1990ICRC....4...68E

DIFFUSIVE SHOCK ACCELERATION OF DECAY POSITRONS IN SUPERNOVAE

Donald C. Ellison

Department of Physics, North Carolina State University
Raleigh, NC 27695-8202 USA

Frank C. Jones and Reuven Ramaty

Laboratory for High Energy Astrophysics, NASA/GSFC
Greenbelt, MD 20771 USA

Abstract

Positrons have been observed in cosmic radiation at a flux level which, at energies above ~ 10 GeV, may be too high to be explained as secondary products of cosmic-ray collisions with the interstellar medium. In addition, diffuse 0.511 MeV γ-radiation indicates that positrons are widely distributed in the galaxy. Here we examine the diffusive shock acceleration (also called first-order Fermi acceleration) of positrons emitted by radionuclei in supernova ejecta. These decay positrons are emitted at energies near 1 MeV, high enough to eliminate problems of injection into the acceleration mechanism. Furthermore, once accelerated to 10's of MeV, some fraction of positrons which otherwise would remain trapped in the ejecta can escape from the supernova envelope.

Introduction Observations of positron annihilation radiation at 0.511 MeV (Leventhal *et al.* 1978; Riegler *et al.* 1981; Share *et al.* 1988) provide evidence for powerful galactic positron sources, producing positrons at a rate which exceeds by nearly two orders of magnitude the positron production rate in cosmic-ray interactions in the interstellar medium (see Ramaty and Lingenfelter 1979a). Many processes can produce positrons, but nucleosynthesis leading to e^+-emitting radionuclei (^{56}Co, ^{44}Ti, ^{22}Na) is one of the most promising ones (Ramaty and Lingenfelter 1987; Woosley and Pinto 1988). The decay of these radionuclei is accompanied by positron emission, typically of energies around 1 MeV. Furthermore, the radionuclei are expected to be produced in supernovae, presumably in regions traversed by shocks and containing large energy densities in MHD turbulence. The possibility that positrons from radioactive decay in supernovae maybe accelerated and thus make a contribution to the cosmic-ray positron flux was suggested by Ramaty and Lingenfelter (1979b).

A seed population of ~ 1 MeV positrons eliminates problems with injection into the diffusive shock acceleration (DSA) mechanism. These problems stem from the apparent lack of magnetic fluctuations of sufficiently high frequency and of low phase velocity with which low-energy electrons can scatter. In addition, since protons with large gyroradii smooth the shock transition on a scale large compared to electron gyroradii, thermal electrons would be accelerated much less efficiently than protons even if high frequency waves were available. However, if electrons and/or positrons are injected into the system with gyroradii comparable to those of the thermal ions, there are no fundamental barriers to their being accelerated in exactly the same manner as the ions. Here, we calculate the acceleration via DSA of test particle positrons injected at 1 MeV into a supernova remnant (SNR) reverse shock which has been smoothed by the backpressure of accelerated protons.

Ramaty and Lingenfelter (1987) have shown that all of the galactic positron 0.511 MeV annihilation line observations over a 15 year period are consistent with a model in which variable emission from a compact source at or near the Galactic Center is superposed on a time independent flux of distributed emission from the galactic plane. This diffuse component requires the annihilation of $\sim 2 \times 10^{43}$ positrons s^{-1} in the interstellar medium. Cosmic-ray interactions with interstellar gas (e.g., Protheroe 1982) cannot be the source of the observed diffuse 0.511 MeV annihilation line, because such an origin would imply a high-energy (> 100 MeV) γ-ray luminosity from neutral pion decay nearly two orders of magnitude larger than observed (see Ramaty and Lingenfelter 1979a). Furthermore, the positron flux has been measured up to ~ 30 GeV showing that above ~ 10 GeV the $e^+/(e^- + e^+)$ ratio increases with increasing energy. This increase could result from the contribution of primary positron sources.

About 20% of the positrons could result from ^{26}Al decay, as implied in a model-independent fashion by observations of the 1.809 MeV line (Mahoney *et al.* 1984; Share *et al.* 1985). The dominant positron sources, however, are expected to be ^{56}Co (Ramaty and Lingenfelter 1981) and ^{44}Ti decaying into ^{44}Sc (Woosley and Pinto 1988), where both the radioactive Co and Ti are produced in Type I supernovae (Woosley and Weaver 1986). We estimate that if 2×10^{43} positrons s^{-1} are accelerated in the vicinity of supernovae in the galaxy, and if the resultant differential positron energy spectrum has the same form as the inferred cosmic-ray proton source spectrum (i.e., $E^{-2.2}$), then shock accelerated positrons from radioactive decay could become the dominant cosmic-ray positron source above 10 GeV.

