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GEOLOGICAL ISOTOPE ANOMALIES AS SIGNATURES OF NEARBY SUPERNOVAE

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Abstract

Nearby supernova explosions may cause geological isotope anomalies via the direct deposition of debris or by cosmic-ray spallation. We discuss the relative importance of these two mechanisms as a function of the supernova distance, and focus attention on a number of isotopes such as ^{10}Be, ^{26}Al, ^{53}Mn, ^{60}Fe, and ^{59}Ni, as well as longer-lived trans-Fe nuclei which could serve as diagnostic tools. We emphasize the value of radioactive nuclei on the high-mass side of abundance peaks. It is also noted that the spallogenic component has two sources: (1) production via the cosmic rays from the supernova, and (2) the spallogenic products in the interstellar medium swept up by the supernova shock. We discuss whether the 35 and 60 kyr-old ^{10}Be anomalies observed in the Vostok antarctic ice cores could be due to supernova explosions, and the prospects for extending the search for nearby supernovae using ice cores back to $\mathcal{O}(300)$ kyr ago, and using deep ocean sediments back to several hundred Myr. In particular, we discuss the prospects for identifying isotope anomalies due to the Geminga supernova explosion, and signatures of the possibility that supernovae might have caused one or more biological mass extinctions.

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1 Introduction

The most violent events likely to have occurred in the solar neighbourhood during geologic (and biological) history could have been supernova explosions. The likelihood of such events has recently been impressed upon us by the discovery that Geminga is a nearby and recent supernova remnant (Gehrels & Chen 1993) and the discovery of a nearby pulsar (Halpern & Holt 1992). If a supernova explosion occurred sufficiently close to Earth, it could have dramatic effects on the biosphere (Ruderman 1974). Various processes have been discussed, including an enhanced flux of cosmic radiation and possible stripping of the Earth's ozone layer followed by the penetration of solar ultraviolet radiation (Reid, McAfee, & Crutzen 1978; Ellis & Schramm 1995) and absorption of visible sunlight by NO_2 (Crutzen & Brühl 1995), which could be life-threatening, and direct deposition of supernova debris. Any attempt to identify one of the many well-established mass extinctions must remain speculation in the absence of tools to diagnose the explosion of a nearby supernova using either the geophysical or the astrophysical record.

This paper discusses isotope anomalies as possible geological signatures of a nearby supernova explosion. This is a not a new idea: in fact it was the motivation for the Alvarez search (Alvarez et al. 1980) that discovered the Iridium anomaly which is now believed to be due to an asteroid or comet impact (van den Bergh 1994) at the time of the K-T transition that probably played a role in the extinction that occurred then. Moreover, ^{10}Be isotope anomalies have actually been discovered in Vostok ice cores from Antarctica (Raisbeck et al. 1987), corresponding to geological ages of about 35 and 60 kyr, and their interpretation in terms of one or more nearby supernova explosions has been discussed (Raisbeck et al. 1987; Sonnet, Morfill, & Jokipii 1987; Ammosov et al. 1991; Sonnet 1992; Ramadurai 1993) This paper is an attempt to update such searches in the light of the current understanding of supernova remnant evolution, following supernova 1987A (reviewed in, e.g., Arnett et al. 1989; McCray 1993) and the recent developments regarding Geminga (Gehrels & Chen 1993) and the Vostok ice cores (Raisbeck et al. 1987).

Whilst we consider here the general issues involved in detecting any nearby supernova, we note that any event within about 10 pc would have had a profoundly deleterious effect upon biology. Thus in our discussion we will place special emphasis on the specific case of an event at a distance of

~ 10 pc.

The total amount of material deposited by a nearby supernova by both direct and indirect means is relatively small; thus if one wants to avoid the large background of isotopes produced during most of the Universe's history, the most easily detectable isotopic signatures of such a supernova are probably radioisotopes and their decay products. A signature may appear as live and/or extinct radioactivity, raising different issues for detectability. In the case of live radiation, the isotopes of interest must have lifetimes less than about 10^9 yr, if one is interested in events that could have had a significant effect on the Earth's biosphere. If, in addition, one is interested in a correlation with one of the well-documented mass extinctions, the isotope lifetime should be longer than about 10^7 yr in order for it still to be present. Shorter-lived extinct radioactivities, detected via correlations of daughter products with stable isotopic partners of the parent radioactivities, are unlikely to be of interest, but cannot be excluded.

The possible candidate isotopes in this lifetime range include ^{40}K, ^{146}Sm, ^{129}I, ^{205}Pb, ^{244}Pu, and ^{235}U. If one is interested in understanding the origin of the Vostok ^{10}Be anomaly, the lower limit on the lifetime may be reduced to about 10^4 yr, in which case ^{14}C, ^{26}Al, ^{41}Ca, ^{53}Mn, ^{60}Fe, ^{59}Ni, ^{107}Pd, ^{150}Gd, and ^{237}Np may be added to the list of relevant isotopes. We provide an Appendix in which interesting isotopes and their relevant properties are listed.

There are two ways in which a nearby supernova explosion could produce anomalous isotopes: either indirectly as cosmic ray spallation products, which would be more important for light isotopes such as ^{10}Be (and perhaps ^{26}Al), or directly via the deposition of supernova debris, which would be more important for intermediate-mass isotopes such as ^{41}Ca and ^{60}Fe. The very heavy r-process isotopes are probably associated with supernovae (Meyer et al. 1992), but alternative sources are also possible (Meyer & Schramm 1986). Thus discovery of r-process anomalies that correlated with an intermediate-mass anomaly would help establish supernovae as the astrophysical r-process source. The relative importance of these classes of anomalies depends on the distance at which the supernova exploded, since supernova ejecta are slowed down and eventually stopped by the interstellar medium (ISM). Later in this paper, we give a quantitative discussion of the ratio of spallogenic and direct deposition isotopes as a measure of the distance of any putative supernova explosion. It should be noted that the spallogenic products have two possible origins: (1) those made by the cosmic rays produced by the nearby supernova, and (2) those already present in the ambient ISM, produced by galactic cosmic rays. The sweeping up of the ISM by the supernova shock will enhance the latter, while the proximity to the supernova enhances the former.

We then discuss the usefulness of this diagnostic tool for understanding the origin of the Vostok ^{10}Be anomalies (Raisbeck et al. 1987), and review the prospects for extending anomaly searches back to $\mathcal{O}(300)$ kyr ago using older ice cores, and back to $\mathcal{O}(500)$ Myr ago using deep ocean sediments. In particular, we discuss whether one or the other of the Vostok anomalies (or both, due to the possibility of a reverse shock) could be associated with the supernova explosion that created Geminga (Gehrels & Chen 1993). This seems unlikely, in view of the spin-down age of Geminga and the size of the local bubble in the interstellar medium, but cannot be excluded in view of the large uncertainties in the Geminga age estimates, and can be explored by looking for a correlated ^{26}Al anomaly. Even in the absence of such a correlation with the Vostok ^{10}Be anomalies, this technique could be used to search for a geological signature of the Geminga explosion if it occurred up to $\mathcal{O}(300)$ kyr ago, as generally believed.

2 Isotope Production

2.1 Direct Deposition: Supernova Remnant Dynamics

Consider the direct terrestrial deposition of the supernova blast matter. Note that this in fact contains two components: (1) material ejected from the supernova itself, and (2) material swept up by the ejecta as it traverses the ISM on its way to Earth. Imagine a supernova exploding at a distance D from Earth and ejecting a mass $M_{\rm ej}$ of which a fraction $X_i^{\rm SN}$ is composed of isotope i. If the amount of matter swept up is $M_{\rm sw}$, with composition X_i^{ISM}, then the total mass arriving at Earth is $M_{\rm tot} = M_{\rm ej} + M_{\rm sw}$, with a composition that is a weighted average of the two: $X_i = (X_i^{\rm SN} M_{\rm ej} + X_i^{\rm ISM} M_{\rm sw})/M_{\rm tot}$. The proportion of this matter that reaches the Earth is just given by the fraction of the solid angle the Earth subtends. The mass in i deposited terrestrially is thus

$$M_i^{\rm dep} = f_{\rm dep}\, X_i\, \left(\frac{R_\oplus}{2D}\right)^2 M_{\rm tot}$$
$$= 8.5 \times 10^{13}\ {\rm g}\ f_{\rm dep}\, X_i \left(\frac{D}{10\ {\rm pc}}\right)^{-2} \left(\frac{M_{\rm tot}}{100\ M_\odot}\right) \quad (1)$$

Note that the deposited mass $M_{\rm tot}$ depends on the distance D to the supernova via the contribution of the swept material $M_{\rm sw}$; this dependence can be understood in terms of supernova remnant evolution, and will be considered shortly. Note also that we have inserted in eq. (1) a factor $f_{\rm dep} \leq 1$ to account for partial exclusion of ejecta from the solar cavity due to the solar wind.

