**SHORT-LIVED RADIONUCLIDES IN THE EARLY SOLAR SYSTEM: NOT SO UNUSUAL AFTER ALL.**
E. D. Young[1], [1]Department of Earth, Planetary, and Space Sciences, UCLA (eyoung@ess.ucla.edu).

**Introduction:** Apparent excesses in $^{36}$Cl, $^{26}$Al, $^{41}$Ca, and $^{60}$Fe have been taken as evidence for injection of these short-lived nuclides into the early solar system by a variety of sources, including supernovae (SNe) proximal to the site of solar system formation. Recent models have underscored the importance of enrichment of short-lived radionuclides in star-forming regions by winds from rapidly rotating massive stars in Wolf-Rayet (WR) or anticipatory pre-Wolf-Rayet phases of evolution [1, 2]. The analysis herein shows that apparent excesses in early-solar short-lived radionuclides disappear if one accounts for ejecta from such winds proximal to star-forming regions (SFRs).

**Solar $^{26}$Al/$^{27}$Al is Typical:** Jura, Xu and Young [3] showed recently that the initial $^{26}$Al/$^{27}$Al ratio for the solar system of ~ 5x10$^{-5}$ is similar to star-forming regions today in the Galaxy. This conclusion is based on the observation that if $^{26}$Al is produced locally by massive stars in SFRs, the proper calculation for estimating the concentration of $^{26}$Al in these regions is to divide the Galactic mass of $^{26}$Al by the mass of $H_2$ rather than the mass of total H as is commonly done (because the former traces molecular clouds). This calculation, with correction for buildup of $^{27}$Al over the last 4.6 Gyr [4] yields $^{26}$Al/$^{27}$Al ratios of 3 to 5x10$^{-5}$ for SFRs in general. In addition, white dwarf stars polluted by impacting asteroids show elemental abundances implying rock-metal differentiation. The minimum $^{26}$Al/$^{27}$Al required to produce melting in these bodies can be calculated and is ≥ 3x10$^{-5}$ [3]. Star-forming regions throughout the Galaxy have complements of $^{26}$Al similar to that present in the young solar system.

The fact that solar $^{26}$Al/$^{27}$Al is typical of star-forming regions in the Galaxy renders scenarios for acquiring $^{26}$Al in the solar system by special circumstances unlikely. A more fundamental process is required.

**Mean Live vs. Abundance:** Correlations between radioactive decay mean lives ($\tau_R$, related to half-life by $\tau_R = t_{1/2}/\ln(2)$) and radionuclide abundances [e.g., 5] provide a test of various scenarios for the provenance of solar-system rock-forming elements. In the simplest case of continuous production and radioactive decay, radionuclides with the shortest $\tau_R$ should be least abundant when their concentrations are normalized to their stable counterparts and production rates. We use the correlation between short-lived radionuclide (SRN) abundances and mean life to show that enrichment of SRNs in star-forming regions by WR winds leads to a coherent picture of inheritance of these nuclides from parental molecular clouds with cloud residence times of 10$^8$ years.

We use a modification of the analytical model of Jacobsen [6] for a two-box interstellar medium (molecular cloud vs. diffuse phase). The analytical expression is:

$$\log\left(\frac{N_{\rm R,MC}}{N_{\rm S,MC}}\right) - \log\left(\frac{P_{\rm R}^{\rm SNe} + (\Lambda_{\rm W}/\Lambda_{\rm SNe})P_{\rm R}^{\rm W}}{P_{\rm S}}\right) = 2\log\tau_{\rm R} - \log\left[(1-x_{\rm MC})\tau_{\rm MC} + \tau_{\rm R}\right] - \log T^{*} \quad (1)$$

where $N_{R,MC}$ ($N_{S,MC}$) are numbers of radionuclides (stable nuclides) in the molecular cloud (MC), $P_R^{SNe}$ and $P_R^{W}$ are production terms for radionuclides from supernovae (SNe) and winds (W), respectively, $x_{MC}$ is the fraction of the ISM composed of MC, $\tau_{MC}$ is the residence time in clouds, and $T^*$ is effectively the age of the Galaxy. The terms $\Lambda_W$ and $\Lambda_{SNe}$ characterize the efficiency of capture of wind and supernovae ejecta, respectively. Numerical simulations of mass ejections from young stellar clusters demonstrate that the wind and SNe production terms for the SRNs adjacent clouds reach a steady state consistent with the expression $N_{R,MC}/N_{R,Y} \sim (1/\tau_{inject})/(\tau_R - 1/\tau_{inject})$ where $\tau_{inject}$ is the characteristic timescale for addition to clouds (~ 5 to 10 Myr) and $N_{R,Y}$ is the total yield (Figure 1). Coa-

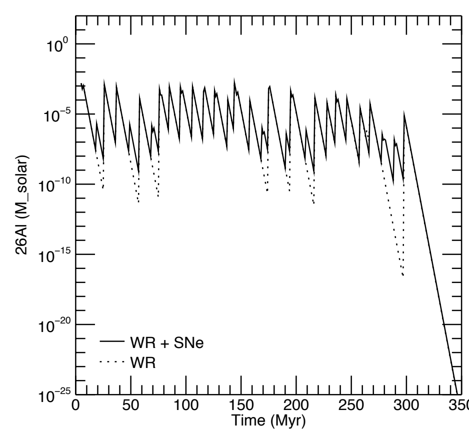


**Figure 1.** Numerical simulation of $^{26}$Al mass vs. time in a cloud supported by WR and proximal SNe inputs. Inputs discontinued at 300 Myr for comparison.

lescence of cloud fragments and staggering of stellar formation times would tend to dampen the sawtooth pattern in Figure 1.