In order to reach the locations of the positron emitters during their lifetimes, a reverse shock passing through the supernova ejecta must produce the initial acceleration. The reverse shock is believed to be a strong one and to form within a few days of the initial explosion (McKee 1974; Jones *et al.* 1981; Chevalier 1982; Hamilton and Fesen 1988).

Besides producing the observed spectrum, the acceleration of positrons has another important consequence. The unvarying nature of the diffuse annihilation line flux, as well as its narrow line width, imply that the positrons responsible for the observed emission escape from the supernova envelope and annihilate in the interstellar medium. Such escape is particularly important for ^{56}Co. It has been estimated (e.g., Ramaty and Lingenfelter 1987) that to account for the observed diffuse emission, ~ 2% of the positrons have to escape from the envelope if the frequency of Type I supernovae is 0.02 per year and the yield of ^{56}Ni is $0.5 M_\odot$ per supernova. But since the mean life of ^{56}Co is relatively short (114 days), it produces positrons in regions from which escape to the interstellar medium may not be possible. The escape probability, however, should be greatly enhanced if the positrons are accelerated to higher energies, since both the stopping range and the gyroradius of the particles increase with increasing energy. Acceleration-aided escape of positrons from supernovae was also suggested by Lingenfelter and Ramaty (1989).

Non-Linear Diffusive Shock Acceleration (DSA) In the test particle limit, DSA when applied to SNR shocks naturally produces a power law spectrum in good agreement with the inferred source spectrum of galactic cosmic rays below about 10^{14} eV (see Axford 1981 and Blandford and Eichler 1987 for reviews). However, if supernovae are responsible for accelerating the bulk of the cosmic rays, energy requirements are such that the acceleration mechanism must be quite efficient ($\geq$ 10% of the energy in the blast wave must go into accelerated particles), and the test particle approximation may need to be modified.

Another important question concerns the injection of ambient particles. Plasma simulations of quasi-parallel shocks (e.g., Quest 1988; Burgess 1989) clearly show that some protons are picked out of the thermal population and accelerated. These particles produce upstream waves which convect into the shock and help determine the shock structure. Similar behavior has been observed at the quasi-parallel Earth's bow shock where thermal protons are accelerated directly from the solar wind (e.g., Ellison and Möbius 1987; Ellison *et al.* 1989). This close relationship between energetic particles and shock structure supports the early contention of Eichler (1979) that quasi-parallel collisionless shocks and particle acceleration always go together and the acceleration of thermal ions may even be essential for quasi-parallel shock dissipation.

Since the relevant parameter for interaction between particles and the background magnetic field is the rigidity [i.e., $R = pc/(Qe)$, where p is the momentum, c is the speed of light, and Qe is the charge], positrons and protons with the same R should act similarly. In the case we examine here, 1 MeV positrons have ~ 4 times the rigidity of thermal protons at $T_{p1} = 1 \times 10^6$ K. Therefore, if the shock accelerates thermal protons, it will accelerate 1 MeV positrons as well.

To calculate this acceleration, we use a steady-state, non-linear Monte Carlo code which includes the dynamic effects of accelerated protons on the shock structure (e.g., Ellison *et al.* 1981). The Monte Carlo techniques allow treatment of thermal and accelerated protons in a unified, self-consistent manner, and the absolute injection and acceleration efficiency can be calculated. The shock structure is smoothed as a result of the backpressure of accelerated protons streaming ahead of the shock (contrast the solid and dashed lines in Fig. 1). Once the shock profile is determined for protons, positrons are injected as test particles. The shock smoothing regulates the injection efficiency and produces spectra which are concave upward rather than power laws (see Ellison and Eichler 1984).

The Monte Carlo model assumes that all particles make elastic and isotropic collisions with a scattering mean free path which is a function of rigidity, i.e., $\lambda \propto R/\rho = \lambda_o(A/Q)(v/u_2)[\rho_2/\rho(x)]$, where ρ is the plasma density, v is the particle velocity measured in the local plasma frame, u_2 is the downstream flow velocity, and λ_o is the downstream mean free path of a particle with $A/Q = 1$ and $v = u_2$.

