EVIDENCE FOR IRRADIATION OF THE SUN'S TRANSITION DISK. Steven J. Desch[1], Alexander Krot[2], and Conel Alexander[3], [1]School of Earth and Space Exploration, Arizona State University, PO Box 1404, Tempe AZ, 85287-1404, USA. [2] Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822. [3] Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington DC 20015. (steve.desch@asu.edu).

Many short-lived radionuclides are known to have existed in the early solar system, including: ^{41}Ca ($t_{1/2}$ = 0.1 Myr); ^{36}Cl ($t_{1/2}$ = 0.3 Myr); ^{26}Al ($t_{1/2}$ = 0.7 Myr); ^{10}Be ($t_{1/2}$ = 1.5 Myr); ^{60}Fe ($t_{1/2}$ = 2.3 Myr); and ^{53}Mn ($t_{1/2}$ = 3.7 Myr) [1]. Their origins are unclear. Isochrons measured in calcium,aluminum-rich inclusion (CAI) minerals have revealed the presence of ^{10}Be, ^{26}Al and ^{41}Ca in these objects. ^{10}Be appears to predate the solar nebula [2]. Most, but not all, CAIs contained ^{26}Al, and ^{41}Ca in CAIs appears correlated with ^{26}Al, implying a late injection of both during CAI formation in the first < 1 Myr of the solar nebula [3]. Based on Li-Be systematics, [4] reported an isochron for the SLR ^{7}Be, which would indicate an irradiation origin (Li-Be-B isotopes are not produced by nucleosynthesis); but this detection has been refuted by [5], who instead interpret the data to indicate mixing with spallogenic Li, as the CAI is known to be disturbed and possibly aqueously altered. The initial abundances of ^{41}Ca, ^{26}Al, ^{10}Be and ^{60}Fe were too high to derive from Galactic background, although ^{53}Mn may have derived from this source [6]. Production of these SLRs (except ^{60}Fe) 0.1 AU from the Sun had been proposed [7], but such "X-wind" models have been refuted [8]. Instead, it seems likely that most ^{10}Be derived from trapped Galactic cosmic rays [2], and the origin of ^{60}Fe is confidently assigned to one [9] or more [10,11] core-collapse supernovae associated with the Sun's birth environment. Other SLRs undoubtedly accompanied the ^{60}Fe, and a late injection of it and ^{26}Al and ^{41}Ca may be inferred. The origins of ^{36}Cl and ^{53}Mn, as well as the Li isotopic anomalies, are less clear. Here we propose that production of ^{36}Cl and the Li isotope anomalies, and possibly significant amounts of ^{53}Mn as well, took place in the late *transition disk* stage of the Sun's protoplanetary disk.

Unlike ^{60}Fe (and probably ^{26}Al and ^{41}Ca), ^{36}Cl does not appear to have a supernova origin. Cl-S systematics in the late stage alteration product sodalite, in an Allende CAI and chondrule, yield an initial value $^{36}\mathrm{Cl}/^{35}\mathrm{Cl} \approx 4 \times 10^{-6}$ [12], and similar studies in the late-stage alteration product wadalite, in another Allende CAI, yield an even higher value, $^{36}\mathrm{Cl}/^{35}\mathrm{Cl} \approx 2 \times 10^{-5}$ [13]. Analysis by [14] shows the wadalite resulted from secondary mineralization of the CAI material, about 2.6 Myr after CAI formation; extrapolation to the time of CAI formation would imply an initial value $^{36}\mathrm{Cl}/^{35}\mathrm{Cl} \sim 10^{-2}$, orders of magnitude higher than typical supernova injection models predict [13,14].

The SLR ^{53}Mn is longer-lived, and significant contributions to it could derive from Galactic nucleosynthesis, a nearby supernova, or irradiation within the solar nebula [15], but not in an X-wind environment [8]. ^{53}Mn is produced abundantly by supernovae in the innermost $\approx 6\,M_{\odot}$; in fact, supernova injection models routinely invoke fallback of this material (e.g., onto a black hole) so that ^{53}Mn is not overproduced relative to solar nebula values [16]. Such models fine-tune the mass cut parameter so that $\sim 1\%$ of the ^{53}Mn is ejected, but it is more probable and natural that the mass cut lies farther out so that essentially no ^{53}Mn is ejected. It is notable that ^{53}Mn does not appear correlated with ^{26}Al [17]. Mn-Cr systematics in early-formed objects like CAIs [18] are difficult to interpret because of Cr isotopic anomalies [19]. There is considerable, strong evidence for ^{53}Mn associated with water, as in carbonates in Kaidun ($^{53}\mathrm{Mn}/^{55}\mathrm{Mn} \approx 9 \times 10^{-6}$ [20], or $\approx 4 - 6 \times 10^{-6}$ [21]), and aqueously produced fayalite grains in the CV chondrite Mokoia ($^{53}\mathrm{Mn}/^{55}\mathrm{Mn} \approx 2 \times 10^{-6}$ [22]).

