

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 in the Earth's atmosphere. We estimate the mass of material deposited terrestrially by these two mechanisms, showing the dependence on the supernova distance. A number of radioactive isotopes are identified as possible diagnostic tools, such as ^{10}Be , ^{26}Al , ^{36}Cl , ^{53}Mn , ^{60}Fe , and ^{59}Ni , as well as the longer-lived ^{129}I , ^{146}Sm , and ^{244}Pu . 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. Combining our estimates for matter deposition with results of recent nucleosynthesis yields, we calculate the expected signal from nearby supernovae using ice cores back to $O(300)$ kyr ago, and we discuss using deep-ocean sediments back to several hundred Myr. In particular, we examine 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.

Subject headings: Earth — nuclear reactions, nucleosynthesis, abundances — supernovae: general

1. INTRODUCTION

The most violent events likely to have occurred in the solar neighborhood 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 (Caraveo et al. 1996) and recent supernova remnant (Gehrels & Chen 1993; Halpern & Holt 1992; Bignami & Caraveo 1992; Bertsch et al. 1992). If a supernova explosion occurred sufficiently close to Earth, it could have dramatic effects on the biosphere (Ruderman 1975). 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 supernova effects in 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 corresponding to geological ages of about 35 and 60 kyr before the present have actually been discovered in ice cores

(Raisbeck et al. 1987; Beer et al. 1992; Raisbeck et al. 1992) and deep-sea sediments (McHargue, Damon, & Donahue 1995; Cini Castagnoli et al. 1995). Their interpretation in terms of one or more nearby supernova explosions has been discussed (Raisbeck et al. 1987; Sonett, Morfill, & Jokipii 1987; Ammosov et al. 1991; Sonett 1992; Ramadurai 1993). This paper is an attempt to update such studies in the light of the current understanding of supernova remnant evolution, following SN 1987A (reviewed in, e.g., Arnett et al. 1989; McCray 1993) and the recent developments regarding Geminga and the ^{10}Be anomalies.

While 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 (Ellis & Schramm 1995). 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, it turns out, are unlikely to be detectable.

The possible candidate isotopes with long lifetimes include ^{129}I , ^{146}Sm , and ^{244}Pu . 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

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which case ^{26}Al , ^{36}Cl , ^{41}Ca , ^{53}Mn , ^{60}Fe , and ^{59}Ni may be added to the list of relevant isotopes. In § 3 we calculate explicitly the supernova signatures, as well as the background, for all isotopes expected to be observable in the Vostok ice cores.

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 , 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 to 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 ambient pressure of 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.

We then discuss the usefulness of this diagnostic tool for understanding the origin of the geologic ^{10}Be anomalies, and review the prospects for extending anomaly searches back to $O(300)$ kyr ago using older ice cores, and back to $O(500)$ Myr ago using deep-ocean sediments. In particular, we discuss whether the ^{10}Be anomalies could be associated with the supernova explosion that created Geminga (Halpern & Holt 1992; Bignami & Caraveo 1992; Bertsch et al. 1992; 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 the possibility cannot be excluded in view of the large uncertainties in the Geminga age estimates. Moreover, this possibility can be explored by looking for correlated anomalies as discussed in § 5. Even in the absence of such a correlation with the ^{10}Be anomalies, this technique could be used to search for a geological signature of the Geminga explosion if it occurred up to $O(300)$ kyr ago, as is generally believed.

2. ISOTOPE PRODUCTION

Nearby supernovae can introduce radioisotopes to the Earth by two mechanisms: direct deposition of material from the ejected shell, or spallative production in the Earth's atmosphere (i.e., cosmogenic production) due to the supernova's enhancement of the local cosmic-ray flux. In this section we discuss the physics of both mechanisms and estimate the total mass deposited on the Earth. We will then use these results in § 3 to determine experimental signatures of these mechanisms in terms of ice-core and deep-ocean sediment observables.

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_{ej} of which a fraction X_i^{SN} is composed of isotope i . If the amount of matter swept up is M_{sw} , with composition (mass fractions)

X_i^{ISM} , then the total mass arriving in the shell as it reaches Earth is $M_{\text{tot}} = M_{\text{ej}} + M_{\text{sw}}$. The composition of this material is a weighted average of the abundances in each component: $X_i = (X_i^{\text{SN}}M_{\text{ej}} + X_i^{\text{ISM}}M_{\text{sw}})/M_{\text{tot}}$. The proportion of this matter that reaches Earth is just given by the fraction of the solid angle the Earth subtends. The mass in i deposited terrestrially is thus

$$M_i^{\text{dep}} = f_{\text{dep}} X_i \left(\frac{R_{\oplus}}{2D} \right)^2 M_{\text{tot}} \\ = 2.3 \times 10^{13} \text{ g} f_{\text{dep}} X_i \left(\frac{D}{10 \text{ pc}} \right)^{-2} \left(\frac{M_{\text{tot}}}{100 M_{\odot}} \right). \quad (1)$$

Note that the deposited mass M_{dep} depends on the distance D to the supernova via the contribution of the swept material M_{sw} ; this dependence can be understood in terms of supernova remnant evolution, and will be considered shortly. Note also that we have inserted in equation (1) a factor $f_{\text{dep}} \leq 1$ 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^{13} 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 (§ 3), 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 equation (1) via the implicit dependence of M_{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, are complicated; recent detailed discussion can be found in, e.g., McKee (1988), and Chevalier & Liang (1989). The propagation phases include the following: (1) free expansion for ~ 4 pc until the ejecta has swept up about its own mass; (2) a subsequent phase in which the ISM dominates the mass and composition; (3) then adiabatic (Sedov) expansion until radiative losses become important; and (4) finally the momentum-conserving "snowplow" phase. In fact, we will not even need to delve into the details of these phases. We only wish to estimate the swept-up mass M_{sw} , and in *all* of these phases the ISM is swept up by the shock. For the purpose of making order-of-magnitude estimates, we construct a simplified model in the following way.

