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ON ^{26}Al AND OTHER SHORT-LIVED INTERSTELLAR RADIOACTIVITY

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ABSTRACT

Several authors have shown that massive stars exploding at a rate of about three per century can account for a large portion, if not all, of the observed interstellar ^{26}Al. In a separate argument using models of Galactic chemical evolution, Clayton (1984) showed that the ^{26}Al/^{27}Al production ratio was not large enough to maintain enough ^{26}Al in the Galactic disk gas of $\sim 10^{10}$ $M_\odot$ having solar composition. We present a resolution of those conflicting arguments. A past history of Galactic infall growing the Galactic disk so dilutes the stable ^{27}Al concentration that the two approaches can be brought into near agreement. *If* massive stars dominate the production of ^{26}Al, we suggest that the apparent shortfall of their ^{26}Al/^{27}Al yield ratio is to be interpreted as evidence for significant growth of the Galactic disk. We also discuss the implications of these arguments for other extinct radioactivities in meteorites, using ^{129}I and ^{146}Sm as examples.

Subject headings: galaxies: abundances — galaxies: evolution — galaxies: ISM — gamma rays: theory — ISM: abundances — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

Recently two instruments aboard the *Compton Gamma-Ray Observatory* (*CGRO*) have reported detection of 1.809 MeV γ-ray line emission from interstellar ^{26}Al (Diehl et al. 1993a, b; Purcell 1993) at flux levels comparable to earlier detections (Mahoney et al. 1984; Share et al. 1985). The *CGRO* observations reaffirm the earlier claims that the interstellar gas contains about 2–3 $M_\odot$ of ^{26}Al, the exact value depending on the assumed distance to the Galactic center and the assumed spatial distribution of aluminum. The *CGRO* observations confirm that the emission must be concentrated in the inner portions of the Galactic disk, i.e., within the Sun's galactocentric radius, and that the emissivity is not a very smooth function of Galactic position. Although some smaller amounts of ^{26}Al should also exist in the interstellar medium (ISM) outside the Sun's orbit, the flux from these regions is small and not yet detected by *CGRO*. However, emission in the latitude range 310°–30° was clearly detected by both COMPTEL (Diehl et al. 1993a, b) and OSSE (Purcell 1993). The astrophysical context of these measurements has recently been summarized by Prantzos (1993) and an earlier review of related astrophysical issues was provided by Clayton & Leising (1987).

The earliest belief was that radioactive ^{26}Al in the ISM would be due to Type II supernovae (SN II's). Indeed, Woosley & Weaver (1980) predicted a possibly observable quantity based on their SN II explosive yields and a mean recurrence rate for those supernovae. They obtained a production ratio $y(^{26}$Al$)/y(^{27}$Al$) \simeq 0.002$. Later work (Woosley 1991) suggested even higher yields. Also, neutrino-induced synthesis of ^{26}Al can significantly boost the yield in the neon shell (Woosley et al. 1990). Prantzos (1993) also presented improved yield estimates for massive stars and showed that 0.2–1.4 $M_\odot$ of ^{26}Al might be maintainable by three SN II's per century, although the upper end of this range requires favorable assumptions. Timmes, Woosley, & Weaver (1993a) used their new yield survey to conclude that four supernovae of Type II and Ib per century maintain 1.78–2.14 $M_\odot$ of ^{26}Al in the ISM. This line of reasoning in simplified form assumes that the explosive processing of a 25 $M_\odot$ star ejects a mass of $M_{ej} \sim 0.67 \times 10^{-4}$ $M_\odot$ of ^{26}Al

(Weaver & Woosley 1993), that 25 $M_\odot$ is reasonably typical of SN II progenitor masses, and that an average rate of $R_{II} = 3$ events per century is representative for the Galactic disk (van den Bergh & Tammann 1991). The mass produced over the past Myr is then

$$M_{26} = M_{ej} R_{II} \tau_{26}$$
$$= (0.67 \times 10^{-4})(3 \times 10^{-2})(1.0 \times 10^{-6}) \sim 2\ M_\odot\ ,$$

consistent with the amount inferred from γ-ray observations.