Equation (1) shows that the order of magnitude of the total mass deposited is 10^{14} g, or about 100 million tons. This is quite small compared, for example, to the K-T object's estimated mass of 2.5×10^{17} g (van den Bergh 1994) Thus one cannot hope to find evidence for this deposited matter using the techniques of Alvarez et al. (1980) which involve searches for isotopic anomalies in stable nuclei. In our case, the amount of material deposited is too small for such anomalies to be detectable above the background material with terrestrial composition. Thus we are instead driven to look for isotopes for which the background is very low, namely those which are unstable but long-lived: the radioisotopes. Below (§??), we will consider in detail both live and extinct radioactivities. For the moment, one need only keep in mind that the species of interest are unstable, and thus it remains to be seen which ones have the best production abundances, the lowest backgrounds, and the best lifetimes to be useful diagnostics of nearby supernovae.

The propagation of the shock is indicated in eq. (1) via the implicit dependence of $M_{\rm tot}$ on D; in fact we can be more specific about the shock's mass and motion. The motion of real shocks, and their interaction with the ISM, is complicated; recent detailed discussion can be found in, e.g., McKee (1988), and Chevalier & Liang (1989). The propagation phases include: free expansion for $\sim$ 4 pc until the ejecta has swept up about its own mass–subsequent to this the ISM dominates the mass and composition; then adiabatic (Sedov) expansion until radiative losses become important, and finally the momentum-conserving "snow plow" phase. In fact, we will not even need to delve into the details of these phases, as we only wish to estimate the swept up mass $M_{\rm sw}$, and in all of these phases the ISM is swept up by the shock. For the purposes of making order of magnitude estimates we construct a simplified model as follows .

The total mass ejected or swept up at distance D from the supernova is

$$\begin{aligned} M_{\rm tot} &= M_{\rm ej} + M_{\rm sw} \\ &= M_{\rm ej} + \frac{4\pi}{3}\,\rho_{\rm ISM}\,D^3 \ . \end{aligned} \tag{2}$$

To determine the swept-up mass, choosing an appropriate value for $\rho_{\rm ISM}$ (or equivalently $n_{\rm ISM}$) is essential. Unfortunately, there is a wide range of reasonable choices. The average ISM number density is $\sim 1\ {\rm cm}^{-3}$, but within hot, supernova-induced bubbles, the density is closer to $\sim 10^{-3}\ {\rm cm}^{-3}$. And while the solar system is presently located on the edge of such a bubble (Gehrels & Chen 1993), it may have only arrived there recently, and at has probably traversed may different environments on the timescales of hundreds of million years associated with mass extinctions. Nevertheless, we conservatively adopt the lower value as a fiducial one; in fact we will see that this only has any impact on the long-lived, supernova-produced radioisotopes.

The accumulation of mass continues until the end of the snow-plow phase when the shock finally stops; we wish to estimate the distance at which this occurs. To do so, we note that in this phase the shock slowing is determined by momentum conservation. Let us assume that the transition to this phase from the adiabatic expansion phase happens at a distance $D_0 \simeq 20$ pc, with velocity $v_0 \simeq 100$ km/s, mass $M_0 \simeq 4\pi/3\ \rho_{\rm ISM} D_0^3 \simeq 1000 M_\odot$, and time $t_0 \sim 40$ kyr (as given, e.g., in Spitzer 1978). The transition momentum is thus $M_0 v_0$, and setting this equal to $M_{\rm tot} v$ we have

$$M_{\rm tot} = \frac{v_0}{v}\,M_0 \ . \tag{3}$$

This accretion process continues until the shock pressure drops to a level comparable to that of the ISM, at which point the shock stops. An estimate of the distance scale for the shock quenching gives a final radius $D_{\rm f} \simeq 70$ pc for a ISM temperature of 10^4 K.

Even if the shock is stopped in the ISM due to ISM thermal pressure, the solar system may pass through it. But in this case the material will be repelled by the solar wind, which at 1 AU has a much higher pressure. It is also possible that the shock may be repelled by the solar wind even before it is stopped by the ISM. In eq. (1) we have indicated this exclusion from the earth by the factor $f_{\rm dep}$, but we may approximate its effect by simply finding a smaller $D_{\rm max} < D_{\rm f}$ appropriate for the solar wind pressure (i.e., we will put $f_{\rm dep} = 1$ for $D \leq D_{\rm max}$ and $f_{\rm dep} = 0$ otherwise). Equating the ejecta pressure $P_{\rm ej} \sim M_{\rm tot} v/(D^2 \Delta t) = M_{\rm ej} v_{\rm ej}/(D^2 \Delta t)$ with the solar wind pressure $P_{\rm sw} \sim m_{\rm p} v_{\rm sw} \Phi_{\rm sw}$ gives a maximum range of $\sim$ 16 pc. Note, however, that this calculation assumes the worst-case geometry, namely that the shock encounters the wind perpendicularly on its way to the earth. A more oblique angle allows more penetration and so a higher $D_{\rm max}$. This effect will be important even if the explosion happens in the plane of the ecliptic as long as the shock duration $\Delta t > 1$ yr, allowing the earth to encounter regions at these oblique angles. Furthermore, one generically expects the explosion to be be out of the ecliptic. A detailed analysis of the possible geometries is beyond the scope of this paper, but it is clear it will lead to a larger $D_{\rm max}$ that this simple estimate. To allow for this and to recognize the uncertainties of the calculation, we will relax the limit by a factor of 3 for the purposes of discussion, and so we have

$$D_{\rm max} \simeq 50 \text{ pc} \left(\frac{M_{\rm ej}}{10 M_\odot}\right) \left(\frac{v_{\rm ej}}{v_{\rm sw}}\right)^{1/2} \left(\frac{\Delta t}{1 kyr}\right)^{-1} \tag{4}$$

where we have used $\Phi_{\rm sw} = 3 \times 10^8$ protons cm^{-2} s^{-1} and $v_{\rm sw} = 400$km/s.

Since sweep-up is effective until the shock dies, we will model the spatial dependence of the deposited material by using eq. (2) until the distance $D_{\rm max}$, which we will take to be a sharp cutoff. Beyond $D_{\rm max}$, the only material deposited is of cosmogenic origin, which we will see in the next section is a much smaller amount. Thus the cutoff sets a crucial distance scale, above which the signal becomes very much weaker. A plot of this behaviour appears in figure ??.

Figure ?? points up a striking feature of the direct deposition mechanism for the case of an explosion within a dense ISM. In the regime 10 pc $\lesssim D \lesssim D_{\rm max}$, the total shock mass varies as $M_{\rm tot} \approx M_{\rm sw} \sim D^3$, while the Earth's solid angle with respect to the supernova goes as D^{-2}. Consequently, the deposited mass actually *increases* linearly with D for the larger distances. On the other hand, the deposition of cosmic and γ radiation monotonically decreases. Since the latter are the cause of the supernova's biohazard, then at the distance of $\sim$ 10 pc most interesting for mass extinctions, the direct deposit material is in fact near its minimum amount. To be sure, the variation is quite small, namely less than an order of magnitude. Nevertheless, it is ironic that some relatively harmless supernovae could in fact leave larger signals than a catastrophic nearby event.

