THE BIRTH ENVIRONMENT OF THE SOLAR SYSTEM ASSESSED USING A BAYESIAN ANALYSIS OF RADIONUCLIDE CONCENTRATIONS. E. D. Young[1], [1]Department of Earth, Planetary, and Space Sciences and iPLEX, University of California Los Angeles (UCLA) (eyoung@epss.ucla.edu).

Introduction: The concentrations of short- and long-lived radionuclides in the early solar system are clues to its origins. Theories for the provenance of these nuclides can be divided into two types of scenarios. In the first scenario type, the radiochemistry of the solar system has no significance beyond purely chance encounters with a variety of nucleosynthesis sources [1, 2]. In the second scenario type, the birth environment of the solar system was like the self-enriched massive star-forming regions (SFRs) of today, leaving no signature of specific and identifiable encounters with individual supernovae (SNe) or AGB stars [3, 4].

In an effort to move past qualitative arguments for and against these disparate theories, Bayesian statistical methods are used to assess quantitatively the relative likelihoods of one scenario type relative to the other. Results of analyses of this type should be considered in formulating a comprehensive theory for the formation of the solar system.

Chance Encounters: The chance-encounter scenarios emphasize the discrete nature, or "granularity", of stellar nucleosynthesis events that could have seeded parental solar system material with nuclides. They are described by an equation based on a geometric series summing individual nucleosynthesis events (encounters) with an average temporal spacing δ followed by a final actual free decay time Δt [1, 5]

$$\frac{N_{\mathrm{R}}}{N_{\mathrm{S}}} = \left[\frac{P_{\mathrm{R}}}{P_{\mathrm{S}}}\frac{\delta}{T}\left(1 + \frac{e^{-\delta/\tau}}{1 - e^{-\delta/\tau}}\right)\right]\exp(-\Delta t / \tau) \quad (1)$$

where N_i and P_i are number and production rates for radionuclides (R) and stable isotope partner (S), respectively, T is the age of the Galaxy, Δt is in this case the time interval between the last event and the birth of the solar system, and τ is the mean life of R against radioactive decay. It is common to examine the abundances of the radionuclides in terms of α = $(N_{\mathrm{R}}/N_{\mathrm{S}})/(P_{\mathrm{R}}/P_{\mathrm{S}})$ versus τ. Equation (1) can be used to derive models of log(α) versus log(τ), resulting in several groupings of radionuclides (Fig. 1). For example, one finds that the relative concentrations of r- and (in one case) p-process radionuclides ^{129}I, ^{146}Sm, ^{244}Pu, ^{235}U and ^{238}U are all explained by δ = 10 Myr and Δt = 100 Myr (Fig. 1). The value for δ is consistent with the frequency of supernova events affecting random positions in the Galactic disk [6] and so is appropriate for these SNe-derived nuclides. We label these isotopes Group I for reference. Similarly, it was shown recently [5] that the same δ and Δt values can explain the relative concentrations of both ^{107}Pd and ^{182}Hf, both nuclides being dominantly s-process products from AGB stars (Fig. 1). Using a value for δ of 50 Myr appropriate for AGB star encounters, a Δt of 40.35 Myr fits the relative concentrations (Fig. 1). We refer to these radionuclides as Group II. ^{53}Mn and ^{60}Fe are treated separately from Group I and II. ^{53}Mn is also fit by the Group II curve but its origin must be distinct as it is a SN product, suggesting a shorter δ interval. ^{60}Fe requires its own Δt (Fig. 1). The shortest-lived nuclides, labeled Group III, are explained with Equation (1) using δ = 50 Myr and Δt = 1.3 Myr (Fig. 1). The latter model reflects the fact that these short-lived nuclides have no "memory" of events prior to their most recent synthesis. Five distinct models defined by five Δt values (δ values are prescribed *a priori* by astrophysical constraints) represented by five curves are therefore required to explain the radionuclide abundances in Fig. 1, one each for Groups I, II, and III and two others for ^{53}Mn and ^{60}Fe.