Clayton's (1984) counterargument followed immediately after the discovery of 1.8 MeV γ-ray emission and presented a less optimistic line of reasoning. In simple models of Galactic chemical evolution, the steady state concentration ratio in the gas phase is approximately

$$\frac{X(^{26}\text{Al})}{X(^{27}\text{Al})} \simeq \frac{y(^{26}\text{Al})}{y(^{27}\text{Al})} \frac{\tau_{26}}{T_G}\ ,$$

where T_G is the age of the Galactic disk. This result is exact for the linear closed-box model with instantaneous recycling. It is almost exact when instantaneous recycling is relaxed, for that assumption affects the problem only slightly. Using a Salpeter IMF, the average over Weaver & Woosley's (1993) mass spectrum of SN II progenitors gives $y(^{26}$Al$)/y(^{27}$Al$) \sim 0.006$, significantly larger than their earlier estimate (Woosley & Weaver 1980; Woosley 1991). The expected interstellar ratio by Clayton's argument would then be

$$\frac{X(^{26}\text{Al})}{X(^{27}\text{Al})} = 0.006 \frac{1.0 \times 10^6}{1.2 \times 10^{10}} \sim 5 \times 10^{-7}\ ,$$

where we have assumed a disk age of $T_G = 1.2 \times 10^{10}$ yr. The total gas mass within the solar orbit is $\sim 10^{10}$ $M_\odot$ and if for simplicity it is assumed to have solar composition such that $X(^{27}$Al$) = 5.8 \times 10^{-5}$ (Anders & Grevesse 1989), the total expected mass of ^{26}Al would be

$$M_{26} = \frac{X(^{26}\text{Al})}{X(^{27}\text{Al})} M_{27} \sim 0.3\ M_\odot\ .$$

This value is ~5–10 times smaller than that expected from the recurrence rate estimate. For this reason Clayton (1984) suggested that novae might be the more likely source for ^{26}Al. The discrepancy remains after taking into account the fact that the average gas metallicity in the Galactic disk is higher than solar.

Both arguments presented above are appealing and conceptually correct but have recognized uncertainties. We therefore point to another possible resolution, emphasizing the important effect of gas infall onto the disk. We do not wish to defend the above numerical estimates as correct or the best that can be done. Those estimates do seem fair, and we use them for displaying the historical conflict of the two competing approaches and for demonstrating the subtle effect of the Galactic infall history.

2. GALACTIC INFALL AND RADIOACTIVITY

The instantaneous recycling approximation (IRA) is acceptable as long as one is not interested in early Galactic evolution when stellar evolution of massive stars and dynamic evolution of the system occur on comparable timescales (e.g., Malinie, Hartmann, & Mathews 1991), or in very late times where the gas fraction is so low that the delayed return from low-mass stars matters, or when one does not discuss a nucleosynthesis product from low-mass stars (e.g., Clayton & Pantelaki 1986). For present-day disk concentrations derived from massive stars, the IRA is not a bad approximation, and because it enables a clear analytic demonstration of abundance effects, we employ it in this study. In the same spirit, choosing a star formation rate proportional to the mass of gas is a plausible and convenient assumption. Although realistic star formation rates could depend on several disk properties, the simple linear density law leads to analytic simplifications and does not bias the theoretical point to be made. With those assumptions, the temporal evolution of the concentration (by mass) in the ISM of a radioactive species is given by

$$\partial_t Z = y_z \omega - \frac{f(t)}{M_g(t)} Z - \lambda Z , \qquad (1)$$

where $f(t)$ is the infall rate of metal-poor gas, λ is the radioactive decay rate, and we have assumed that the radioactive species under consideration is not present in the infalling material. Clayton (1984, 1985, 1988) obtained analytic solutions of this equation for a large number of parameterized families of infall history, not only for stable abundances but for the radioactive ones as well. Clayton (1988) discussed in detail the consequences of mass accretion onto the Galactic disk for the radioactive cosmochronometers (see also Cowan, Thielemann, & Truran 1991), and a concise tutorial of the analytic methods is provided by Clayton (1986). In the analytic family that Clayton (1985) considered as a standard model for analytic comparisons to data and to computer models of chemical evolution, the ratio of the rate of infall, $f(t)$, to the mass of interstellar gas, $M_g(t)$, is defined by an integer parameter (k) and a time constant (Δ) via

