RADIOCARBON PRODUCTION BY THE GAMMA-RAY COMPONENT OF SUPERNOVA EXPLOSIONS

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ABSTRACT. We selected SN1006, the brightest and closest to Earth of all supernovas historically observed, for a study of ^{14}C production by e^-,e^+-bremsstrahlung cascades initiated by hard γ rays (>10 MeV) from that event. During the cascade, bremsstrahlung energies eventually fall within a giant (n,γ), (n,2γ) cross-section, peaking at 23 MeV and approaching effectively zero below 10 MeV and above 40 MeV. The neutrons are absorbed primarily in the reaction $^{14}N(n,p)^{14}C$. Cellulose from single-year tree rings from AD 1003 to AD 1020 was measured to determine $\Delta^{14}C$. Three years after the first visual observation of SN1006, $\Delta^{14}C$ rose and remained above pre-AD 1009 values until AD 1018. Comparison of the 7 years before AD 1009 with the 9 years following show an average increase of 6.1 ± 1.6 (s.d.)‰ (significant at the 99.6% confidence level). Such a pulse of ^{14}C requires a total production of neutrons of 17.1×10^7n cm^{-2}e, implying an input of 11.3×10^4 ergs cm^{-2}e γ-ray energy. This requires the total supernova γ-ray energy (>10 MeV) to have been 1×10^{50} ergs.

INTRODUCTION

Supernova explosions occur at the rate of about two per century in a standard galaxy whose light is equal to 10^{10} Suns, assuming that the Hubble constant is 100 km^{-1} s per Mpc (Murdin 1990). In our galaxy, seven supernovas have been visually observed since the 2nd century AD. There are also two optical supernova remnants and one that is only a radio remnant, for a total of 10 in 18 centuries, or a little more than one every other century (Table 1, Fig. 1). Supernovas are the source of not only visible, but also ultraviolet and infrared light, as well as neutrinos and cosmic rays. Cosmic rays include nuclides (ionized hydrogen and helium as well as heavier elements), X rays and γ rays.

Supernovas are a subject of considerable interest to laymen and philosophers as well as scientists. Unfortunately, the window of observation of supernova events occurring within our galaxy has been quite narrow. Light from the first historically recorded event arrived in AD 185 (Table 1). Light from Kepler's supernova arrived in AD 1604, a few years before the invention of the telescope. Thus, instrumental observations date back less than four centuries. Optical, X-ray and radio observations have allowed identification of 40 remnants within our galaxy. Fortunately, production of cosmogenic isotopes by cosmic rays opens a wider window. For example, ^{10}Be from natural archives such as polar ice (Raisbeck *et al.* 1987) and ocean sediments (McHargue, Damon and Donahue 1995) extends the window of observation back hundreds of thousands of years. ^{14}C in dendrochronologically dated tree rings opens the entire Holocene for observation. Although there is no means of detecting the past arrival of visible light, the γ-ray component of cosmic rays produces a potentially detectable amount of ^{14}C (Kocharov *et al.* 1974). Only the high-energy component of these γ rays is effective in producing (γ,n) and (γ,2n) reactions. Whether they are produced in the expanding shell or in the shock waves resulting from the supernova explosion, high-energy or "hard" γ rays will arrive after the first thermally initiated light pulse. It is of considerable theoretical interest to know the delay time between arrival of photons and the arrival and peak intensity of the hard γ-ray component of cosmic-rays. The hard γ rays produce neutrons, the thermalized neutrons produce ^{14}C by the $^{14}N(n,p)^{14}C$ reaction and the resulting ^{14}C reacts to produce $^{14}CO_2$, which participates in the C-O

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TABLE 1. Historically Observed Supernovas*

Year (AD)	Distance (light yr)	Remnant description†
185	<6,000	O, R, S
393	~1,500 (?)	O (?)
1006	4,200	O, R, X, S
1054	6,500	O, R, X, P, D
1181	28,000	O, R, X, C, D
1572	10,000	O, R, X, S
1604	26,000	O, R, X, S

*To eliminate nova events, where a star throws off a small part of its mass but may, if nearby in the galaxy, be among the brightest stars, only "new stars" that remained visible for at least six months are included. With the exception of AD 393, all have remnants that have been identified unequivocally. References: Data obtained from Murdin (1985: Table 2) and Stephenson and Clark (1976: 103).

