[RADIOCARBON, VOL. 34, No. 2, 1992, P. 239–245]

A SUPERNOVA SHOCK ENSEMBLE MODEL USING VOSTOK ^{10}Be RADIOACTIVITY

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ABSTRACT. Analysis of the Vostok ice-core record of ^{10}Be (Raisbeck *et al.* 1987) suggests that the sharply resolved increases in ^{10}Be at 35 ka (kyr) and 60 ka are due to cosmic-ray (CR) increases. As an alternate to long-term solar modulation or strong decreases in the Earth's magnetic field, supernova (SN) forcing is qualitatively consistent with the generation of a forward-reverse shock ensemble from a spherical blast wave of age very approximately at 75 ka. This age agrees with Davelaar, Bleeker and Deerenberg's (1980) identification of 75 ka for the age of a North Polar Spur SN remnant. Confirmation would be the first geochemical detection of supernova forcing of spallogenic and perhaps cosmogenic isotope production in the atmosphere. The three ^{10}Be increases can be satisfied by a modification of the Sonett, Morfill, and Jokipii (1987) model. This consists of 2 or 3 shock waves from a single SN event, which includes the first stage in the expansion, leading to a forward shock, S_{1+}, and a pair of reverse waves, S_{1-} and S_{2-}. One reverse wave arises from the spherical expansion, itself, and the other is a reflected wave from a remnant precursor shell boundary from a more ancient SN. The model requires the solar system to be immersed in the 'bubble' of the earlier post-SN evolution, possibly affecting estimates of heliospheric boundary distance. However more recent analysis of Camp Century ice core data discloses only the 35 ka ^{10}Be peak. This recent result compounds the difficulty of constructing a completely consistent model for the source of the Vostok spikes. This paper is written in the spirit of suggesting only one of possibly several different models, even within the subclass of SN models.

INTRODUCTION

This paper is a qualitative exploration of a model for the origin of the large ^{10}Be increases discovered in the Vostok ice core by Raisbeck and collaborators. Of the several possible explanations of these increases, I confine my discussion to the proposition that the source of the increases is an enhancement of the cosmic-ray (CR) flux at the top of the atmosphere. The seminal aspect is the source of these increases, which are supposedly the result of interstellar shock waves originating in the interaction of an ancient relatively close supernova (SN) with the ambient interstellar medium. Some aspects of the model fit the data qualitatively, whereas others are more speculative, and no claim is made to their certainty.

Radioactive ^{10}Be from the Vostok ice core discloses three peaks in the record, D_2 at 60 ka before present (BP), only 25 ka from a close pair, D_{1a} and D_{1b} in the neighborhood of 35 ka BP[1] (Fig. 1), uncorrelated with accompanying δ^{18}O. (Raisbeck and Yiou (1991) have reported additional uncorrelated ^{2}H.) An upper bound to the separation of D_{1a} and D_{1b} can be estimated as *ca.* 2 ka. An additional core from Dome C is sufficiently long to confirm the presence of the 35 ka peaks, although the two are unresolved (Raisbeck *et al.* 1987).

Detection of SN relics, either direct or secondary, has been a long-sought-after goal; *e.g.*, Lingenfelter (1969) and Higdon and Lingenfelter (1973) proposed the detectibility of enhanced cosmogenic nuclide production from SN cosmic rays. (See also Kocharov *et al.* 1991.) A prompt gamma flash has also been proposed as the source of thermoluminescence (Castagnoli, Bonino & Miono 1982). Such cosmogenic production has generally relied upon either simple streaming or diffusion for transport of SN cosmic rays through interstellar space. The principal long-lived radionuclides produced by CRs in the atmosphere are ^{10}Be and ^{26}Al (Peters 1957). Though of significantly shorter half-life, ^{14}C also may be of interest to the shock model discussed here.

[1]Raisbeck and Yiou (1991) and Raisbeck (personal communication) report the closely spaced increases in the neighborhood in of 35 ka, but Raisbeck *et al.* (1987) did not report these earlier. Figures in this paper reflect the earlier data.