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

The analytic result for the mass fraction of stable nuclear species in the gas phase is

$$Z - Z_0 = \frac{y_z \omega \Delta}{k + 1} (x - x^{-k}) , \qquad (3a)$$

where x is defined as

$$x = \frac{t + \Delta}{\Delta} . \qquad (3b)$$

The radioactive concentrations are given by

$$Z_\lambda - Z_0 e^{-\lambda t} = y_z \omega e^{-\lambda t} x^{-k} \int_0^t dt' x^k e^{\lambda t'} , \qquad (4)$$

which is an easily derived product of a polynomial and exponential. For very short-lived radioactivities, on the other hand, equation (4) simplifies to

$$Z_\lambda = y_z \omega \left(\lambda + \frac{k}{t + \Delta} \right)^{-1} . \qquad (5a)$$

This result follows also from setting $\partial_t Z = 0$ in equation (1), valid for large values of λ (unless λ is so large that individual stars' ejecta dominate a transient fluctuating abundance, in which case the differential equation approach would not be appropriate), and by replacing $f(t)/M_G(t)$ by $k/(t + \Delta)$, which defines this analytic family. The decay rate of ^{26}Al, $\lambda_{26} = \tau_{26}^{-1} \sim 1.0$ Myr^{-1}, is small enough to implicate $\sim 10^4$ synthesis events, so that $Z(t)$ is expected to be smooth, but large enough that $\partial_t Z \sim 0$. If the radioactive decay rate is much greater than the current rate at which infall replenishes the gas mass of the Galactic disk, as is also true for ^{26}Al, then the even simpler expression

$$Z_\lambda(t) = \frac{y_z \omega}{\lambda} = y_z \omega \tau \qquad (5b)$$

becomes adequate. Thus we use equation (5b), for simplicity, in what follows. That will be appropriate for the decay rates of species we consider here.

Several things are evident from these relationships. First, the simple closed-box model is the family member having $k = 0$, and in that case it is clear by inspection that the interstellar ratio at Galactic age T_G is

$$\frac{X(^{26}Al)}{X(^{27}Al)} = \frac{y(26)}{y(27)} \frac{\tau_{26}}{T_G} . \qquad (6)$$

This reproduces the argument that Clayton (1984) introduced to argue against massive stars being responsible for the observed interstellar ^{26}Al. Second, for other family members whose infall histories are expressed by

$$f(t) = \frac{k M_G(0)}{\Delta} x^{k-1} e^{-\omega t} , \qquad (7)$$

the present ratio becomes

$$\frac{X(^{26}Al)}{X(^{27}Al)} = \frac{y(26)}{y(27)} \frac{(k + 1)\tau_{26}}{T_G + \Delta - \Delta x^{-k}} . \qquad (8)$$

If the age of the Galactic disk is considerably greater than the time parameter Δ, which is chosen to shape the infall, then $x \gg 1$ today, as is the case for many interesting and realistic models. In that case the concentration ratio is approximately equal to

$$\frac{X(^{26}Al)}{X(^{27}Al)} = \frac{y(26)}{y(27)} (k + 1) \frac{\tau_{26}}{T_G} \qquad (9)$$

which is a factor $(k + 1)$ larger than the result of the simple

model used by Clayton (1984). Because values as large as $k \sim 4$ seem plausible from several galactic evolution arguments (Pagel 1989a, b; Malinie et al. 1993), it is apparent that the interstellar aluminum isotope ratio in such models is several time larger than in closed-box models. It is in this way that galactic infall history can solve the apparent conflict between the two arguments.

