COSMIC-RAY VOLLEYS FROM THE GALACTIC CENTER AND THEIR RECENT IMPACT ON THE EARTH ENVIRONMENT

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Abstract. It is proposed that outbursts of cosmic ray electrons from the Galactic Center penetrate the Galaxy relatively undamped and are able to have a major impact on the Solar System through their ability to vaporize and inject cometary material into the interplanetary environment. It is suggested that one such 'superwave', passing through the Solar System toward the end of the Last Ice Age, was responsible for producing major changes in the Earth's climate and for indirectly precipitating the terminal Pleistocene extinction episode. The high concentrations of ^{10}Be, NO_3^-, Ir and Ni observed in Late Wisconsin polar ice are consistent with this scenario. The intensities of the Galactic nonthermal radio background and diffuse X-ray emission ridge are shown to vary with Galactic longitude in the same manner as electron intensity along the proposed superwave 'event horizon'. The high luminosities and unusual structural features which characterize the Crab Nebula and Cassiopeia A are shown to be attributable to the fact that these remnants happen to coincide with this event horizon and are being externally impacted by an intense volley of relativistic electrons travelling from the Galactic Center direction. The same cosmic ray volley is also shown to be able to account for the unusual structure of the extended radio source CTB 80.

1. Introduction

There is now a considerable body of evidence indicating that the nuclei of spiral galaxies periodically enter an explosive phase during which they release large quantities of energy in the form of relativistic electrons. Such outbursts, the most energetic natural phenomenon known to science, may involve total power outputs as high as 10^{61} ergs per year (Burbidge *et al.*, 1974, pp. 51–53). It is believed that active galaxies such as Seyferts, N-galaxies, quasars, and blazars are actually spirals viewed at a time when their nuclei are passing through an explosive phase.

Seyfert galaxies are the most common classification of active galaxy, and according to recent estimates based on IRAS survey data, one spiral galaxy out of every 5–7 is a Seyfert (Miley *et al.*, 1985). Also a spectroscopic study carried out on a sample of 75 spiral galaxies having bright centers has revealed that 25–35% of these galaxies exhibit emission lines characteristic of quasar-like activity (Filippenko and Sargent, 1985). However, the active fraction is expected to be somewhat lower for a more representative galaxy sample that would include Sc spiral galaxies such as our own.

On the basis of this extragalactic evidence it is reasonable to infer that the nucleus of our own Galaxy spends 15–20% of its time in an active state. In which case, it is interesting to consider what effect explosive outbursts from the nucleus might have on the Earth and Solar System. In the past this problem has not received serious

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attention for a number of reasons. First, it has only been in the last 25 years or so that very much has been learned about galactic explosions. Before the development of high resolution radio telescopes and the emergence of X-ray and infrared astronomy, the phenomenon was essentially unknown. Second, there has been the belief that if a Galactic Center explosion did occur the interstellar magnetic field would impede the radial propagation of particles to such an extent that a relatively insignificant quantity of cosmic rays would ultimately reach to solar vicinity. For example, Ginzburg and Syrovatskii (1964, p. 207) consider the effect of a 'small size' Galactic Center outburst involving total particle energies of ~ 3 to 10×10^{55} ergs and conclude that cosmic ray densities in the Earth's vicinity would be increased by no more than a few percent.

A third reason why this subject has not received much attention is that it has been commonly believed that these explosive events typically last $\sim 10^6$ years and recur about every $10^7 - 10^8$ years. Thus since the electromagnetic emission from the Galactic Center has been observed to remain at a relatively low level during the past few decades for which data has been acquired, the current paradigm has led to the inference that the present quiescent state has been in progress for millions of years and will perhaps continue to persist for a comparable length of time. Thus there has been little motivation to investigate whether such cosmic ray events might pose an immediate threat to the Earth, or whether they might be responsible for triggering the puzzlingly abrupt climatic excursions which have repeatedly occurred in the recent geological past.

However, this picture is changing. Evidence reviewed here and discussed more extensively by LaViolette (1983a), suggests that the time duration of a typical galactic center outburst has in the past been overestimated by as much as three orders of magnitude. It is proposed that such outbursts occur much more frequently, lasting on the order of several hundred to a few thousand years and having a recurrence time of on the order of 10^4 years. Moreover as is discussed below, there is mounting evidence that the Galactic Center has undergone explosive activity several times within the last 10^4 years, and that cosmic ray volleys released during such outbursts would penetrate to the solar vicinity relatively unattenuated.

Such Galactic Center outbursts would substantially effect the local cosmic ray energy intensity. For example, it is found that a moderate Seyfert-like outburst involving the release of 10^{48} ergs/sec in relativistic electrons (about 10^{58} ergs over a period of 300 years) would elevate the energy density of cosmic ray electrons in the solar vicinity by about one hundred thousand fold. This would be about a thousand fold greater than the energy density of the current cosmic ray proton background radiation.

Before examining what effects such Galactic cosmic ray volleys may have had on the Earth and Solar System, it is useful to review evidence indicating that Galactic Center outbursts have recently taken place.

2. Evidence of Recent Explosive Activity at the Galactic Center

Although the nonthermal radiation from the massive object at the center of our Galaxy (Sgr A*, IRS 16 Central) appears to be relatively subdued at present, there is substantial evidence that this body has been quite active as recently as within the last 10^4 years. One indication comes from observations of the Ne II (12.8μ) fine-structure line emission within 6 l.y. of the Center, which indicate the presence of ionized gas asymmetrically distributed about the Galactic Center (Wollman, 1976; Wollman *et al.*, 1977). Oort (1977) cites these Ne II results as evidence that major eruptions take place at the Galactic Center (GC) on time scales of at most 10^4 years, each outburst imparting to the surrounding medium a kinetic energy of $10^{49}-10^{50}$ ergs.

High resolution studies reported by Lacy *et al.* (1979, 1980) indicate that the Ne II emission comes from a collection of 14 discrete clouds. These are each found to have a mass of about $1M_\odot$ and ages ranging from 1000–8000 years, suggesting a formation rate of a few clouds every 10^3 years. Since the oldest clouds are found to lie furthest from the GC, a likely interpretation is that they originate from the central radio-emitting source Sgr A* and have been expelled as a result of repetitive explosive outbursts. This would represent a mass ejection rate of $\sim 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$. Thus ionized neon observations indicate that over the past 10^4 years the GC has been active on an ongoing basis.

Additional evidence for recent activity of the Galactic core comes from radio observations made of the region within a few light years of the GC (Brown and Johnston, 1983; Ekers *et al.*, 1983; Lo and Claussen, 1983). Radio maps show the presence of radio-emitting gas in the form of a three-armed spiral with arms emerging from a point within 2 arc seconds of the GC. Brown and Johnston suggest that this feature is composed of hot gas that has been ejected from the core sometime between 7500–22000 years BP. Ekers *et al.* suggest that this gas may either be expelling or accreting at an average rate of $5 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$. Lo and Claussen (1983) suggest that the emission arm which runs in an approximately East-West direction perpendicular to the Galactic plane, and which contains most of the high velocity ionized neon gas, is composed of material falling in toward the GC. They propose that an explosive event occurring about 10^4 years ago, or perhaps slightly earlier, cleared gas and dust out of the inner 5 light year region surrounding the GC and that since then gas has been streaming back toward the Center forming the observed arm-like structure.

The matter is not yet settled as to whether the observed streams and clouds of gas in the immediate vicinity of the GC are being accreted or expelled (Brown and Liszt, 1984). However, there is general concurrence that the GC has been the cite of very recent explosive activity, that this is a recurrent phenomenon, and that we are currently observing the Galactic Center during a temporary lull between its activity.

At distances further out from the GC there is additional evidence of recent activity. For example at a distance of 10–20 l.y. from the Center, neutral oxygen observations indicate the presence of a ring of gas which has a substantial noncircular component to its motion indicating that, in addition to rotating, it is moving radially with respect to the GC, either inward or outward (Genzel *et al.*, 1982). Townes *et al.* (1983) estimate that such noncircular motions could not have persisted longer than 5×10^4 years without having become damped by the ring's rotational motion.

Other features indicating the occurrence of recent explosive activity at the center of the Galaxy include: the observation of neutral hydrogen and H_2CO gas located between 30–600 l.y. from the GC and moving radially outward at about 200 km sec^{-1} (Gusten and Downes, 1981), the Arc, an arc-like radio emission feature lying about 100 l.y. from the GC (Oort, 1977; p. 347; Yusef–Zadeh *et al.*, 1984), the ring-like molecular cloud which is estimated to lie at a distance of 400–600 l.y. from the GC and is seen to be expanding radially at about 150 km s^{-1} (Oort, 1977; p. 345), and the massive neutral hydrogen gas clouds found at distances of 1000–2000 l.y. from the Galactic plane which are observed to be moving radially away from the Galactic nucleus at velocities of $\sim$ 100 km s^{-1} (Van der Kruit, 1970). Finally, there is the three-kiloparsec spiral arm and its complementary arm on the far side of the nucleus which, if not inclined to the line of sight, may be interpreted as receding from the Galaxy's central region at about 100 km s^{-1} (Van der Kruit, 1971).

Due to the large amount of energy, $\sim 10^{55}$–10^{56} ergs, required to explain the formation and motion of the large scale features such as the Arc and the molecular ring cloud, it is unlikely that they could have been produced by single supernova. Multiple supernovae could explain these features only if the explosions occurred in a coordinated fashion. A more plausible explanation is that these features were shaped by an explosive outburst of relativistic particles issuing from the Galactic Center in a manner reminiscent of active galactic nuclei, e.g., see Oort (1977, p. 343).

This scenario is supported by recent radio observations. For example, Sofue and Handa (1984) present evidence indicating that this arc of radio emission is part of a much larger feature that extends perpendicular to the galactic plane and which most likely has been produced by a large scale outflow of matter propelled explosively from the GC direction. Synchrotron radio emission has been detected both in filaments making up the Arc and in streamers connecting the Arc to the central radio continuum region surrounding Sgr A (Yusef-Zadeh *et al.*, 1984; Waldrop, 1985). The relativistic electrons powering this emission could be relics of earlier particle barrages, which may have been active in shaping the Arc's smooth structure.

X-ray observations provide further evidence indicating that large quantities of relativistic particles are present throughout a region surrounding the Arc. For example, Watson *et al.* (1981) report the presence of a 150 by 250 light year region of diffuse X-ray emission having an intensity of 3×10^{36} ergs s^{-1}. They estimate the lifetime of electrons producing this emission to be either 500 or 3000 years, depending on whether the radiation is of synchrotron origin or due to Compton scattering. Thus it appears that the inferred relativistic particles have been produced relatively recently. Most likely they originate from the $4 \times 10^6\ M_\odot$ compact object located at the GC, which is believed to coincide with the synchrotron radio source Sgr A* and with a point X-ray source reported by Watson *et al.* (1981). The positrons responsible for producing the time-variable 511 Mev annihilation radiation, visible in this region prior to 1980, are also believed to originate from this same particle-emitting 'engine' (MacCallum and Leventhal, 1983).

The evidence presented above, seems to suggest that we live in a galaxy which has exhibited Seyfert-like behavior within the last 10^4 years. Given the prevalent evidence of kinematic features surrounding the GC, indicative of recent explosive activity, and noting that the GC currently has a relatively low luminosity, its nonthermal emission being relatively subdued, one is led to the conclusion that the explosive events, if recurrent, must be brief, and that we are currently observing the nucleus during one of its intermission periods. The evidence implies that outbursts last on the order of a few hundred to a few thousand years, and recur about every few thousand to 10^4 years. Such an on/off activity ratio is consistent with the observation that about 15–20% of the spiral galaxies are seen to be passing through their Seyfert phase.

A galaxy's active phase is often stated to last on the order of 10^6 years, with a recurrence time between outbursts of about 10^7 years. It was fashionable to quote such long time spans in order to account for the observation that many active galaxies have radio lobes which project up to several million light years from the galaxy. The reasoning followed was that the lobes are formed as a result of the continuous generation of relativistic electrons at the galaxy's center, the size of the lobes in light years indicating the duration of nuclear activity in years.

However, the same data is consistent with a model which proposes that outbursts occur on a much more frequent basis. For example, Burbidge, Burbidge and Sandage (1963, p. 964) argue that relativistic particles could just as well be supplied to the lobes through a sequence of outbursts, each lasting on the order of 10^3–10^4 years. Alternatively the entire radio lobe emission could be conceivably be produced by a single particle barrage emitted over a period of several hundred to a thousand years. This would naturally follow if the emitted cosmic rays are understood to propagate radially away from the galaxy's center at relativistic speeds beaming their radiation in the forward direction of propagation. The radio lobes would then be visualized to point toward the observer, rather than to extend out in space perpendicular to the line of sight. With such a geometrical arrangement, the radiation emitted by the particles during their entire multimillion light year journey toward the observer would be seen simultaneously, giving the false impression that the source particles occupied a very large volume of space.

For the case of relativistic beaming within forward-directed radio lobes, the radiating particles would necessarily travel through space a much greater distance than for the case of slow diffusion through transversely oriented radio lobes. At the same time the physical size, duration, and total energy content of the particle barrage would be considerably reduced; see LaViolette (1983a, p. 97).

3. Cosmic Ray Penetration Through the Galactic Disk

It has been customary in the past to model the ejecta of a galactic center outburst as being supernova-like, i.e., as consisting of a relativistic, magnetically-bound turbulent plasma (Rees, 1966; Blandford and McKee, 1976). For example, in relativistic blast-wave models, the expanding particle cloud is treated as a relativistic fluid which maximally interacts with the encountered interstellar medium. Interstellar magnetic field lines lying in the path of advance of this fluid are assumed to be swept up and deposited transverse to the radial direction of particle propagation. These swept up field lines and the ionized gas bound to them would then serve as a 'safety net', decelerating the outward advance of the particle blast to subrelativistic speeds.

According to this scenario, cosmic rays generated by a galactic center explosion would be able to escape from the nucleus only by slowly diffusing across magnetic field lines to which they would be bound. Hence if such an explosion were to take place at the GC, it is estimated that it would take on the order of 10^8 years for particles to reach the solar vicinity. Cosmic ray protons would be the only survivors of such a journey since the lifetime of cosmic ray electrons is on the order of 10^6 years.

However, LaViolette (1983a, Ch. 2) has proposed a different model in which cosmic rays expelled in a galactic core outburst are assumed to be emitted free of entrapping magnetic fields. Such an outburst would best be described as a relativistic particle volley. On the condition that the interstellar magnetic field is directed predominantly in a *radial* fashion with respect to the galactic center, this particle volley would be able to stream freely outward from the nucleus unimpeded. In so doing the particle barrage would be able to penetrate through the entire extent of a galaxy at relativistic speed, without experiencing significant attenuation or deceleration. Such a cosmic ray propagation model is capable of accounting for many of the emission phenomena observed in active galactic nuclei, including the production of compact radio sources separating at superluminal speeds; see LaViolette (1983a, Ch. 2).

At this point it is useful to coin the term *galactic superwave* to describe such a radially propagating cosmic ray barrage. More specifically, a superwave is defined to be an ultrarelativistic charge-balanced volley of cosmic ray electrons and positrons which propagates radially outward from the center of a galaxy taking the form of a spherical shell-like region of enhanced radiation (LaViolette, 1983a; pp. 6–9, 67–70). A superwave shell would be on the order of several hundred to a few thousand light years thick, its thickness being determined by the length of time the galactic center had been active. Thus a superwave would have a characteristic dimension that would be relatively small in comparison with the overall size of a spiral galaxy. Synchrotron radiation generated by the particles on their journey through the galaxy would be beamed in the direction of particle propagation. Due to similar propagation velocities, both the cosmic rays and their beamed radiation would coexist together in the relativistically advancing shell.

For superwaves generated by our own Galactic Center, it is assumed that the cosmic ray energy spectrum is similar to that of the unmodulated cosmic ray electron background inferred for the solar vicinity. The mean particle energy would be about 1.5 GeV, the Lorentz factor being about 3000. Consequently the particle volley would undergo a very small amount of radial dispersal as a result of differing particle travel times. For example in the course of the journey from the Galactic Center to the Earth a 100 MeV particle at the low end of the particle energy distribution would lag behind the light event horizon by only about 3 years.

Dust intervening between the Galactic Center and the Solar System would have a negligible effect on the superwave. For example, it is known that relativistic electrons must pass through a column density of about 140 g cm^{-2} in order to decrease their energy by a factor of $1/e$. Given an interstellar hydrogen density of about 10^{-24} g cm^{-3}, a column density of only about 10^{-2} g cm^{-2} would intervene. Thus as a result of dust absorption, a GC cosmic ray volley would only lose about 0.01% of its energy by the time it reached the solar vicinity.

Another factor to consider is whether the electrons would be resonantly scattered from their radial trajectories by Alfvèn or magnetosonic waves which could become generated as the particles passed through the interstellar medium. Holman *et al.* (1979) have pointed out that in a hot magnetized plasma in which the ratio ζ of the plasma's thermal ion energy density (nkT) to its magnetic field energy density ($B^2/8\pi$) exceeds unity, relativistic electrons would be able to stream freely along the plasma's magnetic field lines at velocities approaching the speed of light. They point out that hydromagnetic waves in the plasma, which might otherwise become amplified as a result of the streaming motion of the particles, would become damped by the plasma's own thermal fluctuations. Hence resonant scattering and mirroring of the streaming particles by such waves would not occur.

For the solar vicinity, where the density of ionized hydrogen is $n \sim 0.05$ particles cm^{-3}, the plasma temperature is $T \sim 10^6$ K, and the magnetic field strength is $B \sim 3 \times 10^{-6}$ gauss, a ratio $\zeta \sim 20$ is calculated. Thus if conditions observed in the solar vicinity can be taken as being roughly representative of the rest of the interstellar medium, it may be concluded that hydromagnetic waves would not be present and that superwaves would be able to propagate through the interstellar medium at relativistic velocities.