We note that the anomalies in Li, and the SLRs ^{36}Cl and ^{53}Mn, are all difficult to explain in the context of supernova injection, and are all associated with late-stage (probably aqueous) alteration. We hypothesize that ^{36}Cl, and at least some ^{53}Mn were produced by irradiation by solar energetic particles (SEPs) during a late, low-density disk stage known as the transition disk; the SLRs were incorporated into ices which were then accreted by parent bodies; and then the SLRs were deposited in minerals that are the products of aqueous alteration. The flux of SEPs (with energies $> 100\,\mathrm{MeVnucleon}^{-1}$) from the early Sun is estimated to be $\sim 10^{5}$ times the current flux of $100\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at 1 AU [23]. Scaled to 3 AU, this flux is $3 \times 10^{19}\,\mathrm{cm}^{-2}\,\mathrm{Myr}^{-1}$, in the range necessary to produce measureable isotopic anomalies [24]. However, the stopping lengths of particles in the relevant energy range $10-100\,\mathrm{MeV\,nucleon}^{-1}$

are only $\sim 0.1 - 4\,\mathrm{g\,cm^{-2}}$ [25]. Surface densities in the protoplanetary disk at 3 AU are typically estimated to be $300 - 3000\,\mathrm{g\,cm^{-2}}$ [26], so the isotopic anomalies produced during the protoplanetary disk stage will be diluted by roughly three orders of magnitude and fall well below relevant levels. During the transition disk stage, however, surface densities are $\Sigma \sim 1\,\mathrm{g\,cm^{-2}}$ for a duration $\approx 0.5 - 1\,\mathrm{Myr}$ [27]. The clearing out of the disk can be attributed to an active magnetorotational instability [28] or photoevaporation from the central star [29]. Observations show that the protoplanetary disk stage ends, and the transition disk stage begins, at a typical age $\sim 3\,\mathrm{Myr}$ [27, 30]. Isotopic anomalies due to irradiation by SEPs can during the transition disk stage, and will not be diluted by large amounts of non-irradiated gas. If these isotopic anomalies are incorporated into ices that are accreted by parent bodies, they can be concentrated in products of aqueous alteration.

We estimate the magnitude of the anomalies as follows. We assume a disk with $\Sigma = 1\,\mathrm{g\,cm^{-2}}$ and scale height $H = 2 \times 10^{12}\,\mathrm{cm}$. We assume SEPs are emitted isotropically; it is straightforward to show that they are stopped in < 1 AU if they are within $2H$ of the disk midplane. The fraction of SEPs intercepted in this way between 3 and 4 AU is about 2%, and the number of ($E > 10\,\mathrm{MeV\,nucleon^{-1}}$) SEPs intercepted by the disk over 1 Myr is 1×10^{48}; dividing by the area, the fluence is $F = 5 \times 10^{18}\,\mathrm{cm^{-2}}$, or 5×10^{18} particle per gram of gas. Very roughly, the $^{53}\mathrm{Mn}/^{55}\mathrm{Mn}$ ratio that results from this fluence is $\approx F\sigma(^{56}\mathrm{Fe}/^{55}\mathrm{Mn})$. Assuming solar compositions and a cross section for the reaction $^{56}\mathrm{Fe}(p,\alpha)^{53}\mathrm{Mn}$, $\sigma \approx 100$ mb [31], yields $^{53}\mathrm{Mn}/^{55}\mathrm{Mn} \approx 4 \times 10^{-5}$, encouragingly close to the ratio observed in carbonates. Better calculations should carefully consider the actual composition, the disk structure, as well as the spectrum of SEPs, but this preliminary estimate shows that late-stage irradiation can produce the $^{53}\mathrm{Mn}/^{55}\mathrm{Mn}$ ratios observed in carbonates, provided the irradiation occurs in a transition disk and is not diluted in a protoplanetary disk. The more complete calculation including realistic compositions and the SEP spectrum [24] shows that irradiation sufficient to produce $^{53}\mathrm{Mn}/^{55}\mathrm{Mn} \approx 7 \times 10^{-5}$ in 1 Myr will produce $^{36}\mathrm{Cl}/^{35}\mathrm{Cl} \approx 5 \times 10^{-5}$ in the same time interval. This is also encouragingly close to the value observed in wadalite [13,14]. We note that a slightly lower $^{53}\mathrm{Mn}/^{55}\mathrm{Mn}$ ratio and lower fluence will produce a proportionally lower $^{36}\mathrm{Cl}/^{35}\mathrm{Cl}$ ratio, although this is somewhat ameliorated by the possibility that the reaction $^{38}\mathrm{Ar(p,ppn)}^{36}\mathrm{Cl}$, not considered by [24], may contribute significantly to $^{36}\mathrm{Cl}$ production. Finally, we note that spallation of O by SEPs, with a presumed cross section $\sigma \sim 10$ mb [31], will produce isotopic anomalies in Li at the level $\mathrm{Li}^{\star}/^{7}\mathrm{Li} > F\sigma(^{16}\mathrm{O}/^{7}\mathrm{Li}) \approx 2\%$. Since spallogenic Li has $^{7}\mathrm{Li}/^{6}\mathrm{Li} \approx 2$, compared to 12 in the original Li, this one reaction alone would reduce $^{7}\mathrm{Li}/^{6}\mathrm{Li}$ below 11.8 in the products of aqueous alteration, and values 10-11 are possible. This is comparable to the observed shifts in the analysis of late-stage disturbed CAI Allende 3529-41 [4].

These estimates are preliminary and represent a plausibility argument only. Further modeling is needed to definitively test the hypothesis, but we conclude that at this stage it appears quite plausible that late-stage irradiation of the Sun's *transition disk* could have produced the $^{36}\mathrm{Cl}$, and possibly spallogenic Li associated with late-stage products of aqueous alteration, as well as contributed significantly to the $^{53}\mathrm{Mn}$ seen in carbonates.

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