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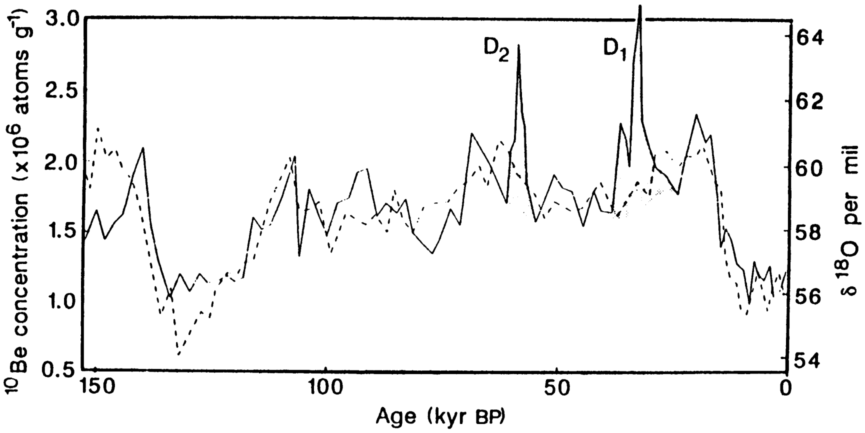

Fig. 1. — = Concentrations of ^{10}Be; - - - - = δ^{18}O from 150 ka to present. Spikes marked by D are putative interstellar shock signatures, D_1 representing the reverse shock, S_-, and D_2, the forward shock, S_+. (Figure adapted from Raisbeck *et al.* 1987).

The model explored here is an extension of that by Sonett, Morfill and Jokipii (1987). It differs in that the CR required for cosmogenic production, though arising from one SN, yields a sequence of shock waves corresponding to the enhancements seen in the ^{10}Be record, but as previously, the cosmogenic and spallogenic production arises from CRs accelerated locally from the interstellar medium (ISM). Thus, its association with SN is with the formation of interstellar shock waves and not necessarily with SN debris.

Qualitative analysis of the mean ages of $D_{1a,b}$ and D_2, based on a Sedov (1959) expansion, yielded an SN age of 45 ka (Sonett, Morfill & Jokipii 1987). The more complete model discussed here accounts for all three increases in the ^{10}Be record, in terms of an SN expansion in a pre-existing remnant bubble from the expansion of a more ancient SN. The age estimate is then determined from the oldest (60 ka) of the three ^{10}Be enhancements. The new shock model age is in reasonable accord with models based primarily upon rocket X-ray, neutral hydrogen and radio data.

ALTERNATE ^{10}Be ENHANCEMENT MECHANISMS

Raisbeck *et al.* (1987) discuss four possible sources of the Vostok ^{10}Be enhancements: 1) a decrease in interplanetary CR modulation due to a concomitant decrease in solar activity (perhaps a kind of timewise superMaunder minimum); 2) a decrease in the intensity of the geomagnetic field leading to a corresponding increase in the galactic cosmic-ray (GCR) flux; 3) a change in the atmospheric circulation pattern increasing the transport of cosmogenic Be from the stratosphere to the troposphere; and finally, by way of elimination, 4) a basic increase in the GCR flux. Raisbeck *et al.* (1987) do not favor the possibility of a change in atmospheric circulation, but they do not rule it out completely.

A Maunder-like decrease in solar modulation lasting several thousand years, and so irregular as to correspond jointly to the time separations of $D_{1a,b}$ and D_2 and to the multithousand-year decreases, seems implausible. Unfortunately, the data needed to test this are available only by proxy from the ^{14}C record, which is far too short.

The possibility of geomagnetic reversals underlying the Vostok CR enhancements cannot be fully ruled out, although recent work decreases the likelihood significantly (Tric *et al.* 1992). Anomalous geomagnetic field values reported from Lake Mungo, Australia (McElhinny & Senanayake 1982) may be due to lightning strikes (McElhinny, personal communication), and Puy de Laschamp (Bonhommet & Babkine 1967) measurements are controversial. Lac du Bouchet shows no evidence for a reversal or excursion of the field in the neighborhood of 30 ka (Creer, personal communication). The Chaîne des Puys discloses two reversals in the Quaternary (Bonhommet & Zahringer 1969), but the ages are in conflict with ^{14}C measurements.

Because the Vostok site is presently almost at the south geomagnetic dip pole, there ought to be no significant local rigidity cutoff (Raisbeck *et al.* 1987). However, the net ^{10}Be flux at the poles is dependent not just on local production, but also upon global production. Note, however, that secular drift of the pole away from the Vostok location would decrease rather than increase cosmogenic production, although sensitivity to reversals would be increased.