Application of Equation (1) to the most recent data where winds from rotating WR stars are ignored ($\Lambda_W$ = 0) leads to the plot in Figure 1. The excesses in the shortest-lived nuclides in Figure 1 relative to curves for $\tau_{MC}$ defined by the longer-lived nuclides are normally taken as the primary evidence for very specific (unusual?) circumstances surrounding solar system formation.

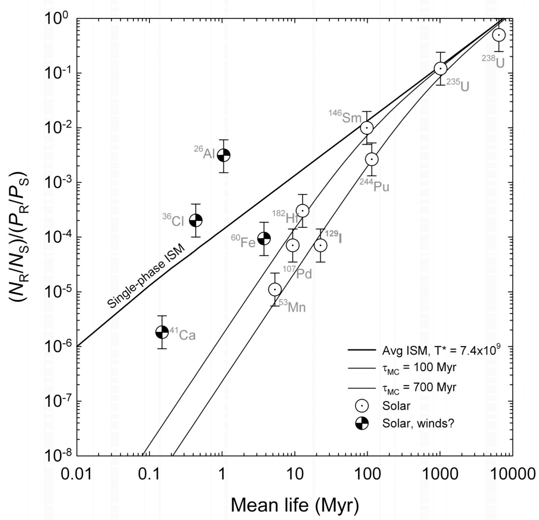


**Figure 2**. Two-phase ISM model compared with early-solar data. Black/white symbols are nuclides in apparent excess relative to others.

The unknown in Equation (1) is $\Lambda_W/\Lambda_{SNe}$. In the absence of *a priori* information, we treat this efficiency ratio as a fit parameter and hypothesize that $^{26}Al$ production is generally dominated by WR winds rather than SNe near star-forming regions, with the term $\Lambda_W/\Lambda_{SNe}$ sufficiently large (~1500) that $^{26}Al/^{27}Al$ normalized by $(P_{26}^{SNe}+\Lambda_W/\Lambda_{SNe}\, P_{26}^{W})/P_{27}$ falls on the residence-time curve defined by the longer-lived nuclides. Most importantly, with this value for $\Lambda_W/\Lambda_{SNe}$ and SRN yields for WR winds [7], all of the SRNs align on a single curve representing a cloud residence time of 200 +/– 100 Myr (Figure 3).

**Discussion:** The alignment of all nuclides in Figure 3 suggests a value for residence time of nuclides in clouds and a value for $\Lambda_W/\Lambda_{SNe}$. Both require independent assessment.

The 200+/–100 Myr residence time in Figure 3 is consistent with the average rate of conversion of molecular cloud mass into stars; the Galactic molecular cloud mass, $M_{MC}$, of 8.4x10$^8$ $M_\odot$ and star formation rate, $\psi$, of 0.9 to 3 yr$^{-1}$ in the present-day Galaxy [8] yield a timescale of $M_{MC}/\psi$ = 280 to 840 Myr.

The low early solar $^{60}Fe/^{26}Al$ relative to the average Galactic value implies $\Lambda_W/\Lambda_{SNe}$ of at least 300. A number of factors may contribute to high $\Lambda_W/\Lambda_{SNe}$. It is thought that the most massive stars (> 30 ~$M_\odot$) will not necessarily produce energetic core-collapse supernovae but rather collapse directly to black holes after mass loss through winds [9]. The effect is for the most massive stars proximal to SFRs to be prodigious producers of winds but not supernovae. In this case, the solar abundances of the short-lived radionuclides could be telling us that winds provide the shortest-lived nuclides ($\tau_R$ < 5 Myr) from the most massive stars proximal to star-forming regions while SNe dominate the sources of longer-lived nuclides produced mainly in the diffuse ISM.

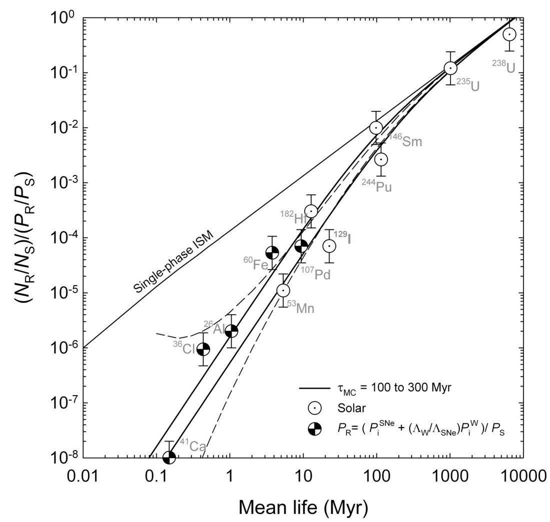


**Figure 3**. Two-phase ISM model where data shown in black/white symbols are adjusted for WR winds and $\Lambda_W/\Lambda_{SNe}$ =1530. Dashed lines account for sawtooth pattern in production (e.g., Figure 1).


**References:** [1] Gaidos E. et al. (2009) *ApJ* 696, 1854-1863. [2] Gounelle M. and Meynet G. (2012) *A&A* 545, A4. [3] Jura M. et al. (2013) *ApJ Letters* 775, L41. [4] Huss G.R. et al. (2009) *Geochim. Cosmochim. Acta* 73, 4922-4945. [5] Wasserburg G.J. et al. (1996) *ApJ* 466, L109-L113. [6] Jacobsen S.B., 2005. in *Chondrites and the Protoplanetary Disk*, A.N. Krot et al., Editors, Astronomical Society of the Pacific, p. 548-557. [7] Arnould M. et al. (2006) *A&A* 453, 653-659. [8] Draine B.T., *Physics of the Interstellar and Intergalactic Medium*. 2011, Princeton University Press. [9] Fryer et al. (2007) Astronomical Society of the Pacific 119, 1211-1232.