GALACTIC CHEMICAL EVOLUTION OF NRLEE DUST.

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Introduction: Isotopic anomalies in planetary materials appear to call for the presence of dust in the early Solar System that was highly enriched in the neutron-rich, iron-group isotopes (e.g., [1,2]). It is well known that significant production of these isotopes occurs in freeze outs of low-entropy, neutron-rich matter [3], but the astrophysical setting for such freeze outs is still under debate. Proposed sites include dense thermonuclear supernovae [4], electron-capture supernovae [5], or thermonuclear electron-capture supernovae (tECSN) [6]. Given the still uncertain identification of the astrophysical site of dominant production of neutron-rich, iron-group species, it is useful to refer to the possible sites generically as NRLEEs (Neutron-Rich, Low-Entropy matter Ejectors). This contribution seeks to shed some light on the dust from NRLEEs that might have been present in the early Solar System and given rise to anomalies in neutron-rich, iron-group isotopes.

Methods: We performed Galactic Chemical Evolution (GCE) calculations with a multi-zone GCE code developed at Clemson. We considered stellar yields from high-mass stars (stellar mass greater than 10 times the Sun's mass) [7] and thermonuclear supernovae [8]. Low-mass stars (mass less than 8 times the mass of the Sun) were taken to return their initial composition. We included NRLEEs as tECSN events from a fraction of 8-10 solar mass stars and computed their yields from a NRLEE model we developed [9]. We chose a Galactic halo infall timescale of 1 Gyr, a star-formation rate linear with Galactic mass, and a star-formation timescale sufficient to produce ^{16}O at its Solar System mass fraction 8 Gyr into Galactic history (when we consider the Sun to have formed).

The model kept track of several dust reservoirs in the Galaxy in addition to a gas and molecular cloud reservoir. In the model, high-mass stars ejected their condensable matter into the snII dust reservoir, low-mass stars ejected condensable matter into the low-mass-star dust reservoir, and NRLEEs ejected condensable matter into the NRLEE dust reservoir. We took thermonuclear supernova (SNIa) to eject matter into the gas reservoir since the high velocities and high degree of radioactivity in these ejecta probably limit the condensation of dust.

In the interstellar medium, spallation and shattering destroy dust and re-accretion builds it back up. We modeled these processes by considering mass to move from the dust reservoirs to the gas reservoir on a timescale of 10^8 years. We also considered gas and dust to mix into the molecular cloud reservoir on a 10^7 year timescale. Non-condensable molecular cloud material mixed back into the gas reservoir while condensable matter mixed into an old dust reservoir. Both of these processes occurred on a 10^7 year timescale.

With this model, we evolved an initial composition of 77% ^{1}H and 23% ^{4}He, which is characteristic of the cosmic abundances after the Big Bang from t = 0 (taken to be 1.2 Gyr into the Universe's history) to the current time, taken to be 12.6 Gyr (that is, 13.8 Gyr after the Big Bang). We considered the Sun to have formed 8 Gyr into our calculation (that is, 9.2 Gyr into the Universe's history and 4.6 Gyr ago). In the model, we evolved a parcel of the Galaxy consisting of 10^6 solar masses.

Results: Figure 1 shows the mass fractions of stable nuclear species at a time of 8 Gyr as evolved in the model compared to Solar System mass fractions [10]. Apart from some notable exceptions, most species have evolved mass fractions that lie within a factor of 2-3 of their Solar mass fraction at Solar time. We took the model mass fractions at 8 Gyr to be our Solar mass fractions for the rest of our calculations.

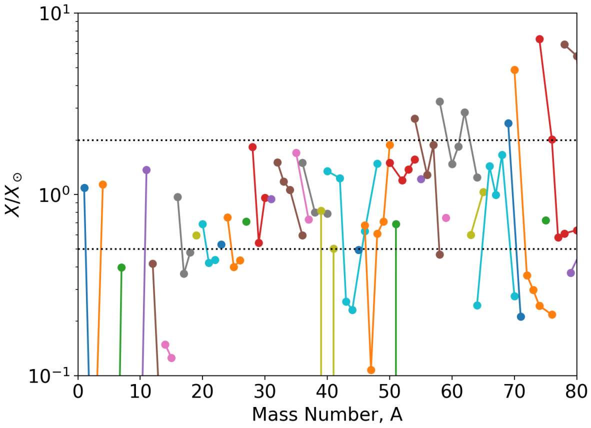

Figure 1: The evolved mass fractions of isotopes in the model at 8 Gyr relative to the Solar-System mass fractions [10]. Isotopes of the same element are connected by line segments of the same color.