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

$$M_{\text{tot}} = M_{\text{ej}} + M_{\text{sw}} \\ = M_{\text{ej}} + \frac{4\pi}{3} \rho_{\text{ISM}} D^3. \quad (2)$$

To determine the swept-up mass, choosing an appropriate value for ρ_{ISM} (or equivalently n_{ISM}) is essential. Unfortunately, there is a wide range of reasonable choices. The average ISM number density is $\sim 1 \text{ cm}^{-3}$, but within hot, supernova-induced bubbles, the density is closer to $\sim 10^{-3} \text{ cm}^{-3}$. And while the solar system is presently located on the edge of such a bubble (Frisch 1994), it may have arrived there only recently, and it has probably traversed many different environments on 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 choice impacts only the long-lived, supernova-produced radioisotopes.

The accumulation of mass continues until the end of the snowplow 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 $D_0 \simeq 20 \text{ pc}$, with velocity $v_0 \simeq 100 \text{ km s}^{-1}$, mass $M_0 \simeq (4\pi/3)\rho_{\text{ISM}}D_0^3 \simeq 1000 M_{\odot}$, and time $t_0 \sim 40 \text{ kyr}$ (as given, e.g., in Spitzer 1978). The transition momentum is thus $M_0 v_0$, and, setting this equal to $M_{\text{tot}} v$, we have

$$M_{\text{tot}} = \frac{v_0}{v} M_0. \quad (3)$$

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 $D_f \simeq 70 \text{ pc}$ for an 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 equation (1) we have indicated this exclusion from the Earth by the factor f_{dep} , but we may approximate its effect by simply finding a smaller $D_{\text{max}} < D_f$ appropriate for the solar wind pressure (i.e., we will put $f_{\text{dep}} = 1$ for $D \leq D_{\text{max}}$ and $f_{\text{dep}} = 0$ otherwise).

We thus need to estimate D_{max} . Equating the ejecta pressure $P_{\text{ej}} \sim M_{\text{tot}} v / (D^2 \Delta t) = M_{\text{ej}} v_{\text{ej}} / (D^2 \Delta t)$ with the solar wind pressure $P_{\text{sw}} \sim m_p v_{\text{sw}} \Phi_{\text{sw}}$ gives a maximum range of $\sim 16 \text{ pc}$. Note, however, that this calculation assumes the worst-case geometry, namely, that the shock encounters the wind perpendicularly on its way to Earth. A more oblique angle allows more penetration and so a higher D_{max} . This effect will be important even if the explosion happens in the plane of the ecliptic as long as the shock duration $\Delta t > 1 \text{ yr}$, allowing the Earth to encounter regions at these oblique angles. Furthermore, one expects, in general, that the explosion will be out of the ecliptic. A detailed analysis of the possible geometries is beyond the scope of this paper, but it is clear that it will lead to a larger D_{max} than 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

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

where we have used $\Phi_{\text{sw}} = 3 \times 10^8 \text{ protons cm}^{-2} \text{ s}^{-1}$ and

$$v_{\text{sw}} = 400 \text{ km s}^{-1}.$$

Since sweep-up is effective until the shock dies, we will model the spatial dependence of the deposited material by using equation (2) up to the distance D_{max} , which we will take to be a sharp cutoff. Beyond D_{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 behavior appears in Figure 1.

Figure 1 points up a striking feature of the direct deposition mechanism for the case of an explosion within a dense ISM. In the regime $10 \text{ pc} \lesssim D \lesssim D_{\text{max}}$, the total shock mass varies as $M_{\text{tot}} \approx M_{\text{sw}} \sim D^3$, 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 $\sim 10 \text{ pc}$ most interesting for mass extinctions, the direct deposit material is in fact near its minimum amount. To be sure, the variation is relatively 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

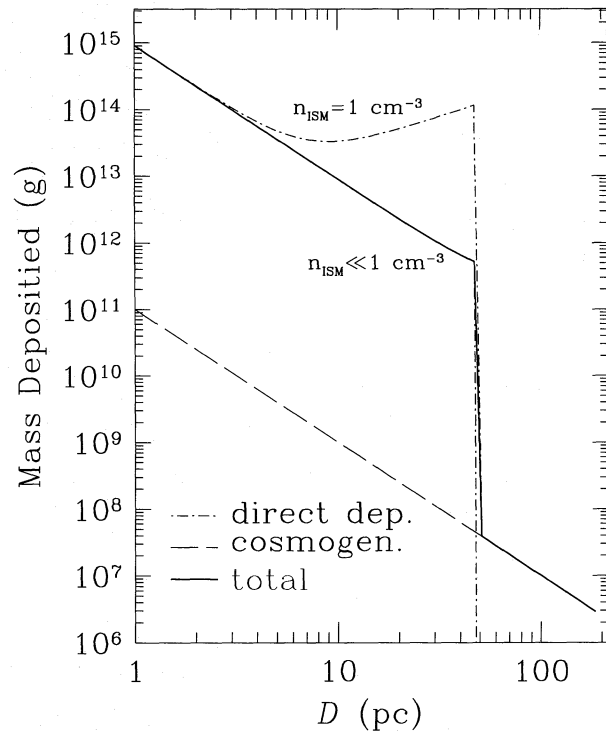


FIG. 1.—Deposited mass as a function of distance D from the supernova. The total mass deposited is shown, as well as the component due to direct deposition and to cosmogenic production. Note the increase of material above about 7 pc, which continues until the cutoff at $\sim 45 \text{ pc}$. Note that 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.