Recurrent superwaves would keep the interstellar magnetic field disposed in a radial fashion. For example, consider a Seyfert-like outburst radiating 10^{48} ergs s^{-1} in relativistic electrons ($\sim 10^{58}$ ergs over a period of ~ 300 years). Assuming that the cosmic ray intensity decreases according to the inverse square of radial distance from the Galactic Center, the energy density of the superwave in the solar vicinity would amount to $\sim 3 \times 10^{-9}$ ergs cm^{-3}. This is about 10^4 times greater than the energy density of the local interstellar magnetic field. Consequently, even at distances as great as the solar galactocentric distance, the superwave particle blast would control the dynamics of the interstellar field. Since superwaves would pass through a given location in the galaxy at least every 10^4 years, equivalent to $< 10^{-4}$ of a

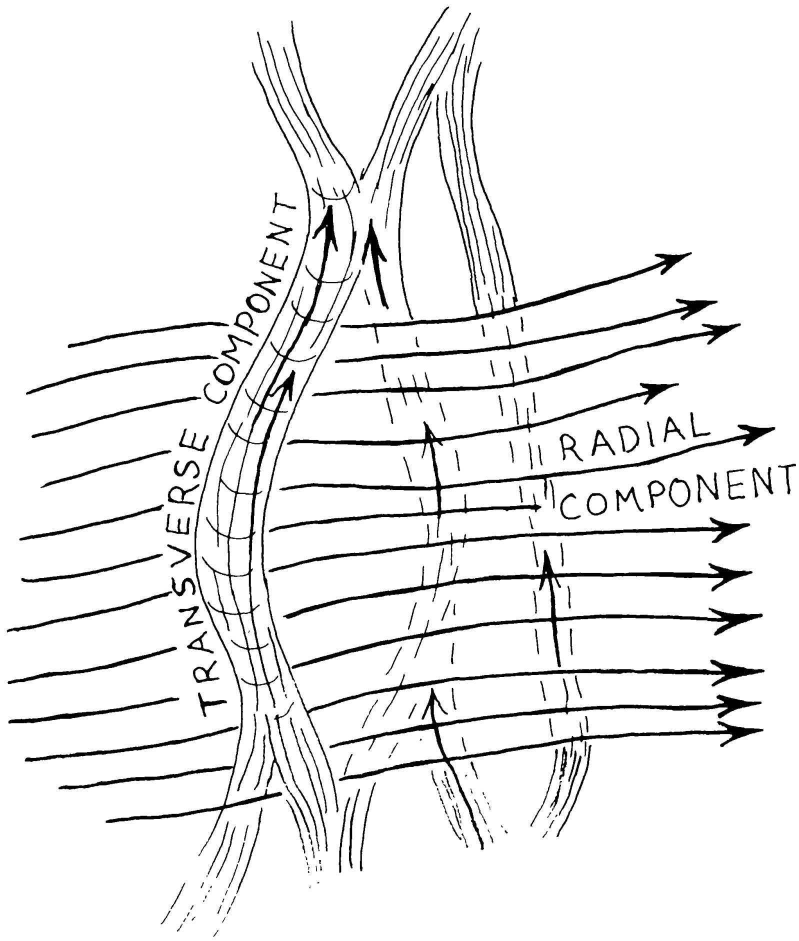


Fig. 1. A model of the Galactic magnetic field illustrating the penetration of the transverse field component by a radial component.

galactic rotation at the Sun's distance, the Galactic magnetic field would be maintained radially aligned despite the effect of galactic rotation. The interstellar gas wind, whose outward flow would be maintained by the periodic passage of Galactic superwaves would also be effective in keeping the Galactic magnetic field combed out in a radial fashion.

The scenario proposed here does not exclude the existence of a transverse field component. There could actually be an interpenetration of both radial and transverse magnetic field streams in the interstellar medium as shown in Figure 1. Measurements made of the Faraday rotation of extragalactic and Galactic radio sources (Simard-Normandin and Kronberg, 1980) indicate the presence of a radial field component directed along the line of sight to the GC, while starlight polarization measurements (Mathewson and Ford, 1970) indicate the presence of a transverse field component. However, on the basis of such astronomical observations, it is difficult to determine what the small scale Galactic field structure and orientation actually is. It is quite likely, though, that the coexistence model proposed by Figure 1 is largely correct and that radial field streams penetrate in this fashion through the entire extent of the Galactic disk.

The notion that cosmic rays emitted by sources considerably distant from the Sun ($\sim$ 10 kpc) might penetrate to the solar vicinity at relativistic speeds following nearly rectilinear trajectories becomes quite plausible in light of the recent findings for Cygnus X-3. It has been discovered that cosmic ray air showers originated by $10^{12}-10^{15}$ eV primary particles approaching from the direction of Cygnus X-3 are correlated with Cygnus X-3's characteristic 4.8 hour electromagnetic emission period (Marshak *et al.*, 1985). As one possibility, Marshak *et al.* (op. cit.) suggest that the muon flux they observe might be produced by a new type of stable neutral particle. However, a more conservative guess would be that these 'mystery' particles are really proton primaries which despite their charge are able to penetrate through the interstellar medium in a nearly straight-line fashion. Thus the discussion presented above in regard to the propagation of charged particles from Sgr A may equally well be applied to Cygnus X-3.

In addition to relativistic electrons, it is quite likely that cosmic ray protons and other heavy particles would also be emitted from the Galactic Center during an explosive outburst. However, on the basis of extragalactic observations, it is difficult to determine what the relative abundance of this heavy particle component would be. Most likely the energy flux of the emitted nucleonic component would not exceed that of the emitted electron component. However, few particles making up thus nucleonic component would be expected to survive the journey to the Earth due to the fact that they would have much lower Lorentz factors. Because the nucleons would be considerably less relativistic than the electron component ($\gamma \sim 1$), particles having differing kinetic energies would have substantially different travel times. Hence the nucleon particle volley would tend to disperse longitudinally, decreasing its energy density. Individual particles would then be more subject to scattering and capture by interstellar magnetic field lines. The highly relativistic fraction of the emitted proton flux $\gamma > 10^2-10^3$ would be expected to propagate together with the electron blast. However, this would make up less than a percent of the total energy of the cosmic ray volley and could therefore be neglected.

If by the time they reach the solar vicinity, superwaves are composed predominantly of electrons, one might wonder why it is that protons are roughly two orders of magnitude more abundant than electrons in the local cosmic ray background. Such a discrepancy could be readily explained if the proton background happened to be primarily of extragalactic origin, and that this average extragalactic flux now happens to be greater than the cosmic ray electron component which presently would be at low ebb due to the fact that we are in the intermission period between superwaves.

On the other hand, if it is assumed that a large fraction of the proton background is of Galactic origin, still one is led to the conclusion that cosmic ray protons should presently be observed in the solar vicinity in greater abundance. The reason for this is that protons emitted from the GC would reach us primarily by diffusion, and therefore the present flux would represent the time-averaged flux of successive periodic outbursts. Since the highly relativistic electron component would pass by us

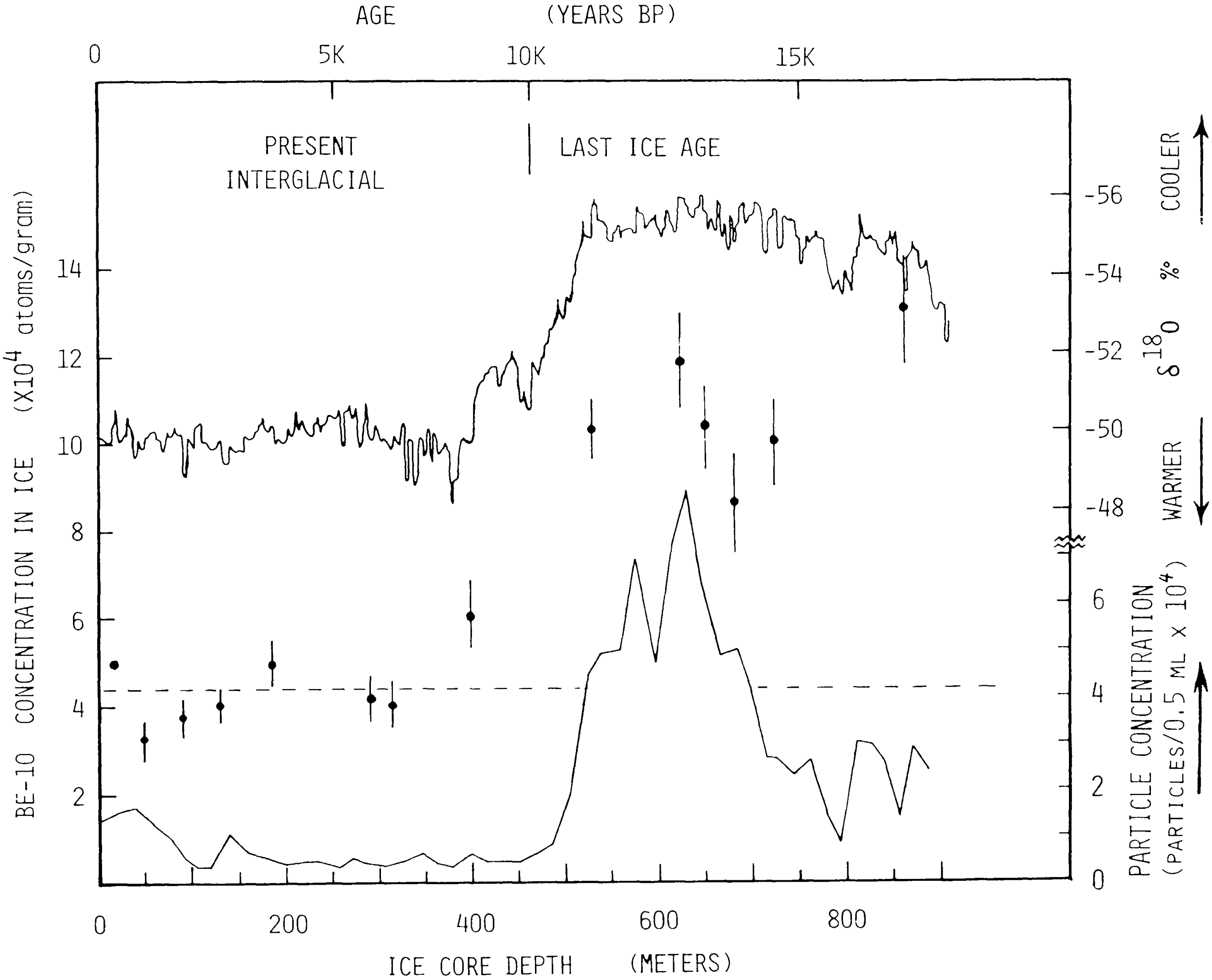


Fig. 2. The ice core record from Dome C, East Antarctica. Filled circles indicate ^{10}Be concentration in the ice, which serves as a measure of cosmic ray intensity (after Raisbeck *et al.*, 1981). Upper profile (after Lorius *et al.*, 1979) plots the δ^{18}O ratio in the ice which serves as an indicator of climate. Lower profile (after Thompson and Mosley-Thompson, 1981) plots the concentration of dust microparticles $< 0.65\mu$ in diameter. The lower horizontal scale gives the ice equivalent core depth.

in the form of discrete periodic volleys, the local cosmic ray electron energy density would be highly time-variable. Being presently in between Galactic superwaves, we should now be observing the electron component at its low ebb level which would necessarily be lower than the time-averaged proton flux.

4. Terrestrial Evidence of a Recent Superwave Passage

a) ^{10}*Be in Polar Ice*

If cosmic ray outbursts are able to propagate relatively undamped through the entire extent of a galaxy, then it is interesting to consider what effect they might have on the Solar System. For example, if a superwave having a total power output of 10^{48} ergs s^{-1} were to present a cosmic ray electron energy density of 3×10^{-9} ergs cm^{-3} in the solar vicinity, the ambient cosmic ray electron background would become elevated by a factor of $\sim 10^5$ above current cosmic ray electron intensities ($\sim 10^3$ fold higher than current cosmic ray proton intensities).

One way of determining whether the cosmic ray background has undergone appreciable short term variation within the last few ten thousand years is to check the Earth's polar ice core record to see if there have been any major changes in the beryllium-10 deposition rate. ^{10}Be is produced in the stratosphere through collisions between cosmic ray nucleons and atmospheric nitrogen and oxygen nuclei. The beryllium atoms thus produced quickly attach themselves to nearby atmospheric aerosols and precipitate to the ground within a year of their formation. Fortunately the polar ice caps preserve for us a detailed undisturbed record of past precipitation dating back through the Last Ice Age. By measuring the concentration of ^{10}Be in ice samples at various ice core depths, it is possible to deduce the rate at which this isotope was being deposited on the Earth's surface in the past and hence indirectly gauge the manner in which the local cosmic ray background intensity has varied.

Thus if a Galactic superwave had passed the Earth within the past ten to fifteen thousand years, one would expect to find evidence of elevated concentrations of ^{10}Be. Such an increase is in fact observed. Analysis performed on the Dome C, East Antarctica polar ice core shows that prior to 10000 years ago the ^{10}Be concentration was 2–3 times higher than current levels; see Figure 2 (filled circles) after Raisbeck *et al.* (1981). The transition from cool ice age temperatures to warm interglacial temperatures is illustrated by the oxygen isotope ratio (δ^{18}O) profile which is plotted as the upper curve (after Lorius, 1979). More negative δ^{18}O indicates cooler temperatures and greater ice sheet extent. A comparable increase in ^{10}Be is also seen during this period in the Dye 3 ice core penetrated in southeastern Greenland (Beer *et al.*, 1982). Since the ice accumulation rate at Dome C has not changed appreciably over the past 20000 years (Thompson and Mosley–Thompson, 1981), it may be concluded that the increase reflects an actual increase in ^{10}Be production rate. Thus these findings are consistent with the hypothesis that toward the end of the Last Ice Age there had been a temporary increase in the Galactic cosmic ray background radiation intensity (LaViolette, 1983a, p. 434).

Although only a 2–3 fold increase is registered for the ^{10}Be production rate, the actual increase of the incident cosmic ray electron intensity should have been much greater. The ^{10}Be record would underestimate the actual change in cosmic ray intensity since currently the majority of the ^{10}Be is produced by cosmic ray protons. Not only are cosmic ray protons much more efficient producers of ^{10}Be, but they are currently two orders of magnitude more abundant than cosmic ray electrons. Also one must consider that only a fraction of the incident cosmic ray electron intensity would have penetrated to the Earth's vicinity due to heliospheric modulation. Thus a several fold increase in ^{10}Be production rate is not inconsistent with a 10^5 fold increase in Galactic cosmic ray electron intensity, provided that the nucleonic component made up no more than 0.2% of the superwave's energy.

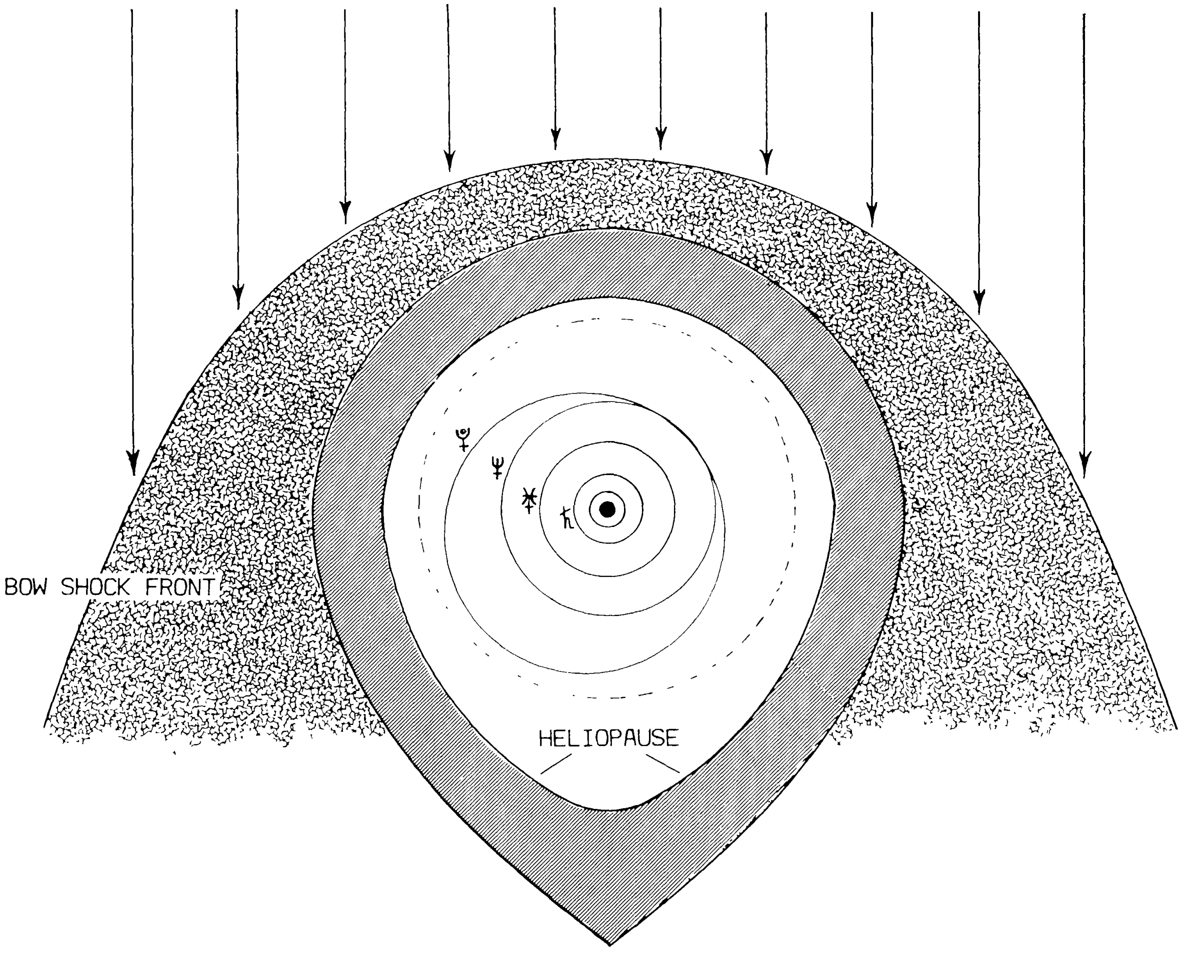


Fig. 3. The heliopause sheath shown with its surrounding bow shock front formed by the impacting superwave cosmic ray volley. The textured area indicates a region of magnetic field compression in which cosmic rays would become trapped and cometary material would become vaporized. Hydromagnetic shock fronts forming in this region would propel vaporized material into the Solar System.

b) *Cosmic Dust Incursions and Climatic Change*

The fact that the ^{10}Be production rate was at its highest value during the Last Ice Age is worth taking note of. This raises the question as to whether Galactic superwaves might be connected with the initiation and termination of the Earth's glacial cycles. The cosmic ray volley considered above would have had an intensity of about 10^{-4} suns outside of the heliopause and would have had an even lower intensity in the Earth's vicinity. So the energy carried by the superwave electron blast by itself would not be expected to have had an appreciable effect. The possibility that particle energy densities very much higher than this might have struck the Earth may be ruled out both by the Earth's ^{10}Be and ^{14}C records, neither of which show very high levels for these isotopes. If there is a climatic connection, it is more likely to be due to the superwave's ability to propel light-scattering and light-absorbing cosmic dust grains into the Solar System. These would in turn alter the radiation transmission properties of the interplanetary medium and of the Earth's upper atmosphere and, in so doing, could precipitate climatic change.