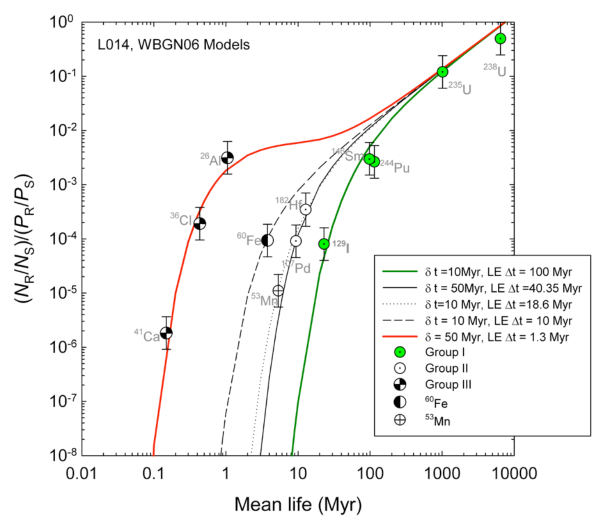

Figure 1. Encounter models discussed in text.

SFR Enrichment: The self-enrichment of star-forming regions includes the effects of winds from Wolf-Rayet (WR) stars. In one recent formulation, all 12 radionuclides considered in Fig. 1 are explained by a single model involving a two-phase interstellar medium with the present-day molecular cloud mass fraction $x_{\mathrm{MC}} \sim 0.17$ [3, 7]:

$$\log(\alpha) = 2\log\tau_R - \log\left[(1 - x_{MC})\tau_{MC} + \tau_R\right] - \log T \quad . \qquad (2)$$

The model fits the solar-system data using two independent parameters, the enhancement of WR wind production over SN production in SFRs, Λ_W/Λ_{SNe} = 4000, and the sequestration time of nuclides in molecular cloud (MC) dust, τ_{MC} = 200 Myr (Fig. 2) [3].

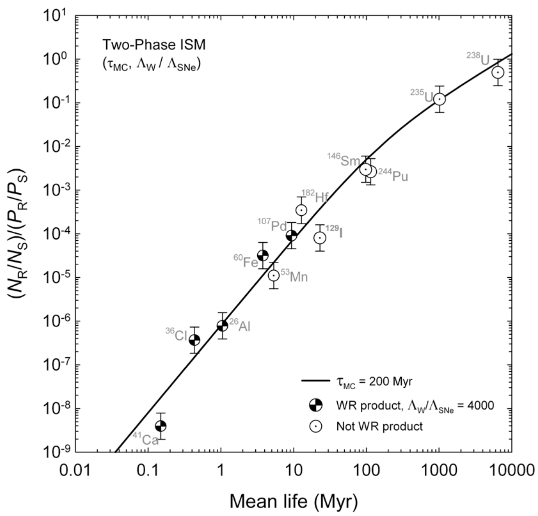

Figure 2. SFR enrichment model.

Statistical Analysis: Bayes'/Laplace's theorem can be used to assess the relative likelihoods of the two explanations shown in Figures 1 and 2. The relevant equation is

$$\frac{P(h_1 \mid \vec{x})}{P(h_2 \mid \vec{x})} = \underbrace{\frac{P(\vec{x} \mid \vec{\theta}_1 h_1)}{P(\vec{x} \mid \vec{\theta}_2 h_2)} N^{-1/2(n_{\theta,1} - n_{\theta,2})}}_{\text{Bayes Factor}} \overbrace{\frac{P(h_1)}{P(h_2)}}^{\text{Priors}} \qquad (3)$$