2.2 Direct Deposition: Composition

Note also that swept-up material has the composition of the ISM, which is very different from that of the supernova ejecta. Further, the ratio of these two sources depends on the amount of material swept up, and thus on the distance to the supernova. Specifically, the ratio is

$$\begin{aligned} \frac{M_i^{\rm sw}}{M_i^{\rm ej}} &= \frac{X_i^{\rm ISM}}{X_i^{\rm SN}} \frac{4\pi/3\ D^3\ \rho_{\rm ISM}}{M_{\rm ej}} \\ &= 11\ \frac{X_i^{\rm ISM}}{X_i^{\rm SN}} \left(\frac{D}{10\ \rm pc}\right)^3 \left(\frac{n_{\rm ISM}}{1\ \rm cm^{-3}}\right) \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-1} \end{aligned} \quad (5)$$

i.e., the swept-up component increases like D^3 relative to the supernova ejecta, and is dominant before a distance of 10 pc *if there is significant abundance of i in the ISM.*

In fact, one can deduce three categories of deposited (radio)isotopes, depending on their production sources and lifetimes. First, there are the isotopes which are not significantly produced by supernovae, but are created by cosmic-ray interactions, e.g., ^{10}Be. While the supernova ejecta will not itself contain these isotopes, they will exist in an equilibrium abundance in the ISM, and so will appear in the swept material. We will wish to compare this with the cosmogenic production from the interactions of supernova cosmic rays in the Earth's atmosphere. We thus need to know the ISM abundance of cosmic ray-produced radionuclides such as ^{10}Be and ^{26}Al. If we assume that production is in equilibrium with decay losses, we have

$$n_i = \sum_{jk} n_j^{ISM}\ \langle \sigma_{jk}^i\ \Phi_k \rangle \tau_i \quad (6)$$

where σ_{jk}^i is the cross section for $k_{CR} + j_{ISM} \rightarrow i + \cdots$, and the brackets denote an average over the galactic cosmic ray flux Φ. Thus the ISM mass fraction is $X_i \simeq A_i\ n_i/n_{\rm H}^{\rm ISM}$, and so the deposited mass is

$$M_i^{\rm dep} = \frac{\pi}{3}\ A_i\ m_{\rm p} n_{\rm ISM} R_\oplus^2 D\ \sum_{jk} y_j^{\rm ISM}\ \langle \sigma_{jk}^i\ \Phi_k \rangle \tau_i \quad (7)$$

We will evaluate the importance of this source, along with cosmogenic production at earth, in the following section (§??).

Next we consider radioisotopes that are produced by supernovae. These fall into two classes depending on the lifetime. Long-lived isotopes will have a significant ISM abundance, as the products of many supernovae will accumulate during a lifetime; thus these will appear in the swept matter which will be the dominant source for long-lived isotope deposition. Shorter-lived isotopes, on the other hand, will die out too soon to have a large ISM abundance, and so the deposition will be dominated by the supernova ejecta.

The separation of these categories can be seen by computing the swept contribution to supernova radioisotopes. This is quite similar to the swept spallogenic nuclide calculation. The ISM equilibrium density of a supernova isotope i is

$$\rho_i = \lambda \tau_i \, \frac{X_i^{\rm SN} M_{\rm ej}}{V_{\rm gal}} \tag{8}$$

where $\lambda \simeq (100 \text{ yr})^{-1}$ is the galactic supernova rate, and $V_{\rm gal} = \pi R_{\rm gal}^2 h$ is the volume of the galactic disk with radius $R_{\rm gal} \simeq 10$ kpc and scale height $h \simeq 100$ pc. The total swept-up mass of i is $M_i^{\rm sw} = 4\pi/3 \; \rho_i D^3$, and the ratio of the swept to ejected mass in i is

$$\begin{aligned} \frac{M_i^{\rm sw}}{M_i^{\rm ej}} &= \frac{4}{3} \lambda \tau_i \, \frac{D^3}{R_{\rm gal}^2 h} \\ &= 1.3 \times 10^{-4} \left(\frac{\tau_i}{1 \text{ Myr}} \right) \left(\frac{D}{10 \text{ pc}} \right)^3 \% \end{aligned} \tag{9}$$

which is small for moderate lifetimes; thus for isotopes having $\tau_i \lesssim$ Gyr, the ejecta composition dominates. However, if $\tau_i \gtrsim 1$ Gyr, then for $D \gtrsim 20$ pc, the swept component dominates *if the explosion does not occur within a rarefied bubble.* These very long-lived isotopes are the best signatures of very ancient mass extinctions; thus it is fortuitous that for just these nuclides there can be a significant addition to their supernova ejecta abundance.

Note that the different classes of isotopes have different distance dependences. In particular, those which are dominated by the ejecta just drop off as D^{-2}, while those dominated by swept matter increase like D. Thus measurements of each of these types provides a independent way of determining the distance to the supernova; moreover, their ratio provides an important consistency check. Indeed, it is possible that the problem could be turned around and one could learn about supernova ejecta by comparing ratios of sedimentary radionuclides.

2.3 Cosmogenic Production

The directly-deposited material is to be compared to cosmogenic production from the enhanced cosmic rays coming from the supernova. An exploding supernova will invest some fraction $\epsilon \simeq 0.01$ of its mechanical energy in the production of cosmic rays; we will put

$$U_{\rm CR} = \epsilon\, U_{\rm SN} \simeq \frac{1}{2}\, \epsilon\, M_{\rm ej}\, v_{\rm ej}^2 \tag{10}$$

where $U_{\rm SN}$ is the kinetic energy of the blast wave. If the average cosmic ray kinetic energy is $\langle E \rangle_{\rm CR} \simeq m_{\rm p}c^2$, then the total cosmic ray exposure at Earth (specifically, the time-integrated flux, or the fluence) is just

$$\Phi\, \Delta t = \xi_{\rm CR} f_{\rm CR}\, \frac{U_{\rm CR}/\langle E \rangle_{\rm CR}}{4\pi D^2} \tag{11}$$

where $\xi_{\rm CR} \leq 1$ accounts for losses due to propagation to the solar system, and $f_{\rm CR}$, in analogy to $f_{\rm dep}$, allows for exclusion from the solar cavity.

Note that the propagation is very different from that of the blast material: since the cosmic rays are much more diffuse and have a lower pressure, they do not sweep up matter but move through it, spiraling around local magnetic field lines. Therefore, ξ will have some dependence on the magnetic fields the cosmic rays follow. A detailed discussion of such an effect is beyond the scope of this paper. We will instead simply assume that there is not a conspiracy in the magnetic field structure that would deflect the cosmic rays away. In this case, the dominant means of cosmic ray loss in transit to the Solar System will be through ionization losses to the ISM. In this case we have $\xi \simeq \exp(-X/X_0)$, where X_0 is the ionization stopping length in $\rm g cm^{-2}$, and $X = \rho_{\rm ISM} D$ is the amount of matter traversed. For GeV protons, $X/X_0 = 2 \times 10^{-7}\ (D/10\ {\rm pc})$ and $\xi \simeq 1$. Thus cosmic ray losses in transit are minimal, so we will put $\xi_{\rm CR} = 1$ henceforth.

The physics behind $f_{\rm CR}$ is an accounting of the solar wind's exclusion of cosmic rays; this is of course the well-known solar modulation first described by Parker (1958), and more recently re-examined by Perko (1987). A detailed treatment would account for the dependence of the modulation on cosmic-ray energy and on the solar cycle. However, to our level of accuracy, we will simply note that the integrated flux decreases by roughly a factor of 10 from its interstellar value, and we consequently will take $f_{\rm CR} = 1/10$. We note in passing that cosmic rays could reduce the solar cavity size and maybe make the earth more vulnerable to the subsequent direct deposit of material.

