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EVIDENCE FOR THE STOCHASTIC ACCELERATION OF COSMIC RAYS IN SUPERNOVA REMNANTS

T. W. HARTQUIST[1]
University College London

AND

G. E. MORFILL
Max-Planck-Institut für Kernphysik, Heidelberg
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ABSTRACT

Molecular observations can be used to place strong constraints on the point of origin and the spectrum of cosmic rays in the vicinity of *o* Per in the Per OB2 association. We argue that stochastic acceleration by the second-order Fermi effect in the nearly fully ionized supernova remnant associated with the region will produce cosmic rays of precisely the correct characteristics.

Subject headings: cosmic rays: general — nebulae: supernova remnants — particle acceleration

I. INTRODUCTION

A supernova can generate cosmic rays in several ways including stochastic acceleration due to the second-order Fermi effect occurring in the ionized material of the supernova remnant (Chevalier, Oegerle, and Scott 1978; Schwartz and Skilling 1978; Morfill and Scholer 1979). We interpret observational evidence to imply that stochastic acceleration of low-energy cosmic rays is occurring in the vicinity of the Per OB2 association. We first present summaries of the observations of the distribution of interstellar gas in the direction of the association and of the ionization rates derived for several lines of sight in the vicinity. In § III, we discuss possible acceleration mechanisms for the cosmic rays, and we show that the production of cosmic rays by second-order Fermi acceleration and subsequent losses through ionization explains the observations. Section IV summarizes and discusses our conclusions.

II. SUMMARY OF OBSERVATIONS

Sancisi (1974) and Snow (1976) have discussed in detail the kinematics of the Per OB2 association, first identified by Blaauw (1952). Most of the stars appear to lie on the far side of a shell of gas expanding away from the Sun with a speed of roughly 5 km s^{-1} relative to a central point where a supernova probably occurred some 10^6 years ago. The radius of the SNR in the direction of the dense shell is $\sim 6 \times 10^{19}$ cm. A shell of much lower density is approaching the Sun with a speed of 50 km s^{-1} relative to the site of the supernova progenitor. Apparently, the density in the vicinity of Per OB2 decreases in the Sun's direction. While the presence of the high-velocity material supports the hypothesis that the association is related to an old supernova remnant, we will not refer to the lower density shell again, as its velocity differs so greatly from that of the denser shell that the two are easily distinguished observationally. The gas density inside the SNR is ~ 10 cm^{-3}.

The ultraviolet spectrometer on the *Copernicus* satellite has been used to determine the abundances of a number of molecular species along the lines of sight to the stars ξ Per (Spitzer *et al.* 1973), and *o* Per (Snow 1976), and ζ Per (Snow 1977). Together with radio observations and by applying ion-molecule reaction theory, detailed models of the ambient physical conditions in the dense shell have been constructed (Black, Hartquist, and Dalgarno 1978, 1982; Hartquist, Doyle, and Dalgarno 1978). The results are summarized in Table 1.

The stars ξ Per and ζ Per appear to lie well beyond the expanding shell. However, some confusion concerning the location of *o* Per relative to the shell exists (Snow 1976). Below, we examine the consequence of observations of several molecules in its direction.

CO measurements.—The detection of more CO in radio emission (Solomon 1975) than in UV absorption indicates that the star *o* Per is located inside the shell, probably on the near side of a dense molecular cloud (Snow 1976).

OH measurements.—The formation rate of OH in diffuse clouds is proportional to the H^+ concentration

TABLE 1
IONIZATION RATES

Direction	Pressure (cm^{-3} K)	Column Density (cm^{-2})	Ionization Rate (s^{-1})
o Per	3.5×10^4	1.6×10^{21}	2.5×10^{-16}
ζ Per	1.2×10^4	1.6×10^{21}	2.2×10^{-17}
ξ Per	2.2×10^4	1.5×10^{21}	6.0×10^{-18}

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(cf. Dalgarno and Black 1976), which, in turn, is produced by cosmic ray ionization. In the direction of o Per, the UV absorption measurements of OH (Snow 1975) and the radio measurement of OH emission (Sancisi *et al.* 1974) imply that all of the OH is on the near side of the star, if the f-value of Ray and Kelly (1975) is adopted for the UV transition.