the supernova. Specifically, the ratio is

$$\begin{aligned} \frac{M_i^{\text{sw}}}{M_i^{\text{ej}}} &= \frac{X_i^{\text{ISM}}}{X_i^{\text{SN}}} \frac{(4\pi/3)D^3 \rho_{\text{ISM}}}{M_{\text{ej}}} \\ &= 10.3 \frac{X_i^{\text{ISM}}}{X_i^{\text{SN}}} \left(\frac{D}{10 \text{ pc}} \right)^3 \left(\frac{n_{\text{ISM}}}{1 \text{ cm}^{-3}} \right), \end{aligned} \quad (5)$$

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

In fact, one should distinguish three categories of directly deposited (radio)isotopes, according to 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 . (We will treat cosmogenic production separately in § 2.3.) Since these isotopes are absent from the ejecta, we are only concerned with the nuclei accumulated by the sweeping of material in the ISM. These will have an equilibrium abundance in the ISM, given by the cosmic-ray production rate averaged over the lifetime. It turns out, however, that the lifetimes are short enough that this component is negligible compared to the in situ cosmogenic component (which also benefits from the target abundances being atmospheric and so dominated by N and O, which are the main spallative ^{10}Be progenitors).

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-up matter that 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-up contribution to supernova radioisotopes. This is quite similar to the swept-up spallogenic nuclide calculation. The ISM equilibrium density of a supernova isotope i is

$$\rho_i = \lambda \tau_i \frac{X_i^{\text{SN}} M_{\text{ej}}}{V_{\text{gal}}}, \quad (6)$$

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

$$\begin{aligned} \frac{M_i^{\text{sw}}}{M_i^{\text{ej}}} &= \frac{4}{3} \lambda \tau_i \frac{D^3}{R_{\text{gal}}^2 h} \\ &= 1.3 \times 10^{-4} \left(\frac{\tau_i}{1 \text{ Myr}} \right) \left(\frac{D}{10 \text{ pc}} \right)^3, \end{aligned} \quad (7)$$

which is small for moderate lifetimes; thus, for isotopes having $\tau_i \lesssim 1 \text{ Gyr}$, the ejecta composition dominates. However, if $\tau_i \gtrsim 1 \text{ Gyr}$ and $D \gtrsim 20 \text{ pc}$, the swept-up 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 drop off as D^{-2} , while those dominated by swept-up matter increase as D . Thus measurements of each of these types provide an independent way of determining the distance to the supernova; moreover, their ratio provides an important consistency check. Indeed, it is conceivable 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

$$U_{\text{CR}} = \epsilon U_{\text{SN}}, \quad (8)$$

where U_{SN} is the kinetic energy of the blast wave. If the average cosmic-ray kinetic energy is $\langle E \rangle_{\text{CR}} \simeq 1 \text{ GeV}$, then the total cosmic-ray exposure at Earth (i.e., the time-integrated flux, or the fluence) is just

$$\Phi \Delta t = \xi_{\text{CR}} f_{\text{CR}} \frac{U_{\text{CR}}/\langle E \rangle_{\text{CR}}}{4\pi D^2}, \quad (9)$$

where $\xi_{\text{CR}} \leq 1$ accounts for losses due to propagation to the solar system, and f_{CR} , in analogy to f_{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 diffusively, spiraling around local magnetic field lines. The most significant means of cosmic-ray losses in transit are due to ionization losses to the ISM; however, for the path lengths important here, these are completely negligible. Thus cosmic-ray losses in transit are minimal, so we will put $\xi_{\text{CR}} = 1$ henceforth. The physics behind f_{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 reexamined by Perko (1987). For the purposes of estimation, we will simply note that the integrated flux decreases by roughly a factor of 10 from its interstellar value. Thus we take $f_{\text{CR}} = 1/10$.

The total number of cosmic-ray interactions with the Earth is $4\pi R_{\oplus}^2 \Phi \Delta t$; the fraction of these that produce isotope i in the process $j + k \rightarrow i$ is given by the branching ratio $y_j^{\text{CR}} y_k^{\text{atm}} \sigma_{jk}^i / \sigma_{\text{tot}}$, the ratio of spallogenic production of i to the total inelastic cross section multiplied by the cosmic-ray and atmospheric abundances y_j^{CR} and y_k^{atm} , respectively. It will be useful to introduce the definition

$$Y_i = \sum_{jk} y_j^{\text{CR}} y_k^{\text{atm}} \frac{\sigma_{jk}^i}{\sigma_{\text{tot}}}, \quad (10)$$

which amounts to a weighted branching ratio for spallation production of isotope 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

$$M_i^{\text{CR}} = f_{\text{CR}} A_i Y_i \left(\frac{R_{\oplus}}{D} \right)^2 M_{\text{ej}} \left(\frac{\epsilon U_{\text{SN}}}{c} \right)^2. \quad (11)$$

It is of interest to compare the strength of the two mechanisms, direct deposition versus cosmogenic production. As we have already noted, if the species is not produced in supernovae, the cosmogenic component dominates the contribution from swept-up ISM material. However, when there is a significant supernova contribution, a straightforward analysis shows that this component dominates that due to cosmic rays; this reflects the fact that cosmic-ray spallation is a very inefficient mechanism for nucleosynthesis, and is only relevant for nuclides which have no other known astrophysical sources (e.g., ${}^6\text{Li}$, Be , and B).