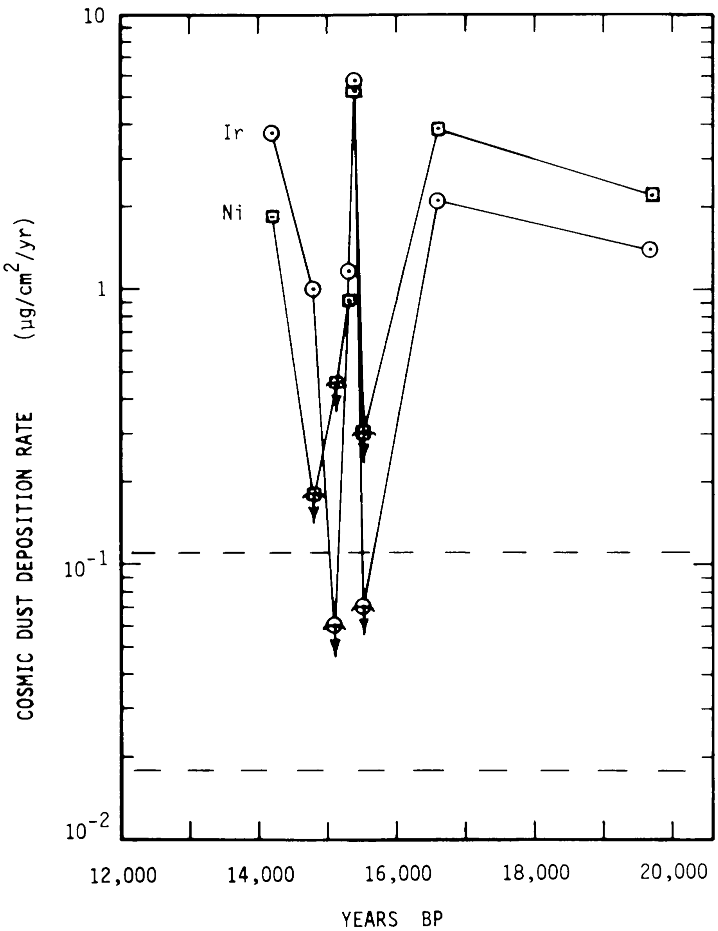


Fig. 4. Cosmic dust deposition rates recorded in the Camp Century ice core for the period 20000–14000 years BP. Curves marked Ir and Ni were respectively determined on the basis of measured iridium and nickel concentrations (LaViolette, 1985a).

The means by which a superwave would trigger such a nebular incursion may be understood as follows. The heliopause sheath, which surrounds the Solar System at a distance of about 70 AU, would be relatively impermeable to the electron barrage of a Galactic superwave. Consequently a bow shock front would form on the sheath's upwind side as shown in Figure 3. Behind this shock front, the interstellar magnetic field would become compressed and the incident electrons trapped into spiral orbits. Thus a 'radiation belt' region would form. It is estimated that as a result of such magnetic trapping superwave electron densities behind the shock front would increase by 10^5 fold relative to the energy density of the incident superwave particle volley. This would allow particle energy intensities of on the order of a few suns to be generated.

Consequently, any comets passing through this radiation zone would begin to vaporize, the radiation intensity being sufficient to raise the temperature of the outer 1 meter layer of a cometary body to about 400–500 K. As a result of such vaporization, a large cloud of dust and gas would be produced. This material would then be propelled into the Solar System by cosmic-ray-driven hydromagnetic shock fronts formed in the turbulent region behind the bow shock front. Cosmic dust grains which had acquired sufficiently large electrostatic charges or magnetizations would be particularly susceptible to the sweeping action of these fronts.

A good way of testing whether there had been any cosmic dust incursion episodes close to the end of the Last Ice Age would be to examine whether during that period there had been a detectable increase in the concentration of cosmic dust in the Earth's polar ice record. Such a test was actually carried out with this purpose in mind. In fact, it led to the discovery that for the period studied, 20000–14000 years BP, the cosmic dust deposition rates registered in the Camp Century (Greenland) deep ice core were on several occasions higher than the current rate by one to two orders of magnitude (LaViolette, 1983a, 1983b, 1983c, 1985, 1987). Figure 4 shows the deposition rates found for this Late Wisconsin period (LaViolette, 1985). Comparably high cosmic dust deposition rates were also found to be present in two 14 400 year BP samples from the Byrd Station ice core penetrated in West Antarctica (LaViolette, 1983a; Ch. 12). On the basis of these measurements, it may be concluded that the high concentrations of cosmic dust expected to be present in the Earth's upper atmosphere and in the interplanetary environment would have been sufficiently large to have been climatically significant.

Related to this, it is found that during the latter portion of the Last Ice Age the concentration of mineral dust in polar ice rose to levels over an order of magnitude higher than concentrations typical of the current interglacial. This dramatic increase, which is evident in polar ice cores penetrated both in Greenland and Antarctica, is displayed in Figure 2 for the Dome C ice core (lower profile). This data, taken from Thompson and Mosley-Thompson (1981), charts the concentration (per 0.5 ml of ice) of microparticles having a size greater than 0.65μ. As may be seen, the dust deposition rate reached a peak around 15000–12000 years BP. Note the proximity to the ^{10}Be increase.

These high Late Wisconsin dust concentrations have been interpreted as being caused by excessive windiness (Cragin *et al.*, 1977; Thompson, 1977; Petit *et al.*, 1981). Based on their findings that marine aerosol inputs to the Dome C site during the Late Wisconsin increased by a factor of ~ 5 over present input rates, Petit *et al.* (1981) estimate that wind speed was globally 1.5–1.8 times higher during that time. However, this raises several questions. If wind activity was a major factor producing the dusty atmospheric conditions at the end of the Wisconsin, then what caused the winds? Moreover why did the windiness occur when it did, particularly at the end of the glacial period? A reasonable explanation would also have to account for the rapid modulation of these episodes, dusty periods being found to begin and terminate on time-scales as short as a few weeks to a few years (LaViolette, 1983a; p. 408).

One possibility is that these meteorological phenomena were precipitated by changes in the light transmission properties of the Earth's atmosphere and interplanetary medium, these changes being brought about by the incursion into the Solar System of light scattering and absorbing cometary dust particles. In fact, in view of the high levels of cosmic dust reported for the Late Wisconsin polar ice

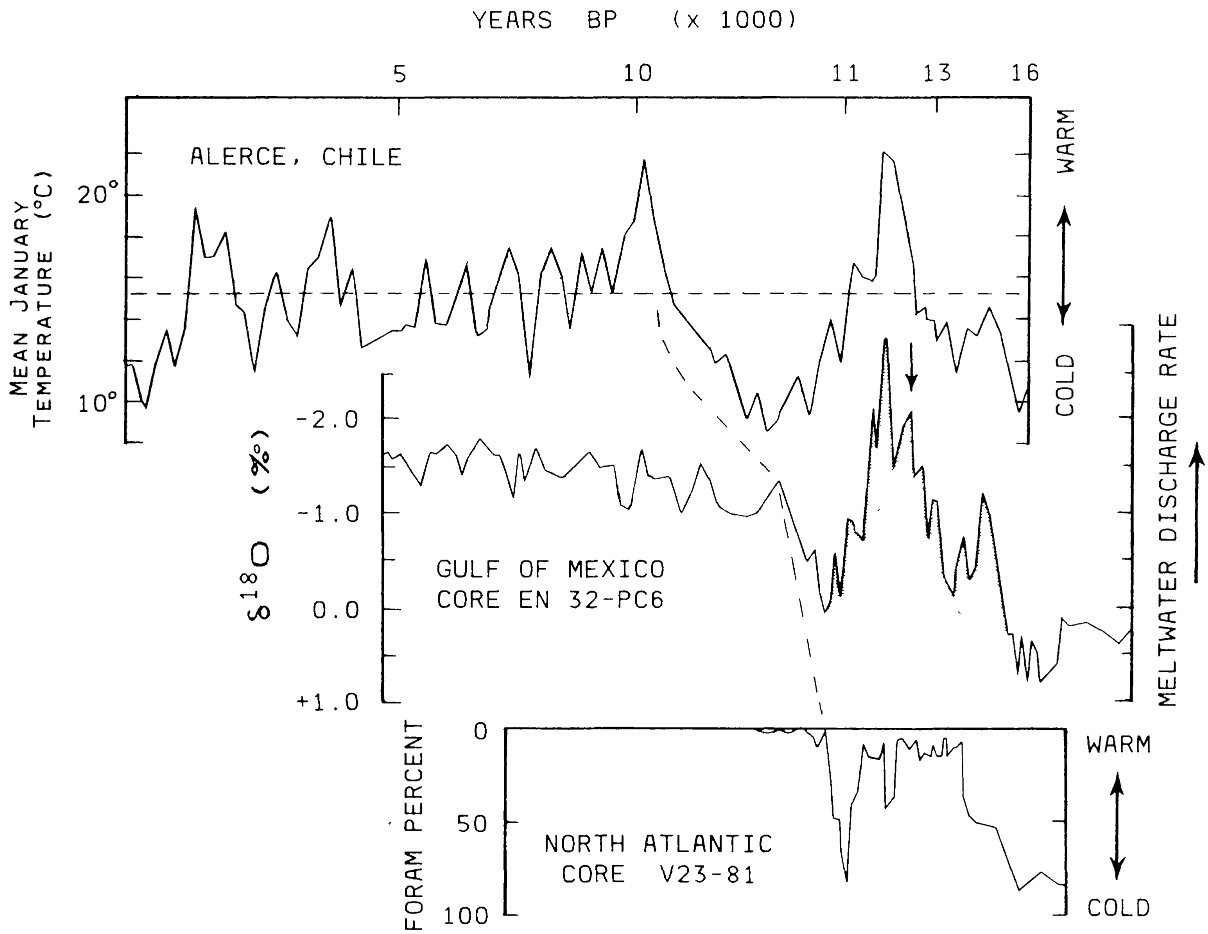


Fig. 5. Evidence of the Terminal Pleistocene Interstadial at a variety of locations. Upper profile plots average summer air temperature estimated from fossil pollen in a lake core penetrated in Alerce, Chile (41.4°S, 72.9°W). Middle profile plots oxygen isotope ratio of foraminifera shells retrieved from a Gulf of Mexico sediment core (26.9°N, 91.3°W); shaded region represents the portion of the curve indicating the influx of isotopically light meltwater. Lower profile plots, as an indicator of ocean surface temperature, the percentage of G. Pachyderma foraminifera found in a North Atlantic sediment core (54.2°N, 16.8°W). Data is taken respectively from Heusser and Streeter (1980), Leventer *et al.* (1982), and Ruddiman *et al.* (1977).

samples from Camp Century and Byrd Station, it may be inferred that a large fraction of the dust present in the Late Wisconsin portion of the Dome C ice core may also be of cosmic origin. It is expected that unusually high cosmic dust deposition rates will be found for the period of maximum dustiness, spanning the interval 14000–10000 years BP.

c) *The Terminal Pleistocene Interstadial*

There is considerable evidence indicating that the Earth's ice age climate became significantly warmer about the time of the proposed superwave passage. This warming trend began about 16000 years BP and accelerated significantly about 12 900 Years BP. About 2000 years later it ended very abruptly with the onset of the Younger Dryas stadial (~ 11000 years BP). With the termination of the Younger Dryas around 10000 years BP came the ending of the Last Ice Age.

This two millenial warming period appears to have been a global event since it is recorded at geological sites all over the world (LaViolette, 1983a; pp. 448–453). Depending on the specific geographic local where evidence of it has been found, this period has acquired a variety of names, being known in Scandinavia as the 'Ågard', 'Bölling', and 'Alleröd' interstadial sequence, in Great Britain as the 'Windermere' interstadial, and in the Great Lakes region as the 'Erie', 'Cary-Port Huron', and 'Two Creekan' interstades. Here we refer to this sequence by the generic term 'Terminal Pleistocene Interstadial' (TPI).

Evidence of the TPI is seen in the upper profile plotted in Figure 5 which charts summer temperature at a peat bog site in Alerce, Chile (Heusser and Streeter, 1980). At the interstadial's maximum (12 400–11 500 years BP), temperatures reached about 12 °C above values which had prevailed 4000 years earlier near the glacial maximum. Interestingly at the interstade's climax, temperatures at Alerce were 7 °C warmer than the average temperature prevailing there during the present interglacial! In the British Isles an overall warming of about 9 °C is indicated for this period (Coope, 1977). An ocean sediment core penetrated in the North Atlantic also shows evidence of the TPI; see lower profile in Figure 5 (adapted from Ruddiman *et al.*, 1977). Not only is the rapidity of the warming surprising, but also the fact that it occurred at a time when continental ice sheets were covering the Earth near their maximum extent!

The severe climatic amelioration which took place during the TPI apparently caused very rapid melting of the continental ice sheets. Tauber (1970) notes that at the beginning of the Bölling Interstadial (~ 12 400 years BP) the Scandinavian ice sheet was retreating at the rate of 350 meters per year, faster than any other time during its entire glacial retreat. The North American ice sheet also displayed a very rapid retreat during this period. During the Cary-Port Huron interstade, which began in the Great Lakes Region about 13 300 ± 400 C-14 years BP, the ice sheet receded at up to 500 m per year (Dreimanis and Goldthwait, 1973).

As a result of this accelerated ice sheet melting, the Mississippi River was discharging meltwater into the Gulf of Mexico at an unusually high rate. Evidence of this meltwater influx is indicated by the shaded portion of the oxygen isotope profile shown in Figure 5 (middle curve). The data here is taken from a study done by Leventer *et al.* (1982) on a sediment core from the northwestern portion of the Gulf. Excessively negative $\delta^{18}O$ values, such as those registered in the shaded region, would correlate with a more rapid rate of influx of isotopically light glacial meltwater. Note that the contour of the shaded region closely matches the temperature profile determined for the Alerce peat bog core.

The TPI also appears quite pronounced in the oxygen isotope profile for the Vostok ice core from East Antarctica; see upper curve in Figure 6 (after Gordienko *et al.*, 1982). This interval is found to correlate with a major dust peak, indicated by an increase in aluminum concentration (lower profile, solid line). Nitrate ion concentration (lower profile, dashed line) is also found to peak during this time (data from De Angelis *et al.*, 1984). The NO_3^- peak is of particular interest in that this ion

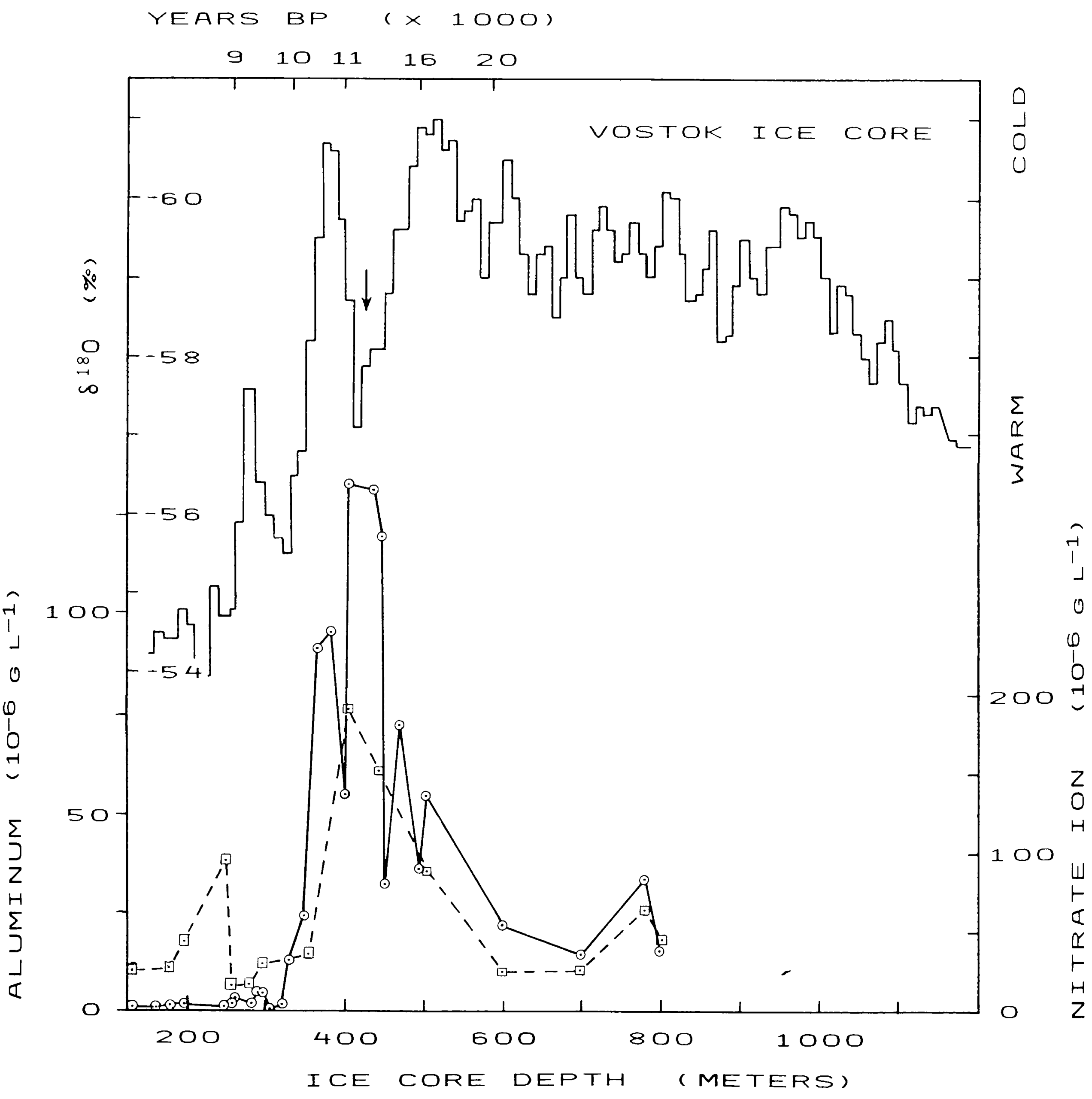


Fig. 6. The Vostok ice core climatic profile (upper solid line) shown together with concentration profiles for aluminum and nitrate ion (lower solid and dashed lines). Data is taken from Gordienko *et al.* (1982) and De Angelis *et al.* (1984).

is produced in the upper atmosphere primarily through ionization by galactic cosmic rays, solar-mediated aurorae, and giant solar flares (Parker *et al.*, 1982).