The production of ^{10}Be is a strong function of latitude, varying by a factor of 10 to 100 from equator to pole (Lal & Peters 1967); the peak production rate is achieved at 15 km altitude at most latitudes. Although the production rate is maximum at the poles, the solid-angle factor favors the equator; the effect is to reduce the latitude-dependence of production and enhance the equatorial contribution. Raisbeck *et al.* (1981) discussed the possibility of a change in atmospheric circulation possibly increasing the stratosphere/troposphere exchange. Because the stratosphere is estimated to provide 70% of ^{10}Be production and the troposphere 30%, the polar reservoir of Be to some extent depends upon transfer from the global reservoir and also from the stratosphere downward. A change in the atmospheric transfer system would be required to satisfy the Vostok data. Although this cannot be ruled out, the modification would mean a basic change in the thermal structure. There is no evidence to support such a drastic requirement.

Shock System Geometry

Spherical explosions yield an ensemble of waves (Taylor 1946; Courant & Friedrichs 1948; Kuo 1947; Friedman 1961; Boyer 1960; Brode 1955, 1959; Sedov 1959; Parker 1963). All produce an initial forward wave, S_{1+}, which progresses outward into the ambient interstellar medium (ISM). The wave is followed in order by the shocked ISM, a contact surface or tangential discontinuity, and finally, a system of reverse and reflected waves. The expansion of the driver gas is initially adiabatic and, following ejection of most of the SN mass, if continued into a pileup of ISM, becomes radiatively dominated because of the increased interaction as a result of the enhanced density. Figure 2 shows a schematic from a calculation of Boyer for a laboratory-scale explosion.

Shock expansion, S_{1+}, requires a rearward moving rarefaction, R_1, to establish continuity between the outward-directed post-shocked flow and expanding source gas. Because of the divergence in a cylindrical or spherical expansion, an additional rearward facing shock, S_{1-}, is required to connect the flow behind S_{1+} and that through which R_1 has just passed. S_{1-} progresses towards the origin of the explosion, but is convected outward in the post-shocked flow behind S_{1+}. As witnessed in Eulerian laboratory coordinates, S_{1-} is initially swept out faster than it propagates inward. This is analogous to the forward-reverse shock pair in the solar wind (Sonett & Colburn 1965; Colburn & Sonett 1965; Simon & Axford 1966; Sturrock & Spreiter 1966). Secondary, tertiary and progressive reflections can yield a virtual barrage of subsequent waves, which eventually damp into thermal motions. The model discussed here makes the reasonable assumption that the ^{10}Be spikes are associated with the immediate expansion after the onset prior to any plausible secondary reflections.

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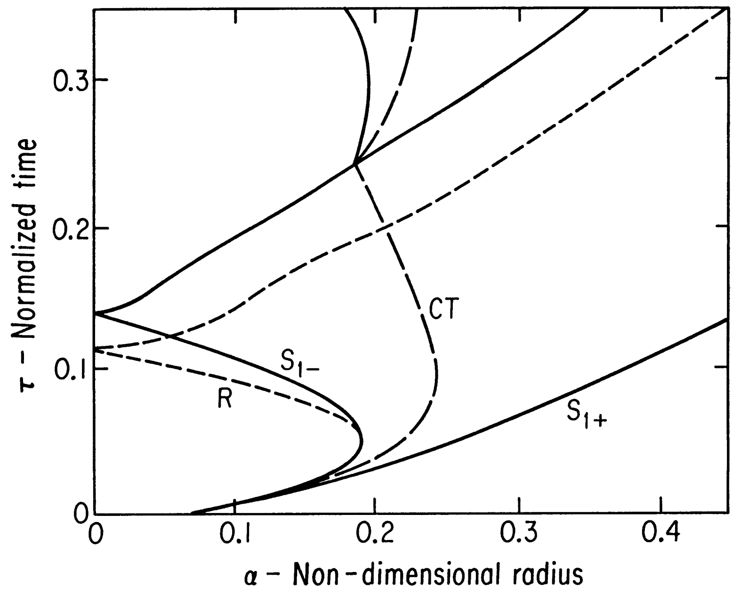

Fig. 2. Example of a shock system arising from the spherical expansion of a blast wave. Waves evolve from the lower part of the figure, expanding to the right. S_{1+} is the forward shock; it progresses to the right followed by a contact discontinuity (CD) (– – –), separating the post-shocked gas behind S_{1+} from the driver gas, reverse shock wave, S_{1-} (—), and rarefaction, (R), which, together with reverse shock, is first swept out, and then, at the end of expansion, reverses (lab coordinates), and progresses to the origin. Subsequent conditions (including reflection at the origin) are indicated qualitatively. The x-axis defines the radius normalized by the quantity, $\alpha = w/P_0$, where w is the total initial system energy, and P_0 the initial pressure; the y-axis is time-normalized by $\tau = \alpha/C_0$, where C_0 is the speed of sound squared (adapted from Brode 1959). This shock configuration is shown to qualitatively indicate the expected expansion regime, though details may differ in the SN case discussed in the paper.