The signatures of the different mechanisms may also be staggered in time. In both cases the terrestrial signal will be delayed after the supernova explosion by the propagation time of the shock and of the cosmic rays. This time of flight is significant for the shock, which can take up to 100 kyr to go 20 pc. On the other hand, in the simplest picture the cosmic rays propagate diffusively ahead of the shock. They are much more rapid, traversing 20 pc in ~ 1 kyr. Thus one does not expect the direct deposition and cosmogenic signals to be coeval. However, if the cosmic rays, in the process of acceleration, remain concentrated in the vicinity of the shock, then there may still be a cosmogenic signal simultaneous with the direct deposition.

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 number of atoms, or 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, & Yiou (1991) in their discussion of ${}^{10}\text{Be}$. 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 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 mass spectrometry measurements of the number of rare atoms per gram of bulk material (call it Λ) is $\Lambda_{\min} \sim 10^4$ atoms g^{-1} . Of course, the determination of Λ is necessarily destructive. On the other hand, one can perform a nondestructive measurement of radioisotopes by measuring the decay rate (i.e., the activity). The relation between the two is simply

$$\Gamma_i = \Lambda_i / \tau_i, \quad (12)$$

with Γ the decay rate per gram of bulk material. Typical sensitivities are $\Gamma_{\min} \sim 10$ dpm kg^{-1} (dpm = decays per minute). For a lifetime of 1 Myr, this threshold corresponds

to an effective number-count threshold of 2×10^9 atoms $\text{g}^{-1} \sim 10^5 \Lambda_{\min}$. It is clear that the mass spectrometry 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 $\rho \Delta t dh/dt$. Thus the number of supernova radioisotopes per unit mass of terrestrial sedimentation is

$$\Lambda_i = \frac{1}{A_i} \frac{M_i / m_p}{4\pi R_{\oplus}^2 \Delta t dh/dt}, \quad (13)$$

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

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

$$\Lambda_i = 5.0 \times 10^7 \text{ atoms } \text{g}^{-1} \left(\frac{X_i^{\text{SN}}}{10^{-5}} \right) \left(\frac{\Delta t}{1 \text{ kyr}} \right)^{-1} \left(\frac{D}{10 \text{ pc}} \right)^{-2} \quad (14)$$

for $A_i = 50$ and $D \leq D_{\max}$. In equation (14) we have assumed a sedimentation density $\rho = \rho_{\text{ice}} \simeq 1 \text{ g cm}^{-3}$ and rate $dh/dt = 1 \text{ cm yr}^{-1}$, in accordance with the Raisbeck et al. (1987) Vostok measurements. We see that the signature is far above threshold, indicating that there should be a strong signal, though not necessarily via decays. In the case of ${}^{26}\text{Al}$ in ice cores, we find $\Lambda_{26}^{\text{ice}} \sim 10^7$ atom g^{-1} at $D = 10$ pc, which is very much larger than the ice-core ${}^{10}\text{Be}$ spike amplitude. Thus we predict that, if the ice-core events were nearby supernovae within direct-deposition range, the signal in ${}^{26}\text{Al}$ and other supernova-produced radioisotopes should be observable.

For the cosmogenic component produced in situ, we have

$$\begin{aligned} \Lambda_i &= f_{\text{CR}} \epsilon \left(\frac{U_{\text{SN}}}{m_p c^2} \right) \frac{Y_i}{4\pi \rho D^2 \Delta t dh/dt} \\ &= 7.7 \times 10^6 \text{ atoms } \text{g}^{-1} \\ &\quad \times \left(\frac{Y_i}{10^{-2}} \right) \left(\frac{\Delta t}{1 \text{ kyr}} \right)^{-1} \left(\frac{D}{10 \text{ pc}} \right)^{-2}, \end{aligned} \quad (15)$$

using a value of Y_i appropriate for ${}^{10}\text{Be}$ 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 timescale means that one should concentrate on longer-lived isotopes, 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).³ From this point of view, the optimal isotope

³ The optimal choice is different for the decay rate, which has $\Gamma \propto e^{-(t_0 - t_d)/\tau_i}$ and so is maximized by $\tau_i = t_0 - t_d$. In practice this makes little difference given the paucity of available radionuclides with $\tau \gtrsim 10^8$ yr.

lifetime should be as long as possible, with an upper limit of about the age of the Earth (to ensure that any initial protosolar abundance has decayed away). A catalog and discussion of isotope candidates can be found in § 5.

For ocean sediments there is a lower limit to the time resolution $\Delta t \geq 1$ kyr, the origin of which is biological. That is, as noted in Beer et al. (1991), small organisms dig into the sea floor and disturb it for depths of a few centimeters, corresponding to a time ~ 1 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, although they have their own environmental peculiarities.

We thus reemphasize that the above discussion does not take into account possible fractionation due to chemical, atmospheric, geophysical, or even biological effects. Given the longer timescales 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 in equations (13) and (12) could be depleted by such effects. However, the possibility of fractionation also suggests that the isotope abundances could even be enhanced in some favorable cases. A detailed study of the likelihoods of fractionation for the above-mentioned isotopes goes beyond the scope of this paper.