How is it that past infall changes this expectation by such a large factor? Comparison of equations (3) and (5) shows that past infall has reduced the concentration of stable ^{27}Al by a factor approximately equal to $(k + 1)$ relative to the value it would have had in the closed-box model having the same yield and the same astration rate. The concentration of radioactive ^{26}Al is, on the other hand, almost independent of the infall parameter k. Thus, for ^{26}Al, the product of current supernova yield and recurrence rate is correct, as it must be. But the same cannot be said for the stable counterpart. Its growth over galactic time has been slowed by the infall of metal-poor matter, so that $Z(^{27}$Al$)$ is considerably less today than one would have anticipated in the absence of infall.

Even if past infall can be fitted to analytic models of this type, it is hard to argue for the most realistic value of the infall parameter k. A good fit to past infall may not reproduce the current infall rate. The central issue is how more massive the disk is today than when nucleosynthesis began in its smaller initial state. The factor by which infall has increased the total disk mass from its initial value $M_G(0)$ is quasi-linear in the parameter k (Clayton 1985; see also eq. [2]), so that a disk mass an order of magnitude greater than its initial value suggests $k \geq 1$. In a numerical study of chemical evolution, Timmes, Woosley, & Weaver (1993a, b) found good agreement with both 2 $M_\odot$ of ^{26}Al and the interstellar mass of ^{27}Al, a result that we understand in terms of the large infall rate used by them: $f = f_0 \exp(-t/4 \text{ Gyr})$, which increased the disk mass by a factor 40 between $t = 0.1$ Gyr and $t = 15$ Gyr.

Observations of high-velocity clouds as well as chemical evolution arguments suggest a present-day infall rate of only $\sim 1\ M_\odot\ \text{yr}^{-1}$ (e.g., Lacey & Fall 1985; Tosi 1988) and interchange processes among the ISM phases could lead to a present mass circulation rate between disk and halo of $\sim 1.6\ M_\odot\ \text{yr}^{-1}$ (Li & Ikeuchi 1989). Infall by mergers of more massive fragments with the disk is constrained through the resulting heating of the stellar component of the disk. Tóth & Ostriker (1992) have shown that over the past 5 Gyr the mass within the solar radius could not have grown by more than $4 \times 10^9\ M_\odot$ by sinking satellites, thus limiting the average infall rate to $\sim 1\ M_\odot\ \text{yr}^{-1}$. This stronger argument would limit values of the infall parameter to $k \leq 5$, but might also question the shape flexibility of this analytic family. Another factor is the reduced number of low-mass stars with low metallicity relative to the numbers expected in the closed-box model, i.e., the G-dwarf problem. Attempts to resolve it by early infall and disk growth indicate $k \sim 4$ (Lynden-Bell 1975; Clayton 1985; Pagel 1989a, b; Malinie et al. 1993). The age-metallicity relation (Twarog 1980; Carlberg et al. 1985) is not very sensitive to the value of k, and has notorious difficulty for fixing model parameters. One very helpful line of attack comes from any argument that limits the size of the ratio of early star formation in the disk in comparison with that today. A small ratio suggests, but does not require, large values for k. We will not address these hard problems here, for our purpose has been to suggest the following proposition: If the ^{26}Al has resulted pri-

marily from massive stars, its amount inferred from γ-ray observations then suggests that growth of disk mass by a substantial factor has occurred.

It was Larson (1972) who first described why infall limits the growth of metallicity. He presented an extreme model in which the star formation rate was constant and was exactly balanced by the infall rate. In such a model, all concentrations saturate to asymptotically constant values. If T_* is the time scale (say, 3 Gyr) for star formation to deplete the gas, the concentration ratio would be

$$\frac{X(^{26}\text{Al})}{X(^{27}\text{Al})} = \frac{y(26)}{y(27)} \frac{\tau_{26}}{T_*},$$

which would be larger than closed box predictions by a factor $T_G/T_* \sim 3$–4. We have here made the argument in terms of a more flexible family of analytic models because these can accommodate more realistic assumptions.