The observation that the TPI occurred during a period of excessive atmospheric dustiness and enhanced nitrate ion production is consistent with the proposal that this climatic warming was associated with the passage of a Galactic superwave. These nitrate observations confirm an earlier prediction made by LaViolette (1983a, pp. 436, 588) that nitrates would be found to be high during this critical interstadial period due to the expected enhancement in cosmic ray and solar flare activity. A further test of this astronomical hypothesis could be made by determining whether the concentration of cosmic dust in this particular portion of the Vostok ice core shows a correlated increase.

d) *The Terminal Pleistocene Extinction Episode*

The Pleistocene Epoch lasted almost 2 million years and ended about 10000 years BP with the termination of the Last Ice Age. A study of the fossil record reveals that at no time during the entire Pleistocene did faunal extinction proceed at a more rapid pace than at the terminal Pleistocene boundary when at least 200 genera became extinct. Data accumulated for the United States indicate that by the end of the Wisconsin glacial period 33 mammalian genera had become extinct. By comparison, only 1 genus had become extinct at the end of the Sangamon interglacial, no genera at the end of the Illinoian glacial, 3 genera at the end of the Yarmouth interglacial, and 4 genera at the end of the Kansan glacial (Hibbard *et al.*, 1965).

One of the distinctive features of the Late Pleistocene extinction is its terminal nature. Following this event new genera did not replace extinct species, either by immigration or by evolution (Martin, 1967; p. 78). This circumstance contrasts with the rest of the Pleistocene during which there was a more or less orderly replacement of the old by new genera. Some have even compared the terminal Pleistocene extinction with the disappearance of the dinosaurs at the end of the Cretaceous (Guilday, 1967; p. 122). In both cases the extinctions involved large land animals (greater than 25–50 kg adult body weight) leaving the smaller vertebrates and the plant kingdom relatively unaffected.

Hypotheses speculating about the cause of the Pleistocene extinction range from overkill by prehistoric game hunters (Wallace, 1911; Martin, 1967) to increased climatic severity (Vereshchagin, 1967; Slaughter, 1967). The latter, however, appears to be the best choice. The timing of this extinction suggests that the harsh climatic conditions and continental flooding which prevailed during the TPI were the most likely direct causes (LaViolette, 1983a; Ch. 10).

The frequency distribution of radiocarbon dates for 232 Late Pleistocene megafauna unearthed from 150 North American fossil sites is shown in Figure 7 (Meltzer and Mead, 1983). As may be seen the distribution peaks strongly between 13000 and 11000 years BP. It is instructive to compare this to Vostok profiles shown in Figure 6, which indicates that around this time the dust and nitrate ion deposition rates reached a peak. Also this extinction episode is seen to have reached its maximum severity at a time when meltwater was discharging from the North American ice sheet at its highest rate; compare with Figure 5.

The coincidence of this megafaunal extinction peak with this period of atmospheric dustiness and extreme climate is consistent with the superwave scenario which links the extinction to adverse climatic effects associated with a superwave-induced cosmic dust incursion episode. This tragedy could prove to be a reminder that events taking place at the center of the Galaxy, tens of thousands of light years from our Solar System, at times may have had a significant impact on the Earth and its biosphere.

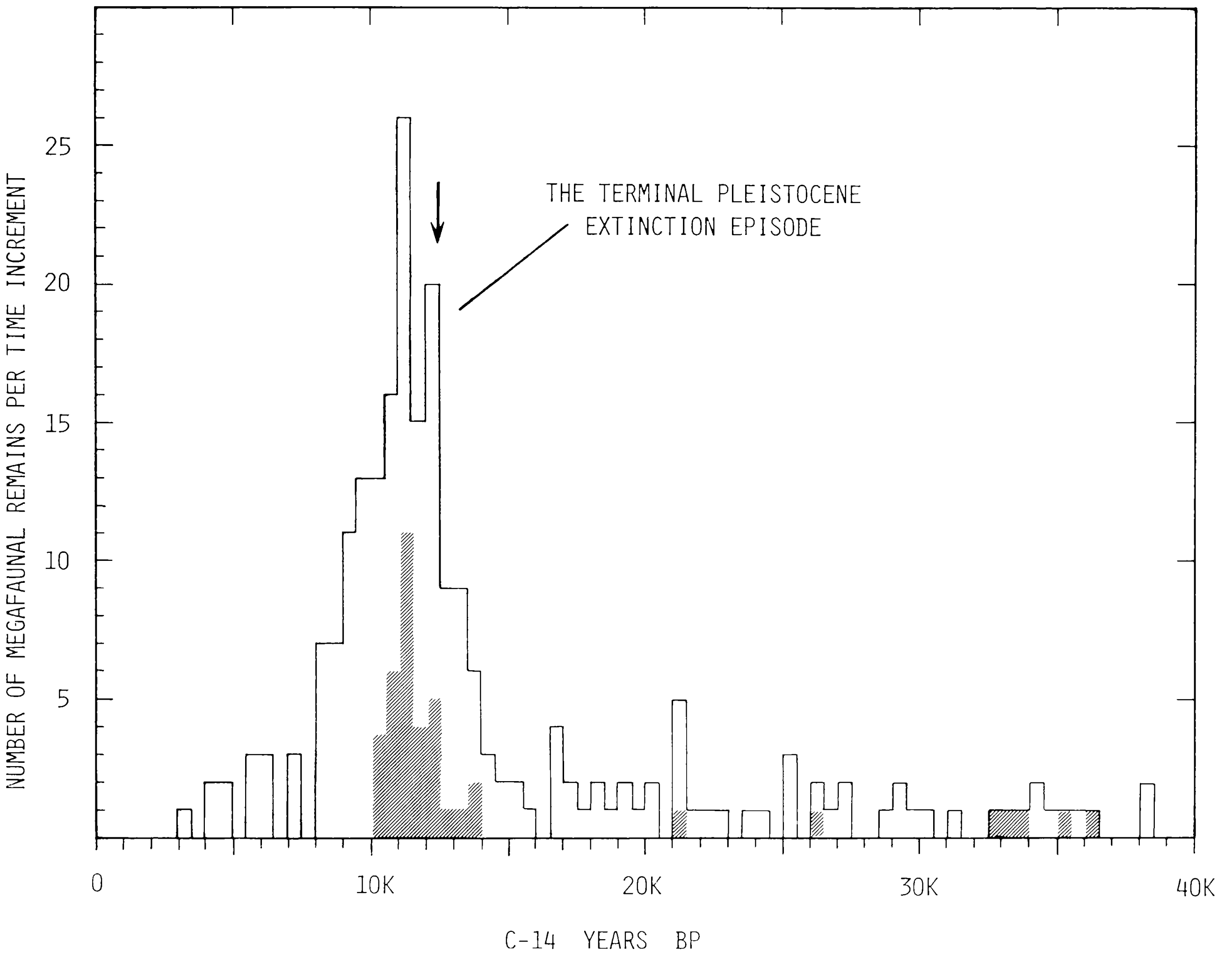


Fig. 7. Frequency distribution of megafaunal extinctions in North America at the end of the Pleistocene (after Meltzer and Mead, 1983). The shaded region indicates the distribution of the most reliable C-14 dates. The vertical arrow indicates the time of a major geomagnetic flip.

e) *The Solar Flare Track Record*

The proposed dust incursion episode would also have had a considerable effect on the Sun. Since the Sun continuously accretes dust and gas from the interplanetary environment, any large increase in the interplanetary dust concentration would cause a corresponding increase in the matter accretion rate. This in turn could affect the magnitude of the Sun's luminosity and its level of solar flare activity. The cosmic dust concentrations estimated to have been present in the terrestrial vicinity during the Late Wisconsin would have produced mass accretion rates sufficiently high to have produced a significant increase in both solar luminosity and flare activity (LaViolette, 1983a; pp. 192–194).

There is in fact evidence that solar flare activity was unusually high toward the end of the Last Ice Age. Zook *et al.* (1977) have studied solar flare tracks left in the glassy surfaces of lunar micrometeorite craters and have come to the conclusion that solar flare activity was about 50 fold higher about 16000 years ago; see Figure 8. Their

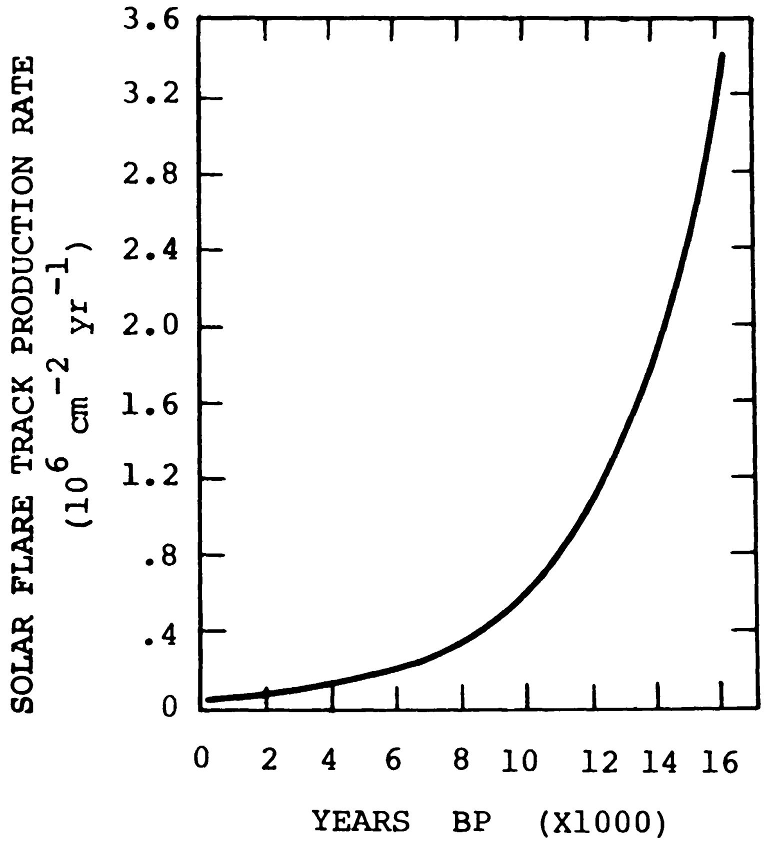


Fig. 8. Solar flare track production rate in lunar micrometeorite craters as a function of time (adapted from Zook *et al.*, 1977).

estimate assumes that the cratering rate has not varied appreciably. However, in view of the elevated cosmic dust deposition rates which apparently prevailed during the Ice Age, the cratering rate was probably higher prior to 10000 years BP. Consequently, the track production rate peak would have to be increased in magnitude and shifted to a more recent date.

It is interesting to note that a major geomagnetic excursion occurred around 12400 years BP (Mörner and Lanser, 1974; Mörner, 1977; LaViolette, 1983a; pp. 386–392). This geomagnetic flip could have been initiated as a result of overloading of the Earth's radiation belts with solar cosmic rays. Solar flare particles trapped in the Earth's radiation belts tend to drift equatorially and the ring current so produced generates a magnetic field opposed to that of the Earth. The enhanced solar flare activity which apparently took place at the end of the ice age could have charged the radiation belts sufficiently to cause a cancelation of the Earth's field, thus initiating a geomagnetic flip; see LaViolette (1983a; pp. 202–207). Note that this geomagnetic event occurred at a time when NO_3^- and dust concentration in the Vostok ice core were at a peak; see vertical arrow in Figure 6. Also the vertical arrows in Figures 5 and 7 indicate the timing of this flip relative to the terminal Pleistocene flood and extinction episodes. This event is seen to have occurred close to the time of deposition of the nonlaminated, homogeneous, shell-free, mud layer found at a

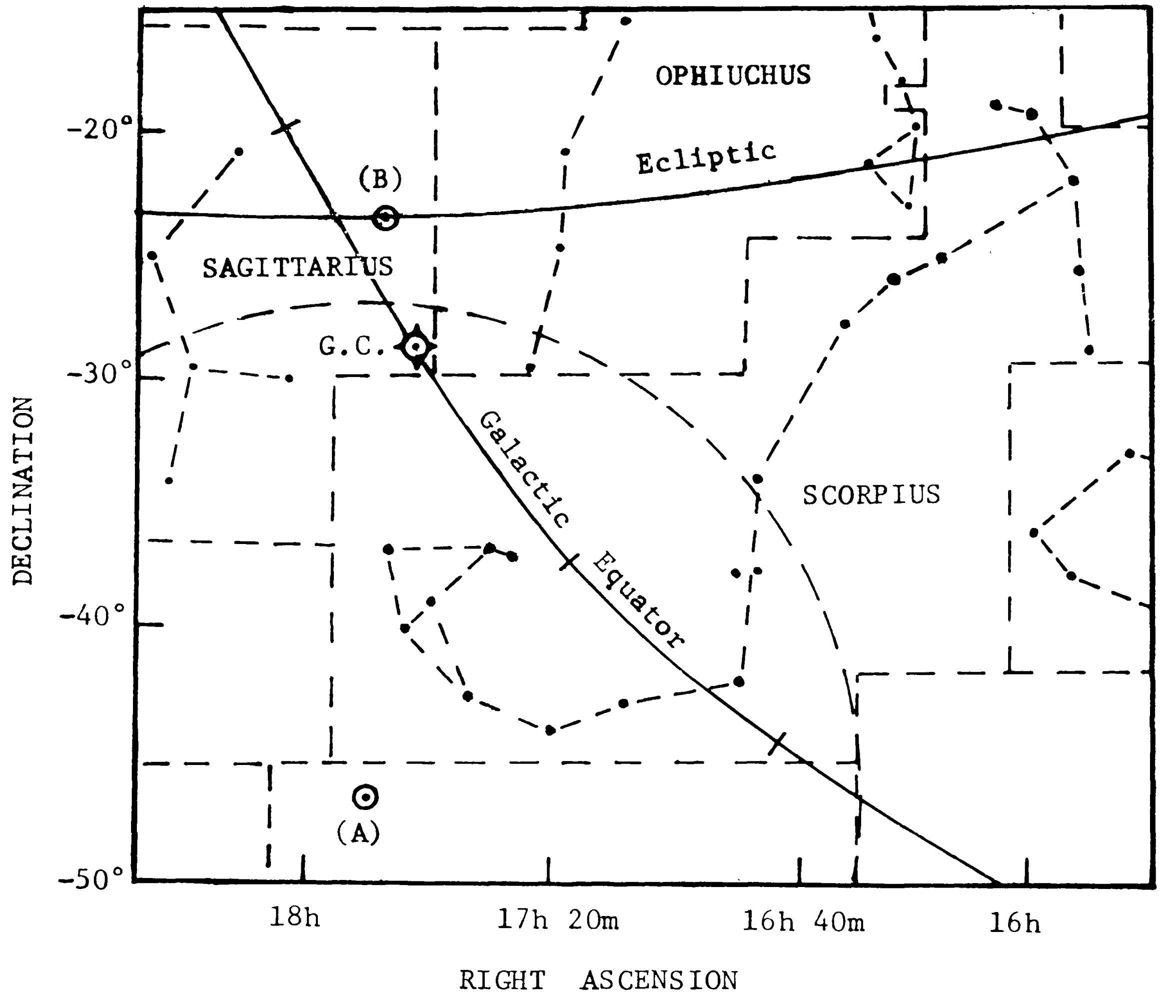


Fig. 9. Sky map of the Scorpius region showing: a) the direction from which the interstellar wind approaches the local standard of rest, and b) the position of the ascending node of the zodiacal cloud. The Galactic Center is marked as GC.

depth of 537–509 cm in Gulf of Mexico core EN 32-PC6. Leventer *et al.* (1982) have concluded that this clayey layer was formed rapidly during a period of unusually intense meltwater discharge.