In Figure 2 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 pro-

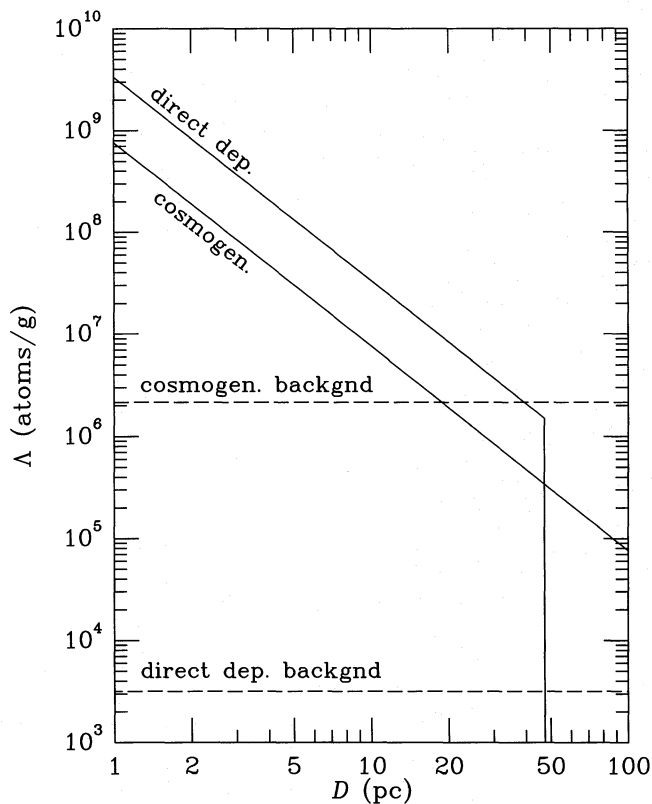


FIG. 2.—Expected number of radioisotopes per unit mass of sediment, Λ . Cosmic-ray backgrounds and detection sensitivity are indicated. The direct-deposition yields are for ^{26}Al , and cosmogenic yields are for ^{10}Be . These can be scaled using Table 1 to give the dependences for other isotopes.

duction due to Galactic cosmic rays (discussed below in § 4.1).

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 $^i\mathcal{P}$ (e.g., ^{26}Al) that decays to a daughter isotope $^i\mathcal{D}$ (e.g., ^{26}Mg). A signal of the presence of $^i\mathcal{P}$ would be a correlation of a $^i\mathcal{D}$ excess with the \mathcal{P} elemental abundance, both measured in a ratio to the major isotope of \mathcal{D} (e.g., Mg). For example, one finds $^{26}\text{Mg}/^{24}\text{Mg}$ 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 $\delta^i\mathcal{D}/\mathcal{D}$ in the daughter isotopic fraction must be detectable and not due to fractionation; i.e., the variations must be at least of the order of a percent. This means that the supernova contribution to $^i\mathcal{D}$ must be at least of order $^i\mathcal{D}_{\text{SN}} \gtrsim 0.01^i\mathcal{D}_{\text{BG}}$; expressed in terms of number compared to Si, we have $^i\mathcal{D}_{\text{SN}}/\text{Si} \gtrsim 0.01(^i\mathcal{D}/\mathcal{D})(\mathcal{D}/\text{Si})_{\text{BG}}$. If we take typical abundances of $\mathcal{D}/\text{Si} \sim 10^{-2}$, and $^i\mathcal{D}/\mathcal{D} \sim 0.01$, we get a limit of $^i\mathcal{D}/\text{Si}_{\text{SN}} \gtrsim 10^{-4}$. But in sediments we have signals of order $\Lambda_i \sim 10^9$ atoms g^{-1} , i.e., $^i\mathcal{D}$ atoms are extremely rare. Hence, even if the sediment is only 1% Si, this means an abundance of $^i\mathcal{D}/\text{Si} \leq 10^{-11}$, which is much less than the minimum detectability. So it appears that extinct radioisotopes will have too feeble a signal to be measurable.

4. BACKGROUND SOURCES

Radioisotope backgrounds arise from two mechanisms: the normal cosmogenic production in the atmosphere, as well as terrestrial radiological production due to fission of ambient heavy nuclei such as uranium.

4.1. 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 the result that the rate of background atmospheric production of isotope i is

$$\frac{d}{dt} N_i^{\text{BG}} = 4\pi Y_i R_{\oplus}^2 \Phi_p, \quad (16)$$

using the notation of § 2.3, and where Φ_p is the total (modulated) cosmic-ray proton flux. 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

$$\Lambda_i^{\text{BG}} = Y_i \frac{\Phi_p}{\rho dh/dt}. \quad (17)$$

We can check the calculation by estimating the background production of ^{10}Be , for which $Y = 1.36 \times 10^{-2}$. We take a cosmic-ray proton flux of $\Phi_p = 10 \text{ cm}^{-2} \text{ s}^{-1}$. With an ice density of 1 g cm^{-3} and a deposition rate of 1 cm yr^{-1} , we have

$$\Lambda_{\text{Be}}^{\text{BG}} \simeq 4 \times 10^6 \text{ atoms g}^{-1}, \quad (18)$$

in rough agreement with the ^{10}Be concentrations measured in the ice cores. The fact that this simple estimate is appar-

ently too high by a factor of ~ 2 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; we will account for it here by lowering the effective cosmic-ray flux to $5 \text{ cm}^{-2} \text{ s}^{-1}$.

One may also estimate the ^{26}Al background by this method; O'Brien et al. (1991) calculate a cosmogenic production ratio of $^{26}\text{Al}/^{10}\text{Be} \simeq 2 \times 10^{-3}$. This gives a cosmogenic ^{26}Al background of order 300 atoms g^{-1} . However, while this background is lower, the expected supernova signal would be stronger than that of ^{10}Be (if ^{26}Al is produced in supernovae). Thus, an ^{26}Al signature would be very large and would far exceed background.

To make this point more broadly, we now compare the background due to Galactic cosmic rays to the signals of supernova deposition mechanisms. For direct deposition of pure supernova products, a straightforward comparison of equations (13) and (17) shows the signal to be very much larger than the background. To wit, for all cases of interest, we estimate the signal-to-background ratio to be $\gtrsim 10^2$. Direct deposition should thus be readily observable if it has occurred.

