GALACTIC CHEMICAL EVOLUTION AND THE STEADY-STATE ABUNDANCES OF SHORT-LIVED RADIOACTIVITIES IN THE INTERSTELLAR MEDIUM. B. S. Meyer[1] and G. R. Huss[2], [1]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, mbradle@clemson.edu. [2]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, 1680 East-West Road, Honolulu, HI 96822, ghuss@higp.hawaii.edu.

Introduction: Over the history of the Galaxy, stars have created new nuclei and ejected them into the interstellar medium (ISM). In this way, the abundance of the chemical elements has built up over time. While this process is complex in detail owing to the complicated structure of the different phases of the Galaxy, simple but realistic models of Galactic Chemical Evolution (GCE) provide a useful description. Such models, which treat the build up of the Galactic disk mass by metal-poor infall and the primary and secondary nucleosynthetic aspects of species under consideration, can also provide valuable baseline predictions of the steady-state abundances of short-lived radioactivies for comparison to their inferred abundances in the early Solar System (e.g., [1,2]). Here we present some details of such models.

Gas Mass in the Solar Annulus: Mixing by shear or similar forces in the Galactic disk is easier in the azimuthal than in the radial direction. For this reason, it is convenient to consider the chemical evolution of an annulus centered on the Sun's orbit in the Galaxy. This so-called "solar annulus" consists of gas, stars, and stellar remnants. In the "instantaneous recycling approximation", in which stars form from gas and then immediately return a fraction R of their mass back to the gas, the gas mass M_G is governed by the equation

$$\frac{dM_G}{dt} = -(1-R)\psi(t) + f(t) = -\omega M_G + f(t) \qquad (1)$$

where $\psi(t)$ is the mass per unit time going from gas into stars, and $f(t)$ describes the rate at which metal-poor gas is falling into the galaxy at the Sun's location to build up the galactic disk. In the second equality, we assume a linear star-formation rate, that is, one proportional to the gas mass: $(1-R)\times\psi(t) = \omega M_G(t)$, where ω is the (constant) rate of mass consumption.

Clayton [3] considered a "standard model" in which infall occurs continuously and behaves in time according to the function

$$\frac{f(t)}{M_G(t)} = \frac{k}{t+\Delta}. \qquad (2)$$

k and Δ are constant parameters that shape the infall function. For integer k, analytic solutions to equation (1) exist [3]. The mass of gas builds up by infall but decreases as it is locked up into stars. Note that k=0 corresponds to no infall. This is the so-called "closed-box" model in which the mass of the disk remains constant in time and the mass of the gas decays exponentially as gas converts into stars and stellar remnants. For $k > 0$, the galactic disk builds up by infall that extends over longer time for larger k.

To solve for the gas mass in the Solar annulus, we chose Δ=0.1 Gyr, a standard value (e.g., [4]) and required that the gas comprises 10% of the mass of the Solar annulus at the current time [5], which we took to be 12 Gyr. With these conditions, we solve numerically for ω and find, ω=0.192 Gyr^{-1} (k=0), ω=0.299 Gyr^{-1} (k=1), ω=0.396 Gyr^{-1} (k=2), ω=0.488 Gyr^{-1} (k=3), and ω=0.577 Gyr^{-1} (k=4). Figure 1 then shows the mass of gas in the annulus normalized to its maximum value as a function of time.

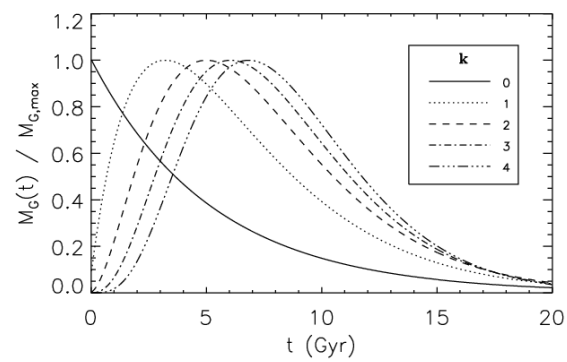

Figure 1

Mass Fractions in the Gas: It is now possible to follow the build up of metals (in astronomers' parlance, species heavier than hydrogen and helium) in the gas mass. In particular, we seek Z_i, the fraction of the gas mass that is in species i in the Solar annulus. The relevant equation is

$$\frac{dZ_i}{dt} = y_i\omega - \frac{Z_i}{\tau_i} - (Z_i - Z_{if})\frac{f(t)}{M_G(t)} \qquad (3)$$

where y_i is the yield of species i (that is, the increase in the mass of species i in the gas per unit increase in the mass of stars and stellar remnants), τ_i is the lifetime of the species against radioactive decay, and Z_{if} is the mass fraction of species i in the infalling matter. For simplicity, we consider the infalling matter to be completely free of metals; thus, $Z_{if} = 0$.