Normally, ^{10}Be production rate tends to anticorrelate with solar activity due to solar modulation of the galactic cosmic ray intensity (Raisbeck *et al.*, 1981). However, if the solar activity were sufficiently high, it is possible that close to the time of the polarity flip a significant portion of the ^{10}Be production in the Earth's atmosphere may have been due to solar flare protons.

f) *The Interstellar Wind Direction*

Observations of the velocities of optical interstellar lines in the direction of nearby stars ($d < 100$ pc) indicates that the Sun is immersed in a local interstellar medium moving in a coherent fashion and approaching the local standard of rest at ~ 15 km/sec from the direction ($l = 345° \pm 20°$, $b = -10° \pm 20°$). As may be seen in Figure 9, the Galactic Center lies within one standard deviation of this upwind

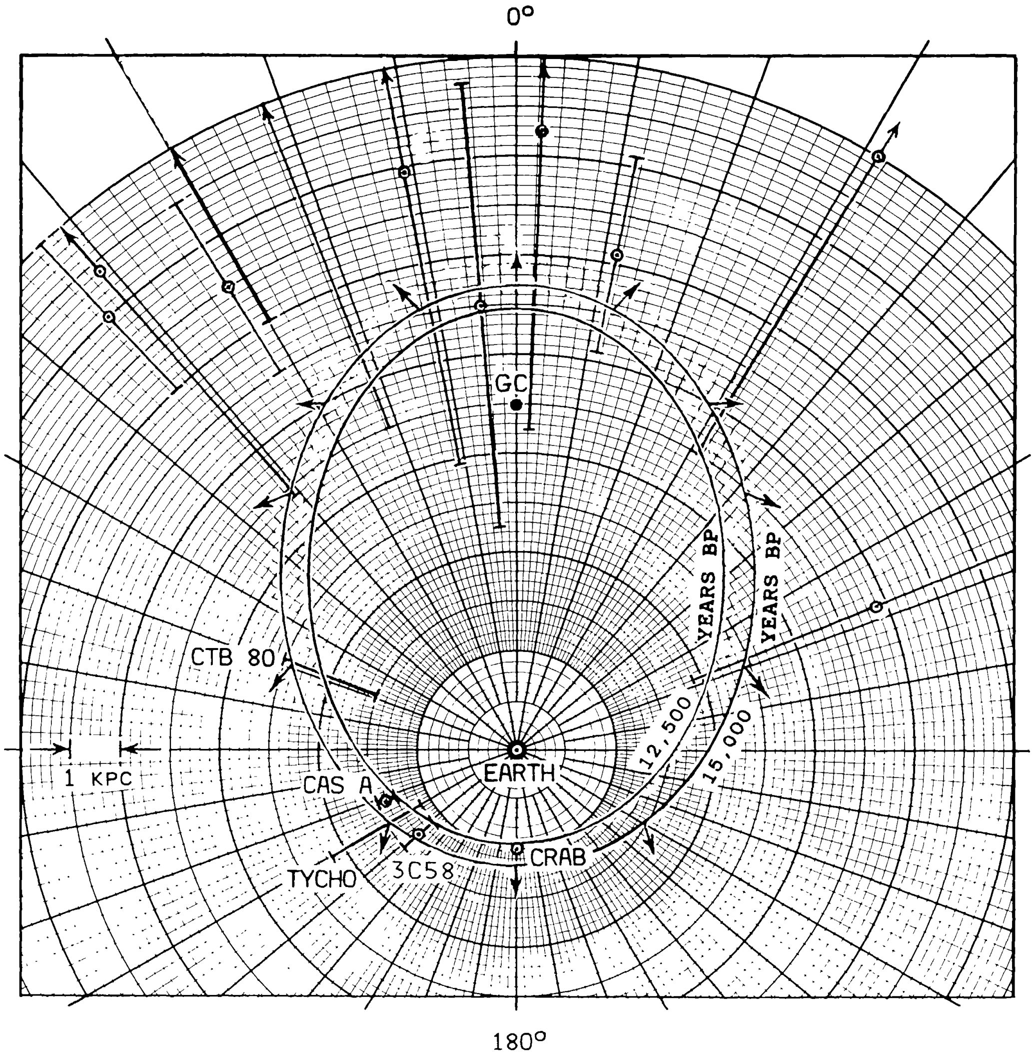


Fig. 10. The current positions of the 12500 and 15000 years BP superwave event horizons. Circles indicate the positions of the 16 brightest supernova remnants in the Galaxy ($\Sigma > 1$ fu/(′)^2). Bars indicate the degree of positional uncertainty. Also shown are the positions of 3C 58, and CTB 80.

direction, designated by point (A). A close proximity to the Galactic Center direction would be expected if indeed the solar neighborhood was bombarded at periodic intervals by volleys of cosmic ray electrons issuing from the Galactic Center.

Related to this is the finding that the zodiacal dust cloud, which is inclined by about 3° with respect to the ecliptic plane, has its ascending node near ecliptic longitude 87° (Hauser *et al.*, 1984). This falls just 2° east of the point where the ecliptic makes its closest approach to the Galactic Center; see point (B) in Figure 9. This close proximity is consistent with the proposal that the dynamics of dust particles orbitting in the zodiacal cloud are influenced by the arrival of particle volleys propagating from the direction of the Galactic Center, and in particular that such volleys are effective in driving outlying cometary dust into the Solar System.

5. Astronomical Evidence of a Recent Superwave Passage

If a superwave had passed through the solar vicinity toward the end of the Last Ice Age, its cosmic ray shell should presently be observed to have the shape of an ellipsoid, one focus of which would be positioned at the Galactic Center and the other focus at the Earth. The elliptical shape would be due to light travel time effects. For superwaves passing the Earth around 12500 years BP and 15500 years BP, the intersection of the event horizon shell with the Galactic plane, would appear as shown in Figure 10. The major and minor axes of these event horizons would have dimensions: $a = (r_0 + t)/2$ l.y. and $b = [a^2 - (r_0/2)^2]^{1/2}$ where $r_0 = 23000$ l.y. (7.1 kpc) is taken to be the distance from the Earth to the Galactic Center (Reid *et al.*, 1986; Ebisuzaki, 1984; Frank and White, 1982) and t is the time elapsed in years since the superwave passed the Earth. If the amount of dust in the polar dust record can be used as a rough gauge of superwave intensity, then the superwave dates chosen here should approximately bound the most intense portion.

a) *The Galactic Radio Background Radiation*

Synchrotron radiation generated by the superwave for the most part would be relativistically beamed away from the Galactic Center. Hence if a superwave had already passed the Earth, it would tend to elude observation. However, some fraction of its generated radiation would be detectable. For example, low energy cosmic ray electrons present in the superwave volley would be susceptible to being captured into spiral orbits by transversely disposed magnetic field lines present in the galactic disk, and once captured, would beam their radiation in all directions with equal probability. Hence radiation from this captured population would be visible to Earth-based observers. Since superwave electrons propagating parallel to the Galactic plane would have the greatest chance of being captured, the observable synchrotron radiation would be expected to be concentrated in a band along the Galactic equator. Moreover it would be expected that this radiation would reach its peak intensity in the direction of the Galactic Center. In that direction the superwave would be observed at earlier times when it was closer to its point of origin and hence more intense.

The Galactic nonthermal radio background emission in many respects fits the description of the proposed synchrotron radiation field. Not only is it concentrated toward the galactic plane but also its intensity reaches a maximum in the direction of the Galactic Center. Moreover this diffuse radiation has been interpreted as being produced by Galactic cosmic ray electrons spiralling around interstellar magnetic field lines (Ginzburg, 1956; Kraus, 1966; p. 377; Alexander and Clark, 1974). In the past it has been assumed that these electrons originate from supernova explosions in the galactic disk. However, such particles might equally well be supplied by passing superwaves.

The hypothesis that this radio background radiation is powered by superwave electrons may be checked by noting whether the longitudinal variation of intensity predicted by the superwave model matches the observed intensity variation.

TABLE I
Parameters used in modeling the galactic radio background radiation

$l°$	$r(l)$ 12.5 k (kpc)	$r(l)$ 15 k (kpc)	κ	T_b 12.5 k (K)	T_b 15 k (K)	T_b AVG. (K)
0	1.92	2.30	1.00	5000	5000	5000
2/358	1.93	2.31	1.005	4970	4980	4975
5/355	2.00	2.43	1.04	4790	4660	4720
10/350	2.20	2.60	1.08	4110	4230	4170
15/345	2.47	2.80	1.15	3470	3880	3670
20/340	2.81	3.18	1.27	2960	3320	3140
40/320	4.83	4.61	1.54	1220	1920	1570
60/300	6.21	6.40	1.62	780	1050	910
90/270	8.00	7.70	1.42	410	630	520
120/240	8.40	8.82	1.15	300	390	345
180	8.92	9.30	1.00	230	310	270

According to the Rayleigh–Jeans Law, the observed radio brightness temperature, T_b (K), should be proportional to the observed radio brightness (in units of Watts/m^2/Hz/rad^2), which in turn should be proportional to the ambient cosmic ray electron density (Kraus, 1966; p. 85). Moreover, since the electron density within a given longitudinal increment varies along the elliptical event horizon according to the inverse square of the horizon's distance r from the Galactic Center, the following relation should hold:

$$T_b \propto \kappa \cdot 1/r^2, \tag{1}$$

where κ is a correction factor which accounts for the fact that the line-of-sight distance through the superwave shell varies as a function of galactic longitude.

Model values of r for two superwave event horizons (12000 yrs BP and 15000 yrs BP) for various values of galactic longitude l are listed in Table I together with values for the correction factors κ. Columns (5) and (6) give corresponding model brightness temperature values T_b computed for the two event horizons with the values being normalized to $T_b = 5000$ K for $l = 0°$. Temperatures listed in columns (5) and (6) have been averaged together in column (7) and are plotted in Figure 11 (dashed line) for comparison to the observed 150 MHz temperature distribution (solid line). The data for the observed profile was compiled and normalized by Price (1974) from the data of Landecker and Wielebinski (1970), Wielebinski *et al.* (1968), and Hamilton and Haynes (1969). The profile represents a longitudinal scan of the Galaxy along the equator ($b = 0°$) with an angular resolution of 3°. As may be seen the Galactic superwave model curve makes a very good fit to the general shape of the observed radio distribution.

Setti and Woltjer (1971) and Alexander and Clark (1974) have modeled the Galactic radio background emission by assuming the Galactic disk to be populated

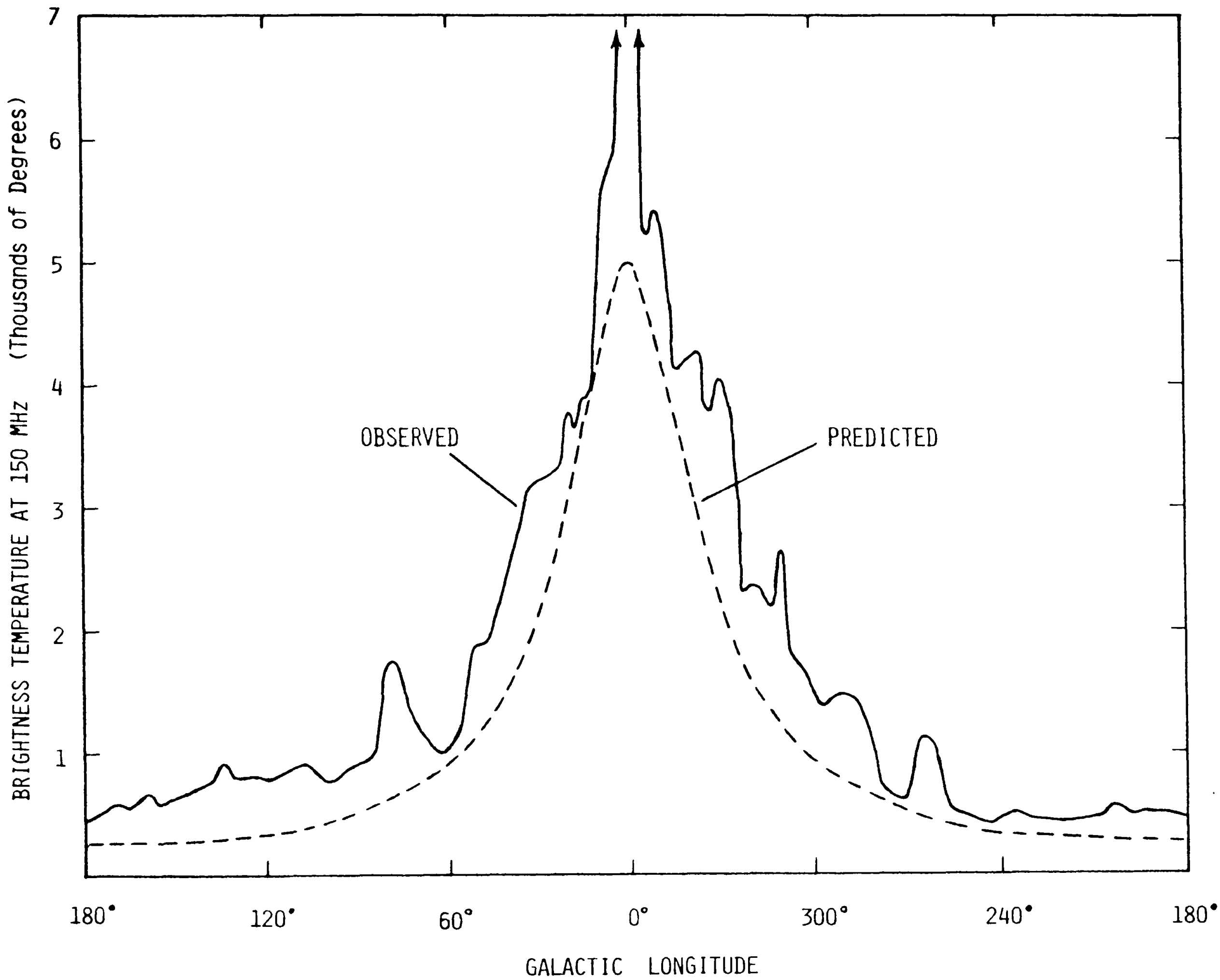


Fig. 11. Brightness temperature of the Galactic radio background emission as a function of galactic longitude. Solid line: the distribution observed at 150 MHz (after Price, 1974). Dashed line: the distribution predicted by the superwave model.

throughout by cosmic ray electrons having densities 5–10 times above local levels at 3 GeV. If their models were to assume that the electrons were instead concentrated within a smaller volume, e.g., within a 3000 l.y. thick shell rather than throughout the disk, then proportionately higher cosmic ray energy densities would be required, of the order of $\sim 10^{-12}$–10^{-11} ergs cm^{-3}. A region of the superwave subtended between the 12500 BP and 15000 BP event horizons and extending vertically from the Galactic plane by $z \sim \pm 1$ kpc would comprise a total volume of about 10^{66} cm^3. Thus a total particle energy of about 10^{54}–10^{55} ergs would be involved in producing the observed nonthermal radio emission, a small fraction of the total energy modeled for the superwave. Thus the superwave model may reasonably account for the magnitude of the observed radio emission.

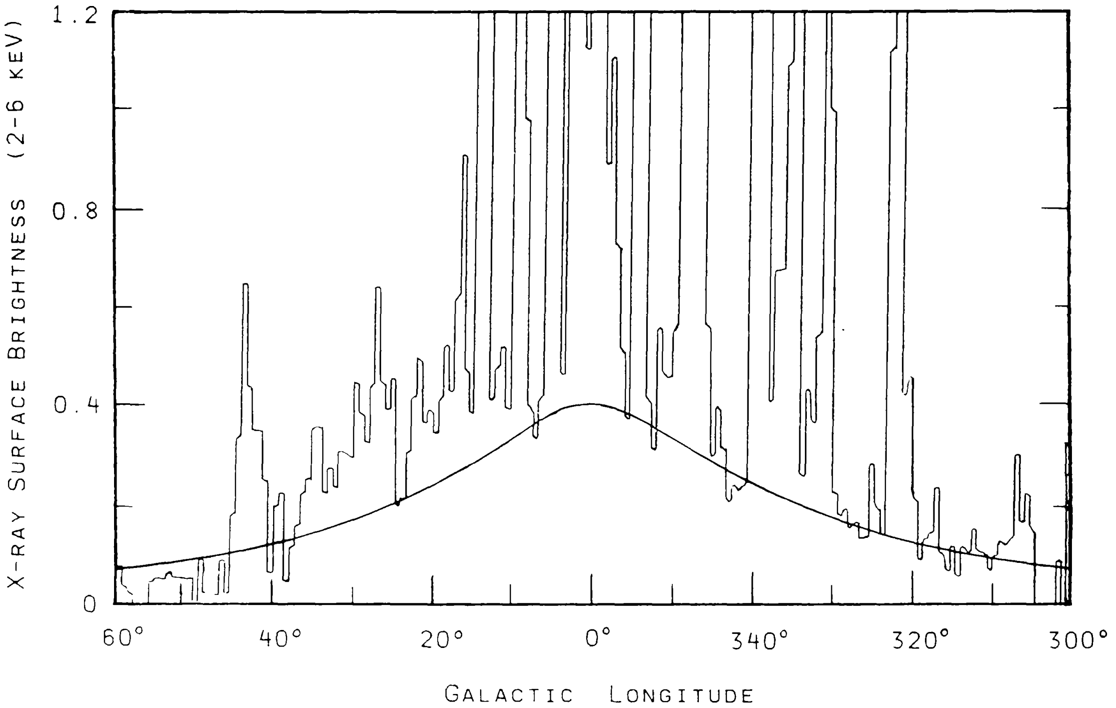


Fig. 12. The intensity of the galactic X-ray emission ridge plotted as a function of galactic longitude (after Warwick *et al.*, 1985). The emission profile expected from a superwave shell bounded by the 12500 and 15000 year BP superwave event horizons is shown for comparison.

b) *The Diffuse X-Ray Emission Ridge*

The Late Wisconsin superwave could also account for the diffuse hard X-ray emission presently observed to come from the galactic plane. The emission is found to be most concentrated in a 2° wide strip extending about 40° of longitude on either side of the GC. The intensity profile of this emission as a function of galactic longitude is plotted in Figure 12 (after Warwick *et al.*, 1985). The superimposed contour illustrates how X-ray intensity would vary with longitude for the proposed superwave event horizon. The profiles was constructed from the data given in Table I (last column) normalized to an intensity of 0.4 at $l = 0°$.