THE PRE-EXISTING SUPERNOVA SCENARIO

An important modification of this scenario results from the case of the SN exploding within a pre-existing remnant bubble formed from a previous SN. In this case, as the boundary of the bubble is a leftover region of enhanced density and temperature, it represents a discontinuity of enhanced sound speed to S_{1+}, resulting in both a transmitted, S_{2+}, and reflected, S_{2-} shock (Courant & Friedrichs 1948). Because S_{2-} moves in the post-shocked flow of S_{1-}, by definition being a shock, it eventually overtakes and merges with S_{1-}.

In the progression of events noted in the Eulerian (laboratory) frame, S_{1+} passes over the observer, O, at time, T_1, a contact surface (or in hydromagnetics, a tangential discontinuity, (TD), at time, T_2, and no other discontinuity is detected so long as the velocity of the reverse shock, S_{1-}, never satisfies $v_{1-} - v_c < 0$, where v_c is the lab velocity (outward) of the post-shocked flow behind S_+. The reverse shock is predicted to eventually leave a second CR record because of a final passage inbound to the supernova when $v_{S1-} - v_c < 0$ is satisfied. The turning point where velocity reversal takes place, $dr/dt = 0$ or $v_{1-} - v_c = 0$ is mentioned for completeness, but its detection would be less probable.

THE FORWARD SHOCK, S_f

In the model explored in this paper, the sequence of hypothesized shock waves yielding the atmospheric spallogenic ^{10}Be is encountered in the remnant bubble. Otherwise, if S_{1+} or S_{2+} were outside the bubble, S_{1-} and S_{2-} would not display an interaction with the heliosphere. Calculation of the properties of the forward shock, S_{1+}, is easier than for S_{1-} or S_{2-}. Following the earlier Sonett *et al.* calculation, and using the same plasma parameters, the age of the explosion is modified to 72 ka. This value is 75% of that deduced by Cox and Anderson (1982) for a putative SN. The post-shock flow behind S_{1+} is unsteady and varies with time. Passage of the TD over the heliosphere is not accompanied by a change in the CR flux.

The Reverse and Reflected Shocks, S_{1-} and S_{2+}

To some extent, the 35 ka Vostok events are complicated by the bifurcated peak recently reported by Raisbeck and coworkers. The theory of point explosions does not account for a dual shock with the small separation indicated in the data. But if the explosion takes place within the confined volume of the bubble of a previous SN (Borken & Iwan 1977), then a shock, additional to the basic reverse wave, is created *via* a reflection, when S_{+1} reaches the bubble boundary (Courant & Friedrichs 1948). As the boundary consists of hotter gas with higher sound speed, the system finally consists of a forward wave, S_{+1}, propagating within the bubble cavity up to the boundary, S_{+2}, propagating into fresh ambient ISM, the reverse wave, S_{1-}, and the reflected wave, S_{2-}. As noted earlier, this model requires that the solar system is immersed within the bubble, so that the cosmo- and/or spallogenic consequences of the panoply of waves can be observed from within the solar system.

Candidate Supernovae Shock Sources

Using v_f = 1000 km for the speed of s^{-1}, and an age of 72 ka from the ^{10}Be estimate, I calculate a span of 2×10^{15} km or 60 parsec (pc). Davelaar, Bleeker and Deerenberg (1980) report that a SN remnant associated with the North Polar Spur (NPS) has an age of 75 ka, originating in an explosion within a region of already anomalously low density (10^{-2} cm^{-3}). Berkhuijsen (1973) reports a distance to Loop I center of 130 ± 75 pc.

A major difficulty in reconciling various NPS radio and x-ray parameters is the differing age estimates for the (old) dense H1 region and the (young) x-ray data (Egger 1991). This problem has led to the model of Borken and Iwan (1977) of a SN exploding in the pre-existing relict shell of a more ancient SN event ($E = 6 \times 10^{50}$ ergs, density = 10^{-3} gm/cm^3, and temperature = 2×10^6 K). A second, somewhat less preferred, source is the Cygnus shell (Higdon 1981); identification with the NPS seems preferable, on the basis of age and distance estimates.

