GALACTIC CHEMICAL EVOLUTION AND THE ABUNDANCES OF SHORT-LIVED RADIONUCLIDES INHERITED BY THE SOLAR SYSTEM FROM THE INTERSTELLAR MEDIUM.

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Introduction: In order to understand the origin of the short-lived radionuclides (SLRs) in the early solar system, it is necessary to have a clear, astrophysically based picture of galactic chemical evolution and the resulting SLR abundances in the interstellar medium (ISM). A discussion of the origin of the SLRs in the early solar system, including a detailed model of galactic chemical evolution as it relates to SLRs, is given in [1]. In [2], we present the galactic evolution model from [1]. Here we present some implications of that model for the SLRs in the early solar system. The main features of this discussion are summarized in Fig. 1, which compares the data for the early solar system to predictions of steady-state abundances in the ISM and two classes of models for the abundances that could have been inherited by the early solar system from the ISM.

Steady-State Abundances: The straight solid line represents the steady-state abundances of the SLRs at a galactic age of 7.5 Ga, when the solar system formed. For times that are much longer than the mean lifetimes of the SLRs, the slope of this line is given by the mean life, τ, divided by the galactic age, t. As the mean life approaches t, the steady-state abundance falls below the τ/t line and the trend asymptotically approaches the effective production ratio (y = 1 on this plot). The vertical position of this line and the curves derived from it on Fig. 1 depend on our choice of t.

Newly synthesized elements are injected into the interstellar medium from dying stars in discrete events. The abundances of SLRs in a particular region of the ISM depend on the mean lives of the nuclides, the mixing time for that region, and on the repeat time of injection of newly synthesized material. For longer-lived nuclides, such as ^{146}Sm (τ = 149 Ma) and ^{244}Pu (τ = 115 Ma), the repeat time and mixing time are short compared to the mean lives, so the abundances should be relatively homogeneous over an annulus of the galaxy. However, the SLRs with very short mean lives (e.g., ^{41}Ca, τ = 0.14 Ma; ^{36}Cl, τ = 0.43 Ma; ^{26}Al, τ = 1.05 Ma), mixing and repeat times are long compared to the mean lives and abundances probably vary widely around the steady-state abundances. Nuclides with intermediate lifetimes will have intermediate behavior.

Free-Decay Interval: Beginning with the discovery that ^{129}I was present in the early solar system [3], cosmochemists have used the concept of a free-decay interval between the last input of nucleosynthetic material and the formation of the solar system. The curved solid lines in Fig. 1 show how free-decay intervals of 50 Ma and 100 Ma affect abundances. A free-decay interval of ~100 Ma provides a reasonable match to the ^{129}I/^{127}I in the early solar system [4], but the presence of ^{26}Al in the early solar system is inconsistent with such a long period of free decay. A late addition of newly synthesized material is required [e.g., 5]. However, a free-decay model does not describe the real astrophysical situation.

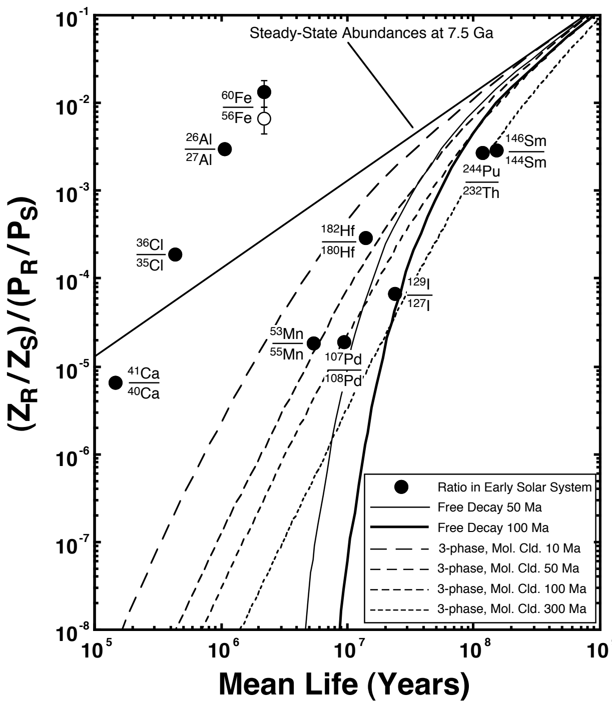

Fig. 1: Abundance ratios (Z_R/Z_S) of SLRs normalized their effective production ratios (P_R/P_S) plotted against mean life [1].

Three-phase mixing models: An astrophysically based model for the SLRs in the ISM was first presented by [6], based on the work of [7]. The ISM consists of three phases: 1) molecular clouds, from which stellar systems form; 2) large HI (neutral H) clouds that are too large to be evaporated by supernova shocks; and 3) smaller HI clouds that can be evaporated by supernova shocks and the surrounding hot medium [6, 7]. Newly synthesized material is injected primarily into the hot medium and mixes into the large neutral clouds and then into the dense molecular clouds on timescales of 10^7 to 10^8 years. In this picture, the so-called free-decay interval is actually the time it takes on average for newly synthesized matter to be distributed through the three phases in the ISM and to become available for incorporation into a stellar system. The dashed lines in Fig. 1 show four models that assume different mixing times. The models shown are broadly consistent with the early solar system abundances of SLRs with mean lives ≥5 Ma. Note that the choice of models for the SLRs inherited from the interstellar medium plays a critical role in how much of a late injection is required for these isotopes.

