A Model for the Origin of High-Energy Cosmic Rays

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Abstract. We suggest that cosmic rays, up to the highest energies observed, originate in the galaxy and are accelerated in astrophysical shock waves. If there is a galactic wind, in analogy with the solar wind, we expect a hierarchy of shocks ranging from supernova shocks to the galactic wind termination shock. This leads to a consistent model in which most cosmic rays, up to perhaps 10^{14} eV energy, are accelerated by supernova shocks, but that particles with energies of 10^{15} eV and higher are accelerated at the termination shock of the galactic wind.

Introduction. It appears that supernova blast waves are the major site for acceleration in the galaxy. While this mechanism is attractive, the energy to which particles can be accelerated is only of the order of 10^{14} eV (Lagage and Cesarsky, 1983). However, the observed cosmic-ray spectrum extends well beyond this cutoff, and one is forced to consider separately the origin of very high energy particles.

Two main factors limit the energy to which particles may be accelerated - their gyroradius (which is related to the mean-free path) and the time available. The time scale for particle acceleration is given by (e.g., Krymsky et al, 1979, Forman and Morfill, 1979, Axford, 1980)

$$t_{acc} = 4\kappa/V_{sh}^2, \qquad (1)$$

where is the diffusion coefficient (which is a function of energy) and V_{sh} is the shock velocity. Clearly, since increases with energy, at any time there will be an energy above which the energy spectrum cuts off. We set the mean free path a constant of order unity times the gyroradius in the ambient magnetic field. For particles of rigidity R (in electron volts) in a magnetic field of B (gauss) we have

$$t_{acc} \simeq \frac{4cR}{900 B V_{sh}^2} \qquad (2)$$

The velocity of a supernova shock wave may be written

$$V_{sh}^2 = \alpha E_{sn}/M_G, \qquad (3)$$

where α 1.33 for a pure blast wave and α 2.5 for evaporative solutions (Mckee and Ostriker, 1977), where E_{sn} is the energy of the explosion and M_G is the mass of gas swept up by the blast.

The value of M_G may be found from the Sedov approximation. For a supernova of age t_5 times 10^5 years, and α 1, the maximum cosmic-ray energy in volts is

$$R(V) = 6.5\text{x}10^{13}\, t_5^{-1/5}\, n_{-2}^{-2/5}\, E_{51}^{2/5}\, B_3 \qquad (4)$$

where $\rho_0 = n_{-2}\times 10^{-2} m_p$, $E_{SN} = E_{51}\times 10^{51}$ ergs, and $B = 3\times 10^{-6} B_3$ Gauss. See also Lagage and Cesarsky(1983). The possible interaction of cosmic rays with more than one shock does not appreciably alter this limit (Blandford and Ostriker, 1980). The spectrum of cosmic rays accelerated by supernovae, therefore is expected to steepen above a few times 10^{14} eV.

The observed cosmic-ray spectrum displayed in figure 1 shows that, although there is an apparent change in the spectrum in the vicinity of 10^{14} eV, the acceleration process is still quite vigorous above this energy. It remains to find the source of the particles above approximately 10^{14} eV.

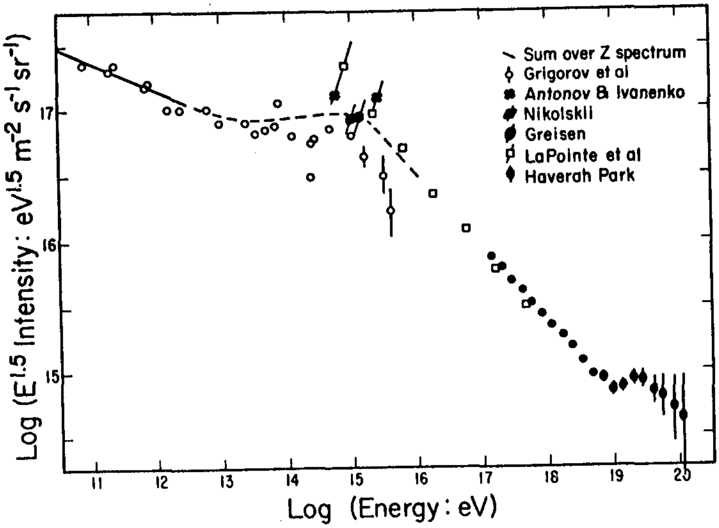

Figure 1. Spectrum of cosmic rays presented by Linsley (1980).

The above discussion indicates roughly that shocks with a greater age and/or greater spatial extent can accelerate particles to a higher energy. Single supernovae shock waves presumably produce most cosmic rays, up to perhaps 10^{14} eV. Supershells, containing the energy of about 100 supernovae, all occurring in a short time, may also contribute. From equation (4) we find that the maximum cosmic-ray energy obtainable in supershells may be expected to increase only by a factor ~ 5 over that of a single supernova.

The largest shock structure associated with our galaxy, and presumably the one with the greatest age, is the termination shock of the galactic wind. Presumably there will also be intermediate-scale shocks resulting from various processes in the galactic wind, similar in nature to those found in the solar wind.