The total number of cosmic-ray interactions with the Earth is $\Phi \Delta t \, \pi R_{\oplus}^2$; the fraction of these that produce isotope i in the process $j + k \to i$ is given by the branching ratio $y_j^{\rm CR} y_k^{\rm atm} \sigma_{jk}^i / \sigma_{tot}$, the ratio of spallogenic production of i to the total cross section multiplied by the cosmic-ray and atmospheric abundances $y_j^{\rm CR}$ and $y_k^{\rm atm}$, respectively. It will be useful to introduce the definition

$$Y_i = \sum_{jk} y_j^{\rm CR} y_k^{\rm atm} \frac{\sigma_{jk}^i}{\sigma_{\rm tot}} \tag{12}$$

which amounts to a weighted branching ratio for spallation production of i, summed over all production channels; a tabulation of Y_i for many isotopes of interest is found in O'Brien et al. (1991). Then cosmic rays from a nearby supernova will have a mass yield of isotope i of

$$M_i^{\rm CR} = f_{\rm CR} \; A_i \; Y_i \; \epsilon \left(\frac{v_{\rm ej}}{c}\right)^2 \left(\frac{R_\oplus}{2D}\right)^2 M_{\rm ej} \quad . \tag{13}$$

It is of interest to compare the strength of the two mechanisms, direct deposition versus cosmogenic production. For any two species i and ℓ, this ratio is

$$\frac{M_i^{\rm CR}}{M_\ell^{\rm dep}} = f_{\rm CR} \; \epsilon \left(\frac{v_{\rm ej}}{c}\right)^2 \frac{A_i}{X_\ell} \; Y_i \; \frac{M_{\rm ej}}{M_{\rm tot}} \tag{14}$$

which holds for $D \lesssim D_{\rm max}$. If we put $\ell = i$, we may compare the relative importance of the production mechanisms. This will of course only be relevant for isotopes produced significantly by cosmic rays. Note that if the supernova makes the isotope as well (e.g., ^{41}Ca), then this shows that direct deposit is by far the predominant effect. However, if the isotope is not made by supernovae, we may take the ratio of eq. (??) to eq. (1) as applied to swept-up cosmic ray products, to obtain

$$\frac{M_i^{\rm CR}}{M_i^{\rm sw}} = \epsilon \; f_{\rm CR} \frac{y_k^{\rm atm}}{y_k^{\rm ISM}} \left(\frac{v_{\rm ej}}{c}\right)^2 \frac{M_{\rm ej}}{4\pi/3 \; \rho_{\rm ISM} D^3} \; (\sigma_{\rm tot} \tau_i \Phi_p)^{-1} \tag{15}$$

for $D \lesssim D_{\rm max}$, which gives something of order $10^4 y_k^{\rm atm}/y_k^{\rm ISM}$ for canonical numbers and for $\tau_i = 1$ Myr. Thus the supernova cosmic ray component dominates that of the ISM whenever there is a significant target abundance in the atmosphere.

3 Signatures and Their Detectability

When some amount of a radioisotope is deposited in the Earth's atmosphere, it will eventually precipitate out and accumulate in the ice cores and the sea sediments. Analysis of this material counts the rate of decays per gram of ice or sediment. In this section, we estimate the magnitude of the expected signal from a nearby supernova.

In the following, we will assume that the material deposited in the atmosphere will precipitate out uniformly around the Earth's surface. This ignores important considerations of the details of the mixing of atmosphere and any chemical fractionation taking place during its deposition. These effects can be important ones, as noted by, e.g., Beer, Raisbeck, and Yiou (1991) in their discussion of ^{10}Be. Despite these difficulties, we forge ahead to see what sort of signature we would naively expect. Clearly, however, a detailed treatment must address the issue of chemical, atmospheric, geophysical and even biological effects.

3.1 Live Radioactivity

Thus far we have computed the total mass deposited at the earth by a nearby supernova via the relevant mechanisms. What is actually measured is the number of atoms, or of decays, per gram of sediment. Before making the connection between the deposited mass and its final sedimentary abundance, a word is in order about the experimental options and their sensitivities. A typical sensitivity for measuring number of rare atoms per gram of bulk material (call it Λ) is around $\Lambda_{\rm min} \sim 10^4$ atoms/g. Of course, the determination of Λ is necessarily destructive. On the other hand, one can perform a non-destructive measurement of radioisotopes by measuring the decay rate. The relation between the two is simply

$$\Gamma_i = \Lambda_i/\tau_i \ , \tag{16}$$

with Γ the decay rate per gram of bulk material. Typical sensitivities are $\Gamma_{\rm min} \sim 10$ dpm/kg (dpm = decays per minute). For a lifetime of 10^6 Myr, this threshold corresponds to an effective number count threshold of 2×10^9atoms/g $\sim 10^5 \Lambda_{\rm min}$. It is clear that the techniques for counting rare atoms are much more favorable for our purposes. Thus we suggest this method, unless destructive tests are unavailable or unreliable.

We now wish to connect our calculation of total mass deposition with the observables. If a mass M_i of isotope i is deposited on the Earth, on average it will precipitate out with a surface density $M_i/4\pi R_\oplus^2$. This will happen over the time Δt it takes for the Earth to receive the material, either directly as the supernova blast passes through, or indirectly as the cosmic rays arrive. If the bulk of the sediment or ice accumulates with a density ρ and its height increases at a rate dh/dt, then over a time Δt the surface density of the new sedimentation is $\rho \; dh/dt \; \Delta t$. Thus the number of supernova radioisotopes per unit mass of terrestrial sedimentation is

$$\Lambda_i = \frac{1}{A_i} \frac{M_i/m_{\rm p}}{4\pi\rho \; R_\oplus^2 \; dh/dt \; \Delta t} \tag{17}$$

where M_i will depend on the deposition method, as we now discuss.

For short-lived direct-deposition isotopes produced by supernovae, we have $M_i = X_i^{\rm SN} M_{\rm ej}$, and so

$$\Lambda_i = 2 \times 10^9 \text{ atoms g}^{-1} \left(\frac{A_i}{50}\right)^{-1} \left(\frac{X_i^{\rm SN}}{10^{-4}}\right) \left(\frac{\Delta t}{1 \text{ kyr}}\right)^{-1} \left(\frac{D}{10 \text{ pc}}\right)^{-2} \tag{18}$$

for $D \leq D_{\rm max}$, where we have assumed a sedimentation density $\rho = \rho_{\rm ice} \simeq 1$ g cm^{-3} and rate $dh/dt = 1$ cm/yr, in accordance with the Raisbeck et al. (1987) Vostok measurements. This is far above threshold, indicating that there should be a strong signal, though not necessarily via decays. In the case of ^{26}Al in ice cores, we find $\Lambda_{26}^{\rm ice} \simeq 4 \times 10^8$ atom g^{-1} at $D = 10$ pc, which is very much larger than the Vostok ^{10}Be spike amplitude. Thus we predict that, if the Vostok events were nearby supernovae within direct-deposition range, the signal in ^{26}Al and other supernova-produced radioisotopes should be observable.

We note that the longest-lived direct-deposition isotopes are produced by supernovae in abundances as small as 10^{-8}; thus the signal would be of order 10^5 atoms/g, which is still above detection threshold. In fact, the signgal can be somewhat larger than this due to sweeping of ISM material if the medium is dense. However, as seen in eq. (9), the enhancement will be large only for distances D approaching $D_{\max}$. Thus we will not treat this case explicitly, though it is straightforward to do so.

For directly-deposited material that is only produced spallatively, we have $M_i = X_i^{\rm ISM} M_{\rm sw}$, and for $D \leq D_{\max}$ eq. (??) now reduces to

$$\begin{aligned} \Lambda_i^{\rm dep} &= \frac{1}{12} \frac{X_i^{\rm ISM}}{A_i} \frac{n_{\rm ISM} D}{16\pi\rho \, dh/dt \, \Delta t} \\ &= \frac{n_{\rm ISM} D}{12\rho \, dh/dt \, \Delta t} \sum_{jk} y_j^{ISM} y_k^{\rm CR} \, \langle \sigma_{jk}^i \, \Phi_p \rangle \tau_i \\ &= 4 \times 10^2 \text{ atoms g}^{-1} \end{aligned}$$

at 10 pc, a level below the detection threshold. However, as we noted above, we expect the cosmogenic component to dominate. For that, we have

$$\begin{aligned} \Lambda_i &= f_{\rm CR} \epsilon \left(\frac{v_{\rm ej}}{c} \right)^2 Y_i \frac{M_{\rm ej}/m_{\rm p}}{16\pi\rho D^2 dh/dt \Delta t} \\ &= 2.6 \times 10^6 \text{ atoms g}^{-1} \\ & \quad \left(\frac{f_{\rm CR}}{0.1} \right) \left(\frac{Y_i}{10^{-2}} \right) \left(\frac{\Delta t}{1 \text{ kyr}} \right)^{-1} \left(\frac{D}{10 \text{ pc}} \right)^{-2} \left(\frac{M_{\rm ej}}{10 \, M_\odot} \right) \end{aligned} \qquad (19)$$

using a value of Y_i appropriate for ^{10}Be in ice cores.