This particular analytic family is not the only infall shape that can illustrate the basic effect. Developing the analytic families for cosmochronology, Clayton (1988) also provided solutions for a family with exponential infall, defined arbitrarily by $f(t) = f(0)e^{-\omega't}$. Results from that family are very similar provided that the total infall grows the disk by comparable factors over comparable epochs. This is the infall function used by Timmes et al. (1993a, b).

Although the factor $(k + 1)$ resulting from the infall history may increase the simple model estimate enough to account for the total interstellar mass of ^{26}Al, it does not account for the tenfold higher isotopic ratios $X(^{26}\text{Al})/X(^{27}\text{Al}) \sim 5 \times 10^{-5}$ that are found in carbonaceous meteorites (e.g., Lee, Papanastassiou, & Wasserburg 1977). That large ratio probably represents instead a local enhancement of the solar cloud, a topic that we are not addressing here. The Galactic γ-ray observations represent an average of the inner ISM over the past few Myr. Nor do we address the issue of whether all of the meteoritic effects represent fossils of ^{26}Al that was still alive in the solar system bodies in which those samples are found (e.g., Clayton & Leising 1987).

3. OTHER EXTINCT RADIOACTIVITIES IN METEORITES

Meteorites contain several excesses in radiogenic daughter abundances that are attributed to the existence of their parent nuclei at the time the samples formed. These lead to very interesting astrophysical questions, because the observed ratios must always be compared to an expectation from continuous nucleosynthesis. And it is herein that the factor $(k + 1)$ has physical significance. Rather than reviewing this complicated subject, we illustrate the point with two of the most important examples, ^{146}Sm, with a discrepancy similar to that of ^{26}Al, and ^{129}I which is very different.

3.1. ^{146}Sm

Consider the case of ^{146}Sm with mean lifetime of $\tau_{146} = 1.5 \times 10^8$ yr. The corresponding decay rate $\lambda = 6.6\ \text{Gyr}^{-1}$ is nonetheless still comfortably greater than $f/M = k/(t + \Delta)$, so that using equation (5b) for its expected mean concentration remains valid. It is produced in the p-process with a best estimate production ratio of $y(^{146}\text{Sm})/y(^{144}\text{Sm}) = 0.1$, although that result remains uncertain until some open nuclear questions are resolved (Woosley & Howard 1990). Howard & Meyer (1993) obtain a somewhat smaller ratio (0.04) in a later

calculation based on Type Ia supernova models. The expected mean interstellar concentration ratio obtained from equation (9) is then

$$\frac{X(^{146}Sm)}{X(^{144}Sm)} = 0.1(k+1) \frac{1.5 \times 10^8 \, yr}{1.2 \times 10^{10} \, yr} \sim 1.25 \times 10^{-3}(k+1) \,.$$

Prinzhofer, Papanastassiou, & Wasserburg (1989, 1992) estimate from Sm-correlated ^{142}Nd excess in meteorites that at the birth of the solar system the live ratio was $^{146}Sm/^{144}Sm \sim 0.006-0.009$, at least a factor of 5 greater than the result in the case of closed-box ($k = 0$) models. This has been interpreted as a perceived need for a greater production ratio (Woosley & Howard 1990), but in light of the present discussion suggesting that $k \sim 4$, there may be little discrepancy at all. This is of high interest for p-process theory and for nucleosynthesis theory in general, because the p-process is a fairly reliably calculable theory, or at least will be so ultimately. Another similar interesting case is ^{244}Pu, whose concentration relative to long-lived ^{232}Th is also increased by the factor $(k + 1)$ (Clayton 1983).