This implies that the cosmic rays responsible for the enhanced ionization must originate in the SNR and can, in addition, not propagate further into the dense shell than the star, o Per. Significant ionization losses must, therefore, occur in a column density of $\lesssim 1.6 \times 10^{21}$ cm^{-2}, i.e., the ionizing cosmic rays must have energies less than a few MeV (Black, Hartquist, and Dalgarno 1978, 1982).

HD measurements.—The production rate of HD in diffuse clouds is also proportional to the H^+ density (Dalgarno, Black, and Weisheit 1973). Measurements have shown a very high HD abundance in the direction of o Per. The $|D|/|H|$ ratios in the "Copernicus clouds" in the directions toward ζ Oph, ζ Per, and o Per appear to be consistent with the average value of $(1.8 \pm 0.4) \times 10^{-5}$ derived by York and Rogerson (1976) from studies of atomic hydrogen within 200 pc of the Sun (Hartquist, Black, and Dalgarno 1978), and using this value for the $|D|/|H|$ ratio and the observed HD abundance (Snow 1976), one concludes that almost all deuterium between the near edge of the shell and o Per is in HD. Hence, the cosmic rays must be energetic enough to propagate through a column of 1.6×10^{21} cm^{-2}, and their energy cannot be much less than the few MeV upper bound derived from the OH data.

The ionization rate toward o Per is at least a factor of 10 larger than the usual values; and implies a local source of cosmic rays (Hartquist, Doyle, and Dalgarno 1978). From the energy constraint (MeV particles), we conclude that the cosmic ray energy density ϵ_c is about 10^{-14} ergs cm^{-3} (compare, e.g., Field, Goldsmith, and Habing 1969).

Thus, the molecular observations particularly of OH and HD in the direction of o Per place very strong restrictions on the cosmic-ray source.

In the following section we will show that stochastic acceleration in the supernova remnant leads to a cosmic-ray spectrum having very few particles at energies exceeding a few MeV. We believe that the entire ionized region of the remnant is a source of low-energy cosmic rays. The lower ionization rates observed toward ζ Per and ξ Per result from the magnetic field entering the shell at very small angles as a consequence of the shock magnifying the component of the field perpendicular to the shell. Thus, low-energy cosmic rays suffer very large ionization losses in a very thin region at the shell's inner edge where very little material is molecular and OH cannot be formed efficiently. The density enhancement in which o Per lies should, on the other hand, concentrate magnetic field lines, and hence cosmic ray access into the shell should be more direct. Figure 1 illustrates the general properties of the large-scale field configuration which will have turbulent structure superposed upon it.

III. COSMIC RAY PRODUCTION

a) *Wave Production and Diffusion*

Low-energy cosmic-ray production by second-order Fermi acceleration in expanding supernova remnants has been discussed recently by Chevalier, Oegerle, and Scott (1978), Schwartz and Skilling (1978), and Morfill and Scholer (1979). The wave turbulence is produced, e.g., by shock accelerated particles during the phase in the remnant evolution when it is expanding with speeds greater than the Alfvén speed in the ambient interstellar medium. The waves are overtaken by the shock; during this interaction amplification takes place, and both forward and backward traveling waves are produced inside the remnant (McKenzie and Westphal 1968). The wave frequencies correspond to the resonant interaction frequencies of the cosmic rays. The wave energy can then be lost by a variety of damping processes, including acceleration of energetic test particles. During the early (super-Alfvénic) phase of the remnant expansion, the wave energy density may be quite high $\alpha \equiv \delta B/B \sim 1$, whereas afterward a gradual decay must set in, in particular when recombination becomes important (Morfill and Scholer 1979). Other processes which may modify the self-excited wave spectrum once the waves have been convected into the SNR are nonlinear Landau damping, and it is also feasible that the wave spectrum may evolve continuously into a Kolmogoroff-type spectrum (e.g., Kraichnan 1975). Some observational evidence for the latter exists (Lee and Jokipii 1976), and we shall assume that such an evolution is possible, fully aware that the processes in magnetohydrodynamics are not understood yet. The longest wavelength (and lowest frequency f_0) obtained by self-excitation at the SN shock is given by the gyroradius of the highest energy particles which are accelerated while the SN shock is still sufficiently strong. The acceleration time is (e.g., Forman and Morfill 1979)