A similar approach can be used to estimate the possible isotope signal in deep-ocean sediments, which precipitate at a rate dh/dt typically 10^{-3} of the rate of accumulation of ice cores, and may provide a fossil isotope record extending back several hundred Myr. The longer time scale means that one should concentrate on longer-lived isotopes, so as to avoid a strong suppression of the decay rate by an overall decay factor $e^{-(t_0 - t_d)/\tau_i}$, where t_0 (t_d) is the time at present (at deposition).[1] From this point of view, the optimal isotope lifetime should be as long as possible, with an upper limit of about the age of the earth (to assure that any initial protosolar abundance has decayed away). A catalog and discussion of isotope candidates can be found in §??.

[1] The optimal choice is different for the decay rate, which has $\Gamma \propto e^{-(t_0 - t_d)/\tau_i}/\tau_i$ and so is maximized by $\tau_i = t_0 - t_d$. In practice this makes little difference given the paucity of radionuclei with $\tau \gtrsim 10^8$ yr.

For sea sediments, there is a lower limit to the time resolution $\Delta t \geq 1$ kyr, the origin of which is biological. Namely, as noted in Beer et al. (1991) small organisms dig into the sea floor and disturb it for depths of a few cm, corresponding to a time of $\sim$ kyr. This effect, known as "bioturbation," is an example of the possible subtleties that must be addressed in a more detailed account of our subject. This particular effect is presumably not a problem with ice core samples, though they have their own environmental peculiarities.

We thus re-emphasize that the above discussion does not take into account possible fractionation due to chemical, atmospheric, geophysical or even biological effects. Given the longer time scales and greater exposure to such effects, the assumptions of uniform deposition and stratification made above are more questionable than for ice cores, and our estimate eqs. (??,??) could be depleted by such effects. However, the possibility of fractionation also suggests that the isotope abundances could even be enhanced in some favourable cases. A detailed study of the likelihoods of fractionation for the above-mentioned isotopes goes beyond the scope of this paper.

In figure ?? we plot the expected signal for both kinds of deposition as a function of supernova distance. Also indicated is a rough estimate of the experimental sensitivity, as well as a calculation of the background cosmogenic production due to galactic cosmic rays (discussed below in §??).

3.2 Extinct Radioactivity

The technique here is similar to the one used by the Alvarez search (Alvarez et al. 1980). Consider a parent isotope ${}^{i}P$ (e.g., ^{26}Al) which decays to a daughter isotope ${}^{i}D$ (e.g., ^{26}Mg). A signal of the presence of ${}^{i}P$ would be a correlation of a ${}^{i}D$ excess with the P abundance, both measured in a ratio to the major isotope of D (e.g., Mg). E.g., one finds ^{26}Mg/^{24}Mg to be positively correlated with Al/Mg; this allows one to deduce the protosolar ^{26}Al abundance (Lee, Papanastassiou, & Wasserburg 1977).

For this procedure to work, the variations $\delta^{i}D/D$ in the daughter isotopic fraction must be detectable and not due to fractionation; i.e., the *variations* must be at least of order of a percent. This means that the SN contribution to ${}^{i}D$ must be at least of order ${}^{i}D_{\rm SN} \gtrsim 0.01{}^{i}D_{\rm BG}$; expressed in terms of number compared to Si, we have ${}^{i}D_{\rm SN}/{\rm Si} \gtrsim 0.01({}^{i}D/D)(D/{\rm Si})_{\rm BG}$. If we take typical abundances of $D/{\rm Si} \sim 10^{-2}$, and ${}^{i}D/D \sim 0.01$, we get a limit of

${}^iD/\mathrm{Si}_{\mathrm{SN}} \gtrsim 10^{-4}$. But in sediments we have signals of order $\Lambda_i \sim 10^9$ atom/g. Even if the sediment is only 1% Si, this means an abundance of ${}^iD/\mathrm{Si} \leq 10^{-11}$, which is much less than the minimum detectability. So it appears that extinct radioisotopes will have too feeble a signal to be measurable.

4 Cosmic Ray Background

Any signature we find must lie above the background of radioisotopes continually produced in the atmosphere by normal galactic cosmic rays, which is just the usual cosmogenic production. This problem has been well-studied and is summarized in, e.g., O'Brien et al. (1991). For our purpose, we may use the machinery of the previous two sections to derive that the rate of background atmospheric production of isotope i is

$$\frac{d}{dt}N_i^{\mathrm{BG}} = 4\pi Y_i \, R_\oplus^2 \, \Phi_{\mathrm{p}} \quad . \tag{20}$$

If this is incorporated into sedimentation or ice with a surface density accumulating at a rate $\rho dh/dt$, then the number of atoms per unit mass is

$$\Lambda_i^{\mathrm{BG}} = Y_i \, \frac{\Phi_{\mathrm{p}}}{\rho dh/dt} \tag{21}$$

We can check the calculation by estimating the background production of $^{10}\mathrm{Be}$, for which $Y = .01$. We take a total (modulated) cosmic-ray proton flux of $\Phi_{\mathrm{p}} = 1 \ \mathrm{cm}^{-2} \ \mathrm{s}^{-1}$. With an ice density of 1 g cm^{-3} and a deposition rate of 1 cm yr^{-1}, we have

$$\Lambda_{\mathrm{Be}}^{\mathrm{BG}} \simeq 3 \times 10^5 \ \mathrm{atoms} \ \mathrm{g}^{-1} \tag{22}$$

in rough agreement with the $^{10}\mathrm{Be}$ concentrations measured in the Vostok ice cores. The fact that this simple estimate is apparently too high by a factor of about two could be due to the geomagnetic cutoff on some cosmic rays at low latitudes, so that the average flux over the Earth's surface is reduced. Such a possible error is smaller than other uncertainties in our estimates.

One may also estimate the $^{26}\mathrm{Al}$ background by this method; O'Brien et al. (1991) calculate a cosmogenic production ratio of $^{26}\mathrm{Al}/^{10}\mathrm{Be} \simeq 2 \times 10^{-3}$, which gives a yield far below the typical size of the error bars on the $^{10}\mathrm{Be}$ data.

The astrophysical abundances of heavy isotopes feature well-known peaks, notably for ^{56}Fe. Since cosmogenic production favours isotopes lighter than the peak species, isotopes heavier than the peak species are more promising in the search for a supernova signal. In particular, ^{60}Fe and ^{59}Ni look like promising ice-core signatures for a recent nearby supernova explosion.

We now compare the background due to galactic cosmic rays to the signals of supernova deposition mechanisms. For direct deposition of pure supernova products, there is by definition only a small cosmic ray production in the ISM, so we expect a fairly small background. Comparing equations (??) and (??), we have

$$\begin{aligned}\frac{\Lambda_i^{\rm dep}}{\Lambda_i^{\rm BG}} &= \frac{X_i^{\rm SN}/A_i}{Y_i^{\rm atm}} \frac{M_{\rm ej}/m_{\rm p}}{4\pi D^2 \Phi \Delta t} \\ &= 3 \times 10^6 \frac{X_i^{\rm SN}/A_i}{Y_i^{\rm atm}} \\ &\quad \times \left(\frac{M_{\rm ej}}{10\ M_\odot}\right) \left(\frac{D}{10\ {\rm pc}}\right)^{-2} \left(\frac{\Phi}{10\ {\rm cm^{-2}\ s^{-1}}}\right)^{-1} \left(\frac{\Delta t}{1{\rm kyr}}\right) \qquad (23)\end{aligned}$$

This indeed shows the signal to be very much larger than the background. Further, since the mass fraction in the supernova is by assumption much larger than the spallation branching ratio, the signal-to-background ratio is even larger than the already huge factor indicated above.

