

Live Radioisotopes as Signatures of Nearby Supernovae

Brian D. Fields

*Center for Theoretical Astrophysics, Dept. of Astronomy, U. Illinois
Urbana, IL 61801 USA*

Abstract

Nearby ($\lesssim 1$ kpc) supernovae were almost certainly common in earth's geological history. Such events allow the direct study of their freshly synthesized live radioisotopes, opening new windows onto supernovae. Very close supernovae (within a few tens of pc) may deposit radioisotopes directly on the earth. Recent high-sensitivity accelerator mass spectrometry measurements of deep-ocean samples find live ^{60}Fe at levels that greatly exceed background, suggesting an explosion occurred within 30 pc during the last 5 Myr. Somewhat more distant – but also more frequent – supernovae leave observable signatures of radioisotopes whose decay includes γ -ray line emission. In particular, a large, old supernova remnant was recently discovered at ~ 100 pc, and appears to contain ^{26}Al . If confirmed, this would be the first detection of ^{26}Al in a single remnant, and would be a new probe of supernova nucleosynthesis and astrophysics.

Key words: supernovae, nucleosynthesis, gamma-rays

PACS: 26.30.+k, 98.70.Rz, 97.60.Bw, 92.20.Td

1 Introduction: When Stars Attack!

The grandeur of supernova explosions and their remnants, normally observed at great distances, becomes all the more compelling—and even sinister—when one imagines an event occurring close to home. The prospect of a near-earth supernova explosion, and the resulting impact on the local ISM, the solar system, and the biosphere, has been a topic running through the literature for decades (e.g., Schindewolf, 1954; Shklovskii, 1968; Ruderman, 1974; Ellis, Fields, & Schramm, 1996; Iyudin, 2002). As we will see, events that occur within $\lesssim 1$ kpc offer a unique astrophysical probe, and we will take this distance scale as a working definition of “nearby.”

How common are nearby events? We can roughly estimate the rate $\lambda(< r)$ of supernovae within a distance r based on assumptions about the distribution of Galactic supernovae, and the present Galactic supernova rate $R_{\text{SN}} \sim (30 \text{ yr})^{-1}$ (see Pavlidou & Fields, 2001, and refs. therein). In a simplistic but instructive model (Shklovskii, 1968), we envision star birth (and death) to occur homogeneously in a disk of radius 15 kpc and scale height $h \sim 100 \text{ pc}$, Supernovae explode randomly in this volume, with a constant global rate R_{SN} . Then we expect

$$\lambda(< r) = \frac{V_{\text{disk}}(< r)}{V_{\text{disk,total}}} R_{\text{SN}} \sim \begin{cases} (10 \text{ Myr})^{-1} \left(\frac{r}{30 \text{ pc}}\right)^3, & r < h \\ (0.3 \text{ Myr})^{-1} \left(\frac{r}{100 \text{ pc}}\right)^2, & r > h \end{cases} \quad (1)$$

We immediately see that events within 100 pc are very common even within the history of hominids, and that over the 4.55 Gyr history of the earth we expect multiple events to have occurred down to distances within a few pc. Of course, this estimate is crude; it can be improved by including additional demographics of supernovae: they occur in molecular clouds (clustered in OB associations), they follow Galactic spiral arms, and they trace a disk distribution that falls off in the radial and axial directions (e.g., Talbot & Newman, 1977; Scalo & Wheeler, 2002; Hartmann, Kretschmer, & Diehl, 2002; Gehrels et al., 2003, and refs. therein). Nevertheless, in light of eq. (1) we can be essentially certain that *some* nearby supernovae have occurred, and those beyond a few pc have been rather frequent.

The observability (and lethality!) of an nearby explosion depends on its distance, and probably other factors as well. Explosions inside 100–200 pc can yield MeV γ -ray lines that are bright enough to be observed by COMPTEL and now INTEGRAL. The rarer supernovae inside 10–30 pc may directly contaminate the earth, and possibly even wreak biological damage. Indeed, the (un?)holy grail of nearby supernova studies would be the association of terrestrial samples of supernova radioisotopes with geological evidence of a mass extinction. No such link yet exists, but recent experimental progress has demonstrated that this goal is becoming technically feasible.