$$t_a \approx \frac{4\kappa_r}{v_s^2}\,, \tag{1}$$

where κ_r is the spatial diffusion coefficient. For a strongly turbulent field ($\alpha \approx 1$), particle transport is described in the Bohm diffusion limit. The mean free path is approximately equal to the gyroradius, r_g; hence, the diffusion coefficient is isotropic and given by

$$\kappa_r \approx \tfrac{1}{3} r_g \beta c\,, \tag{2}$$

where βc is the particle speed. The shock speed, v_s, must be sufficiently large so that acceleration is possible. We choose $v_s = 3v_A$ and employ the Sedov solution for the blast wave evolution, i.e.,

$$v_s = \frac{2}{5}\left(\frac{2E_{SN}}{\rho}\right)^{1/5} t_R^{-3/5} \equiv 3v_A\,, \tag{3}$$

where E_{SN} is the total energy released by the SN, ρ is the ambient interstellar gas mass density, and t_R is the age of the remnant when $v_s \equiv 3v_A$. Using $v_A \sim 10^6$ cm s^{-1}, $E_{SN} \sim 10^{51}$ ergs, $n \sim 10$ cm^{-3} and putting $t_R = t_a$

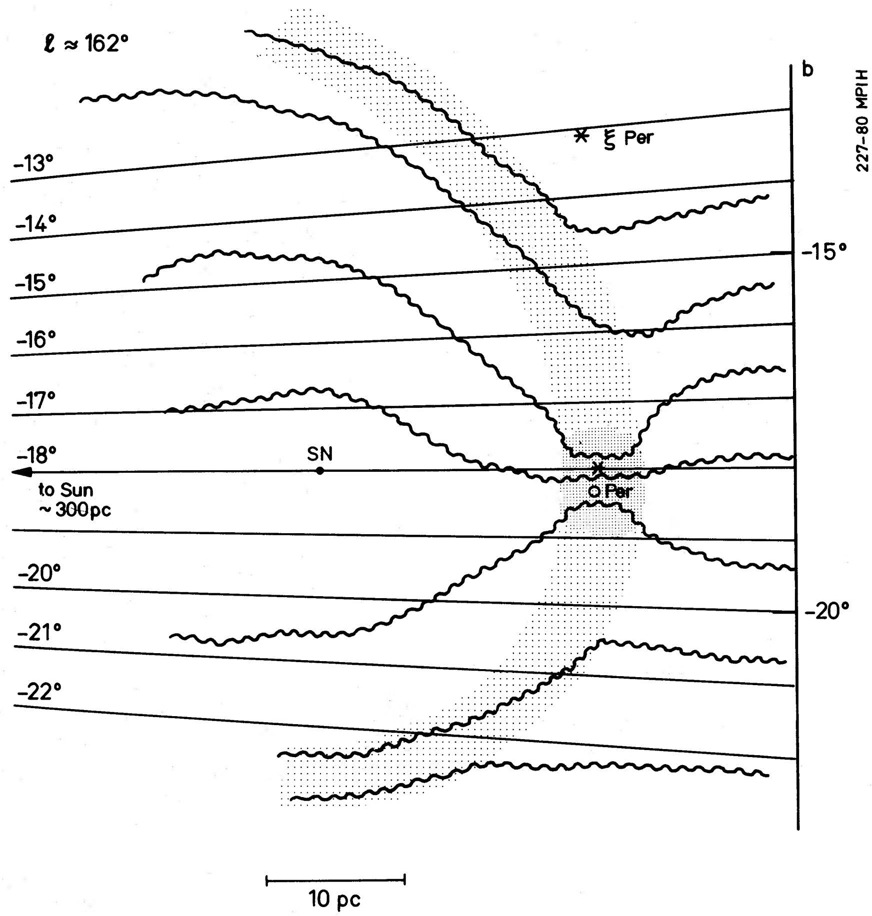

FIG. 1.—Suggested topology of the old supernova remnant near Per OB. The kinematic model was taken from Sancisi 1974; the magnetic topology is suggested as a result of the conclusions reached here.