If the species is produced by galactic cosmic rays in the ISM, then assuming this component to dominate the swept-up material, we have

$$\begin{aligned}\frac{\Lambda_i^{\rm dep}}{\Lambda_i^{\rm BG}} &= \frac{1}{3} \frac{Y_i^{\rm ISM}}{Y_i^{\rm atm}} \frac{\tau_i}{\Delta t}\ n_{\rm ISM}\sigma_{\rm tot} D \\ &\simeq \frac{y_k^{\rm ISM}}{y_k^{\rm atm}} \frac{\tau_i}{\Delta t}\ n_{\rm ISM}\sigma_{\rm tot} D \\ &= 3 \times 10^2\ \frac{y_k^{\rm ISM}}{y_k^{\rm atm}} \left(\frac{\tau_i}{1\ {\rm Myr}}\right) \left(\frac{\Delta t}{1\ {\rm kyr}}\right)^{-1} \left(\frac{n_{\rm ISM}}{10^{-3}\ {\rm cm^{-3}}}\right) \left(\frac{D}{10\ {\rm pc}}\right) \qquad (24)\end{aligned}$$

where we have assumed production to be dominated by collisions with a target species k. Note that while the abundance ratios $y_{\rm CNO}^{\rm ISM}/y_{\rm CNO}^{\rm atm} \sim 10^{-3}$, for most other targets of interest $y_k^{\rm ISM}/y_k^{\rm atm} > 1$. So even for production from CNO targets, the signal still dominates the background, and for other targets it is even larger than the fiducial number above.

For matter deposition by supernova cosmogenic production, the signal-to-background ratio is simply the efficiency for the supernova to produce cosmic rays times the ratio of the supernova cosmic ray flux to the galactic cosmic ray flux. Specifically,

$$
\begin{aligned}
\frac{\Lambda_i^{\rm CR}}{\Lambda_i^{\rm BG}} &\simeq \frac{1}{2} f_{\rm CR} \epsilon \left(\frac{v_{\rm ej}}{c}\right)^2 \frac{M_{\rm ej}}{m_{\rm p}} \frac{X_j/A_j}{y_j^{\rm GCR}} \frac{(4\pi D^2 \Delta t)^{-1}}{\Phi} \\
&= 16 \, \frac{X_j/A_j}{y_j^{\rm GCR}} \\
&\quad \times \left(\frac{f_{\rm CR}}{0.1}\right) \left(\frac{M_{\rm ej}}{10 M_\odot}\right) \left(\frac{\Delta t}{1 {\rm kyr}}\right)^{-1} \left(\frac{\Phi}{1 \ {\rm cm}^{-2} \ {\rm s}^{-1}}\right) \left(\frac{D}{10 \ {\rm pc}}\right)^{-2}
\end{aligned}
\tag{25}
$$

where we have now assumed the production to be dominated by the projectile species j. The signal-to-background in this case is, of course, much smaller than that for direct deposition.

Note also that at a distance of 40 pc the cosmogenic signal drops below background. But this is roughly the distance of the cutoff for the direct supernova ejecta. Thus it appears that there is either a strong direct deposition signal for a very nearby supernova, or perhaps a feeble cosmic ray signal for one a little further, or no signal at all for larger distances.

5 Implications of the Geminga Supernova

Thus far, discussion of the Vostok ^{10}Be measurements has focussed on direct passage of the shock wave past the Earth (Raisbeck et al. 1987; Sonnet, Morfill, & Jokipii 1987; Ammosov et al. 1991; Sonnet 1992; Ramadurai 1993). This work has concluded that the Vostok data may indicate a supernova explosion occurred at distances of $\lesssim 100$ pc, and perhaps even shows something of the detailed shock structure. Further, these authors have suggested that the supernova causing the ^{10}Be might be Geminga itself. The "double-bump" structure of the Vostok ^{10}Be anomaly could conceivably be due to the shock wave bouncing back from the boundary of a previously-cleared low-density bubble in the ISM. However, there may be problems reconciling Geminga event dating from Vostok with estimates from pulsar spin-down (Gehrels & Chen 1993). The former gives something like 60–100 kyr, while the latter give something more like 300 kyr. One should bear in mind, though, that the spin-down times give an upper bound to the time since the explosion, as neutron starquakes can lead to very rapid mass redistribution and slowing of angular velocity, know as "glitches." If there were a number of such glitches, then the Geminga event might be more recent and the age estimates could be brought into agreement.

Despite the possible difficulties in reconciling the age determination, it is interesting to consider eq. (??) in the light of the Vostok ice-core data. If the peaks therein are indeed due to supernovae, then they have signal-to-background ratios within the generous range of $1 \leq \Lambda_{peak}/\Lambda_{bg} \leq 4$, and the width of the peaks shows that indeed $\Delta t \sim 1$ kyr. Interpreting the peaks as signal, then eq. (??) gives 20 pc $\lesssim D \lesssim$ 40 pc. This suggests that if the Vostok peaks came from a supernova, it was quite close and indeed may have been a near miss.

If the ^{10}Be signal does have its origins in the Geminga blast, then eq. (??) and figure ?? indicate that ^{27}Al should be much more abundant in the ice cores. So long as Geminga occurred within $D \lesssim D_{max}$, then we expect $^{26}\mathrm{Al}/^{10}\mathrm{Be} \simeq 100$. Detection of ^{26}Al spikes at the same strata as those of ^{10}Be would lend strong support to the notion of a nearby supernova origin for the Vostok ^{10}Be signal. Further, since the ^{10}Be component arises from enhanced cosmogenic production, where the ^{26}Al component is dominated by direct deposition, the detection of the latter would also confirm that both mechanisms indeed happen and are important.

6 Isotope Candidates

Having presented the various effects and backgrounds, we turn to the possible isotope candidates, both for probing the Geminga event and for mass-extinction events. Note that since the swept ISM component only makes an important contribution for long-lived elements when the explosion is in a dense medium, this mechanism is for the most part not important. Thus the only isotopes that are important are those having their origin in (1) supernova explosions, or (2) cosmic ray production. These are further subdivided into short- and long-lived radioactivities, and so can be classified:

1. short-lived ($t_{1/2} < 10^7$ yr) SN products
2. long-lived ($t_{1/2} \geq 10^7$ yr) SN products

3. short-lived CR products

as there are not any long-lived CR products. All isotopes with half-lives in the range of interest are indicated in tables 1 and 2.

Note that while some isotopes are definitely of supernova origin (e.g., those in the Ex-SN and ν categories in tables 1 and 2), and some are definitely *not* of supernova origin (e.g., those arising from novae or the s-process), with others the situation is less clear (e.g., those arising from the the r- and p-processes). Thus we have indicated all of the sources that could be important. Note, however, that when several processes create the same isotope, they generally do so at very different levels. Typically, the r-process (and s-process) is much more efficient than the p-process, which in turn dominates the ν and CR processes.

Short-lived isotopes are good as Geminga signatures or as extinct radioactivity; it is clear that they are unable to provide signatures of mass extinctions. Good short-lived SN products are notably ^{26}Al, ^{41}Ca, ^{60}Fe, and ^{59}Ni. If supernovae are the source of the r-process, then additional isotopes of interest are indicated in the tables. Good short-lived cosmic-ray products are ^{10}Be, which is by far the most abundant, perhaps also ^{26}Al, and maybe even ^{41}Ca.

The long-lived isotopes can provide a long enough signal to give evidence of a mass extinction. As is clear from comparing table 2 to table 1, there are much fewer of these. Further, given that the most interesting mass extinctions occurred at epochs $\gtrsim 10^8$ yr ago, there are only three isotopes with lifetimes in this range, and they can be discussed individually. The origin of ^{40}K is not clear and may include explosive nucleosynthesis and Ne burning, as well as the s-process. ^{146}Sm is produced in the p-process, which presumably has its site in supernovae although the protosolar abundance is poorly reproduced by specific supernova models (i.e., photodissociation; see Prinzhoffer et al. 1989; Lambert 1992). The U isotopes come from the r-process. Thus there are no long-lived CR products, and it is not clear that the long-lived nuclei are SN products. However, they should appear in the swept-up material due to their ISM equilibrium abundance, if the nearby explosion occurs in a dense ($n_H \gtrsim 1$ cm^{-3}) medium. Indeed, turning the problem around, detection of these isotopes could teach us about the source of r-process nuclei.

7 Conclusions

We have considered in this paper various origins for geological isotope anomalies as possible signatures of nearby supernova explosions, including the supernova ejecta themselves, material swept up from the ISM, and isotopes produced by cosmic-ray collisions in the atmosphere. We have explored the prospects for searches in ice cores, which could be useful in understanding the origin of the Vostok ^{10}Be anomalies and possibly finding a trace of the Geminga explosion, as well as in deep-ocean sediments, which could provide evidence for any supernova explosion near enough to have affected the biosphere and possibly caused a mass extinction. We have explored the possibilities of searches for live and extinct radioactivities, and for low-level trace abundances.