In Figure 2, we show the masses in the various dust reservoirs. In the model, star formation peaks about 2 Gyr into the calculation. Galactic gas mass builds up due to infall but declines as gas mass gets locked up into long-living, low-mass stars. The masses of the snII and NRLEE dust reservoirs initially grow and then decline. These stars have short lifetimes compared to the that of the Galaxy and thus their rate of production of dust tracks the star-formation rate well. In contrast, the mass in the low-mass-star dust reservoir grows throughout Galactic history. This is because low-mass stars live for billions of year so that their return of dust and gas to the Galaxy is delayed. The same is true for the processed (old) dust.

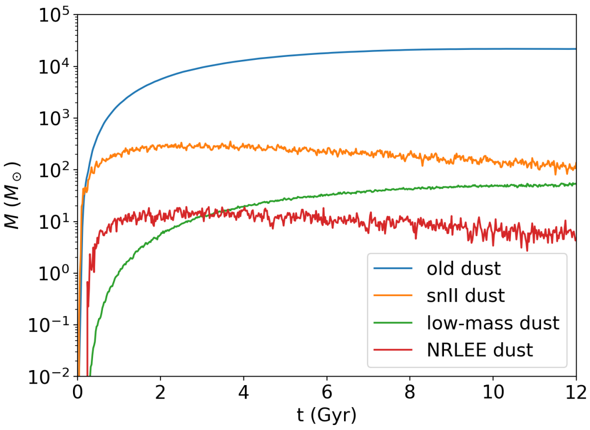

Figure 2: Mass (in solar masses) of the indicated dust ensembles.

In Figure 3, we show the excesses and deficits of calcium abundances relative to our evolved Solar abundances at 8 Gyr model time. The excesses are presented as per mil mass fraction deviations from the evolved Solar mass fractions (donated as $\bar{X}_\odot$) normalized to the deviation for ^{44}Ca; that is,

$$\delta(^{i}\mathrm{Ca}/^{44}\mathrm{Ca}) = 1000 \times \left(\frac{X(^{i}\mathrm{Ca})/\bar{X}_\odot(^{i}\mathrm{Ca})}{X(^{44}\mathrm{Ca})/\bar{X}_\odot(^{44}\mathrm{Ca})} - 1 \right)$$

A negative δ for a species indicates that the mass fraction of that species in the particular dust ensemble is less than that for the evolved Solar abundance relative to ^{44}Ca. The numbers in the figure legend for each dust ensemble indicate the fraction of the total dust mass and the fraction of the total calcium that dust ensemble contributes. Thus, for example, NRLEE dust contributes 0.05% of total dust mass in our modeled Solar System and contributes 0.24% of our modeled Solar System's budget of calcium.

Discussion: From Figure 3, it is clear our model predicts that most dust (nearly 99%) in the early Solar System is in the form of processed (old) dust. This dust is re-accreted dust that is not anomalous. NRLEE dust contributes only 0.05% of the total dust mass in the early Solar System. Nevertheless, that dust is extremely anomalous with a huge enrichment in ^{48}Ca (nearly 30,000 per mil). Results for Ti and Cr in NRLEE dust show similarly huge anomalies in ^{50}Ti (~14,000 per mil) and ^{54}Cr (~4,000 per mil). In an accompanying abstract [11], we show that heterogeneous mixes of our modeled dust ensembles can reproduce observed anomalies in these neutron-rich, iron-group isotopes in planetary materials.

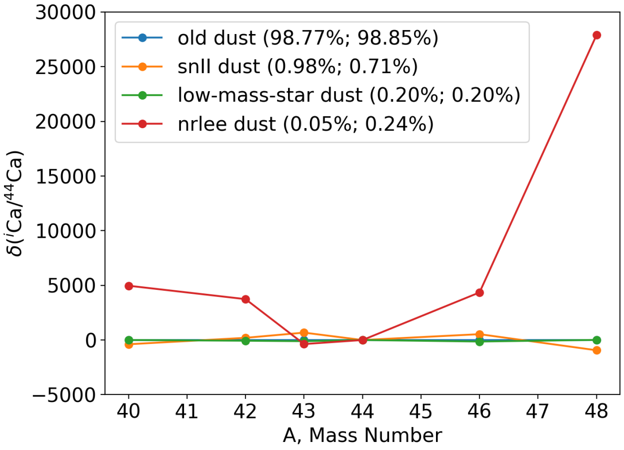

Figure 3: Per mil excesses and deficits of the calcium isotopes relative to the evolved solar abundances for the different dust ensembles relative to ^{44}Ca. Numbers in the plot legend refer to the percent contribution of the dust ensemble mass to the total dust mass and to the contribution of the dust ensemble to the Solar System's supply of calcium, respectively.

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