Worrall *et al.* (1982) have shown that this emission may be modeled as synchrotron radiation produced by 10^{14} eV cosmic ray electrons. Since the lifetime of such particles is on the order of 10^4 years, new particles would have to be supplied at the rate of 10^{48} ergs yr^{-1} to maintain this radiation at its observed intensity. This source of injection must itself be diffusely distributed since the particles are capable of diffusing only about 500 l.y. due to their short lifespan. A Galactic superwave would satisfy both the energy requirements and would provide a means of diffusely injecting particles over an extended region.

c) *Supernova Remnants as Galactic Cosmic Ray Intensity Probes*

Young supernova remnants (SNRs), being made up of a magnetically bound, fluid-like turbulent plasma, would present a unified impermeable barrier to a passing superwave. Consequently, during passage of a superwave cosmic ray volley, a bow

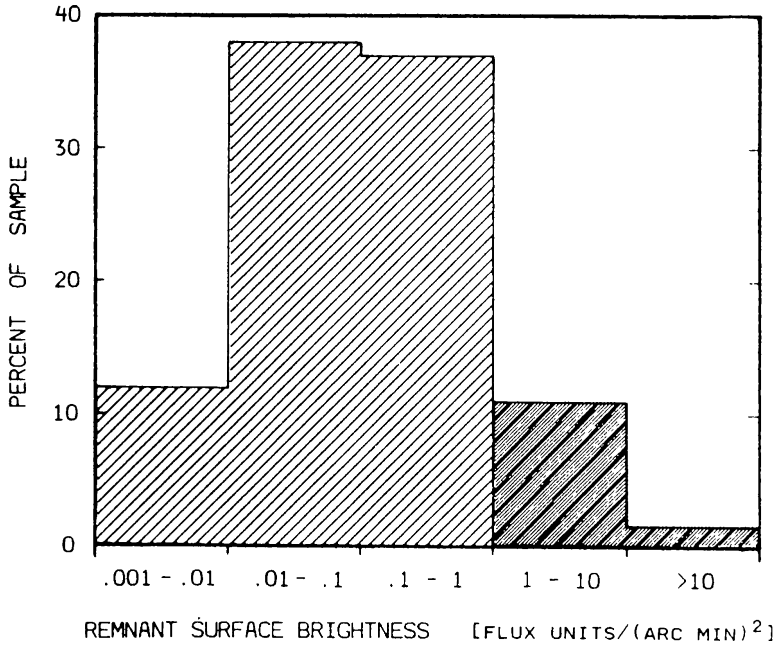


Fig. 13. Histogram showing the percentage of supernova remnants in each of 5 surface brightness categories for a sample of 125 remnants published by Milne (1979). The dark shaded region represents the 16 remnant subset that was selected for study.

shock front would be expected to form around such remnants. The phenomenon is essentially the same as that described earlier for superwave electrons encountering a stellar magnetopause sheath only here the shock front covers a much larger area.

Behind the bow shock front, and also in the interior of the remnant shell, superwave cosmic ray electrons would become trapped in spiral orbits. The synchrotron radiation they would produce would be beamed in a relatively isotropic fashion and, hence, would be quite visible to an Earth-based observed. In the absence of such an obstacle, superwave electrons would beam their synchrotron emission away from the GC, and hence would tend to elude observation. Thus because of their cosmic ray trapping ability, young supernova remnants should serve as excellent probes for indicating the location of energetic cosmic ray fronts propagating through the Galaxy. Remnants which happened to lie in the midst of a sufficiently intense cosmic ray volley would be expected to be more luminous than those lying in intermediary regions where the Galactic cosmic ray electron intensity would be particularly low.

Older remnants in which the shell had become considerably expanded and decelerated through interaction with the interstellar medium would be expected to be far less efficient in trapping superwave cosmic rays. For such remnants the magnetically bound plasma fabric would have fragmented and become penetrated by the interstellar gas wind. Thus superwave electrons would be able to channel through such remnants relatively unimpeded. Even so, old remnants would also be expected to radiate more intensely than normal if they happened to be in the presence of a sufficiently intense superwave.

TABLE II

Data for the 16 brightest galactic supernova remnants

(1) Name	(2) l (deg)	(3) b (deg)	(4) ϕ (arc′)	(5) S_{1GHz} (f.u.)*	(6) Σ_{1GHz} f.u./(′)^2	(7) d (kpc)	(8) t (yrs)	(9) ref.**
1 Kepler	4.5	+ 6.8	3.8	20	1.76	9 ± 5	378	1
2 G 11.2−0.3	11.2	− 0.3	4.2	22	1.59	(11.9 ± 6)		2
3 G 21.5−0.9	21.5	− 0.9	1.0	6.5	8.3	(15 ± 8)		2
4 4C−0.370	29.7	− 0.2	2.4	10	2.2	(18.9 ± 9)		2
5 3C 391	31.9	0.0	4.2	22	1.6	11 ± 2, (16)		2
6 3C 397	41.1	− 0.3	3.6	20	2.0	(12.8 ± 6), >7.5		2
7 W 498	43.3	− 0.2	4.2	36	2.6	12 ± 2, (11.6)		2
8 Cas A	111.7	− 2.1	4.2	3400	245	2.8 ± .2	300	2
9 Tycho	120.1	+ 1.4	7.9	58	1.2	2.2 ± 4.3	420	3
10 Crab	184.6	− 5.8	6 × 4	1000	53	2.0 ± .1	928	4
11 MSH 11−54	292.0	+ 1.8	2.3	15	3.6	(7.8 ± 4)		2
12 MSH 15−57	328.4	+ 0.2	4.0	17	1.35	(14.0 ± 7)		2
13 CTB 37A	348.5	+ 0.1	8.0	77	1.5	10.2 ± 2, (8.0)		2
14 CTB 37B	348.7	+ 0.3	5.1	38	1.9	10.2 ± 2, (9.9)		2
15 G349.7 + 0.2	349.7	+ 0.2	1.7	21	9.3	18.3 ± 2, (18.7)		2
16 MSH 17−39	357.7	− 0.1	4.3	38	2.6	(12.5 ± 6), >6		2

* f.u. (flux unit) = 10^{-26} Watts/m^2/Hz.

** 1: van den Bergh and Kamper (1977); 2: Milne (1979); 3: Reid *et al.* (1982); 4: Trimble (1986).

To check whether there might be a correlation between the locations of the brightest SNRs and the present position of the 15000 and 12500 year BP superwave event horizons, a sample of 125 Galactic SNRs catalogued by Milne (1979) was considered. From among these the sixteen brightest remnants were selected, i.e., those having 1 GHz radio surface brightnesses greater than 1 flux unit/(arc min)^2. Since a remnant's radio surface brightness is a good distance-independent indicator of its intrinsic radio luminosity, this subset would represent the 16 most luminous SNRs in the Galaxy. As is seen in Figure 13, this subset constitutes about 13% of the total SNR sample. Since the remnants with the highest surface brightness should also be those that are most easily distinguishable, there is a minimum of sample bias introduced in selecting this group.

Relevant data for these 16 remnants is listed in Table II. Values are given for the remnants' l and b coordinates (columns 2 and 3), the angular diameters of their shells (col. 4), their radio luminosities at 1 GHz (col. 5), their 1 GHz radio surface brightnesses (col. 6), their geocentric distances (col. 7), and their ages if known (col. 8). The data is taken from Milne (1979), except for the distances to some of the remnants, references for which are given in column 9. The inequalities listed in column 7 indicate distances that are based on line absorption measurements. The distance quantities in parentheses are rough estimates determined on the basis of Milne's (1979) surface-brightness-diameter relationship corrected for remnant height above the galactic plane. These $\Sigma - D$ distances may be uncertain by a factor of two or more.

The (l, d) locations of these 16 SNRs have been plotted on the polar coordinate Galactic plane map shown in Figure 10. Only three of these high surface brightness remnants are found within 7 kpc of the Earth, or four, if the sample is expanded to include 3C 58. All three are young remnants and have historically recorded supernova dates. Of these, the Crab Nebula and Cassiopeia A (Cas A), whose distances are the best determined for the 16 SNRs, are found to make an excellent fit to the 12500/15000 year BP superwave event horizons. Moreover both of these remnants have the highest surface brightness of the subsample. In fact, their surface brightnesses exceed the sample mean of 3.0 ± 2.6 f.u./($'$)^2 by over an order of magnitude; see Table II. The fact that the two brightest SNRs in the Galaxy should both happen to lie so close to the positions of the proposed superwave event horizons is difficult to attribute just to chance. Compared with the Crab and Cas A, Tycho's distance is less certain; however, it is interesting to note that for the range of distances quoted the position of this remnant does intersect these event horizons.

Remnant 3C 58, which is associated with the historically recorded supernova of 1181 AD, is also worthy of consideration. This remnant is not only about the same age as the Crab Nebula, but also it is elliptical in shape, has a filled-center (plerionic) radio emission distribution, and like the Crab, lies in the vicinity of the proposed superwave event horizons. Although its 1 GHz radio surface brightness is almost two orders of magnitude less than that of the Crab, it is quite bright compared with the other SNRs in Milne's sample. In fact, if the 16 remnant subset were to be slightly expanded, 3C 58 would be the next to be included.

TABLE III

A sample of 46 medium surface brightness galactic supernova remnants

Name	l (deg)	Σ_{1GHz} f.u./(′)^2	d (kpc)	Name	l (deg)	Σ_{1GHz} f.u./(′)^2	d (kpc)
1 G 2.4 + 1.4	2.4	0.28	(7.2)	24 Kes 17	304.6	0.40	9.4
2 Milne 56	5.3	0.20	(5.0)	25 G308.7 + 0.0	308.7	0.29	(14.1)
3 W 28	6.4	0.17	(2.4)	26 G311.5 – 0.3	311.5	0.31	(16.9)
4 G 11.4 – 0.1	11.4	0.16	(15.2)	27 MSH 14–57	316.3	0.11	(7.7)
5 G 12.0 – 0.1	12.0	0.15	(19.1)	28 RCW 89	320.4	0.12	4.2
6 G 15.9 + 0.2	15.9	0.24	(16.5)	29 Kes 24	322.3	0.19	> 20.0
7 MSH 18–18	18.9	0.17	9.5	30 MSH 15–56	326.3	0.14	(2.4)
8 MSH 18–113	21.8	0.17	6.3	31 G 330.2 + 1.0	330.2	0.12	(7.8)
9 W 41	23.3	0.17	(5.0)	32 MSH 16–51	332.4	0.19	(8.2)
10 G 23.6 + 0.3	23.6	0.19	(11.9)	33 RCW 103	332.4	0.36	3.3
11 Kes 73	27.4	0.19	(25.7)	34 CTB 33	337.0	0.42	(11.3)
12 G 33.6 + 0.1	33,6	0.24	(10.8)	35 G 337.2 – 0.7	337.2	0.18	(13.3)
13 W 44	34.6	0.40	(3.1)	36 Kes 40	337.3	0.14	(6.2)
14 G 35.6 – 0.4	35.6	0.25	(8.1)	37 Kes 41	337.8	0.19	(10.0)
15 3C 396	39.2	0.58	> 11.3	38 G 338.3 – 0.1	338.3	0.13	(13.7)
16 W 51	49.2	0.29	4.1	39 G 338.5 + 0.1	338.5	0.22	(8.3)
17 CTB 87	74.9	0.30	> 12	40 G 340.4 + 0.4	340.4	0.18	(12.1)
18 Dr 4	78.1	0.11	(1.6)	41 G 340.6 + 0.3	340.6	0.27	(14.7)
19 IC 443	189.1	0.13	2.0	42 MSH 16–48	341.9	0.15	(14.0)
20 MSH 11–61A	290.1	0.53	(5.0)	43 G 346.6 – 0.2	346.6	0.19	(11.7)
21 MSH 11–62	291.0	0.25	(9.9)	44 G 350.1 – 0.1	350.1	0.42	(15.4)
22 G 298.5 – 0.3	298.5	0.50	(16.1)	45 G 351.2 + 0.1	351.2	0.19	(16.2)
23 G 299.0 + 0.2	299.0	0.10	(10.6)	46 G 352.7 – 0.1	352.7	0.18	(15.9)

* After Milne (1979).

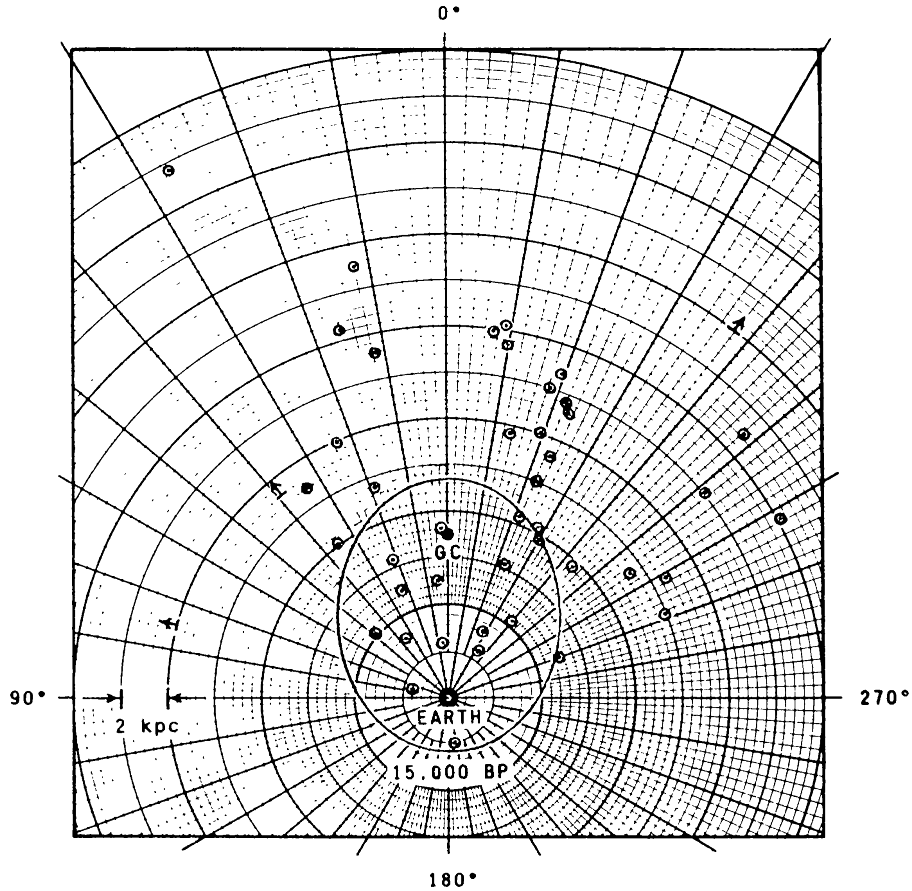


Fig. 14. The 15000 Year BP Superwave Event Horizon compared with the approximate locations of 46 medium surface brightness supernova remnants ($0.1 < \Sigma < 1.0$ f.u./$(')^2$).

As for the remaining SNRs of this 16 remnant subsample, a definite conclusion cannot be reached since their geocentric distances are not accurately known. However, as may be seen in Figure 10, there is a relative absence of high surface brightness SNRs closer than 7 kpc in directions that lie within $\pm 60°$ of the GC, whereas in the supplementary range $60° - 300°$, three remnants are found, all relatively closely aligned with the proposed event horizons. The absence of bright SNRs in the interior portion of this ellipsoidal region is consistent with there being a relative lull in Galactic superwave activity from about 10,000 years BP to the present, a period which is found to be relatively free of major climatic excursions and to correlate with low ^{10}Be concentrations in the polar ice record. There is evidence of two possible events around 6000 BP and 393 AD (LaViolette, 1983a; Ch. 6); however, these would have been relatively minor episodes.

For comparison to the 16 SNR subsample, 46 SNRs from Milne's sample having lower surface brightnesses in the range $0.1 < \Sigma < 1$ (see Table III) have been plotted in Figure 14. Distance error bars would probably extend from at least $+d$ to $-d/2$,

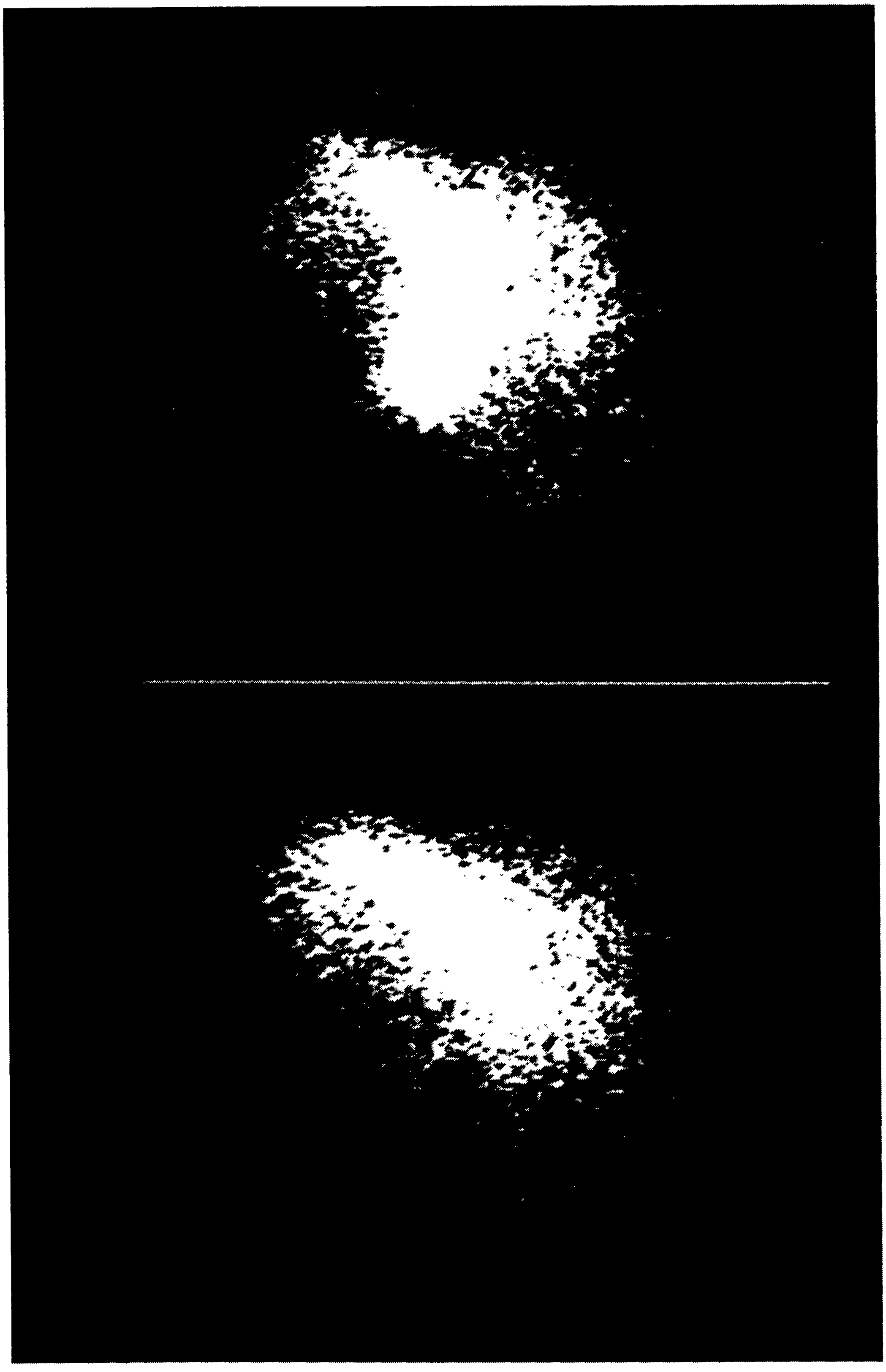


Fig. 15. An X-ray image of the Crab Nebula exposed at pulsar maximum (upper frame) and minimum (lower frame). (Photo courtesy of F. R. Harnden)

but these have been omitted for diagrammatic clarity. Although there is some degree of clustering among the remnant positions, there is no indication of a void being present within the boundary of the 12500 year BP event horizon. In fact, about 30% of the SNRs in this subsample lie within this boundary. This differs considerably from the high surface brightness subsample, and is consistent with the suggestion that this portion of the Galaxy has a much lower cosmic ray density than that existing in the vicinity of the superwave event horizons.