†Key to description: O = optical remnant; R = radio remnant; X = X-ray emitter; P = known pulsar; S = shell; D = disc; C = compact stellar remnant.

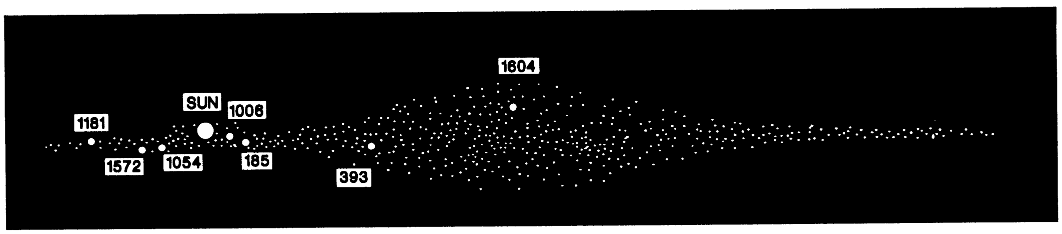

Fig. 1. Positions of historical supernovas (large white dots) in our galaxy. The diameter of our galaxy is *ca.* 100,000 light yr. SN1006 at 4200 light yr was the closest to Earth. (After Stephenson and Clark (1976).)

cycle; therefore, accurately dated tree rings constitute an ideal natural archive of the arrival of the hard γ rays.

Early research at the Ioffe Institute (Kocharov *et al.* 1974) sought to detect the hard component of supernova-generated γ rays from Tycho, Kepler and Cassiopea A. The Tycho supernova was visible for 18 months in AD 1572–1573. Measured $\Delta^{14}C$ was at a minimum in AD 1572 but increased by 2.0 ± 0.8‰ during the period from AD 1573 to 1576, relative to the preceding years, AD 1567–1571. This suggests that γ rays producing the γ,n reaction arrived after the visible photo-flash. However, no increase is observed in the single-year, high-precision data of Stuiver and Braziunas (1993).

CHOICE OF SUPERNOVA TO BE STUDIED

We chose the supernova that was observed in AD 1006 for this study (Table 1, Figure 1). This supernova was the brightest and closest to the solar system (4200 light yr) of those observed historically (Table 1). Most information on this supernova comes from Arabic, Japanese and Chinese sources. Although it was too far south and below the horizon to be observed by most northern European observers, the monk Hepidannus of St. Gallen, Switzerland (47°30′N) observed the star in the constellation Lupus. The main eyewitness source, according to Murdin (1985), was the Egyptian Ali ibn Ridwan, who recorded a list of the exact positions of the planets at the time of first sighting of the supernova. From this list, the exact date of its appearance can be deduced: April 30, 1006. He states that "it was a large nayzak, round in shape and its size two and a half or three times the size of Venus.

Its light illuminated the horizon and it twinkled a great deal. It was a little more than a quarter of the brightness of the Moon" (Murdin 1985: 15). The radio remnant of SN1006 is shown in Figure 2.

Fig. 2. Radio image of the remnant of SN1006. It appears as a ring, but in three-dimensional perspective it more nearly resembles a shell. This image, obtained through the courtesy of Professor Stephen P. Reynolds, was made with the Very Large Array of the National Radio Astronomy Observatory operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation. The three points of light are common background extragalactic radio sources (Reynolds and Gilmore 1986).

Production of ^{14}C by Hard γ Rays (>10 MeV) in the Earth's Atmosphere

Primary γ rays entering the Earth's atmosphere will initiate e^+,e^- bremsstrahlung cascades. However, to be effective in producing ^{14}C by the reaction $^{14}N(n,p)^{14}C$, their energy must exceed 10 MeV. This limitation is the result of the giant neutron cross-sections between 10 MeV and 40 MeV for (γ,n) and (γ,2n) reactions (IAEA 1987). The cross-sections peak at 23 MeV and are negligible below 10 MeV and above 40 MeV. The positrons and negatrons produced in the cascade undergo close encounters with the nuclei primarily of oxygen and nitrogen. These encounters result in production of bremsstrahlung that react with nuclei to produce other pairs, and so on, until eventually the bremsstrahlung energy falls within the giant cross-section, producing neutrons. About 65% of the neutrons reach thermal energies and are used in producing ^{14}C.

The total hard γ-ray energy from supernova explosions has been estimated to vary between 10^{47} ergs to as high as 10^{50} ergs (Berezinskii *et al.* 1990; Chupp 1976; Lingenfelter and Ramaty 1970).