To compute Z_i, we require the yield y_i. Chemical evolution theory distinguishes between primary and secondary species. Primary species are those whose yields are independent of the initial metallicity of the star. Classic examples of primary isotopes are ^{16}O, ^{28}Si, and ^{56}Fe. Secondary species are synthesized in stars from pre-existing species; thus, the synthesis of a secondary species is proportional to the initial metallicity. Classic examples of secondary isotopes are ^{14}N and ^{17,18}O. The yield of a primary species then may be denoted by α_i, a constant, for each species i. By summing over all primary metals, we thus compute the primary metallicity yield $\alpha = \sum_i \alpha_i$. We then solve for the primary metallicity $Z^{(p)}$. The solution is [2]

$$Z^{(p)}(t) = \frac{\alpha\omega\Delta}{k+1}\left[\left(\frac{t+\Delta}{\Delta}\right) - \left(\frac{t+\Delta}{\Delta}\right)^{-k}\right] \xrightarrow[t>>\Delta]{} \frac{\alpha\omega t}{k+1} \quad (4)$$

This equation shows the classic linear time dependence of primary metallicity in GCE models. For a stable primary species then, $Z_i^{(p)}(t)$ is exactly analogous to equation (4) except α is replaced by α_i.

For a short-lived primary species, we may consider the limit $dZ_{(i)}^{(p)}/dt \rightarrow 0$. The result is that

$$Z_i^{(p)}(t) = \alpha_i \omega \tau_i, \quad (5)$$

which is valid for $t >> \tau_i$.

For secondary species, the yield is proportional to the primary metallicity. It may thus be denoted $\beta_i Z^{(p)}$ [6]. The solution for the gas mass fraction for the secondary species in the limit $t >> \Delta$ is

$$Z_i^{(s)} = \frac{\beta_i \alpha \omega^2}{(k+1)(k+2)} t^2. \quad (6)$$

This equation shows the classic quadratic dependence of secondary metallicity on time. For a short-lived radioactive species, the steady-state abundance is given by

$$Z_i^{(s)} = \frac{\beta_i \alpha \omega^2}{k+1} t \tau_i. \quad (7)$$

With these solutions, it is now possible to consider abundance ratios of species in the gas in the solar annulus. In particular, for a short-lived species i and a stable species j, if we decouple the primary and secondary aspects of each species, we find [1] for $t >> \Delta$

$$\frac{Z_i}{Z_j} = \frac{\left[(k+1)(k+2)\alpha_i + (k+2)\beta_i \alpha\omega t\right]}{\left[(k+2)\alpha_j + \beta_j \alpha\omega t\right]} \frac{\tau_i}{t}. \quad (8)$$

Example: ^{26}Al/^{27}Al and ^{60}Fe/^{56}Fe. We compute in [1] the yields for various species of interest from the models of [7]. Figure 2 shows the ratio of ^{26}Al/^{27}Al in the average ISM from equation (8) using our yields. At the time of Solar System formation (t ≈ 7.5 Gyr), the ratio is less than the canonical value 5x10^{-5}. From gamma-ray observations, the ^{26}Al/^{27}Al ISM ratio has been inferred to be ~8.4x10^{-6} [8], but this estimate used Solar abundances for the current ^{27}Al mass fraction. If we correct for evolution of ^{27}Al from the time of the Sun's birth to today, the inferred ratio for a *k=1, Δ=0.1* Gyr model would be ~2.5x10^{-6}, in excellent agreement with the 12 Gyr value in Figure 2. Gamma-ray observations also provide an estimate of the ^{60}Fe mass in today's ISM [9]. From this number and a ^{56}Fe mass fraction evolved forward from the time of the Sun's birth to today, we infer a current ^{60}Fe/^{56}Fe ISM ratio of ~3x10^{-8}. This is in good agreement with the value we compute from equation (8) for a *k=1, Δ=0.1* Gyr GCE model.

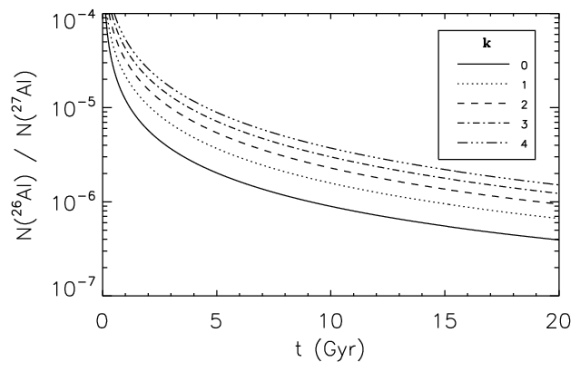

Figure 2

Further analysis of ISM abundances of short-lived radioactivities is presented in [1,2].

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