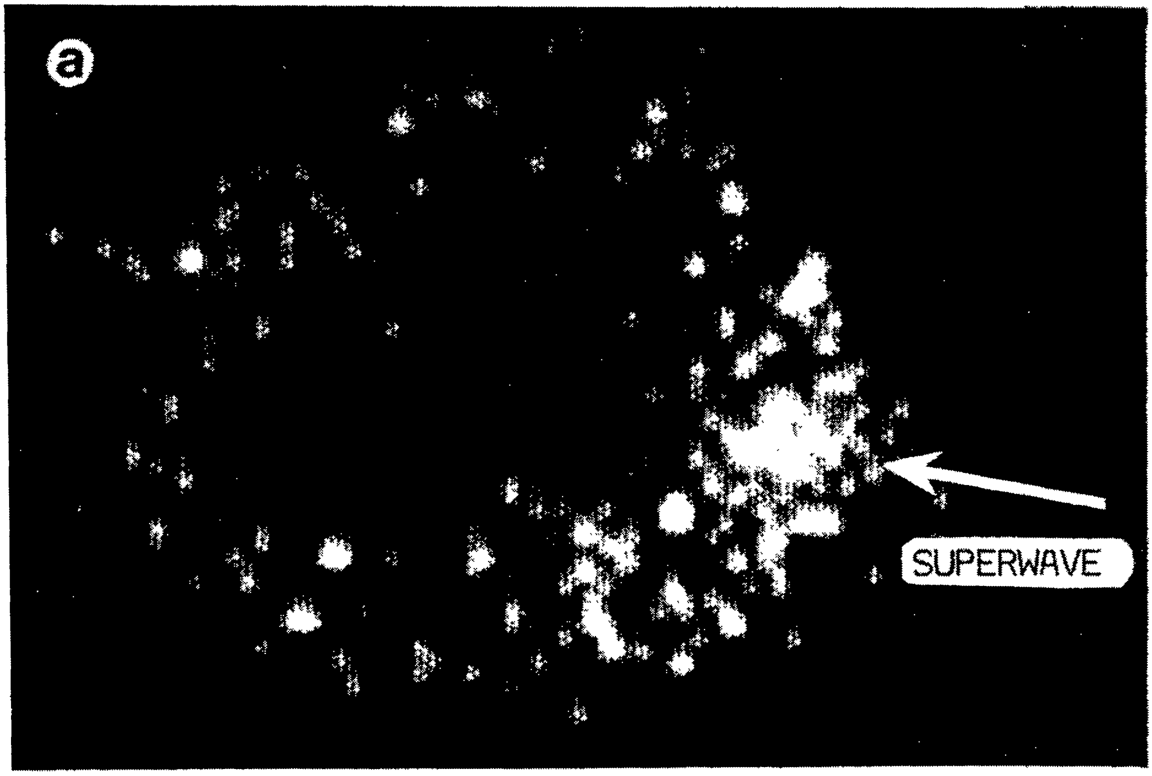
d) *The Crab Nebula and Cassiopeia A*

The Crab Nebula and Cassiopeia A are of particular interest, not only because they are the most luminous SNRs in the Galaxy, but also because they require a *continuous* input of relativistic particles in order to account for their strong X-ray emission and, in the case of the Crab, γ-ray emission. Let us begin by considering the Crab Nebula.

The Crab pulsar has been conventionally regarded to be the power source supplying the relativistic particles to the Crab. However, this hypothesis encounters several difficulties. First of all, the pulsar's synchrotron spectrum is significantly different from that of the Crab Nebula; see Erickson *et al.* (1972). Second, the pulsar is not centered on the nebula's X-ray emission region, as may be seen in Figure 15 (Harnden, 1983). Since cosmic rays must be continuously injected to keep this broad X-ray emission region illuminated, the proximity of this emission region to the injection source is of critical importance. Thus the pulsar's off-center location raises questions as to whether it could be the sole source of the illuminating cosmic rays. A third difficulty involves the short synchrotron lifetimes of the X-ray radiating cosmic ray electrons, relative to the time required for them to make the journey from the pulsar. Even if the cosmic rays were to travel rectilinearly from the pulsar, which is unlikely, it would take on the order of 1 year for these particles to travel to the boundaries of the X-ray emitting region. This may be compared to the synchrotron lifetimes for the X-ray emitting particles which are as short as a few months.

The Crab's X-ray emission may be accounted for in a less problematic way if it is assumed that cosmic rays are being continuously injected into the remnant from a *diffuse* external source, rather than from an internal point source. Because the remnant has a relatively low kinetic energy, particles accelerated at the remnant's outer boundary would be inadequate as a cosmic ray power source. A Galactic superwave, on the other hand, could supply the required diffuse particle flux. As was pointed out under (c) of this section, a volley of superwave electrons should presently be impacting on the side of the remnant that faces the Earth and GC. Given that the Crab has a luminosity of $\sim 6 \times 10^{37}$ ergs s^{-1} at X-ray and γ-ray wavelengths and that this radiation comes from a region that is approximately 0.75 by 1.5 l.y. in size ($\sim 10^{36}$ cm^2), the radiated energy flux is estimated to be about 60 ergs s^{-1} cm^{-2}, which is comparable to the particle energy flux carried by the proposed superwave.

In the case of the Cas A remnant, it is not possible to attribute the emission to a pulsar since no such compact object is found. A continuous injection of cosmic ray


a
SUPERWAVE

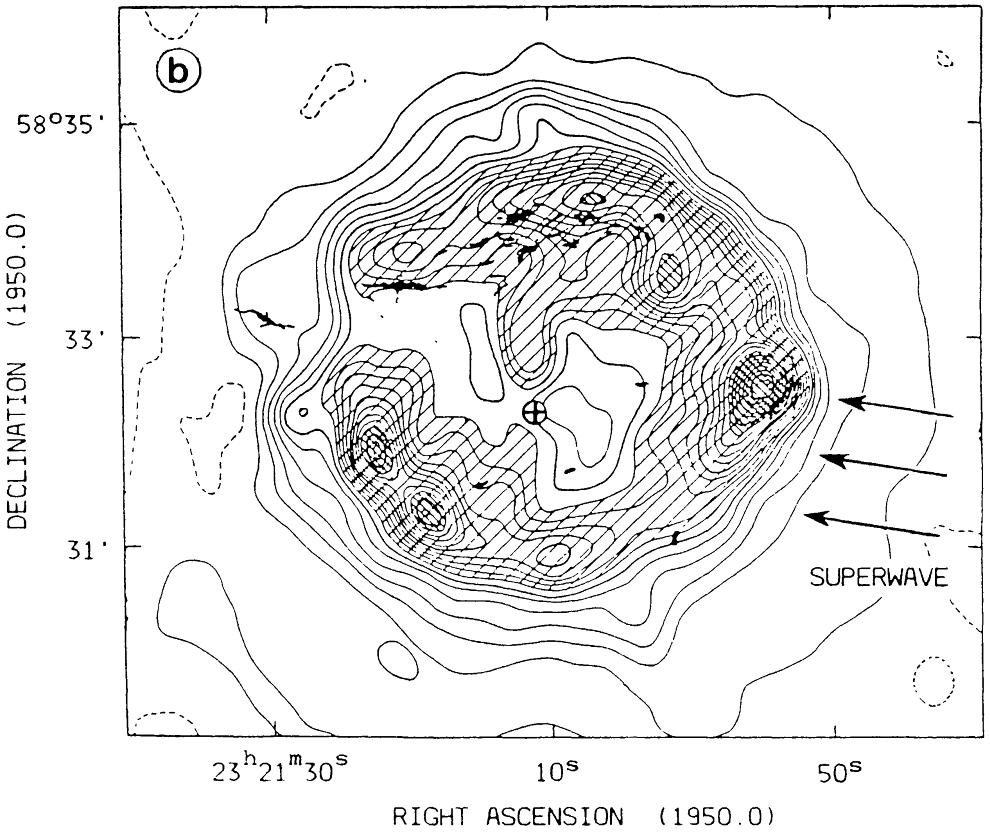

b
58°35'
33'
31'
DECLINATION (1950.0)
SUPERWAVE
23^h21^m30^s
10^s
50^s
RIGHT ASCENSION (1950.0)

Fig. 16a–b.

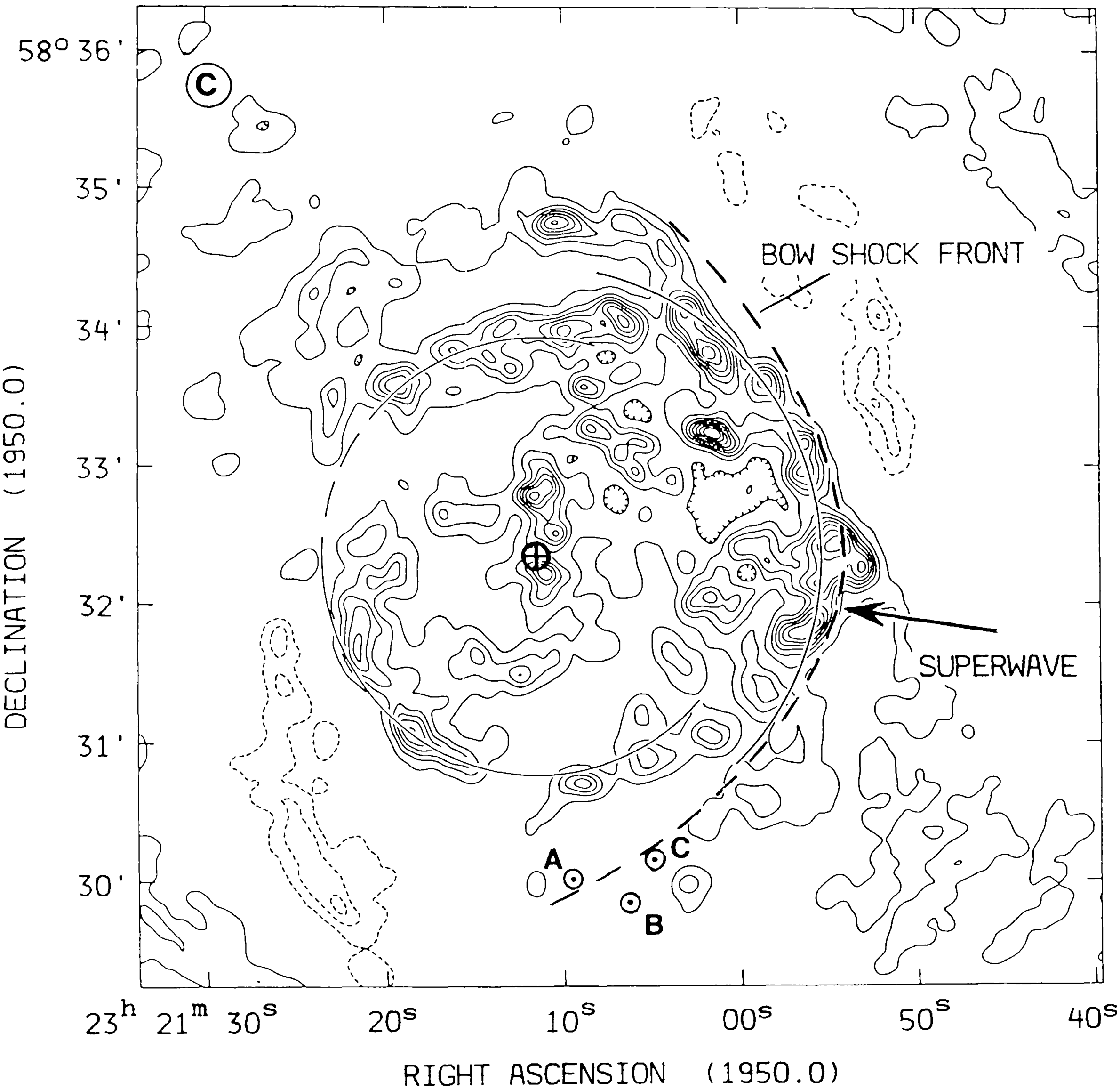


Fig. 16c.

Fig. 16a–c. (a) Distribution of the high energy X-ray flux (normalized to total X-ray flux) for the Cassiopeia A remnant (photo courtesy of S. Murray, Smithsonian Astrophysical Observatory). (b) Radio contour map of Cassiopeia A (1410 MHz) showing also the principal optical filaments as dark patches (adapted from Ryle, Elsmore, and Neville, 1965). The central cross indicates the remnant's dynamical center of expansion. (c) High resolution radio contour map of Cas A (2695 MHz) with arcs (solid lines) drawn to illustrate the asymmetry of the remnant (adapted from Dickel and Greisen, 1979). The central cross again indicates the dynamical center of expansion. The added dashed line illustrates the position of the proposed bow shock front. Arrows in all three diagrams indicate the direction of superwave impact.

electrons, however, is needed to account for the remnant's strong X-ray emission. It has been suggested that the shell itself is actively accelerating particles to relativistic velocities as it plows forward through the interstellar medium (Gull, 1973; Scott and Chevalier, 1975; Shirkey, 1978). However, there are several reasons for believing that Cas A, like the Crab, is being externally impacted and illuminated by a relativistic volley of Galactic cosmic ray electrons; see LaViolette (1983a; pp. 335–349).

The strongest piece of evidence has to do with the asymmetry of the remnant's emission distribution. As may be seen in Figure 10, our line of sight to Cas A is such that if the remnant were to intercept a superwave volley, the strongest emission should be observed on the side of the remnant facing low galactic longitudes. This is in fact found to be the case. As is seen in Figure 16a (Murray *et al.*, 1979), the upwind, western side of the remnant is particularly luminous in the hard X-ray region (2.4–3.6 keV). The arrow added to the diagram indicates the direction from which the superwave would be approaching. This same asymmetry is visible in the 1410 MHz radio map shown in Figure 16b (Ryle *et al.*, 1965). Again, the western side of the remnant displays one of the most intensely radiating regions of the entire remnant shell. The fact that the radio emission is minimal on the remnant's eastern 'leeward' side is also consistent with the superwave scenario. In fact, a line drawn from the western emission peak through the eastern gap (radio minimum) is found to lie parallel to the Galactic equator. Also it is worth noting that filamentary material is conspicuously absent from the western side of the remnant. So the western radio peak and coincident hard X-ray peak cannot be ascribed to the asymmetric distribution of such remnant material.

The high resolution 2695 MHz map published by Dickel and Greisen (1979) is particularly revealing; see Figure 16c. They note that the centroid of the radio emitting shell is displaced westward from the remnant's center of expansion (marked by the +). To illustrate this asymmetry they have drawn two circular arcs of radius 1.3 pc and 1.7 pc centered on the point of expansion. They suggest that this difference arose either as a result of an anisotropy in the initial supernova explosion or as a result of an inhomogeneity in the encountered interstellar medium. For this latter hypothesis they require that the ambient medium be three to four times more dense on the remnant's eastern side. However, this asymmetry may quite reasonably be explained if it is assumed that the western emission peak is actually a *bow-shock front* formed around the remnant by the impacting superwave. The presence of this front would also account for the elliptical shape of the X-ray and radio images displayed in Figures 16a and 16b. The approximate contour of this shock front has been outlined by the dashed line added in Figure 16c.

The 'radio knots' which appear in this high resolution map are observed to have random velocities averaging 2600 km s^{-1} in the tangential direction and 3000 km s^{-1} in the radial direction. Dickel and Greisen (1979) do not offer an explanation for the knots but on the basis of their observations they conclude that these features most probably do not participate in the mean nebular motion. The superwave model offers one possible interpretation of this phenomenon: namely, the radio knots would be emission features embedded in the surface of the bow shock front. The impacting superwave would then serve as the energy source that both diffusely excites the knots and causes their high velocity displacement.