A distance of 4200 light yr equals 3.97×10^{21} cm. Upon arrival at Earth, the γ-ray flux would extend over an area of 1.80×10^{44} cm^2. A total γ-ray energy of 10^{49} ergs arriving at the top of the atmosphere would yield 1.4×10^4 ergs $cm^{-2}{}_e$. An estimate of the multiplicity factor resulting from the cascades is beyond the scope of this paper. We accept for purposes of calculation the yield to be about 10^3 neutrons per erg of γ-ray energy (Lingenfelter and Ramaty 1970). About 65% of these neutrons are thermalized and available to produce ^{14}C almost quantitatively by the reaction $^{14}N(n,p)^{14}C$. Thus 1.4×10^4 ergs $cm^{-2}{}_e$ yields 0.9×10^7 thermal neutrons that are available to produce ^{14}C. If this flux arrived in one year, the rate of production of ^{14}C would be 0.3 a $cm^{-2}{}_e s$, or 13%

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of the steady-state production rate by galactic cosmic rays of 2.4 a $cm^{-2}{}_e s$. This quantity would not be measurable unless the flux continued for ≥4 yr.

Design of the Experiment

We decided to measure samples dating to before and after the historical observance of SN1006. Precisely dated annual samples of sequoia wood from the Big Stump Grove in Sequoia National Park were available for the years AD 995–1020. The Big Stump Grove is at 36°44′N, 118°58′W, elevation 1845 m asl. Unfortunately, only a few grams were available for each year. The weight of cellulose extracted was much too small to produce enough benzene for our high-precision, underground scintillation counters (capable of routinely obtaining ±2‰ or better precision), so it was necessary to use the NSF-Arizona AMS Laboratory, with which ±5‰ analyses could be obtained on one target at the time of dating. Consequently, we planned to measure three targets for each year from AD 1003–1020, to obtain an expected precision of ±2.9‰. Unfortunately, during our two measurement periods only a ±7‰ precision was obtainable for one graphite target, meaning that four graphite targets were required to obtain ±3.5‰. Sample preparation techniques were essentially the same as described in Damon *et al.* (1992).

Results

The data are presented in Table 2 and plotted in Figure 3. $\Delta^{14}C$ is the age and isotopic fractionation-corrected value calculated as ‰ difference from the accepted NIST HOxI standard sample value (Stuiver and Polach 1977). It increases after AD 1009, 3 yr after the visual observation of SN1006, by *ca.* 9.5‰. $\Delta^{14}C$ remains high for *ca.* 9 yr, after which the values are indistinguishable from pre-1010 values. If we compare the 7 yr before 1009 (average $\Delta^{14}C = -20.6 \pm 3.7$ (s.d.)‰) with the 9 yr

TABLE 2. Preliminary Results on Sequoia Wood from Time of SN1006

Year (AD)	$\Delta^{14}C$ (‰)	σ* (‰)	Number of analyses	$\delta^{13}C$ (‰)
1003	–26.6	± 4.0	3	–18.6
1004	–14.6	± 3.9	4	–18.9
1005	–18.7	± 4.0	3	–19.0
1006	–21.8	± 4.0	3	–18.7
1007	–19.3	± 3.7	4	–18.9
1008	–21.1	± 3.4	5	–19.3
1009	–22.2	± 3.8	4	–19.9
1010	–15.2	± 3.3	5	–19.5
1011	–10.0	± 3.5	5	–19.7
1012	–17.1	± 3.3	5	–19.1
1013	–11.1	± 3.2	5	–19.1
1014	–16.7	± 3.0	6	–18.8
1015	–11.8	± 4.1	3	–19.3
1016	–18.3	± 3.4	5	–18.8
1017	–17.7	± 4.6	4	–19.4
1018	–12.6	± 3.2	5	–19.3
1019	–20.3	± 3.8	3	–18.6
1020	–21.5	± 3.9	3	–19.3

