SHORT-LIVED RADIOACTIVITIES AND GALACTIC CHEMICAL EVOLUTION.

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Introduction: A proper accounting for the inferred abundances of the roughly 10 short-lived radioactivities in the early Solar System requires a comparison to their expectations from an appropriate model of Galactic chemical evolution (GCE) (e.g., [1]). Because the timescale for mixing between phases in the interstellar medium (ISM) is comparable to the lifetime of many of the short-lived radioactivities, the GCE model should follow different ISM phases and the mixing between them. The model must also account for the long temporal distance between the rare astrophysical events that produce many of the short-lived species, such as mass transfer from a low-mass star to its white dwarf companion leading to a thermonuclear supernova or a neutron star-neutron star collision that may lead to production of r-process isotopes. In this work, we present expectations for the abundances of short-lived radioactivities in the early Solar System with a detailed GCE model that accounts for these effects.

Methods: We model inhomogeneous GCE with the NucNet Project ICE (Inhomogeneous Chemical Evolution). ICE is built on top of the multi-zone NucNet Tools module, which follows time-dependent mixing and nuclear reactions in a set of coupled reaction networks. For this particular study, we constructed a circular array of 32 zones to represent the Solar annulus. The mass of the annulus builds up by infall of gas from a metal-poor halo. We choose an infall timescale for the annulus of 1 Gyr and a final total mass of 10^8 Solar masses (1 Solar mass = 1 $M_\odot$). Stars form in the gas according to a Schmidt law with an exponent of 1 [2]. We include the effect of 3 spiral arms by allowing mass to concentrate in particular zones in the annulus according to a time-varying law such that each zone experiences a mass build-up (and enhanced star formation) 3 times every 200 Myr.

By comparing the resulting gas mass fraction in our models to the gas mass fraction of ~0.15 at the current Galactic time (taken to be 13 Gyrs) [3], we established a star-formation rate of one star per 1550 years per 10^6 $M_\odot$. During each time step, we compute the number of stars from the star-formation rate, distribute their masses according to an appropriate initial-mass function [4], and record their metallicities and lifetimes. Each star can be either single or part of a two- or three-star system. When a star dies, we follow its injection of new nuclei into the surrounding medium and allow that material to mix on an appropriate timescale. Low-mass stars leave behind white dwarf remnants, which, if part of a binary star system, can explode in ~10^8 years as a thermonuclear supernova. High-mass stars leave behind either neutron stars or black hole remnants. If a massive-star binary system develops into a neutron star-neutron star pair, those remnants can spiral into each other (due to release of gravitational radiation) on a timescale of ~2 x 10^8 years and eject r-process isotopes [5]. We use calculated yields for massive stars [6,7] and thermonuclear supernova [8], and a Solar-system r-process distribution for the neutron star-neutron star collisions. We keep track of the initial abundances in Solar-mass stars that form near the time of the Sun's birth.

Results: Our models with star-formation rates consistent with the current Galactic gas mass ratio and a mixing time for ejecta into star-forming regions of ~10^7 years provide abundances of ^{53}Mn, ^{60}Fe, and ^{146}Sm in Solar-mass stars forming at the time of the Sun's birth that are in reasonable agreement with the inferred values [1,9]. As has been found by many studies, the ^{26}Al/^{27}Al ratio is too low and requires special injection (e.g., [10]). In our models, as the ^{41}Ca abundance varies widely, the observed value [11] can be accommodated, although this species might be injected along with ^{26}Al [12]. The models have difficulty accounting for the abundance of ^{36}Cl, which may be produced by irradiation in the early Solar System [13]. We can account for the abundances of the r-process radioactivities, ^{107}Pd, ^{129}I, and ^{244}Pu, as products of neutron star-neutron star mergers and interpret the abundance of ^{182}Hf via production in the shells of massive stars, which also contribute to the abundances of ^{107}Pd and ^{129}I.

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