# THE MEANING OF IRON 60: A NEARBY SUPERNOVA INJECTED SHORT-LIVED RADIONUCLIDES INTO OUR PROTOPLANETARY DISK.

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In this abstract we discuss the sources of the known short-lived radionuclides (SLRs) in the early Solar System, those with half-lives $\sim 1$ Myr ($^{41}$Ca, $^{36}$Cl, $^{26}$Al, $^{10}$Be, $^{60}$Fe, $^{53}$Mn, $^{107}$Pd, $^{182}$Hf and $^{129}$I [1,2,3,4]). We conclude that the presence of some, especially $^{60}$Fe, demands a nearby supernova source. Astronomical images suggest the supernova was very close ($< 1$ pc) and occurred after the protoplanetary disk had formed. We briefly discuss the consequences of solar system formation near massive stars, including disk survival and structure, and the abundances of short-lived and stable isotopes.

**Sources of the SLRs**: There are three possible origins for the SLRs: **inheritance**, **irradiation** and **injection**. The SLRs $^{10}$Be ($t_{1/2} = 1.5$ Myr) and $^{129}$I ($t_{1/2} = 15.7$ Myr) are likely *inherited*, meaning that they pre-existed in the material from which the Solar System formed. Harper [5] has shown that type II supernovae in the Galaxy (mostly its spiral arms) produce copious amounts of $^{129}$I, maintaining a level $^{129}\mathrm{I}/^{127}\mathrm{I} \sim 10^{-2}$, 100 times greater than the level inferred for the early Solar System [6]. This fact implies that the Solar System material was isolated from spiral arms for $\sim 100$ Myr (about 7 half-lives) [5]; the more important point, though, is that inheritance of shorter-lived radionuclides is almost impossible without inheriting orders of magnitude too much $^{129}$I. In particular, the level of $^{60}$Fe that is maintained in the Galaxy by the same mechanisms is only $^{60}\mathrm{Fe}/^{56}\mathrm{Fe} \sim 3\times10^{-7}$ [5]: whatever is the isolation time, the Solar System must contain either far too little $^{60}$Fe or far too much $^{129}$I (as well as $^{107}$Pd, $^{182}$Hf and $^{53}$Mn). While $^{129}$I may be inherited, other SLRs probably are not, with the sole exception of $^{10}$Be: it is not created by the same (nucleosynthetic) sources. A very high fraction of Galactic cosmic rays are $^{10}$Be nuclei, and predictions of the number that are trapped in the Sun's molecular cloud core as it collapses yield an early-Solar-System ratio $^{10}\mathrm{Be}/^{9}\mathrm{Be} \sim 10^{-3}$, consistent with observations [7]. We conclude that $^{10}$Be is inherited, $^{129}$I may be, but that other SLRs, and especially $^{60}$Fe, are not.

SLRs may be created within the Solar System by nuclear reactions induced when *irradiated* by energetic particles accelerated in solar flares. On this premise Shu and others have modeled the abundances of SLRs once in CAIs, including $^{41}$Ca, $^{26}$Al, $^{10}$Be and $^{53}$Mn [8]. However, the irradiated material must lie within the stellar magnetosphere and be heated to temperatures $\approx 1200$ K, and no lower than 750 K [9]. It is not clear that $^{36}$Cl produced in the same region could condense into CAIs (chlorine condenses at 970 K [10]). Nor is it clear that the elements (S, Cl, Ar and K) that can be irradiated to produce $^{36}$Cl could reside stably inside the stellar magnetosphere. We also note that irradiation models fail by about three orders of magnitude to produce the observed quantities of $^{60}$Fe [11,12], as well as $^{107}$Pd and $^{182}$Hf [12]. While irradiation may contribute partially to some SLRs, injection is required to explain the presence of $^{60}$Fe, $^{107}$Pd, $^{182}$Hf, and perhaps $^{36}$Cl.

SLRs can be produced by stellar nucleosynthesis and then *injected* into the Solar System either soon before or after its formation. Asymptotic-giant-branch (AGB) stars have been suggested as the source, since they can explain most of the non-inherited SLRs, with the notable exceptions of of $^{53}$Mn and $^{182}$Hf [13]. On this basis alone AGB stars can be rejected, but we reject AGB stars based on their extreme rarity. Stars a few times the mass of the Sun end their lives of many Gyr as AGB stars, after orbiting the Galaxy several times. The odds of one chancing by a newly forming solar system are accordingly rare; based on observations, a *conservative* upper limit to the probability our Solar System was contaminated by an AGB star is $\approx 3 \times 10^{-6}$ [14]. Supernovae, on the other hand, are the end products of very massive stars that only live a few Myr, usually without even leaving the rich stellar clusters in which they are born. Supernovae very often explode in the vicinity of other newly formed solar systems. Moreover, supernovae are known to produce and eject all of the known SLRs (except $^{10}$Be), and in roughly the proportions seen in meteorites [1].