20,000–30,000-Year-Old ^{14}C

Using uranium-thorium systematics, Vogel (1983) found a ^{14}C level in a stalactite from the Cango caves, South Africa, elevated to twice nominal at 35 ka ago, followed by a dip to just below normal at 28 ka ago, and finally, 1.5 times nominal (based on U-Th) at 18 ka ago (Fig. 3). Qualitatively, this behavior mimics the ^{10}Be values seen in Figure 1, and strongly implies that the spallogenic production of ^{10}Be at both 35 and 60 ka was accompanied by a corresponding cosmogenic production increase of ^{14}C. The increase of ^{14}C at 18 ka is less certain, for it appears to be accompanied by an increase in ^{18}O.

Dating of Barbados coral (Bard *et al.* 1990), also using U-Th as a standard, shows ^{14}C elevated by a factor of 2 to 4 in the 20–30 ka interval (referred to unit amplitude per Vogel (1983)). Whether part or all of this elevation of the atmospheric inventory of radiocarbon is related to the putative SN is uncertain. But the Bard *et al.* (1990) data errors prevent any disclosure of a putative double maximum, as noted in Vogel's (1983) results. These extraordinary changes in the ^{14}C inventory are

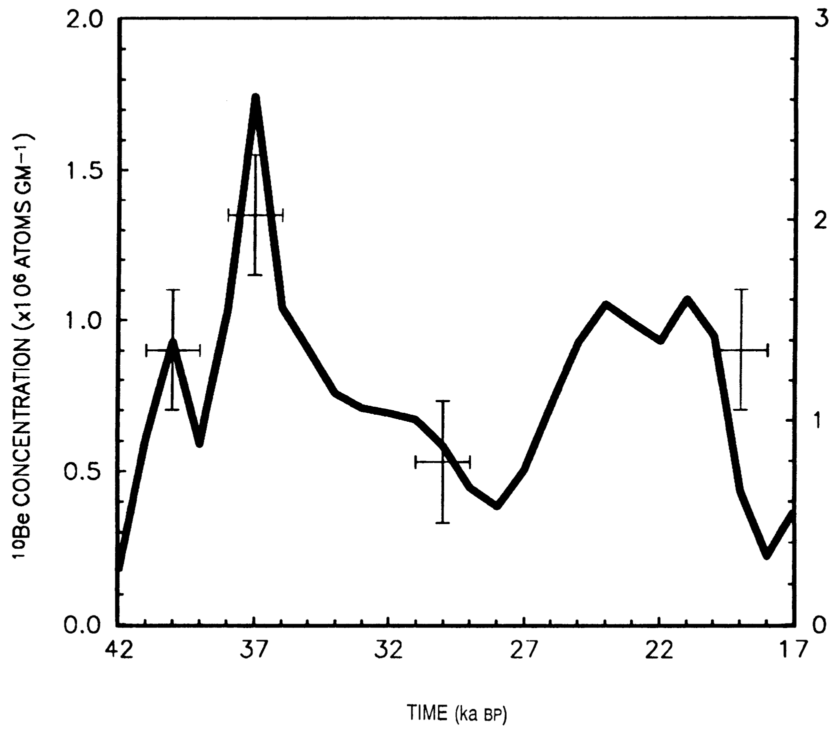

Fig. 3. Vostok ^{10}Be between 17 and 42 ka BP (adapted from Raisbeck *et al.* 1987) with relative ^{14}C from South African stalagmite (Vogel 1983). Error-bar limits for Vogel data are only approximate (visually scaled from Vogel: Fig. 3) and are presumed to be 1 σ limits. The Vogel data is shifted left (to increased age) by 1 ka to match the Rasibeck data. Note that this brings all but the rightmost error bars into close coincidence with the ^{10}Be. This figure should be regarded as only suggestive of a basic relation (cosmic-ray forcing?).

in qualitative accord with the ^{10}Be record for this time interval. Without further research, we cannot be certain that all these results are a consequence of SN CR enhancement. A more complete analysis of the Vostok core data awaits a better partitioning of the covariant and acovariant parts of the ^{10}Be and ^{18}O isotopes and detailed modeling of the blast-wave problem.

Acknowledgments

I am indebted to my colleagues, J. R. Jokipii and G. E. Morfill for extensive discussions and illumination of the CR and shock dynamics. I am equally indebted (though at the expense of decreased confidence as to the uniqueness of the model discussed herein) to J. Beer for kindly providing a preprint of the analysis by him and coworkers of the isotope record from Camp Century ice. This work was partially supported by a grant from the NSF Atmospheres program.

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