Acceleration at the Galactic Wind Termination Shock. The existence of a galactic wind flowing outward from our galaxy cannot be regarded as established, although it seems likely on the basis of several considerations. A mixture of gas, magnetic field and cosmic rays similar to the hot phase of the interstellar medium is expected to form a supersonic wind (e.g., Johnson and Axford, 1971, Ipavich, 1975, Jokipii,1976, Kopriva and Jokipii, 1983). In addition, the energy dependence of cosmic-ray composition suggests a general outflow from the galactic disk (see, e.g. Jones,1978, Jokipii and Higdon, 1979). We will assume the existence of a galactic wind in which the galactic-halo gas (the intercloud medium) flows outward, and terminates in a shock which can accellerate particles. We can estimate the properties of the galactic wind from some simple considerations. Irrespective of how the wind is driven, the energy source is the supernova explosions. We take a supernova energy input rate into the interstellar medium of

$$\dot{E}_{SN} = 10^{42} \text{ ergs/sec}$$

and assume an energy redistribution between cosmic rays and galactic wind in the ratio 1:1 The energy input rate into cosmic rays, and hence into the galactic wind, is then of order

$$\dot{E}_c = \dot{E}_w = \dot{M}V_w{}^2/2 = 5\text{x}10^{40} \text{ ergs/sec.}$$

We see immediately that the available time for acceleration at the galactic terminal shock is the lifetime of the galactic wind, which in turn is T_{gal}, the age of our galaxy, or 1.5×10^{10} years (Hoyle 1961).

__Energies of particles accelerated in a galactic wind terminal shock__ We use our previous estimate for the energy input rate into the wind, $E_W = 5 \times 10^{40}$ ergs/sec. We express the mass loss rate M in units of the present diffuse galactic matter ($5\times10^9 M_\odot$) divided by the lifetime, t_{gal} of the galaxy (1.5×10^{10} yrs.). i.e., M $2\times10^{25}\times F$ g/sec. where F is a scaling parameter. This yields a wind velocity $V_w \sim 500/\sqrt{F}$ km/sec. A constraint is that $V_w > V_E = 300$ km/sec, the escape velocity. This implies that $F < 4$. In any case, mass loss should not be great, restricting F to perhaps < 1. Thus we do not expect mass balance problems.

Because of galactic rotation, the field lines will be wound up much as in the solar wind. Hence, we use the Parker Archimedean spiral form for the magnetic field and write for the magnetic field B at the shock in terms of that at the reference radius, B_o:

$$B \simeq B_o \left(\frac{R_o}{R_{sh}}\right)^2 \left[1 + \frac{R_{sh}^2 \Omega_{gal}^2}{V_w^2}\right]^{1/2} \tag{5}$$

where $\Omega_{gal} = 10^{-5}$ sec^{-1} is the galactic rotation rate. Defining $\eta = R_o/R_{sh}$, and substituting for V_w^2 and setting $t_{acc} = T_{gal}$ in equation (2) yields

$$R_{max}(eV) = \frac{450\, T_{gal}}{c} \frac{E_w}{\dot{M} F} B_o \eta^2 \left[1 + \frac{\Omega_{gal}^2 R_o^2 \dot{M} F}{2 E_w \eta^2}\right]^{1/2} \tag{6}$$

In Table I are displayed R_{max} for various using = 10 kpc, B_o= G, and F = 1. The choice R_o = 10 kpc is in agreement with a lower limit of 4 kpc for the static halo, using I.U.E. observations (Savage and DeBoer, 1981, Pettini and West, 1982).

__Table I.__ Maximum rigidity (and energy of Fe nuclei) of cosmic rays accelerated at the galactic wind termination shock.

	R_{sh}(kpc)	R_{max}(eV)	E_{Fe}(eV)
0.2	50	7×10^{18}	1.8×10^{20}
0.1	100	3.2×10^{18}	$.8\times10^{20}$
0.05	200	1.6×10^{18}	$.4\times10^{20}$
0.02	500	6.4×10^{17}	$.2\times10^{20}$

The distance to the shock, R , should be about half the mean separation of the galaxies in our local cluster, or about 200 kpc.

Finally, we note that particles accelerated at the terminus of the galactic wind will be subject to modulation by the galactic wind. Recent models of the solar problem (see e.g. Jokipii and Kopriva, 1979, Jokipii and Kota, 1983) suggest that the cosmic-ray intensity behaves roughly as if the particles were decelerated in a potential field equal to the electro-static potential difference between the heliospheric pole and equator. Using our standard values and setting $\rho_o \simeq 10^{-3} m_p$ yields a value of 10^{15} eV. This suggests that cosmic-ray particles with energies greater than this value will not be significantly modulated by the galactic wind, whereas lower-energy particles will be modulated. In this picture, galactic cosmic rays with energies less than about 10^{14} eV are primarily accelerated by supernova shocks, whereas those with energies above 10^{15} to perhaps 10^{19} eV are accelerated at the galactic wind termination. Those with intermediate energies may be accelerated by intermediate-scale shocks in the wind, in analogy to blast waves and co-rotating shocks observed in the solar wind.

__Further Considerations and summary.__ The galactic disk cosmic rays represent an average over many super-novae, at different stages (e.g., Bogdan and Volk 1983), whereas the galactic terminal shock is of more constant strength (and probably a higher Mach number), leading to a somewhat different source spectrum.

Since the acceleration process which we propose is quite slow, we must compare it with loss processes. For high-energy nuclei, interaction with the 2.7° K microwave background is the major consideration (Greisen, 1966). Starlight is less important because of the distance from the galaxy. Puget, et al. (1976) showed that photodisintegration is the dominant process. Examination of their figs. 2 and 8 indicates that protons and Fe have a loss time of t_{gal} for energy > 2 X 10^{19} - 10^{20} eV. Therefore, the present mechanism appears capable of accelerating cosmic rays to the highest observed energies. Finally, we suggest that the observed anisotropy in high-energy cosmic rays from north galactic latitudes may be related to the apparent motion of the galaxy, and the pushing of the termination shock closer to the galaxy in that direction.

Hence, a single acceleration process in our galaxy may be responsible for the production of cosmic rays with energies up to 10^{20} eV. The generally uniform spectral characteristics of the cosmic rays over more than ten decades in energy are then easily understood to be a consequence of the same acceleration process - diffusive shock acceleration - and the fact that the shocks all share the same basic energy source - the supernovae explosions in the galactic disk.

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