gives (on substituting eq. [2] for κ) $r_g \sim 10^{15}$ cm and $f_0 \sim 10^{-9}$ Hz. The wave power spectrum is then fully determined by our model, $P(f) = \frac{1}{3}\alpha^2(B^2/f_0)(f/f_0)^{-5/3}$, and using quasi-linear wave-particle interaction theory (e.g., Hasselmann and Wibberenz 1968; Jokipii 1971), we obtain κ as a function of particle energy,

$$\kappa_r \approx 7 \times 10^{27}\alpha^{-2}B^{1/3}n^{-1/3}\beta^{4/3} . \tag{4}$$

The only free parameter in the model is $\alpha \equiv \delta B/B$, which allows for the possibility that old SNRs (where shock effects have long ceased and which have already reached the shell stage) should have less wave activity than young ones. Wave damping by Fermi acceleration of test particles alone should have some effect in this direction, quite apart from other possible damping processes.

b) Fermi Acceleration and Losses in the Shell

The Fermi acceleration time scale becomes, as $\beta \ll 1$ (see Morfill and Scholer 1979)

$$\frac{1}{\tau_F} \approx \frac{2\kappa_F}{\beta^4} , \tag{5a}$$

where κ_F is the energy diffusion coefficient. We may express equation (5a) in terms of κ_r (e.g., Wibberenz and Beuermann 1971) and obtain

$$\frac{1}{\tau_F} \approx \frac{v_A{}^2}{\kappa_r} , \tag{5b}$$

where v_A is the local Alfvén speed. There are two loss times of interest, the losses due to spatial diffusion and absorption in the shell

$$\tau_R = \frac{R^2}{\pi^2\kappa_r} , \tag{6}$$

and the adiabatic loss time due to the remnant expansion

$$\tau_{ad} = R/v , \tag{7}$$

where R is the remnant radius and v is the expansion speed of the shell. The ratio $\eta \equiv [(1/\tau_R) + (1/\tau_{ad})]/(1/\tau_F)$ determines the energy to which second-order Fermi acceleration in the SNR is effective. We have

$$\eta = \left(\frac{\pi^2\kappa_r}{R^2} + \frac{v}{R}\right) \frac{v_A{}^2}{\kappa_r} . \tag{8}$$

When $\eta \ll 1$, acceleration dominates, and when $\eta \gg 1$, it is quenched. Solving for κ_r in equation (8) with $\eta = 1$ gives

$$\kappa_r = \frac{vR}{2\pi^2}\left\{-1 + \left[1 + \left(\frac{2v_A \pi}{v}\right)^2\right]^{1/2}\right\}. \tag{9}$$

We have already mentioned that for the Per SNR $v_A > v$. Thus to a good approximation we can simplify equation (9) to become

$$\kappa_r \approx \frac{v_A R}{\pi}. \tag{10}$$

Inspection of equation (8) shows that this implies that adiabatic losses are negligible compared with absorption in the shell. Substituting for $P(f)$ in the quasi-linear expression for κ_r and using values appropriate for the region, we obtain the result that losses dominate, if

$$\begin{aligned} T &= \tfrac{1}{2}mc^2\beta^2 \\ &\geq 3(\text{MeV})\left(\frac{\alpha^2}{0.2}\right)^{3/2}\left(\frac{B}{3 \times 10^{-6}\ \text{G}}\right) \\ &\quad \times \left(\frac{n}{1\ \text{cm}^{-3}}\right)^{-1/4}\left(\frac{R}{6 \times 10^{19}\ \text{cm}}\right)^{3/2}. \end{aligned} \tag{11}$$

Since $B \propto n^{1/3} \sim n^{2/3}$, we see that equation (11) depends only weakly on the poorly known quantity n. We also see that η depends strongly on β ($\sim \beta^{8/3}$), and hence the spectral cutoff due to absorption in the shell is quite rapid.

c) *Internal Consistency of the Model*

Note that the values for the various parameters (B, n, R) substituted in equation (11) are those which come from the best available observations, whereas the value for $\delta B^2/B^2 \equiv \alpha^2$ (≈ 0.2) has been inferred.