2 Terrestrial Signatures: Geological Isotope Anomalies

To my knowledge, Ellis, Fields, & Schramm (1996) made the first detailed, systematic study of the terrestrial signatures of nearby supernovae. These authors considered the transport and deposition of material by (a) cosmic rays, and by (b) the ejecta itself. Cosmic rays are accelerated in supernova explosions and then propagate diffusively (Biermann, 2003). Thus, they will

precede the blast wave and enhance the ambient cosmic-ray flux. Upon arrival at earth, this cosmic-ray spike will increase spallation in atmosphere and thus produce the cosmogenic radionuclides ^{14}C , ^{10}Be , ^{36}Cl , and ^{129}I . The terrestrial surface density of this spike is set by the cosmic-ray flux (in fact, the fluence) and thus scales as $\propto \Phi_{\text{cr}} \propto 1/r^2$.

The more important signature comes in the direct deposition of supernova ejecta. If the blast wave can overcome the solar wind at 1 AU, then *all* supernova products are dumped on the earth, including ^{26}Al , ^{60}Fe , and possibly *r*-process nuclides (such as ^{182}Hf and ^{244}Pu). The terrestrial surface density of species *i* follows $\sim M_{\text{ej},i}/r^2$. However, there is a maximum distance cut-off, which is set by the requirement that the blast overcome the solar wind: $P_{\text{blast}} \gtrsim P_{\text{solar wind}}$ leads to $r \lesssim r_{\text{max}} \sim 30$ pc.

The terrestrial signature of supernova debris would take the form of radioisotope anomalies in the geological record. Potential “natural archives” include ice cores, sea sediments, and deep-ocean crusts. A figure of merit is the specific concentration, i.e., the number $\Lambda_i = n_i/\rho_{\text{sed}}$ of atoms of species *i* per gram of sediment. This scales as $\Lambda_i \propto M_{\text{ej},i} r^{-2} (\text{sed rate})^{-1} \Delta t_{\text{dep}}^{-1}$, so that events with a short deposition time Δt_{dep} , and material with a slow sedimentation rate are preferred. For example, the ^{10}Be signature of a 10 pc event in ice cores is $\Lambda_{10} \simeq 5 \times 10^7$ atoms g^{-1} . The smallness of the specific concentration implies an unfeasibly low activity, thus accelerator mass spectrometry (AMS) is required (Knie, 2003; Vockenhuber, 2003; Winkler, 2003; Paul et al., 2001).

The tiny signal demands low backgrounds, which leads to a focus on radioisotopes. However, even these are not free of backgrounds, of both terrestrial and solar system origin, including meteoritic dust that as been exposed to cosmic rays, the normal cosmogenic production in the atmosphere, as well as natural (and anthropogenic) fission (Ellis, Fields, & Schramm, 1996; Fields & Ellis, 1999). Other systematics include the fallout pattern of the radionuclides on the earth, and their chemical uptake in the substrate, and possibly the disturbance of these substrates by “bioturbation” – the crawling of small creatures!

A promising candidate for a supernova signature was identified in the pioneering work of the München AMS group. Knie et al. (1999) analyzed a ferromanganese (FeMn) crust taken from a deep and geologically inactive region of the Pacific Ocean. The crust is ideal in that it has an extremely small growth rate ~ 1 mm/Myr. AMS techniques find live ^{60}Fe ($\tau = 2.2$ Myr) and live ^{53}Mn ($\tau = 5.3$ Myr), though the measurements are difficult—only 63 atoms total were identified. The estimated background for ^{60}Fe is ~ 100 times below signal, indicating that the anomaly is real and apparently extrasolar. The ^{53}Mn signal, however, may be consistent with background.

Thus, Knie et al. (1999) have found the first hints of a nearby supernova. One puzzle is that the ^{60}Fe is seen in multiple layers in the crust, not a punctuated “spike” expected from a single encounter with a blast wave. This might point to problems in the analysis, but may also be due to mixing in the sample, or a more complex astrophysical situation, for example dispersion of dust created by the supernova and then accreted into the heliosphere. If the ^{60}Fe is due to a supernova, then all of the signal should be summed, to yield a total surface density. Using this, one can place limits on the supernova event (Fields & Ellis, 1999; Knie et al., 1999): if explosion occurred “yesterday,” then $t/\tau \sim 0$ and using the inverse square law one find $r \lesssim 30$ pc. Note that this distance is not built into the problem, yet is of just the right order of magnitude; this is one of the most impressive aspects of the ^{60}Fe signal. Alternately, if $r \lesssim 10$ pc, the supernova would be both unusually rare and too dangerous!¹ Using this limit, we require $\tau \lesssim 5$ Myr.

Thus the ^{60}Fe data suggest a very recent and nearby supernova, which is likely to have originated in an OB association that still exists. Benítez, Maíz-Apellániz, & Canelles (2002) point out that the Sco-Cen OB association is ~ 120 pc away now, but its kinematics point to a closest approach ~ 100 pc (40 pc at 2σ). They suggest that this may be the source of the ^{60}Fe event and possibly also the hot Local Bubble in which the Sun currently resides.