<u>**Results**</u> To model DSA at the reverse supernova shock we use a shock velocity, $u_1 = 1 \times 10^4$ km s^{-1}, an unshocked proton temperature, $T_{p1} = 1 \times 10^6$ K, and a shock compression ratio, $r = 4$. In using $r = 4$, we neglect dynamic effects from particles escaping from the shock and from changes in the ratio of specific heats brought about by the presence of relativistic particles. Both of these effects will tend to increase r along with the efficiency for accelerating particles. Due to limits on computation, the acceleration is cutoff at $E_{\max} = 100$ GeV. If supernovae produce cosmic rays up to 10^{14} eV, the modeling should extend three orders of magnitude higher, however our low $E_{\max}$ should not produce results which are qualitatively different from those with a higher cutoff. On the order hand, our assumption of steady-state may be unrealistic in the early stages of the supernova, where acceleration times become comparable to the shock lifetime (see Lagage and Cesarsky 1983; Bogdan and Völk 1983; Moraal and Axford 1983). The results we present here are preliminary and discussions of acceleration times are left to later work.

The solid line in Fig. 1 shows the smooth flow velocity profile which approximately conserves momentum and energy fluxes across the shock. Figure 2 shows the spectrum of protons (light line) accelerated by the modified shock shown in Fig. 1. The test particle DSA mechanism accelerates particles such that the number density, N, is a power law in momentum, i.e., $N \propto p^{-\sigma}$, where $\sigma = [(r+2)/(r-1)]$. The dashed line in Fig. 2 shows this test particle spectrum in the proper energy units calculated for $r = 3.5$, the compression ratio which gives $\sigma = 2.2$ above a few GeV. The test particle solution and the proton spectrum from our modified shock are indistinguishable at observed cosmic-ray energies. Also shown in Fig. 2 is the positron spectrum (heavy line) obtained by injecting 1 MeV positrons into the shock profile of Fig. 1. This spectrum is also indistinguishable from the inferred cosmic-ray source spectrum above a few GeV. As a result of the shock smoothing, both the positron and proton spectra are concave upward compared to a power law.

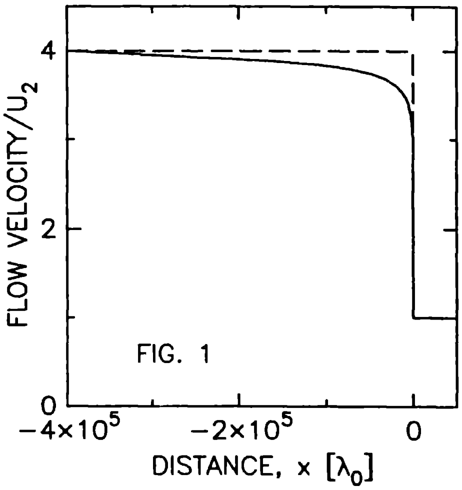

FIG. 1

For a preliminary look at the question of escape from the supernova remnant we consider an explosion that ejects $1 M_\odot$ of stellar material with a velocity of 10^4 km s^{-1}. Assuming that the remnant expands homologously, after 100 days the remnant's radius will be $\sim 9 \times 10^{15}$ cm and the density will be $\sim 7 \times 10^{-16}$g cm^{-3}. For these conditions, the path length from the center to the outside of the remnant is ~ 6 g cm^{-2}. A positron of ~ 12 MeV will have a range this large in oxygen. In Fig. 3, we show the fraction of *energy density* above energy E (curves labeled 'En'), and the fraction of *particle density* above E (curves labeled 'D') for protons (dashed lines) and positrons (solid lines). Approximately 0.7% of the positrons, injected at 1 MeV, will be accelerated to 12 MeV (arrow in Fig. 3) where they have a good possibility of escape. This is lower than the simple test particle result (i.e., $\sim 4\%$ using $N \propto E^{-2.2}$) because the positron spectrum is steeper than the power law at low energies due to the effects of the shock smoothing. Of course the true situation is much more complicated; particles will diffuse out of the remnant rather than travel in straight lines so the path will be longer. On the other hand the typical particle is emitted and accelerated closer to the outer edge than the radius of the remnant (the volume averaged distance from the center is $4R/3$) so this factor works toward shorter paths. In any event, on the order of 1% of the positrons can be expected to escape.

Conclusions The cosmic-ray positron spectrum and diffuse 0.511 MeV γ-ray line emission suggest that primary sources of positrons exist in the galaxy. We have calculated the diffusive shock acceleration of radioactive decay positrons in supernova ejecta and find that the resultant spectrum is consistent with cosmic-ray observations and that on the order of 1% of the decay positrons might escape to the interstellar medium.

The authors wish to thank Denis Cioffi for helpful comments. This work was supported in part by NASA Grant NAG 5-1131.