The best prospects seem to be offered by searches for trace amounts of supernova ejecta, followed by material swept up from the ISM. Both of these sources may be considerably stronger than the background induced by conventional cosmic rays. The atmospheric production of spallation isotopes by cosmic rays from a nearby supernova explosion may be observable if the supernova was sufficiently close, namely within about 40 pc.

Table 1 lists the shorter-lived radioisotope candidates that are of particular interest for searches in ice cores, which may extend back to about 300 kyr ago. The isotopes ^{26}Al, ^{41}Ca, ^{59}Ni and ^{60}Fe may be the most promising signatures of a nearby supernova such as Geminga during this period, particularly ^{26}Al. It would be very interesting to look for a correlation with the Vostok ^{10}Be anomalies, to test the hypothesis that these could be due to the Geminga or another nearby supernova. We re-emphasize that this identification does not seem exceedingly likely, given the usual estimates of the age and distance of the Geminga remnant (Gehrels & Chen 1993), but cannot be excluded and should be explored.

Table 2 lists the longer-lived radioisotopes that could be of interest for searches in deep-ocean sediments, which may extend back to several hundred Myr ago. Either ^{40}K and/or ^{146}Sm could be produced in supernovae, via explosive nucleosynthesis or the p-process, respectively. Although the origin of the U isotopes is unclear, they should be present in the ISM, and their detection could tell us something about the source of r-process nuclei.

The abundances of all isotopes depend strongly on the distance of any supernova explosion, in different ways for different production mechanisms.

Thus a deep-ocean sediment search may be able to tell us whether an explosion could have occurred sufficiently nearby (less than about 10 pc) to have affected the biosphere, or whether there might have been a "near miss". However, we re-emphasize that our estimates of the possible abundances do not take into account fractionation, which could be important for deep-ocean sediments.

Any radioisotope signal above the background from conventional sources would provide a unique tool, not only to learn about a possible mechanism for a mass extinction, but possibly also about supernovae themselves and the various processes that synthesize different elements in the cosmos.

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References

Alvarez, L., Alvarez, W., Asaro, F., & Michel, H. 1980, Science, 208, 1095

Ammosov, A.E., et al., Izv. Akad. Nauk. SSSR, Ser. Fiz. 1991 55, 10

Anders, E., & Grevesse, N., 1989, Geochim. et Cosmochim. Acta, 53, 197

Arnett, W.D., Bahcall, J., Kirshner, R. & Woosley, S. 1989, ARAA, 27, 629

Beer, J., Raisbeck, G.M., & Yiou, F., in The Sun in Time, ed. C.P. Sonnet, M.S. Giampapa, & M.S. Mathews (1991: Tucson, Univ. of Arizona Press), 343

Chevalier, R.A., & Liang, E.P. 1989, ApJ, 344, 332

Crutzen, P.J., & Brühl, C. 1995, Max-Planck-Institut für Chemie, Mainz preprint

Ellis, J. & Schramm, D.N. 1995, Proc. Nat. Acad. Sci., 92. 235, (1995)

Frisch, P.C. 1994, Science, 256, 1423

Halpern, J.P., & Holt, S.S. 1992, Nature, 357, 222

Lambert, D.L., 1992, Astron. Astrophys. Rev., 3, 201

Gehrels, N., and Chen, W. 1993, Nature, 361, 706

Lee, T., Papanastassiou, D.A.,& Wasserburg, G.J. 1977, ApJ, 211, L107

McCray, R. 1993, ARAA, 31, 175

McKee, C.F., in IAU Colloquium 101, The Interaction of Supernova Remnants with the Interstellar Medium, ed. T. Landrecker and R. Rogers (1988: Cambridge, Cambridge Univ. Press), 205

Meyer, B. et al. 1992, ApJ, 399, 656

Meyer, B.S., & Schramm, D.N. 1986, ApJ, 311, 406

O'Brien, K., de la Zerda Lerner, A., Shea, M.A., & Smart, D.F. in The Sun in Time, ed. C.P. Sonnet, M.S. Giampapa, & M.S. Mathews (1991: Tucson, Univ. of Arizona Press), 317

Parker, E.N. 1958, Phys. Rev., 110, 1445

Perko, J.S. 1987, A&A, 184, 119

Prinzhoffer et al., 1989 ApJ, 344, L81

Raisbeck, G.M., et al. 1987, Nature, 326, 273

Ramadurai, S. 1993, Bull. Astr. Soc. India, 21, 391

Reid, G.C., McAfee, J.R., Crutzen, P.J. 1978, Nature, 257, 489

Ruderman, M.A. 1975, Science, 184, 1079

Sonett, C.P. 1992, Radiocarbon, 34, 2

Sonett, C.P., Morfill, G.E., & Jokipii, J.R. 1987, Nature, 330, 458

Spitzer, L. 1978, Physical Processes in the Interstellar Medium (Wiley: New York), 255

van den Bergh, S. 1994, Pub. Astron. Soc. Pacif., 106, 689

Figure Captions

1. Deposited mass as a function of distance D from the supernova. The total mass deposited is shown, as well as the component due to direct deposition and to cosmogenic production. Note the increase of material above about 7 pc, which continues until the cutoff at $\sim$ 45 pc. Note that the deposited mass will scale directly with the ISM density, while the cutoff will scale with the solar wind pressure at earth and inversely with the blast duration. Although the cosmogenic contribution is negligible when there is a direct component, it is the only source above the cutoff.

2. Expected number of radioisotopes per unit mass of sediment, Λ. Cosmic ray backgrounds and detection sensitivity are indicated. The curve for $\tau = 1$ Gyr assumes $n_{\rm ISM} = 1 {\rm cm}^{-3}$, whereas the curve for $\tau \ll 1$ Gyr is independent of $n_{\rm ISM}$.

Table 1: Shorter-Lived* Radioisotope Candidates

Isotope	$t_{1/2}$ (yr)	Process†	Isotope	$t_{1/2}$ (yr)	Process†
^{10}Be	1.6×10^6	CR	^{150}Gd	1.8×10^6	P
^{26}Al	7.2×10^5	Ex-SN, Ex-N, CR	^{186}Re	2×10^5	S
^{36}Cl	3.0×10^5	Ex-SN	^{202}Pb	3×10^5	P
^{41}Ca	1.0×10^5	Ex-SN, P, CR	^{208}Bi	3.7×10^5	P
^{53}Mn	3.7×10^6	Ex-SN, P, CR	^{210}Bi	3.0×10^6	R
^{59}Ni	7.5×10^4	Ex-SN, P	^{230}Th	8.0×10^4	R
^{60}Fe	3×10^5	Ex-SN, R, S	^{231}Pa	3.3×10^4	R
^{81}Kr	2.1×10^5	S	^{233}U	1.6×10^5	R
^{93}Zr	1.5×10^6	S	^{234}U	2.5×10^5	R
^{97}Tc	2.6×10^6	P	^{236}Np	1.1×10^5	R
^{98}Tc	4.2×10^6	ν?, CR?	^{237}Np	2.1×10^6	R
^{107}Pd	6.5×10^6	R, S	^{242}Pu	3.8×10^5	R
^{126}Sn	1×10^5	R	^{248}Cm	3.5×10^5	R
^{135}Cs	3×10^6	R			

* $10^5\text{yr} \lesssim t_{1/2} \leq 10^7\text{yr}$

†*Production processes (from Anders & Grevesse 1989)*
CR – cosmic ray spallation
Ex-SN – explosive nucleosynthesis: supernovae
Ex-N – explosive nucleosynthesis: novae
S – s-process
R – r-process
P – p-process
ν – ν-process

Table 2: Longer-Lived** Radioisotope Candidates

Isotope	$t_{1/2}$ (yr)	Process†
^{40}K	1.3×10^9	S, Ex-N
^{92}Nb	3.2×10^7	ν, CR
^{129}I	1.6×10^7	R
^{146}Sm	1.0×10^8	P
^{205}Pb	1.4×10^7	S, P
^{235}U	7.0×10^8	R
^{236}U	2.3×10^7	R
^{238}U	4.5×10^9	R
^{244}Pu	8.1×10^7	R
^{247}Cm	1.6×10^7	R