Implications for solar system SRL abundances: *^{41}Ca, ^{36}Cl, ^{26}Al, ^{60}Fe:* These isotopes are enriched by a factor of ~10^3 over the abundances predicted by our models for molecular clouds, which cover the range of plausible inherited abundances. This is considerably outside of the uncertainties in our analysis. The factor-of-two error bar on the ^{60}Fe abundance provides an idea of the maximum uncertainties in solar system abundances. The uncertainties from nucleosynthesis models are illustrated by the open and filled symbols for ^{60}Fe, which reflect a factor of two in the ^{60}Fe production rate. Another factor-of-two systematic uncertainty in the positions of the data points comes from choices of parameters in our galactic chemical evolution model. Clearly, the average galactic background is not the source of these isotopes; production just before or during solar system formation is required.

Three kinds of sources for SLRs can be envisioned: a nearby stellar source, self-enrichment of the Sun's parent molecular cloud, and production via irradiation, either in the solar system or in the molecular cloud. We will not consider irradiation models. A single stellar source is the most widely discussed scenario. As we discuss in [1], comparisons of solar system abundances and stellar models show that intermediate-mass AGB stars, type II supernovae from stars of >~20 $M_\odot$, and massive stars (>~33 $M_\odot$) that end their lives as type Ib or Ic supernovae could have produced the SLRs in the solar system. However, based on the probability that the solar system would have encountered a given source, AGB stars can probably be excluded. Even supernova models have problems. Total ejecta provides too much ^{53}Mn and ^{60}Fe to match solar system abundances, but models that permit mixing of the ejecta and invoke a mass cut within the mixed region below which the material falls back onto the remnant can match solar system abundances reasonably well [8]. Because most stars form in giant molecular clouds during brief episodes of cluster star formation, because massive stars have short lifetimes, and because winds from massive stars and supernovae are observed to trigger star formation, it is plausible that the solar system was associated with a massive star.

Cluster star formation suggests another scenario, in which the solar system formed from material that had been locally enriched in SLRs from several massive stars from the same cloud. In the largest systems, star formation is observed to progress through a cloud, with explosions of early-formed stars triggering star formation in other parts of the cloud. Ejecta from these early supernovae might mix into the cloud in time to be incorporated into later stars. In this case, SLRs in the solar system could have come from several massive stars. As timescales lengthen sufficiently to allow efficient exchange between the hot medium, HI clouds, and cold molecular clouds where stars form (>10^7 years), this scenario merges into the process that produced average galactic background. Local variations around the average background are expected due to discrete injections of newly synthesized material, with larger variations expected for shorter-lived nuclides. However, if timescales are too long, nuclides such as ^{41}Ca and ^{36}Cl will not survive to enter the solar system.

^{53}Mn and ^{107}Pd: These are examples of nuclides for which the need for a late addition of newly synthesized material depends critically on the choice of galactic background model. If a free-day interval of ~10^8 years is assumed to explain ^{129}I, then ^{107}Pd is 10^3 times and ^{53}Mn is >10^4 times more abundant than can be supplied by the inventory in the ISM. On the other hand, if a more-realistic three-phase mixing model is used, then little or no late addition is required (Fig. 1).

^{182}Hf and ^{129}I: These two nuclides are nominally produced in the *r*-process and their mean lives are long enough for them to have entered the solar system from the ISM. However, if the production ratios relative to their stable normalizing isotopes are of order unity, the difference in their mean lives should result in a lower ^{182}Hf/^{180}Hf compared to ^{129}I/^{127}I. This is not what is observed (Fig. 1). This observation is one line of evidence that *r*-process elements come from at least two sources [9]. Current models suggest that ^{182}Hf and the actinides are produced in type II supernovae of stars with initial masses ≤11 $M_\odot$, while the elements with (~110<A <130), including ^{129}I, are produced in type II supernovae of 12-25 $M_\odot$ stars. Fig. 1 suggests that the background abundances inherited from the ISM had some structure relative to the smooth model curves because of the stochastic nature of the input of newly synthesized material, with a ≤11 $M_\odot$ contributing more recently than a 12-25 $M_\odot$ star. Massive stars (>25 $M_\odot$), which might supply the ^{41}Ca, ^{36}Cl, ^{26}Al, and ^{60}Fe, apparently do not produce *r*-process elements [9].

References: [1] Huss G. R., Meyer B. S., Srinivasan G., Goswami J. N., and Sahijpal S. (2009) *GCA 73*, in press. [2] Meyer B. S. and Huss G. R. (2009) *LPS XL*, this volume. [3] Reynolds J. H. (1960) *Phys. Rev. Lett. 4*, 8-10. [4] Schramm D. N. and Wasserburg G. J. (1970) *ApJ 162*, 57-69. [5] Lee T. et al. (1976) *Gephys. Res. Lett. 3*, 41-44. [6] Clayton D. D. (1983) *ApJ 268*, 381-384. [7] McKee C. F. and Ostriker J. P. (1977) *ApJ 218*, 1334-1337. [8] Takigawa A. et al. (2008) *ApJ 688*, 1382-1387. [9] Qian Y.-Z and Wasserburg G. J. (2007) *Phys. Rep. 588*, 237-268. Supported by NASA grants NNX08AG58G (GRH) and NNX07AJ04G (BSM).