text{Fe}\) a substantial amount of \(^{26}\text{Al}\) could also have been inherited from the progenitor MC.

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