For 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,

$$\begin{aligned} \frac{\Lambda_i^{\text{CR}}}{\Lambda_i^{\text{BG}}} &\simeq f_{\text{CR}} \left(\frac{\epsilon U_{\text{SN}}}{m_p c^2} \right) \frac{X_j/A_j}{y_j^{\text{GCR}}} (4\pi D^2 \Delta t)^{-1} \\ &= 16 \frac{X_j/A_j}{y_j^{\text{GCR}}} \left(\frac{D}{10 \text{ pc}} \right)^{-2}, \end{aligned} \quad (19)$$

where we have now assumed the production to be dominated by the projectile species j . The signal-to-background ratio 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 farther, or no signal at all for larger distances.

4.2. Fission Background

Fission of ambient, long-lived heavy nuclei, notably ^{238}U , leads to significant production of some of the radioisotopes of interest. Since ^{238}U dominates, we will simplify by only considering this parent nucleus. The radiological background will be $\Lambda_i^{\text{BG}} = X_i/(A_i m_p)$, where X_i is the ambient mass fraction in the ice or sediment of interest. We thus need to compute the mass fraction of daughter species i at a present time t_0 , after the deposition time t_d ; this is just given by the integrated U decay rate times the branching ratio for spontaneous fission into species i . This leads to a background of

$$\Lambda_i^{\text{BG}} = \frac{f_i}{A_i} \frac{t_0 - t_d}{\tau_{\text{U}}^{\text{SF}}} \frac{X_{\text{U}}}{m_p}, \quad (20)$$

where $\tau_{\text{U}}^{\text{SF}} = 1.3 \times 10^{16} \text{ yr}$ is the lifetime against spontaneous fission of ^{238}U , and f_i is the fraction of fissions that produce i .

For a time since deposition $t_0 - t_d \sim 100 \text{ kyr}$ (appropriate for ice cores), equation (20) gives a background level of $\Lambda_i^{\text{BG}} \sim 1.5 \times 10^2 f_i$ atoms g^{-1} , assuming that uranium has its average (present) terrestrial abundance. Note that f_i is fairly tightly distributed around mass numbers 100 and 140. While this background is tiny, the signal is small as well; indeed, fission can be an important background source for isotopes near these peaks whose cosmogenic background is small, notably ^{129}I and ^{146}Sm . This is particularly true if one examines longer-lived isotopes in deep-sea sediments deposited on timescales of Myr ago.

5. ISOTOPE CANDIDATES

Having presented the various effects and backgrounds, we turn to the possible isotope candidates, both for probing the Geringa event and for mass-extinction events (specific signature predictions are presented in the next section). Isotopes arise from either supernova explosions or cosmic-ray production, and can be further subdivided into short- and long-lived radioactivities. They can thus be classified as follows: (1) short-lived ($t_{1/2} < 10^7 \text{ yr}$) supernova products, (2) long-lived ($t_{1/2} \geq 10^7 \text{ yr}$) supernova products, and (3) short-lived cosmic-ray products (since there are no long-lived cosmic-ray products). Moreover, as the cosmic-ray products are very few, the bulk of the candidates are potential supernova products. Of course, a supernova origin would not be established equally easily for all candidates of interest. Note that while a few isotopes seem very likely to be supernova products (e.g., ^{26}Al , ^{36}Cl , and ^{59}Ni), for others this is less clear. Indeed, turning the problem around, detection of these isotopes could teach us about the source of the different candidate nuclei.

Short-lived isotopes are good as Geringa signatures or as extinct radioactivity; it is clear that they are unable to provide signatures of mass extinctions. Good short-lived supernova products are notably ^{26}Al , ^{36}Cl , ^{60}Fe , and ^{59}Ni . Indeed, there is now direct evidence for ^{26}Al in the ISM, observed via its 1.809 MeV γ -ray emission line (Knödseder et al. 1996). This emission is concentrated in the Galactic plane and strongly suggests a supernova origin for ^{26}Al (see Prantzos & Diehl 1996 for a review). The only short-lived cosmic-ray product produced in significant abundance is ^{10}Be (with a possible contribution to ^{26}Al as well).

The long-lived isotopes can provide a long enough signal to give evidence of a mass extinction. We note first that while ^{40}K and ^{238}U might seem good candidates, in fact they are not, precisely because their lifetimes are so long ($> 1 \text{ Gyr}$). Their longevity has allowed a significant fraction of their initial abundance to remain in ambient terrestrial matter. For our purposes, this leads to the same difficulties as the stable isotopes: the ambient background overwhelms signal. Thus, we wish to find isotopes sufficiently long-lived to provide signatures of mass extinctions, but with lifetimes that are still short compared to the age of the Earth. There are few of these.

Indeed, since the most interesting mass extinctions occurred at epochs $\gtrsim 10^7 \text{ yr}$ ago, there are only three isotopes with lifetimes in this range, which can be discussed individually. ^{129}I ($\tau = 15 \text{ Myr}$) is thought to be produced in the r -process. If this has its origin in supernovae, it makes a good signature because of its small background (coming from cosmogenic production via rare Xe targets); on the other hand, it is too short lived for the most ancient mass

extinctions. ^{146}Sm ($\tau = 146$ Myr) is produced via the p -process. This presumably has its site in supernovae, although the protosolar abundance is poorly reproduced by specific supernova models (Prinzhofer, Papanastassiou, & Wasserburg 1989; Lambert 1992). Alternatively, Woosley & Howard (1990) have investigated the possible origin of ^{146}Sm via photodissociation in the γ -process. ^{244}Pu ($\tau = 118$ Myr) comes from the r -process. Thus it is not clear that the long-lived nuclei are supernova products. However, even if neither is made in supernovae, they could appear in the swept-up material due to their ISM equilibrium abundance, if the nearby explosion occurs in a dense ($n_{\text{H}} \gtrsim 1 \text{ cm}^{-3}$) medium.