The three circles labeled A, B, and C to the south of the remnant mark the locations of three quasi-stationary luminous flocculi. These features are unusual in that they have a mean outward velocity of only ~ 150 km s^{-1}, as compared with

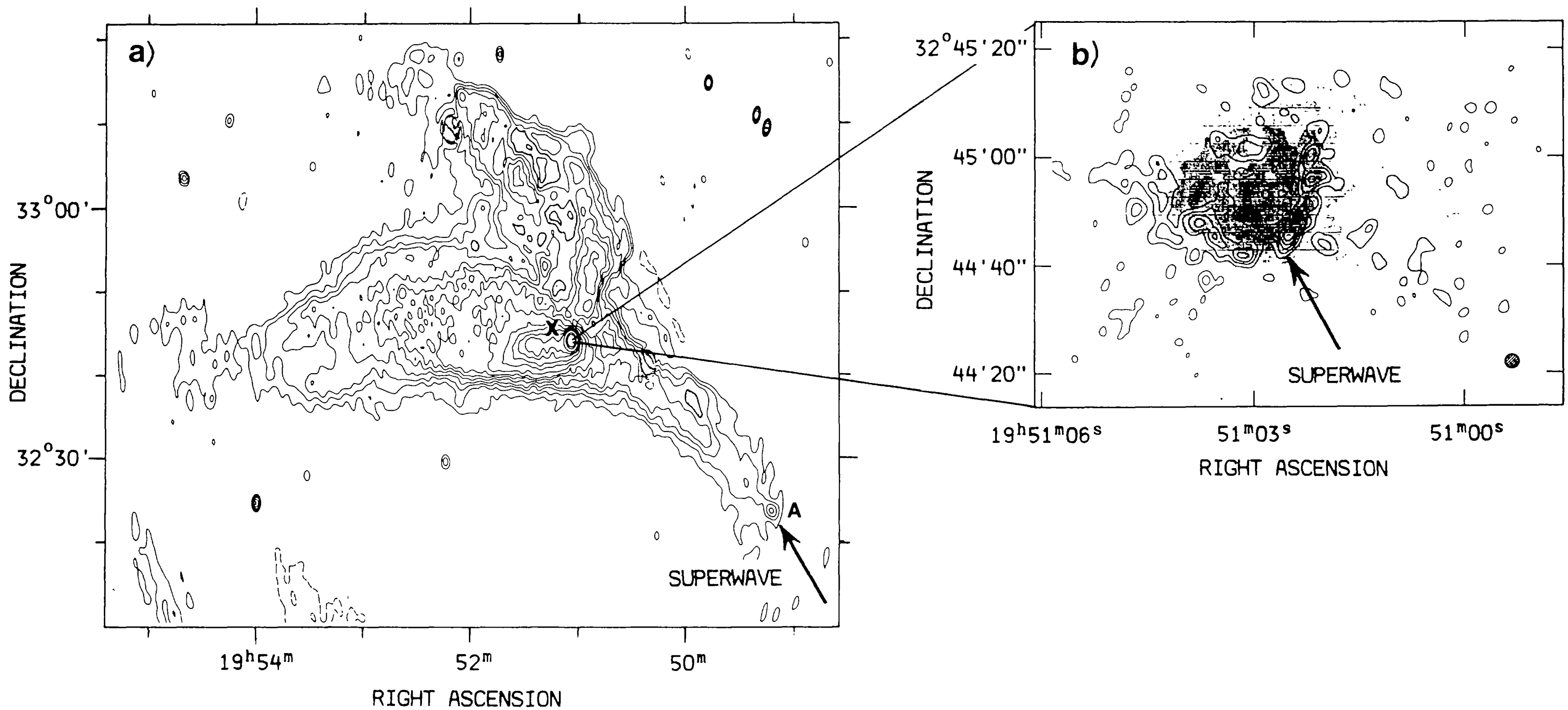


Fig. 17. a) A contour map of the 49 cm radio brightness distribution of CTB 80 (after Angerhofer *et al.*, 1981). Points A and X mark the locations of compact radio sources. b) Detailed radio map (at 6 cm) of the central compact radio source (after Strom *et al.*, 1984). The shaded region indicates total radio intensity. Superimposed contours indicate polarized intensity. Arrows added in both diagrams indicate the superwave's direction of approach.

4100–8500 km s^{-1} which characterizes most of the optically visible condensed material. Their behavior may be explained in a natural manner if they are understood to be gaseous interstellar material external to the remnant which happens to be drifting through the vicinity of the bow shock front. The elevated cosmic ray energy densities existing behind this front would serve as their source of excitation.

e) *The Extended Radio Source CTB 80*

CTB 80 is an unusual galactic radio emission source which happens to lie in the vicinity of the 12500/15000 year BP superwave event horizons at ($l \sim 69°$, $d \sim 2–5$ kpc); see Figure 10. This object shares several features in common with supernova remnants: its radio spectrum is nonthermal; it exhibits a high degree of linear polarization; its emission comes from an extended region ($\sim 1° \times 1°$ of arc); and it happens to be located at a low galactic latitude ($b = +2.7°$). However, it has a very unusual shape, quite different from the circular form that characterizes most SNRs. It is argued here that this extended emission source is not a supernova remnant, but rather a turbulent region created in the wake of two stars being impacted by a galactic superwave.

The unusual shape of CTB 80 may be seen in the 49 cm radio brightness contour map shown in Figure 17a (after Angerhofer *et al.*, 1981). The emission distribution appears to consist of two extended components. One component, whose shape resembles that of a smoke stack plume, extends to the northeast from a compact radio source marked as A. In fact, the northwest edge of this plume extends away from A in a remarkable straight line. Butting up against this emission region, and jutting out to the east, is a second extended radio source. This appears to be spearheaded by a second compact radio source marked as X. This compact source has a very flat radio spectrum and is found to be a very strong X-ray emitter (Becker *et al.*, 1982).

As may be seen in Figure 10, CTB 80 is positioned such that the superwave volley would be propagating almost entirely perpendicular to our line of sight. The added arrow projecting toward source A in Figure 17a indicates the direction from which the superwave would be impacting. As may be seen, this is essentially the same direction in which the radio emission plume is seen to extend from source A. Radio source A could be interpreted as a heavily obscured star which happens to be presenting a barrier to the superwave. Thus the trailing emission plume could be interpreted as a region of turbulent interstellar magnetic field formed in a stationary shocked region in the wake of the star. In this turbulent region superwave electrons would become trapped into spiral orbits and as a result their synchrotron emission would become visible to earth-based observers. For a distance to CTB 80 of about 13000 l.y. this wake would be extending out a distance of 300 light years. However, since this wake is oriented almost perpendicular to the line of sight, the relativistic particle wind emanating from the GC direction would appear to transit this source at superluminal speed, appearing to complete the journey from head to tail in less than 100 years.

The compact radio source marked X could be a second star that is also heavily obscured. The emission region surrounding this source could in a similar fashion be a wake-like turbulent region which is effective in trapping superwave electrons. The reason why this emission region does not similarly extend to the northeast could be due to the fact that source X is so close to A's wake that the two turbulent regions interact with one another, causing X's tail to jut out eastward. The observed interaction pattern is suggestive of the kind of flow interaction effects that are often seen in wind tunnel experiments.

Further evidence favoring the superwave scenario is found when source X is studied in greater detail. Consider, for example, Figure 17b (after Strom *et al.*, 1984) which displays a high resolution map of source X made at 6 cm. The shaded regions denote total intensity contours while the superimposed contour lines denote the intensity of polarized radio emission. Again the arrow (added to the diagram) indicates the direction from which the superwave electrons would be impacting. Note that the polarization intensity contours form what appears to be a bow shock front. Not only is the axis of this shock front oriented in the proper fashion relative to the superwave's direction of impact, but also as would be expected, the peak intensity contours, for both polarized emission and for total (polarized and unpolarized) emission are situated on the brunt of the shock front facing the proposed superwave volley. This same energized region most likely correlates with the unresolved X-ray emission peak reported by Becker *et al.* (1982). The dimensions of the unresolved X-ray source are of the order of < 0.1 light years, suggesting that it is emitted from a region having stellar dimensions.

Angerhofer *et al.* (1980) interpret radio source X as an expanding supernova remnant shell. However, the optical nebulosity which coincides with this source is found to exhibit radial velocities only of the order of ± 35 km s^{-1}, about two orders of magnitude lower than expansion velocities typically observed for SNRs. Also as Strom *et al.* (1984) point out, the gas in this region only has a total mass of $4 \times 10^{-3}\ M_{\odot}$, much less than the amount of material usually expelled in a supernova explosion. Finally, they note that the total particle energy in this compact source is $< 10^{46}$ ergs, more in line with a nova, rather than a supernova. It is interesting to note that on the basis of the radio data for source X, Strom *et al.* estimate a minimum particle energy density of $\sim 2 \times 10^{-9}$ ergs cm^{-3}, which is comparable to the energy density modeled for the proposed superwave.

Strom *et al.* (1984) have also interpreted the radio emission ridge on the southwestern side of source X as being a bow shock front. However, they suggest that this front is formed as a result of the fast motion of a compact object through the interstellar medium. But such an interpretation must address several questions: namely, why is it that the motion of source X would happen to parallel the direction of the radio plume trailing behind source A? Note that for a geocentric distance of 13 thousand light years these two compact sources are separated by about 150 light years. So with such great distances between them, it is difficult to understand why both of these objects would happen to be moving through the interstellar medium in the same direction. Moreover why would these sources happen to be travelling parallel to the galactic plane toward the GC?

Another problem is that the nebulosity surrounding source X shows no indication of any appreciable radial motion with respect to the observer. Yet Strom *et al.* estimate that expansion speeds of 200–300 km s^{-1} are needed in order for particles to be accelerated to sufficient energies to power the observed nonthermal radio emission. Moreover, if source X is interpreted to be a 580 year old SNR, as suggested by Strom *et al.* (1980), then still higher velocities of the order of 100000 km s^{-1} (0.3c) are required in order to account for the large physical size of CTB 80. This is quite inconsistent with the low gas velocities ($\pm$ 35 km s^{-1}) presently observed in source X.

All of the difficulties mentioned above could be avoided if it is simply assumed that the two compact sources are two ordinary stars which happen to be encountering a galactic superwave. If this is indeed the case, then detailed study of radio source A should reveal the presence of a bow shock front similar to that surrounding source X. Also when observed over extended period of time, CTB 80 should be seen to exhibit variations in its radio emission intensity. In fact, high resolution maps could reveal evidence of intensity fronts propagating from southwest to northeast at superluminal speeds. Similar fronts might be observed in the Cas A remnant.

6. The 30 Million Year Cycle of Terrestrial Disturbance

The superwave hypothesis predicts, among other things, that Galactic superwaves would be the primary factor precipitating animal extinctions due to the climatic change which these cosmic dust propelling agents would bring about (LaViolette, 1983a; pp. 3, 236–243). In the year following publication of this prediction, Raup and Sepkoski (1984) announced their discovery of a 26 million year periodicity in the temporal distribution of marine extinction episodes, a signature which appeared to indicate that some sort of extraterrestrial forcing mechanism must be responsible. Rampino and Stothers (1984), reanalyzed their data and found that the mean interval between extinctions is closer to 30 ± 1 million years. They, and independently Schwartz and James (1984), pointed out that this period approximates the time required for the Sun to oscillate vertically about the plane of the Galaxy, which is 33 ± 3 million years. Based on this similarity, they concluded that the extraterrestrial agent precipitating extinctions is very likely of interstellar or Galactic origin. Although, Davis *et al.* (1984) have suggested that these extinction episodes may be produced by cometary bombardments induced by a celestial mass, or ‘death star’, orbiting the Sun.

Of these two competing interpretations, the Galactic plane crossing scenario is more compatible with the superwave hypothesis. However, the causal connection between the solar z-axis oscillation and extinction episodes is construed differently from the version proposed by Rampino and Stothers. They reason that the Solar System has a greater chance of encountering interstellar clouds of gas and dust when it is passing through the Galactic plane and that such encounters might dislodge large numbers of cometary masses from the circumsolar cometary cloud, causing enhanced terrestrial bombardment. As an alternative mechanism, they propose that during cloud encounters hydrogen gas might enter the Solar System in considerable quantities and cause climatic change either by polluting the Earth's upper atmosphere or by raising the Sun's luminosity through gas accretion onto the Sun's surface.

On the other hand, according to the Galactic superwave hypothesis, extinctions occur preferably at times when the Sun is crossing the Galactic plane because it is at such times when superwave episodes become most severe. Why Galactic plane crossings should aggravate the effects of a superwave episode may be understood as follows.

The amount of cometary material in the Solar System's heliopause vaporization zone is the key factor determining the severity with which a superwave affects the Earth. In the absence of a supply of such material to vaporize and propel into the Solar System, Galactic superwaves become relatively harmless. It is only when the vaporization zone is well stocked with cometary material that superwaves are able to precipitate climatic change, and in so doing trigger extinction episodes. The vaporization zone has its greatest chance of becoming stocked with such material during times when the Sun is passing through the Galactic plane. During such times there is a high probability that the Sun would encounter an interstellar cloud or supernova remnant shell and in so doing become surrounded with cometary material of interstellar origin. Thus during plane crossings the Earth would run a greater risk of having its climate adversely affected. Once the Sun left the boundaries of the cloud, the number of cometary bodies passing through the vaporization zone would decrease and any lingering bodies would eventually become vaporized away by successive superwave events. Thus cosmic dust incursions and perturbations to the Earth's climate and biosphere would correspondingly diminish.

According to the above scenario, the Earth's present series of glacial cycles would be due to the fact that the Solar System has either recently encountered an interstellar cloud, or is presently in the midst of one. In fact, there is considerable evidence that we are immersed within the perimeter of one such cloud, the bulk of which lies on the side of the Solar System facing the Galactic Center. For example, evidence discussed by Bruhweiler and Kondo (1982) indicates that the Sun is surrounded by an interstellar cloud having a neutral hydrogen density of $n_{\mathrm{HI}} = 0.1\ \mathrm{cm}^{-3}$, the cloud's outer boundary lying within 6–10 l.y. of the Sun. Finding that the neutral hydrogen density is lower in the Galactic anticenter direction, they conclude that the Sun must lie near the cloud's outer edge. Based on local interstellar polarization measurements, Tinbergen (1982) deduces that a local patch of dust having a visual extinction of ~ 0.01 magnitudes is located between 0–65 l.y. from the Sun in the direction of the Galactic Center. He estimates that this cloud extends from $l = 350°$ to 20° and $b = -40°$ to $-5°$. Frisch and York (1983) have determined that the main part of the local cloud extends from $l = 270°$ to 5° and $b = -60°$ to $+45°$. They estimate the cloud's neutral hydrogen density to be 0.07 cm^{-3} and find that the density reaches a peak about 6–15 l.y. from the Sun in the direction of the Galactic Center. Vidal-Madjar *et al.* (1978) present evidence of a local interstellar cloudlet positioned at ($l \sim 353°$, $b \sim +20°$) and covering about 40° of sky. Although their results indicate that the cloudlet could be anywhere from 0.03–6 l.y. away, they tentatively place its most probable position at the relatively close distance of ~ 0.1 l.y. (10^4 AU), virtually inside of the Oort Cloud, the spherical reservoir of comets hypothesized to surround the Solar System. Crutcher *et al.* (1982) also discuss evidence of several other discrete cloudlets that lie in the immediate solar vicinity.

It is quite probable that the interstellar cloud and cloudlets identified by these various investigators are debris associated with the nearby North Polar Spur supernova remnant, which lies in the constellation of Lupus in the direction ($l \sim 330$, $b \sim +18$). Of all the known supernova remnants, this one lies closest to our Solar System. Although the explosion center of this few million year old remnant is estimated to lie at a distance of about 420 ± 240 light years from the Solar System, it occupies quite a large volume of space, as it is found to cover about 115° of the southern hemisphere sky (Spoelstra, 1972; Berkhuijsen, 1973; Heiles *et al.*, 1980). The perimeter of the remnant shell may actually lie quite close to the Solar System. In fact, Frisch (1981) presents evidence suggesting that the remnant's outer boundary has expanded to the point that it presently *encompasses* the Solar System. Consequently it is possible that the Solar System has accumulated a considerable mass of frozen debris as a result of the Sun's recent passage through this shell.

There is considerable evidence that a large amount of dust indeed resides in the *immediate* vicinity of the Solar System. Observations made with the Infrared Astronomy Satellite indicate the presence of a faint wispy network of clouds that cover the entire infrared sky, the so called 'infrared cirrus' (Low, 1984; Hauser *et al.*, 1984). The temperature of this material suggests that it lies within the circumsolar cometary cloud. This dust is very likely part of a continuous size distribution of frozen cometary material residing within the circumsolar cloud. It is quite possible that the Solar System is presently situated in a region littered with frozen cosmic debris the bulk of which is of a size that is not easily detectable at optical or infrared wavelengths.

There is evidence that the Sun may have captured cometary material from this cloud within the past several million years. For example, it is found that the orientations of the orbital axes of the long-period comets are not distributed in a uniform manner over the celestial sphere, but rather show a preference toward the direction of solar drift (Bogart and Noerdlinger, 1982; Yabushita, 1979; Oja, 1975). Clube and Napier (1984) estimate that the center of the perihelion distribution lies within $\sim 5°-10°$ of the solar apex. Since the apex moves through 360° within 200 Myr due to Galactic rotation, it may be concluded that the observed long-period comets have been in their present orbits for no more than 3–6 Myr. Given the comets' orbital alignments, it is quite possible that these bodies originally resided in this cloud and became captured into their current eccentric orbits as a result of the Sun's passage through the cloud.

Such interstellar cometary material could be the ultimate source of the dust which seems to have been vaporized and propelled into our Solar System during the Last Ice Age and could be the reason why the Earth has been experiencing a series of glaciations during the past 3–5 million years.

7. Conclusions

The following conclusions are proposed:

1) Periodically the center of our Galaxy enters an explosive phase during which it generates an outburst of cosmic rays in the form of highly relativistic electrons and positrons with total particle energies of 10^{57} ergs or more.

2) These outbursts last anywhere from several hundred to several thousand years, major events recurring about once every 5000–15000 years.

3) A given superwave cosmic ray volley travels radially outward through the Galaxy at very close to the speed of light ($\gamma \sim 3000$), streaming along radially disposed magnetic field lines and experiences only moderate attenuation by the interstellar medium.

4) Upon impacting the solar vicinity, a shock front forms around the heliopause sheath and superwave electrons become trapped and cometary ice debris in that region becomes vaporized. Cosmic-ray-driven hydromagnetic shock fronts propel the resulting cloud of nebular dust and gas into the Solar System causing changes in insolation levels and increasing solar flare activity. These effects in turn perturb the Earth's climate, precipitate mass extinctions, and cause geomagnetic reversals.

5) About every 30 million years, as the Sun passes through the Galactic plane, the Solar System encounters interstellar clouds with increasing frequency and during such times the solar and terrestrial disturbances which a Galactic superwave initiates become particularly severe. The present series of ice ages may be attributed to our present immersion within such a cloud.

6) A particularly strong Galactic superwave passed through the solar vicinity toward the end of the Last Ice Age.

In conclusion, it is argued that explosive events generated at the center of the Galaxy have a major impact on the Solar System environment. It is proposed that the present relatively quiescent state of the local interstellar environment is misleading; that our 'calm sea' of space is from time to time interrupted by a 'raging storm', as volleys of cosmic ray electrons pass by on their journey through the Galaxy. It is concluded that as recently as 10^4 years ago an event of this sort was responsible for triggering abrupt changes in the Earth's climate which may in turn have been the cause of the megafaunal extinction episode peaking between 13000 and 11000 years BP.

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* The diagrams for Figures 1 and 2 of this paper were mistakenly interchanged in printing. See erratum in *Meteoritics* **20**(4), 803.

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