*Standard deviation for N separate analyses

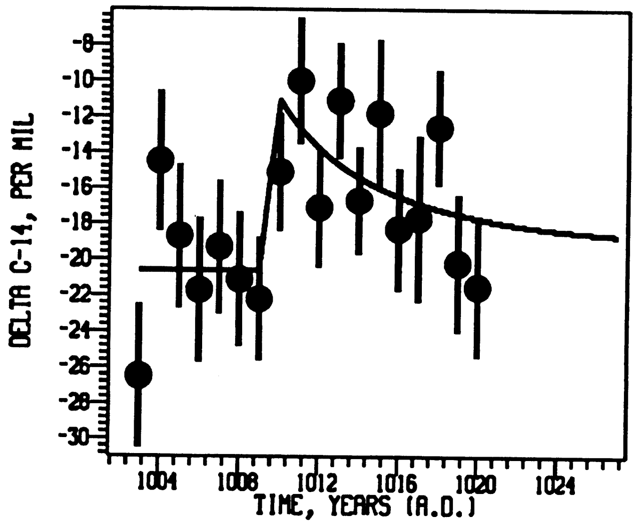

Fig. 3. Measurements of $\Delta^{14}C$ (age and stable isotope-corrected deviations from a standard value). Precision is ±1 σ. The curve is a six-box carbon model with sedimentary sink fit to the data, assuming the γ-rays (>10 MeV) arrive as a pulse immediately after AD 1009. A pulse lasting 2 yr provides an equally good fit to the data.

from 1010 to 1018 (average $\Delta^{14}C = -14.5 \pm 3.2$ (s.d.)‰), t = 3.30 for the Student's t test and the difference is highly significant at 99.6% confidence.

Next we use a six-box carbon-cycle model modified after Bacastow and Keeling (1973), assuming the γ-ray pulse occurs during one year, to obtain a best fit to the data (Fig. 3). The model includes a stratosphere, troposphere, short- and long-lived biosphere, a mixed ocean layer, deep sea and oceanic sedimentary sink. If the radiation path length is 63 g cm^{-2}, then the number of radiation path lengths needed to reduce 1 GeV γ rays to below the critical value, 10 MeV, is 67.7 or 422 g cm^{-2}, corresponding to an altitude that is well within the troposphere. In order to reach the critical value within the stratosphere, a γ ray must have an energy < 50 MeV. Since most of the γ rays have energies in the range of 70 MeV to 10 GeV (Berezinskii *et al.* 1990: 307), the bulk of ^{14}C production will be in the troposphere. Consequently, we chose 20% production in the stratosphere and 80% in the troposphere. We assume the γ rays arrive in a one-year pulse. The best fit curve is shown in Figure 3. Only 4 of 18 measurements fall outside of 1 σ and none fall outside 2 σ from the curve.

To achieve the best fit, we had to change the ^{14}C production rate from 2.4 a $cm^{-2}{}_{e}s$ to 6.0 a $cm^{-2}{}_{e}s$, or a factor of 2.5 for one year. This requires a total production of thermalized neutrons resulting from primary supernova γ rays of 17.1×10^7 n $cm^{-2}{}_{e}$, implying that the input of 11.3×10^4 ergs $cm^{-2}{}_{e}$ γ-ray energy (>10 MeV) was 1×10^{50} ergs, which is within the estimated range for such events.

Conclusion

The duration of the ^{14}C increase event is limited by the carbon cycle. The data requires a sharp rise limiting the duration to, at most, three years. The duration is also limited by the decay, which is due to equilibration with the biosphere and mixed layer of the ocean, followed by a much slower equilibration with the deep sea. The total supernova γ-ray energy (>10 MeV), 1×10^{50} ergs, is not unreasonable. A delay of three years after the visual sighting of SN1006 was not anticipated. However, dendrochronologists responsible for the chronology of the sequoia tree-ring samples are confident that the chronology is accurate to one year (see Acknowledgments below).

Stuiver and Braziunas (1993) have published high-precision single-year $\Delta^{14}C$ data for the period AD 1510–1954. Two supernovas occurred during that time, SN1572 observed by Tycho Brahe and SN1604 observed by Johannes Kepler, both at greater distances from Earth than SN1006. If SN1572 (10,000 light yr) produced the same γ-ray energy (>10 MeV) as SN1006, the expected increase would have been *ca.* 1.5‰ and 0.2‰ for SN1604 (26,000 light yr). It is not surprising that a measurable increase is not observable in the single-year data relevant to these two supernovas.

If a series of very large solar flares were to occur over a 2-yr period, a signal such as in Figure 3 could occur. However, in the 454-yr record of Stuiver and Braziunas (1993) we observe only one other event of similar magnitude and duration as that in Figure 1. It seems unlikely that such a rare event would fortuitously occur 3 yr after SN1006.

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