6. IMPLICATIONS FOR THE GEMINGA SUPERNOVA

Anomalous ^{10}Be abundances at ~ 35 and 60 kyr B.P. (before the present) were first reported for Antarctic ice cores taken in Vostok and Dome C (Raisbeck et al. 1987). Recently, Raisbeck et al. (1992) have taken high-resolution data at Vostok, extending to 50 kyr B.P.. They reconfirm the presence of the 35 kyr peak, which persists and is even amplified when correcting for variations in the precipitation rate.⁴

Other groups have now confirmed the ^{10}Be enhancements. Beer et al. (1992) report positive detections of the 35 kyr peak elsewhere in the Antarctic (Byrd station), as well as in Camp Century, Greenland, ice cores (although they cannot confirm the 60 kyr peak in either sample). A ^{10}Be peak has also been seen at ~ 35 kyr in deep-sea sediments off the Gulf of California (McHargue et al. 1995) and in the Mediterranean (Cini Castagnoli et al. 1995). That the enhancement has been seen in these diverse locations and media strongly suggests that the effect was indeed a global one, as we would predict.

On the other hand, it has been suggested (Mazaud, Laj, & Bender 1994) that the ^{10}Be spikes may derive from variations in the geomagnetic field. To obtain a good correlation, these authors use an ice deposition rate history different from the most recent calculations. To be sure, there remains some correlation with geomagnetic intensity, which may explain part of the ^{10}Be enhancements.⁵

For the most part, however, discussion of the anomalous ^{10}Be measurements has focused on direct passage of the shock wave past the Earth (Raisbeck et al. 1987; Sonett et al. 1987; Ammosov et al. 1991; Sonett 1992; Ramadurai 1993; Lal & Jull 1992). This work has concluded that the Vostok data may indicate that a supernova explosion occurred at distances of $\lesssim 100$ pc, and perhaps even shows something of the detailed shock structure. The “double-bump” structure of the Vostok ^{10}Be anomaly could conceivably be caused by the shock wave bouncing back from the boundary of a previously cleared low-density bubble

⁴ Raisbeck et al. (1992) also discuss the possible relationship between the ^{10}Be enhancement and anomalies in the $^{14}\text{C}/^{12}\text{C}$ ratio. For epochs prior to ~ 10 kyr B.P., there is a discrepancy between ^{14}C and U–Th dating methods; assuming the latter to be accurate, the $^{14}\text{C}/^{12}\text{C}$ ratio shows an unexplained rise reaching to the end of the available data (~ 23 kyr B.P.). Raisbeck et al. note that there is qualitative agreement between the ^{10}Be and ^{14}C behaviors. However, they argue that apparent variations in the $^{14}\text{C}/^{10}\text{Be}$ ratio suggest that the cosmogenic production had a different energy spectrum than at present, perhaps due to, e.g., transients in the development of cosmic-ray shock acceleration.

⁵ Although McHargue, Damon, & Donahue (1993, 1995) suggest that even this might be attributed to extraterrestrial causes.

(Frisch 1994) in the ISM. Further, Ramadurai (1993) has suggested that the supernova causing the ^{10}Be might be Geminga itself. Indeed, recent *Hubble Space Telescope* observations (Caraveo et al. 1996) have measured Geminga’s parallax and so determined that it is quite close, at a distance of 157_{-34}^{+57} pc.⁶

However, there may be problems reconciling the Geminga event dating implied by the ^{10}Be anomalies with dating estimates from pulsar spin-down arguments (Halpern & Holt 1992; Bignami & Caraveo 1992; Bertsch et al. 1992). 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, since neutron starquakes can lead to very rapid mass redistribution and slowing of angular velocity, known as “glitches.” Indeed, Alpar, Ögelman, & Shaham (1993) have argued that Geminga is indeed a glitching pulsar. If there were a number of such events, then Geminga might be more recent and the age estimates could be brought into agreement. Moreover, as noted in § 2.3, the signals will be delayed by the propagation time, which will be significant for the direct debris, and for any cosmic-ray component entangled in the shock. In this case, a time delay of order 300 kyr would indicate a distance ~ 30 pc.

Despite the possible difficulties in reconciling the age determination, it is in any case interesting to consider equation (19) in the light of the Vostok ice-core data. Let us assume that the Vostok ^{10}Be peaks are due to a supernova. Then one may ask, what distance does this imply? In the data, the signal-to-background ratios for the peaks fall within the generous range of $1 \leq \Lambda_{\text{peak}}/\Lambda_{\text{BG}} \leq 4$. Interpreting the peaks as signal, equation (11) implies that $20 \text{ pc} \lesssim D \lesssim 40 \text{ pc}$. This suggests that if the Vostok peaks came from a supernova, it was quite close and indeed may have been a near-miss.

With this result in hand, we have collected the predictions for all isotopic signatures and backgrounds in Table 1. To fix ideas, we have calculated the entries in the table for a supernova at $D = 20$ pc, and the specific abundances Λ_i are for ice-core sedimentation rates. The scalings with distance for each component have been noted both in the text and in Figure 2.

