WOLF-RAYET STARS AND THE ORIGIN OF SOLAR SHORT-LIVED RADIONUCLIDES. A. E. Schneider[1] and E. D. Young[1], [1]Department of Earth, Planetary, and Space Sciences, UCLA (aeschneider714@ucla.edu, eyoung@epss.ucla.edu).

Introduction: The relative abundances of the short-lived radio nuclides (SLRs) in the solar system are key arbiters for competing models for the environs in which the solar system formed. We are influenced by the consistency among short- and long-lived radio isotope abundances when normalized for mean life, stellar production, and residence time in the ISM (Figure 1). The fit among 15 radionuclides for which there are sufficient data (Figure 1) suggests that Wolf-Rayet (WR) stars enhance regions of massive star formation with SLRs. While there is relative agreement that WR stars were important in determining the abundances of SLRs in the early solar system, the details are debated. In particular, the regional enrichment implied by Figure 1 differs from the more local enrichments envisioned for formation of the solar system at the edge of a WR "bubble" carved by the massive winds. Our motivation for the present study comes from the correspondence between the initial solar $^{27}Al/^{26}Al$ value and values for massive star-forming regions; star formation regions are solar to within a factor of 2x or better. It is hard to reconcile this correspondence if the solar value is the result of localized enrichment rather than reflecting a regional average value. It also suggests that mixing of stellar outflows into molecular gas in giant molecular clouds is perhaps more efficient than some models imply.

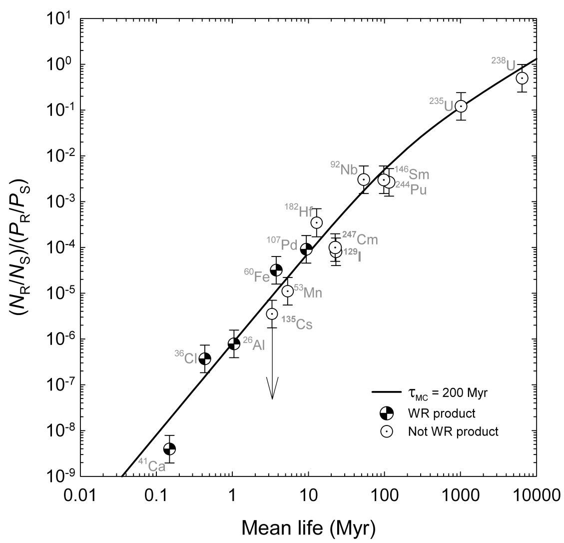

Figure 1. *Relative abundances of solar radionuclides at the time the solar system formed normalized to their stable partners and production ratios, including production from WR winds. Curve is a two-phase ISM model in which the residence time in a GMC against star formation is 200 Myr [1]. Error bars reflect factors of 2 in production ratios. ^{92}Nb is provisional based on the median of estimated production ratios.*

Model: We constructed a statistical model for ^{26}Al production in which we inject ^{26}Al into a giant molecular cloud (GMC) by winds and supernova (SN) explosions. We draw inspiration from the Carina Nebula in which ~80% of the ^{26}Al evidently comes from WR stars [2]. Accordingly, our GMC has a radius of ~70 pc. Similarly, there are at least 8 current open clusters ≤10 Myrs old in Carina [3, 4] so our GMC maintains at least 7 open clusters at any one point in time. The star cluster creation rate is 1.5 $Myrs^{-1}$ in order to maintain the steady state of ~7 clusters. The density of our GMC is 1.0 cm^{-3}, approximating the average density of Carina [2].

We populate each of our star clusters with 2500 stars to maintain open clusters. The cluster radii are ~8 pc, giving a stellar density from 0.1-10.0 $stars/pc^3$ [5]. The average stellar mass in our simulation is ~0.5 $M_\odot$ following a classical initial mass function [6, 7]. Stars that have stellar masses of ≥ 8 $M_\odot$ are considered supernovae (SNe) progenitors and will explode at the end of their lives. Those stars ≥ 25 $M_\odot$ in mass experience a WR phase of 1.0×10^5 yrs before exploding as supernovae. Stellar lifetimes are calculated using a fit to evolutionary track data [8, 9].