3.2. ^{129}I

A meteoritic example showing less activity than the mean ISM is ^{129}I. Excess ^{129}Xe is found in chondritic meteorites in quantities that suggest that when the solar system formed radioactive $^{129}I/^{127}I \sim 1.0 \times 10^{-4}$ (Podosek & Swindle 1988). Both ^{129}Xe (from ^{129}I) and ^{127}I are overwhelmingly products of the r-process in supernovae, where the production ratio is $y(^{129}I)/y(^{127}I) \sim 1.42$, based on the solar abundance ratio $N_\odot(^{129}Xe)/N_\odot(^{127}I)$ (Anders & Grevesse 1989) and on a calculation (Käppeler et al. 1982) showing that the r-process is responsible for $\sim 96\%$ of each nuclear abundance. Current r-process theory (Meyer et al. 1992) is consistent with that yield. Since the 23.1 Myr mean lifetime of ^{129}I allows it to establish a steady abundance but is also short enough for $\partial_t Z = 0$, the expected concentration in the ISM is given by equation (9), except that at that time the Galactic age would have been $T = T_G - T_\odot = 7.4 \, Gyr$,

$$\frac{X(^{129}I)}{X(^{127}I)} = \frac{y(129)}{y(127)} \frac{\tau_{129}}{T} (k+1) \sim 4.4 \times 10^{-3}(k+1) \,,$$

which is ~ 44 times greater than the value observed in meteorites even in closed-box models ($k = 0$). For ^{129}I the problem is that the mean ISM is expected to have *more* than is actually found. Infall widens the discrepancy. The usual attitude for resolving this is to say that the personal molecular cloud was sequestered from nucleosynthesis imput for about 90 Myr, which allows the ^{129}I concentration to decay to its observed value in the meteorites before solar system formation occurred. Clayton (1983) provides a discussion of this interpretation and of a three-phase mixing model between distinct ISM phases that may provide a physical picture of this decay period. The factor $(k + 1)$ affects the interpretation of this model as well.

4. CONCLUSION

We have demonstrated that the history of infall by which the Galactic disk was grown plays a significant role in problems related to the Galactic concentrations of radioactivities. The ratio of ^{26}Al to ^{27}Al presently observed in the interstellar medium may be consistent with a picture in which the entire production of ^{26}Al is due to explosive nucleosynthesis in massive stars, provided that the infall rate was great enough. In terms of convenient analytic infall models presented in § 2 this requires values of $(k + 1) \sim 5$. The same factor, approximately $(k + 1)$, appears in the ratio of the concentration of any short-lived radioactivity to that of a stable reference isotope. In addition to resolution of the ^{26}Al discrepancy, these arguments will be useful for interpretation of numerical models of chemical evolution.

By stressing the role of massive stars we are not alleging that novae and AGB stars are not significant contributors to the total ^{26}Al yield. They do have the advantage of larger production ratios, thereby circumventing the problem raised by Clayton (1984) and readdressed here. Our purpose has been to show that, *if* massive stars dominate ^{26}Al production, chemical evolution models can accommodate this situation.

It is natural to ask for additional nucleosynthetic arguments that can demonstrate the existence of the factor $(k + 1)$. We here suggest two. The first is to compare, for a stable primary supernova product, the abundance it would have in a closed model, $Z = y_z \omega t$, where y_z is the *calculated* supernova yield, while the value from equation (3), $Z = y_z \omega \Delta(k + 1)^{-1} (x - x^{-k})$, in order to see which gives the better answer for observed interstellar concentrations. A method for this is to estimate the product $y_z \omega$ by the current supernova rate, as was done for ^{26}Al in the Introduction. It will already be clear to the reader from the ^{27}Al example used in this work that the factor $(k + 1)^{-1}$ is needed to avoid supernova overproduction by that argument. This application, namely using the conflict between the interstellar abundance of a stable nucleus and its current production rate by supernovae to estimate the history of Galactic infall, seems to have been undeveloped, probably owing to lack of confidence in the accuracy of the supernova rate. A second approach is to compare primary and secondary nucleosynthesis products with calculated yields. Clayton & Pantelaki (1986) solved Clayton's (1985) model exactly and showed that the secondary metallicity has its concentration reduced by infall by a factor near $(k + 1)^{-1}(k + 2)^{-1}$ (see their eq. [19] and the subsequent discussion), an even larger reduction factor than that for the primary product. It is therefore possible in principle to measure past infall by comparing an observed secondary/primary pair with the calculations of their respective yields.

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