The signals computed in Table 1 come from several recent nucleosynthesis calculations. The supernova yields of ^{26}Al , ^{36}Cl , ^{41}Ca , ^{53}Mn , ^{59}Ni , and ^{60}Fe are taken from Woosley & Weaver (1996), for their $20 M_{\odot}$ model S20A. The r - and p -process yields of ^{129}I , ^{146}Sm , and ^{244}Pu are taken from Cameron, Thielemann, & Cowan (1993). The table takes the optimistic view that these long-lived isotopes all have their origin in supernovae. Also, the swept-up component assumes (optimistically) a dense ($n_{\text{ISM}} = 1$) local ISM.

Note also that some signatures are best observed not as an absolute abundance in atoms per gram but in terms of an isotopic fraction, e.g., $^{36}\text{Cl}/\text{Cl}$. For these last cases, the

⁶ This distance implies transverse velocity of 122 km s^{-1} , while the radial velocity remains unknown. The direction of transverse motion is consistent with the suggestion (Smith, Cunha, & Plez 1994) that Geminga originated in Orion. However, for this to be the case, Geminga would have to have a very large radial velocity, making it one of the fastest pulsars known. In any case, the origin site is tied to the age estimate, and so does not resolve this issue.

TABLE 1
ICE-CORE SIGNATURES FOR A SUPERNOVA AT 20 PARSECS (in atoms g^{-1})

Isotope	Supernova Ejecta	Swept-up	Cosmogenic	Total Signal	Cosmogenic Background	Fission Background	Total Background
^{10}Be	1.9×10^6	1.9×10^6	2.2×10^6	...	2.2×10^6
^{26}Al	8.4×10^6	9.3×10^4	3.1×10^3	8.4×10^6	3.5×10^3	...	3.5×10^3
^{36}Cl	4.8×10^6	2.2×10^4	6.6×10^4	4.9×10^6	7.5×10^4	...	7.5×10^4
^{41}Ca	1.5×10^6	6.7×10^3	1.4	1.5×10^6	1.6	...	1.6
^{53}Mn	2.3×10^7	1.3×10^6	0.7	2.4×10^7	0.79	...	0.79
^{59}Ni	1.0×10^7	1.2×10^4	...	1.0×10^7	1.6×10^{-3}	...	1.6×10^{-3}
^{60}Fe	1.2×10^6	5.4×10^3	1.4	1.2×10^6	1.6	...	1.6
^{129}I	6.9×10^3	1.7×10^3	1.4	8.6×10^3	1.6	1.1	2.7
^{146}Sm	0.32	0.50	...	0.82	...	6.7	6.7
^{244}Pu	69	86	...	1.6×10^2

expected signature can be deduced from the known background isotopic fraction and the signal-to-background ratio as deduced from the table.

If the ^{10}Be signal does have its origins in the Geminga blast, then Table 1 indicates that several other isotopes should be much more abundant in the ice cores. Let us take ^{26}Al as an example. So long as Geminga occurred within $D \lesssim D_{\text{max}}$, then we expect $^{26}\text{Al}/^{10}\text{Be} \simeq 4$. 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.

In this regard, it is interesting that Cini Castagnoli et al. (1995) indicate that they performed two ^{26}Al measurements on their Mediterranean core at the peak regions. They do not give a quantitative result, but cite this measurement as evidence against a contribution from cosmic dust. The implication is that there was not a large ^{26}Al signal. While this certainly does not strengthen the Geminga hypothesis, it cannot rule it out. For example, ^{26}Al might not be a supernova product (though interstellar γ -ray line observations argue against this), or the direct ejecta may have been excluded from the inner solar system. Further and more quantitative data would be very helpful in resolving this question. For example, the lack of signal in other relatively abundant cosmogenic nuclides, such as ^{36}Cl , would be strong evidence against the Geminga interpretation.

Of course, aside from ^{26}Al , the other isotopes we have listed are potentially detectable as well. Indeed, ^{53}Mn and ^{59}Ni could even be at somewhat higher levels. Note also the variety of likely candidates; this helps ensure that the possibility of a signal is not overly tied to uncertainties about the supernova origin of a particular radionuclide.

We hope that the promising outlook embodied in Table 1 will prompt a search for these isotopes in the ice cores. Even a null signal would be an important indication that the ^{10}Be peaks are *not* due to a supernova. Also, it is important to note that in ocean sediments the low level of precipitation makes the signal-to-background ratio larger by a factor of $\sim 10^3$. Thus these could provide even clearer evidence of a nearby supernova.

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 them-

selves, 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. These could be useful in understanding the origin of the global ^{10}Be anomalies and possibly finding a trace of the Geminga explosion. We have also considered searches 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. This 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 B.P.. 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. 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 reemphasize that this identification does not seem exceedingly likely, given the usual estimates of the age and distance of the Geminga remnant (Halpern & Holt 1992; Bignami & Caraveo 1992; Bertsch et al. 1992), but cannot be excluded and should be explored.

Also included in Table 1 are longer-lived radioisotopes that could be of interest for searches in deep-ocean sediments, which may extend back to several hundred Myr B.P. ^{129}I is produced by cosmic rays in the atmosphere, and has a small background. ^{146}Sm could be produced in supernovae via the p -process. Although the origin of the r -process (and thus ^{244}Pu) is unclear, it 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 affect the biosphere, or whether there might have been a "near-miss." However, we reemphasize that our estimates of the possible abundances do not take into account fractionation, which could be important for deep-ocean

sediments. In addition, the low precipitation rate for ocean sediments makes signal more pronounced than in ice cores by a factor $\sim 10^3$. So if indeed anomalies are found to be observable in ice cores, they should stand out clearly indeed in ocean sediments (so long as the isotopes are sufficiently long lived).

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 to learn about supernovae themselves and the various processes that synthesize different elements in the cosmos. We are encouraged that the prospects are good for

the detection of a supernova signal over background, and we encourage experimental searches for such signatures.

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