where $P(h_i \mid x)$ is the posterior probability of hypothesis h_i given data $\vec{x}$, $P(\vec{x} \mid \vec{\theta}_i h_i)$ is the conditional probability for data $\vec{x}$ assuming hypothesis h_i represented by parameters $\vec{\theta}_i$ is correct, N is the number of data (in this case 12), $n_{\theta,i}$ are the number of parameters defining the models, and $P(h_i)$ are the *a prior* probabilities for hypotheses i independent of the data. The conditional probabilities are assessed as the integrals of the χ^2 probability densities for each fit. The models in Fig. 1 together are defined by 5 independent parameters yielding 7 degrees of freedom and a combined reduced χ^2 of 1.14, corresponding to $P(\vec{x} \mid \vec{\theta}_1 h_1)$ = 0.335 (0.5 is optimal). The model in Fig. 2 is defined by 2 independent parameters, 10 degrees of freedom, and a reduced χ^2 of 0.95, corresponding to $P(\vec{x} \mid \vec{\theta}_2 h_2)$ = 0.484. Assuming equal priors of 0.5 each for now, Equation (3) leads to

$$\frac{P(h_1 \mid \vec{x})}{P(h_2 \mid \vec{x})} = \underbrace{\frac{0.335}{0.484} 12^{-1/2(5-2)}}_{\text{Bayes Factor}} \overbrace{\frac{0.5}{0.5}}^{\text{Priors}} = 0.017 \quad . \qquad (4)$$

This ratio, being << 1, constitutes "strong" evidence [8] that the SFR hypothesis (h_2) is favored over the chance-encounter hypothesis (h_1). The fits to the data are effectively equally good and can't distinguish the models. Rather, the result in Equation (4) is attributable to the Schwarz criterion portion of the Bayes Factor [9] that penalizes models for many versus fewer fit parameters (~Occam's razor).

Implications: If self-enrichment of an SFR is the explanation for the solar abundances of the short-lived radionuclides (SLRs), the solar-system abundances of these isotopes must be averages of progenitor dust grains with SLR abundances ranging from ~ zero (old grains) to values greater than solar (very young grains). A model for the ^{26}Al/^{27}Al produced by random grain growth from large numbers of SFR grains is shown in Fig 3. The central limit theorem ensures that the ^{26}Al/^{27}Al distribution of the new grains is Gaussian even though the initial distribution is heavily skewed towards very low values due to decay for 10^8 yrs. Using the central limit theorem, one calculates that the range in ^{26}Al/^{27}Al of CAI precursor dust spanned many orders of magnitude given that it takes of order 10^{11} ISM dust grains to make a CAI.

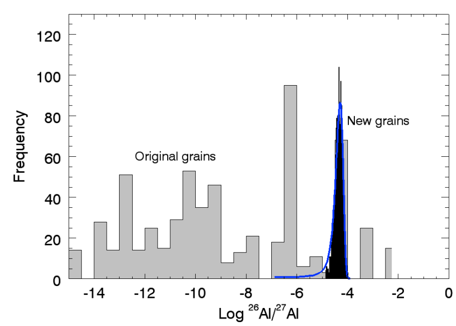

Figure 3. Model ^{26}Al/^{27}Al of grains in an SFR (grey) sampled at random (black). Blue curve is a Gaussian fit to the new grains (note that the abscissa is in log units).

References: [1] Wasserburg G.J. et al. (2006) *Nuclear Physics A* 777, 5-69. [2] Wasserburg G.J. et al. (1996) *ApJ* 466, L109-L113. [3] Young E.D. (2014) *EPSL* 392, 16027. [4] Jura M. et al. (2013) *ApJL* 775, L41. [5] Lugaro M. et al. (2014) *Science* 345, 650-653. [6] Meyer B.S. and Clayton D.D. (2000) *Space Science Reviews* 92, 133-152. [7] Jacobsen S.B. (2005) in *Chondrites and the Protoplanetary Disk*, Astr. Soc. of the Pacific. p. 548-557. [8] Kass R.E. and Raftery A.E. (1995) *J. Am. Statistical Association* 90, 773-795. [9] Schwarz G. (1978) *Annals of Statistics* 6, 461-464.