** 10^7 yr $\leq t_{1/2} \lesssim 10^{10}$ yr

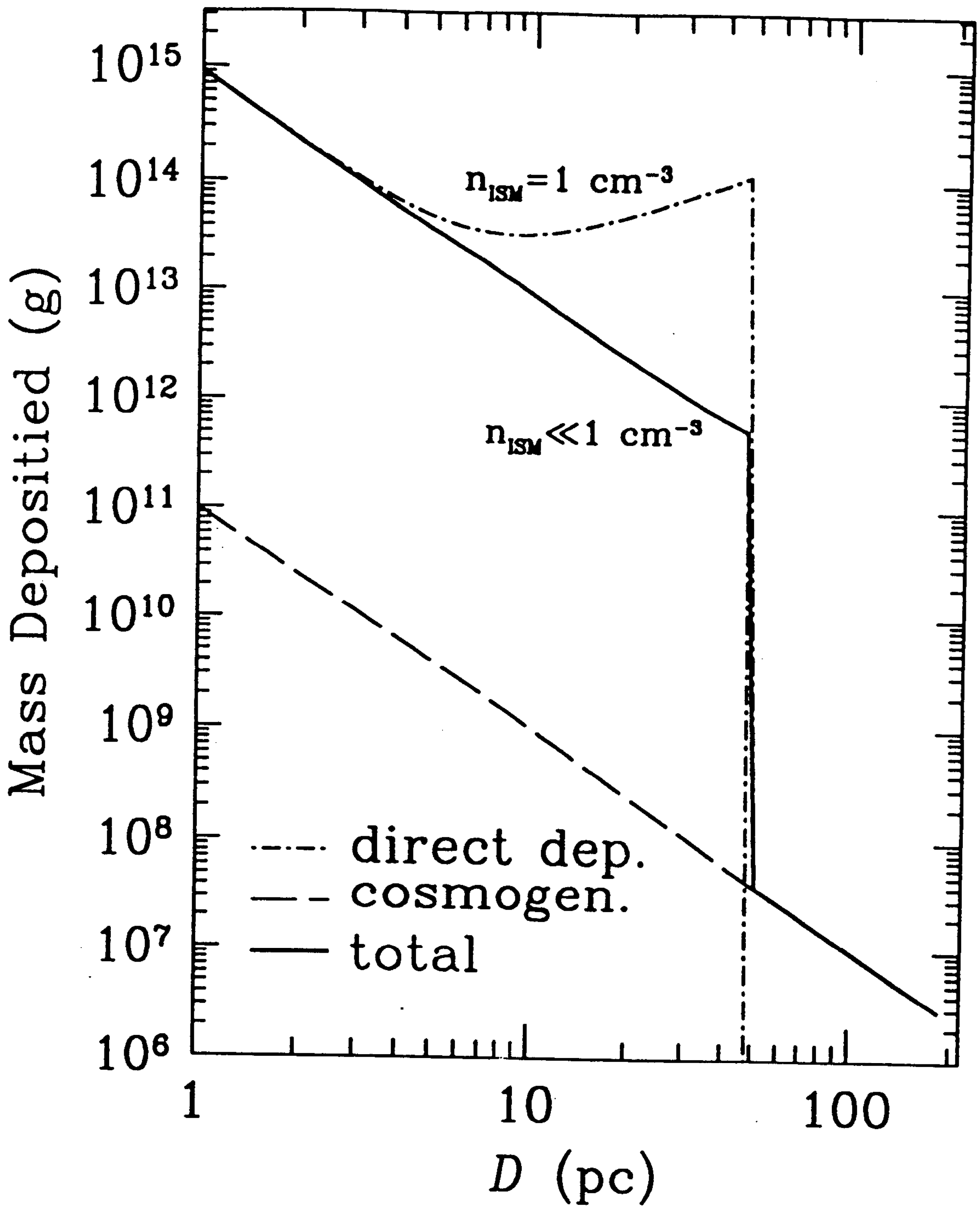
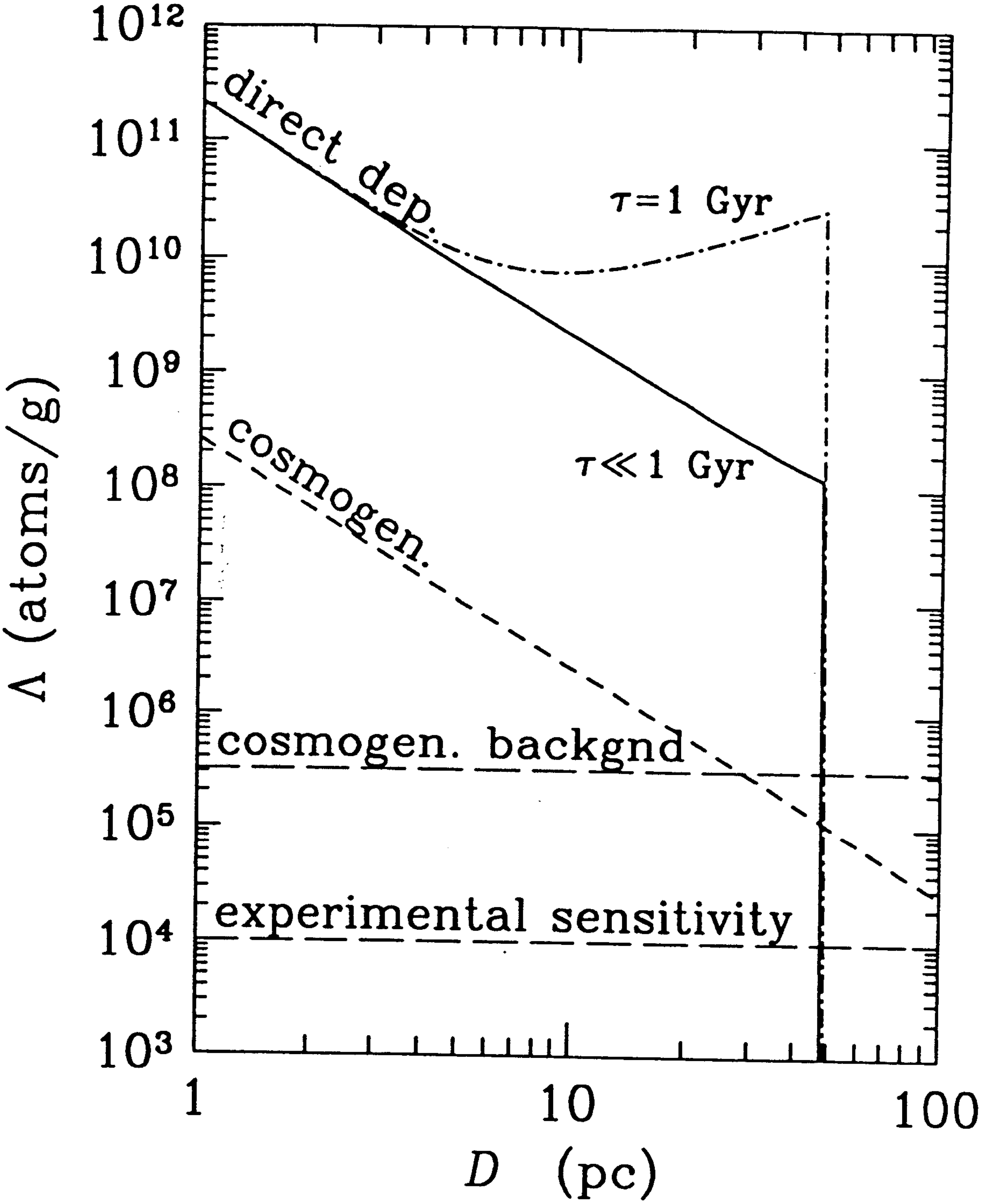

Mass Depositied (g)
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
1
10
100
D (pc)
$n_{ISM}=1\ cm^{-3}$
$n_{ISM} \ll 1\ cm^{-3}$
direct dep.
cosmogen.
total

Fig. 1



direct dep.
τ=1 Gyr
τ≪1 Gyr
cosmogen.
cosmogen. backgnd
experimental sensitivity
Λ (atoms/g)
D (pc)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
1
10
100

Fig. 2