While a value ~ 0.2 seems plausible, we have to check for internal consistency of the model. At the beginning of this section we described how waves may be generated in the interaction of shock accelerated particles with the interstellar medium, how these may be overtaken by the shock and become amplified so that $\delta B/B \equiv \alpha \approx 1$ may be reached in the absence of strong dissipation. When the SN expansion becomes sub-Alfvénic, both wave generation and amplification cease, and wave damping by various processes must become important. A significant process could be the transfer of wave energy to cosmic rays (see, e.g., Morfill and Scholer 1979), and this can be used to check the internal consistency of our model. The wave damping rate is given by

$$\Gamma_w \equiv \frac{1}{\epsilon_{w_0}}\frac{d\epsilon_w}{dt} = -\frac{\epsilon_c}{\tau_F}\frac{1}{\epsilon_{w_0}}, \tag{12}$$

where all quantities refer to the resonant interaction frequency of the accelerated particles. The term ϵ_{w_0} is the wave energy density $\approx P(f_{\text{res}})f_{\text{res}}$ at the time when wave growth just stops, i.e., when $\alpha = 1$. The molecular measurements yield ϵ_c ($\sim 10^{-14}$ ergs cm^{-3}) as well as the typical particle energy ($\sim$few MeV) and thus f_{res}. The corresponding value of τ_F (at f_{res}) has been determined (through eq. [9]) in the previous analysis. Substituting, we get

$$\Gamma_w(f_{\text{res}}) = -\frac{\epsilon_c v_A \pi}{R\epsilon_{w_0}(f_{\text{res}})} \approx \frac{3 \times 10^{-28}}{\epsilon_{w_0}(f_{\text{res}})}. \tag{13}$$

We have assumed throughout that during the super-Alfvénic phase of the remnant, the wave energy is redistributed in frequency according to a Kolmogoroff spectrum (see, e.g., Kraichnan 1975). Using the same power spectrum employed for κ_r (eq. [4]) we obtain

$$\epsilon_{w_0}(f_{\text{res}}) \approx 3 \times 10^{-15}\ \text{ergs cm}^{-3} \tag{14}$$

which yields

$$\Gamma_w = 10^{-13}\ \text{Hz} \tag{15}$$

Thus, we obtain a wave damping time of $\sim 3 \times 10^5$ years when we substitute the cosmic-ray properties derived from molecular data. This time scale is comparable to the lifetime of the SNR ($\sim 10^6$ years), and provided there is no damping process more efficient than stochastic cosmic ray acceleration, a value of $\alpha^2 \approx 0.2$ seems quite reasonable and is internally consistent.

The stochastic acceleration model thus describes all the available and very detailed information deduced from molecular measurements about cosmic rays in the Per region within the framework of a single theory both qualitatively and quantitatively.

IV. CONCLUSIONS AND DISCUSSION

We have presented a simple model of the magnetic field structure of the old supernova remnant observed in the direction of the Per OB2 association. If the production of H II in the neutral shell observed against the background stars, ζ Per, o Per, and ξ Per is due to ionization by low-energy cosmic rays produced in the highly ionized region of the supernova remnant, the model allows us to explain the large variation of the ionization rates in the directions of these stars. The model also implies that low-energy cosmic rays suffer significant ionization losses at the inner edge of the shell.

No pulsar has been observed near this supernova remnant, and the remnant is very old. Calculations show that the cosmic rays almost certainly must be produced by stochastic acceleration occurring in the ionized material interior to the shell where the level of magnetic turbulence is expected to be high.

If most of the low-energy galactic cosmic rays are produced in this manner, we would expect the cosmic ray ionization rate in general to be extremely low except in the inner edges of shells of supernova remnants. Since about 90% or more of the volume of the interstellar medium may be filled with supernova remnants (cf. McKee and Ostriker 1977), the amount of neutral material which would appear to have abnormally low ionization rates is probably small. However, one such region is known (Hartquist, Doyle, and Dalgarno 1978), and its low pressure (1.4×10^3 cm^{-3} $- k$) implies that it is an isolated cloud and not part of a shell. These considerations also suggest that the ionization rates deep inside dense molecular clouds may be lower than generally assumed in most work on dense cloud chemistry (cf. Oppenheimer and Dalgarno 1974).

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T. W. HARTQUIST: Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, England

G. E. MORFILL: Max-Planck-Institut für Kernphysik, Postfach 103980, 6900 Heidelberg, West Germany