Finally, we note that Wallner et al. (2000) find evidence for a ^{244}Pu event in a deep-ocean crust. It is of the utmost importance that this result be confirmed, as it would not only strengthen the case for ^{60}Fe , but moreover it would finally confirm that supernovae produce the r -process.

3 Astrophysical Signatures: Gamma-Ray Lines

Our Galaxy has been strongly detected in diffuse 1.8 MeV line emission from ^{26}Al (Diehl, 2003) and now the first observations of ^{60}Fe lines have been reported (Smith, 2003). Already, ^{26}Al offers a powerful diagnostic of, e.g., the Galactic supernova rate and of supernova nucleosynthesis (e.g., Diehl & Timmes, 1998) However, no individual remnants were seen in ^{26}Al by Knödlseher et al. (1996). The difficulty can be seen in the point source flux

$$\Phi_\gamma = \frac{M_{\text{ej},i} e^{-t/\tau}}{4\pi A_i m_p \tau r^2} = 6 \times 10^{-5} e^{-t/\tau} \text{ cm}^{-2} \text{ s}^{-1} \left(\frac{M_{\text{ej},i}}{10^{-4} M_\odot} \right) \left(\frac{100 \text{ pc}}{r} \right)^2 \quad (2)$$

¹ Space limits prohibit discussion of *Nachbarsternsupernovaexplosionsgefahr*, the supernova biohazard, but both environmental (Schindewolf, 1954; Ruderman, 1974; Ellis & Schramm, 1995) and genetic (Collar, 1996; Scalo & Wheeler, 2002) effects have been considered, and the “minimum safe distance” is ~ 10 pc.

where the numerical values are appropriate for $i = {}^{26}\text{Al}$. For this flux to fall within COMPTEL and INTEGRAL sensitivity requires $r \lesssim \text{few} \times 100 \text{ pc}$, a nearby event.

In fact, the nearest known supernova remnant (except perhaps for the Local Bubble itself) was recently discovered by McCullough, Fields, & Pavlidou (2002). In a large-scale $\text{H}\alpha$ survey of the southern hemisphere, a feature in Antlia Pneumatica showed a shell structure $\sim 24^\circ$ in diameter with a filamentary interior, a characteristic supernova remnant morphology. The large angular size, and the position above the Galactic plane both point to a close distance, and ROSAT X-ray data points to a bubble of hot gas. Various distance estimates give $100 \text{ pc} \lesssim r \lesssim 240 \text{ pc}$, making the Antlia supernova a γ -line candidate.

In fact, the Antlia remnant was in the field of view of the Oberlack et al. (2000) observations of $\gamma^2\text{Vel}$ at 1.8 MeV, and appears at $\sim 3\sigma$ significance. The theoretical nucleosynthesis yields for massive stars (Timmes et al., 1995; Woosley, Heger, & Weaver, 2002; Chieffi & Limongi, 2002) are in rough agreement with each other and give, via eq. (2), $110 \text{ pc} \lesssim r \lesssim 510 \text{ pc}$, consistent with the other distance estimates. Thus these data suggest the presence of ${}^{26}\text{Al}$ in this supernova remnant. If confirmed, this would not only directly verify the massive star origin of ${}^{26}\text{Al}$, but also give a new diagnostic of the physical conditions of the supernova.

A nearby supernova event also suggests that a high-proper-motion neutron star could be produced. McCullough, Fields, & Pavlidou (2002) found that among the few nearby, high- μ pulsars, B0950+08 (Pilkington, Hewish, Bell, & Cole, 1968) is moving away from Antlia, and not only backtracks to the remnant, but event hits ${}^{26}\text{Al}$ “bulls-eye”! When the pulsar data are combined with the COMPTEL ${}^{26}\text{Al}$, one finds $r = 62 - 140 \text{ pc}$, $t = 1.1 - 2.5 \text{ Myr}$.

4 Discussion and Outlook

Nearby supernovae have been a fertile ground for speculation, perhaps because of their dramatic and fateful nature. Recent years have seen the first signs of data that can turn these speculations into science. Live ${}^{60}\text{Fe}$ in the deep ocean appears to originate in an explosion during the last 5 Myr and within $\sim 30 \text{ pc}$.

These data need confirmation, both by the discovery of additional isotopes, and in different samples, all with improved time resolution. In fact, just such confirmation was announced at this meeting, in the form of beautiful high-resolution data on another FeMn crust (Knie talk). We eagerly await the

publication of these results, which will mark a major milestone in this subject, and will even further accelerate the search for other radioisotopes, particularly *r*-process species (Knie, 2003; Vockenhuber, 2003; Paul et al., 2001).