We use a stellar velocity dispersion of 3.0 km/s for the average mass star and apply equipartition of stellar velocities (velocities are proportional to inverse square relation). We employ a GMC average velocity of 22 km/s relative to star clusters, leading to the unveiling of clusters after ~10 Myr as suggested by observations that little or no molecular gas is seen within 25 pc of clusters older than 10 Myr [10, 11, 12]. The velocity of ~22 km/s relative to star clusters is comparable to estimations of relative velocities between GMCs and their associated young massive clusters [13]. The unveiling can be seen as simulating a cluster moving out of its placental cloud as stellar activity creates bubbles, or as GMC material being dispersed before coming back together in a collect and collapse cycle. Exposing the cluster in our model does not always mean exposing the SNe and WR stars, as individual stars in each cluster move with different velocities and trajectories.

Prior to stars entering the WR phase, a gradual injection of their total ^{26}Al yield begins from strong winds, as described previously [14]. The gradual injection accounts for both release from the stellar source and the timescale for mixing into the cloud material. Radioactive decay is accounted for throughout the injection and mixing process [15]. After the WR phase has ended, we allow the star to explode as a SN and the same injection model is applied, but with SNe ^{26}Al yields [16]. Aluminum-26 from SNe with progenitor masses of $8 \leq M_{\odot} \leq 25$ are also included. The gradual injection model for both WR and SNe sources is used here to represent only GMC-averaged ^{26}Al that is available for subsequent star formation. This means that ^{26}Al that has yet to seep out of its host supernova remnant or Wolf-Rayet bubble is not considered available for incorporation into new stars.

In our calculations, massive stars must enter their mass-loss phase while residing within the GMC region to contribute ^{26}Al; if the star is outside of the GMC region, the ^{26}Al yield from that star is lost. We consider that WR winds inside the GMC have injection efficiencies of 100%, while SNe injection efficiencies are dependent upon the distance of the star from the center of the GMC at the time it explodes; our model invokes a piecewise linear injection efficiency that begins at 100% in the center of the GMC and lowers to 0% as it reaches the outermost edge of the GMC. This serves to mimic stellar feedback of SNe explosions on molecular clouds in which material follows paths of least resistance, including paths carved out by prior winds [17]. Our simulations are run for 200 Myrs [15].

Results and Discussion: Our base model yields an average amount of ^{26}Al coming from WR winds of ~89%, with WR winds providing more ^{26}Al to the cloud in every simulation. These results are consistent with the observations of Voss et al. [2]. A typical result is shown in Figure 2 as ^{26}Al yield vs. time for ^{26}Al from WR winds and from SNe.

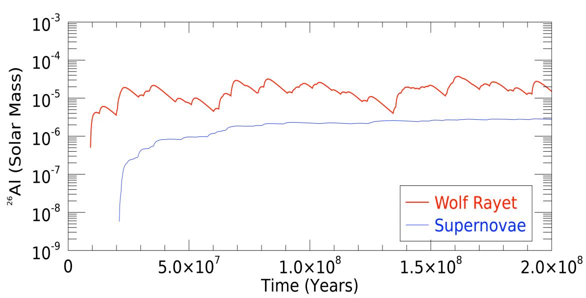

Figure 2. *Wolf-Rayet and Supernovae ^{26}Al contributions vs. time.*

There are three parameters that significantly affect the results shown in Figure 2. The first two are stellar velocity and relative velocity between our GMC and the clusters. The significance of these parameters is sound because they are both involved in how lxong it takes SNe and WR stars to exist outside of the GMC, where their yields are irrelevant. As stellar velocity increases, the steady state result seen in Figure 2 diminishes. This is because the stars escape the cloud more quickly, causing fewer stars to enter the WR phase or explode as SNe inside the GMC. As GMC velocity increases, the fraction of ^{26}Al from WR stars also increases. This is because SNe that explode after 10 Myr deposit their mass in the interstices of the cloud material rather than within it. Nonetheless, stagnant clouds and clusters still result in a WR contribution to ^{26}Al of ~64% and WR winds contributing more ^{26}Al than SNe in ~69% of the runs.

Our model mimics the findings of Iffrig and Hennebelle [17] regarding the relative efficiency of trapping SNe debris. Without this simple radial function for efficiency of trapping, ^{26}Al from WR winds would decrease to ~48% [17].

We conclude that the consistency of the solar abundances of radionuclides is most consistent with formation of the Sun in a well-mixed, self-enriched giant molecular cloud. The apparent mixing evidenced by the correspondence between present-day concentrations of ^{26}Al in massive star-forming regions and the initial solar value requires that the solar value is a regional signal rather than a local one. The statistical model presented here suggests that this is possible from the viewpoint of mass balance and over timescales, but the details of the physics attending mixing are poorly understood.

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