While it has been argued that a supernova several parsecs away triggered the collapse of the Sun's molecular cloud core [15], it is actually likely that the Solar System's formation was triggered by the progenitor O star [16], so that the Sun's protoplanetary disk formed *before* the supernova. To appreciate this likelihood, one has merely to look at the *Hubble Space Telescope* images of protoplanetary disks in the Orion Nebula [17]; there are over 2000

Table 1 *Predicted SLR Abundances*

| Isotopic Ratio | Adopted Value | Predicted Value |
|---|---|---|
| $^{41}$Ca/$^{40}$Ca | $1.4 \times 10^{-8}$ | $2 \times 10^{-5}$ |
| $^{36}$Cl/$^{35}$Cl | $3 \times 10^{-6}$ | $7 \times 10^{-6}$ |
| $^{26}$Al/$^{27}$Al | $5 \times 10^{-5}$ | $5 \times 10^{-5}$ |
| $^{60}$Fe/$^{56}$Fe | $5 \times 10^{-7}$ | $5 \times 10^{-6}$ |
| $^{53}$Mn/$^{55}$Mn | $1.4 \times 10^{-5}$ | $1 \times 10^{-3}$ |
| $^{107}$Pd/$^{108}$Pd | $2 \times 10^{-5}$ | $5 \times 10^{-5}$ |
| $^{182}$Hf/$^{180}$Hf | $2 \times 10^{-4}$ | $6 \times 10^{-5}$ |
| $^{129}$I/$^{127}$I | $1 \times 10^{-4}$ | $3 \times 10^{-5}$ |

protoplanetary disks within 1 parsec of the central O stars in the Orion Nebula [18]. When the central O star ($\theta^1$ Ori C) goes supernova in the next few Myr, there are thousands of disks that will be pelted with radioactive ejecta. Most stars are born in clusters much more massive, and with more O stars, than the Orion Nebula [19]. Given this is an astronomically common event, we argue that the Sun and its protoplanetary disk were within a fraction of a parsec from an O star that then went supernova, and we consider the consequences for the structure and isotopic composition of the protoplanetary disk.

**Consequences**: Can a protoplanetary disk survive a nearby supernova? Chevalier [20] (see also [21]) showed that the momentum of the supernova ejecta is what would destroy the disk: he estimated the momentum transfer and showed survival of a 60-AU disk is assured if the supernova is $> 0.25$ pc away. We have performed 1-D numerical simulations largely confirming these simple arguments [22]. We have found that the momentum of the ejecta from a supernova 0.3 pc away does not strip the disk at 10 AU, nor at 30 AU. However, the momentum of the eject from a supernova 0.1 pc away does strip the disk outside of 30 AU, and very nearly does so at 10 AU. Survival of the disk inside of 30 AU probably requires a minimum distance of about 0.2 pc from the supernova. We are currently expanding our calculations to two dimensions to better constrain disk survival.

A protoplanetary disk about 0.3 pc from a supernova will receive SLRs in very nearly the proportions inferred from meteorites, and after the formation of the first solids, consistent with "late injection" [23]. In Table 1 we have computed the initial ratios of SLRs *immediately* following the injection (which is itself $\sim 30$ years after the supernova), based on a distance of $\sim 0.3$ pc, a disk radius of 30 AU, and a disk mass of $0.01\,M_\odot$. The average ejecta from a $25\,M_\odot$ supernova was assumed [24], despite the fact that real supernova ejecta are *highly* inhomogeneous [25]; and no delay for solids formation was assumed. Despite these oversimplifications, the agreement is not unreasonable.

Other consequences of formation in a rich stellar cluster with massive stars include the following. A Sun-like protostar puts out about $10^{-3}\,L_\odot$ in FUV radiation [25], of which $\sim 10^{-4}\,L_\odot$ is intercepted by the disk. In contrast, an O star puts out $\sim 10^5\,L_\odot$ in FUV radiation, and a 30-AU disk 0.3 pc away intercepts about $6 \times 10^{-3}\,L_\odot$. This greatly enhanced UV flux quite possibly will significantly enhance mass-independent fractionation of oxygen isotopes by CO-photodissociation self-shielding [26]. Also, the size of the Sun's protoplanetary disk would be truncated, either by photoevaporation [27], or supernova stripping [20], to several tens of AU, consistent with the observed edge in the Kuiper Belt [28]. Finally, the inclinations of Kuiper belt objects [29] and the orbit of Sedna [30] have been used to argue for close encounters with other stars, again arguing for formation in a rich cluster. While these circumstances are suggestive of origin in a cluster, they are all reinforced by the presence of $^{60}$Fe in the early Solar System, which firmly places the early Solar System near a supernova.

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