Somewhat more distant supernova events also leave a signature in the form of γ -ray emission. The recently discovered Antlia remnant indeed suggests the presence of ^{26}Al . Confirmation of this would directly establish that ^{26}Al is produced in massive stars. With INTEGRAL, the ^{26}Al signal might even be spatially resolved, and with ^{60}Fe it would be possible to place strong constraints on the supernova properties.

In closing, we note that the terrestrial detection of *live* radioisotopes from recent supernovae would have immediate implications for *extinct* radioisotopes from pre-solar events. In particular, the detection of live species demands a supernova source, and constrains the supernova yields and injection frequency. These in turn shed light on the origin and injection of pre-solar species (e.g., Meyer & Clayton, 2000; Goswami, 2003; Gallino, 2003; Mostefaoui, 2003), and possibly on the ability of supernovae to trigger star formation. Finally, a better measure of the nearby supernova frequency will have implications for the radiation environment of the solar system, and the resulting damage to the biosphere (and perhaps evolutionarily beneficial mutations) these events would cause.

Acknowledgments: I am grateful to the organizers for an outstanding meeting, and the participants for lively and fruitful discussions. I am indebted to my collaborators John Ellis, Peter McCullough, and Vasiliki Pavlidou, and to the anonymous referee whose suggestions improved this paper. This material is based upon work supported by the National Science Foundation under Grant No. AST-0092939.

References

- Biermann, P. 2003, these proceedings
Chieffi, A. & Limongi, M. 2002, *New Astronomy Review*, 46, 459
Collar, J. I. 1996, *Physical Review Letters*, 76, 999
Diehl, R. 2003, these proceedings
Diehl, R. & Timmes, F. X. 1998, *PASP*, 110, 637
Ellis, J. & Schramm, D. N. 1995, *Proceedings of the National Academy of Science*, 92, 235
Benítez, N., Maíz-Apellániz, J., & Canelles, M. 2002, *Physical Review Letters*, 88, 81101
Ellis, J., Fields, B. D., & Schramm, D. N. 1996, *ApJ*, 470, 1227
Fields, B. D. & Ellis, J. 1999, *New Astronomy*, 4, 419
Gallino, R. 2003, these proceedings

- Gehrels, N., et al. 2003, ApJ, 585, 1169
- Goswami, J.N. 2003, these proceedings
- Hartmann, D. H., Kretschmer, K., & Diehl, R. 2002, Nuclear Astrophysics, 154 (astro-ph/0205110)
- Iyudin, A. F. 2002, Journal of Atmospheric and Terrestrial Physics, 64, 669
- Knie, K. 2003, these proceedings
- Knie, K., et al. 1999, Physical Review Letters, 83, 18
- Knödlseher, J., Oberlack, U., Diehl, R., Chen, W., & Gehrels, N. 1996, A&AS, 120, 339
- McCullough, P. R., Fields, B. D., & Pavlidou, V. 2002, ApJL, 576, L41
- Meyer, B. S. & Clayton, D. D. 2000, Space Science Reviews, 92, 133
- Mostefaoui, S., Lugmair, G.W., Hoppe, P., & El Goresy, A. 2003, these proceedings
- Oberlack, U. et al. 2000, A&A, 353, 715
- Paul, M. et al. 2001, ApJL, 558, L133
- Pavlidou, V. & Fields, B. D. 2001, ApJ, 558, 63
- Pilkington, J. D. H., Hewish, A., Bell, S. J., & Cole, T. W. 1968, Nature, 218, 126
- Ruderman, M. A. 1974, Science, 184, 1079
- Scalo, J. & Wheeler, J. C. 2002, ApJ, 566, 723
- Schindewolf, O.H. 1954, Neues Jahrbuch für Geologie und Paleontologie Monatshefte, 10, 457
- Shklovskii, I. S. 1968, Supernovae, New York: Wiley
- Smith, D. 2003, these proceedings
- Talbot, R. J. & Newman, M. J. 1977, ApJS, 34, 295
- Timmes, F. X., Woosley, S. E., Hartmann, D. H., Hoffman, R. D., Weaver, T. A., & Matteucci, F. 1995, ApJ, 449, 204
- Vockenhuber, C. 2003, these proceedings
- Wallner, C. et al. 2000, Nuclear Instruments and Methods in Physics Research B, 172, 333
- Winkler, S. 2003, these proceedings
- Woosley, S. E., Heger, A., & Weaver, T. A. 2002, Rev. Mod. Phys., 74, 1015