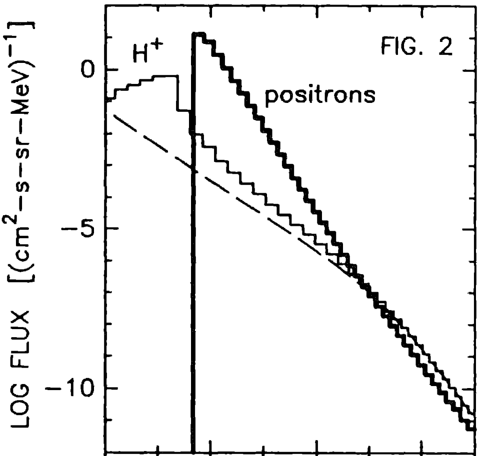

FIG. 2

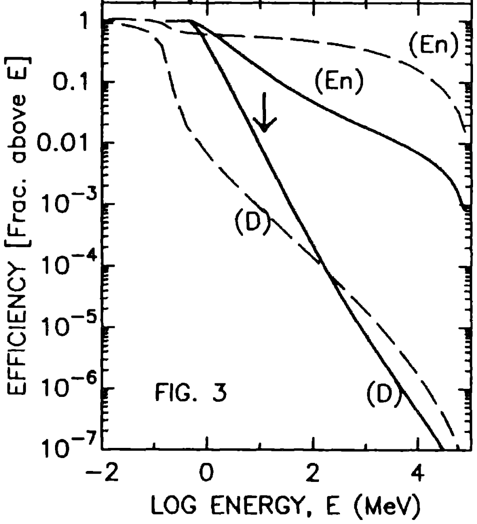

FIG. 3

References

Axford, W.I. 1981, *17th ICRC*, **12**, 155.
Blandford, R.D., and Eichler, D. 1987, *Phys. Rept.*, **154**, 1.
Bogdan, T.J., and Völk, H.J. 1983, *A.A.*, **122**, 129.
Burgess, D. 1989, *G.R.L.*, **16**, 345.
Chevalier, R.A. 1982, *Ap.J.*, **258**, 790.
Eichler, D. 1979, *Ap.J.*, **232**, 106.
Ellison, D.C., and Eichler, D. 1984, *Ap.J.*, **286**, 691.
Ellison, D.C., *et al.* 1981, *J. of Geophysics*, **50**, 110.
Ellison, D.C., and Möbius, E. 1987, *Ap.J.*, **318**, 474.
Ellison, D.C., Möbius, E., and Paschmann, G. 1989, *Ap.J.*, in press.
Jones, E.M., *et al.* 1981, *Ap.J.*, **249**, 185.
Hamilton, A.J.S., and Fesen, R.A. 1988, *Ap.J.*, **327**, 178.
Lagage, P.O., and Cesarsky, C.J. 1983, *A.A.*, **125**, 249.
Lingenfelter, R.E., and Ramaty, R. 1989, in *The Center of the Galaxy*, ed. M. Morris, (Dordrecht: Reidel), p. 587.
Leventhal, M., *et al.* 1978, *Ap.J.(Letts.)*, **225**, L11.
Moraal, H., and Axford, W.I. 1983, *A.A.*, **125**, 204.
Mahoney, W.A., *et al.* 1984, *Ap.J.*, **286**, 578.
McKee, C.F. 1974, *Ap.J.*, **188**, 335.
Protheroe, R.J. 1982, *Ap.J.*, **254**, 391.
Quest, K.B. 1988, *J.G.R.*, **93**, 9649.
Ramaty, R., and Lingenfelter, R.E. 1979a, *Nature*, **278**, 127.
Ramaty, R., and Lingenfelter, R.E. 1979b, *16th ICRC*, **1**, 501.
Ramaty, R., and Lingenfelter, R.E. 1981, *Phil. Trans. R. Soc. Lon. A*, **301**, 671.
Ramaty, R., and Lingenfelter, R.E. 1987, in *The Galactic Center*, ed. D.C. Backer, (AIP: New York), p. 51.
Riegler, G.R., *et al.* 1981, *Ap.J.(Letts.)*, **248**, L13.
Share, G.H., *et al.* 1985, *Ap.J.(Letts.)*, **292**, L61.
Share, G.H., *et al.* 1988, *Ap.J.*, **326**, 717.
Woosley, S.E., and Pinto, P.A. 1988, in *Nuclear Spectroscopy of Astrophysical Sources*, eds. N. Gehrels and G.H. Share, (AIP: New York) in press.
Woosley, S.E., and Weaver, T.A. 1986, *A.R.A.A.*, **24**, 205.