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COSMIC RAY ACCELERATION MECHANISMS

Catherine J. Cesarsky

Section d'Astrophysique
Centre d'Etudes Nucléaires de Saclay, France and
Astronomy Department and Space Sciences Laboratory
University of California at Berkeley, USA

Abstract

We present a brief summary of some of the most popular theories of cosmic ray acceleration: Fermi acceleration, its application to acceleration by shocks in a scattering medium, and impulsive acceleration by relativistic shocks.

Fermi Acceleration

The basic concept of acceleration of particles via encounters with "moving magnetic walls" was introduced by Fermi as early as 1949 (1). Consider a fast particle of velocity v, that encounters a magnetic wall moving at a velocity V. The wall reflects the particle. In the frame of the wall, there is only a static magnetic field, and thus no energy exchange: just an elastic collision. Transforming back to laboratory space, however, one finds that the particle energy has changed by an amount:

$$\Delta E \simeq E\,(1 + 2\,Vv\cos\theta/c^2 + 2\,V^2/c^2) \quad (1)$$

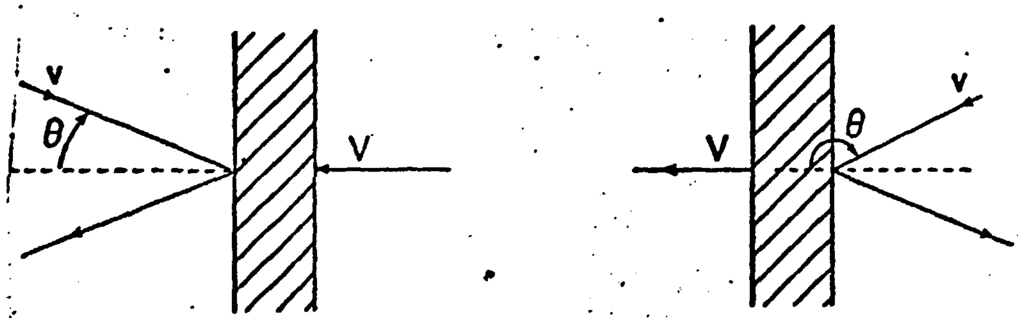

Figure 1

Head-on and overtaking encounters of a particle of velocity v with a magnetic wall of velocity V.

To first order in V/c, particles gain energy if $\cos\theta > 0$ (head-on encounters) and loose energy if $\cos\theta < 0$ (overtaking encounters).

Let λ be the mean distance between moving walls. If somehow the particle only makes head-on collisions -- e.g., if it is trapped between two magnetic walls approaching each other, the rate of energy gain, for relativistic particles, is $dE/dt = a\,VE/\lambda$, where a, of order 1, depends on the distribution of incidence angles θ. This type of process is called "first order Fermi mechanism."

If the walls move at random, the first order terms in equation (1), cancel each other, when summing over all encounters. The second order term in eq. (1) guarantees that the particles still gain some energy; in addition, for a given value of $|\cos\Theta|$, head-on encounters are more probable than overtaking encounters by a factor $(v|\cos\Theta| + V)/(v|\cos\Theta| - V)$. Consequently, the role of energy gain of relativistic particles is only:

$$\frac{dE}{dt} = \frac{2V^2}{c\lambda} E \tag{2}$$

(where we have assumed that particles and clouds have isotropic distributions of velocities). This is called second-order or statistical Fermi mechanism.

One of the main reasons why this process has enjoyed such an endurable popularity among astrophysicists is that, under very simple conditions, it predicts that the energy spectrum of the colliding particles shoud be a power law, and power law spectra are extremely frequent in non-thermal sources of radiation, all over the universe. Assume that a group of particles is undergoing Fermi 1st or 2nd order acceleration in a box, from which they have a constant probability to escape, while particles of energy E_o are being supplied, at a constant rate. For particles in the box,

$$\frac{dE}{dt} = \alpha E, \tag{3}$$

so that at age t, their energy is:

$$E(t) = E_o \exp(\alpha t) \tag{4}$$

If T is the mean escape time, the probability of having an age t is:

$$P(t)\, dt = (dt/T) \exp(-t/T) \tag{5}$$

Therefore, the particle spectrum is:

$$N(E)dE = P(t)dt \quad \frac{1}{E} \exp\left(-\frac{1}{\alpha T} \ln \frac{E}{E_o}\right) dE$$

or:

$$N(E) \propto E^{-\gamma}, \qquad \gamma = (1 + 1/\alpha T) \tag{6}$$

The great drawback of this theory is that the observed exponents γ in cosmic rays and cosmic sources is rather narrow (most freqently $2<\gamma<3$), while here γ and T appear to be completely independent of each other. [but see ref. (2)]

Particle acceleration by parallel shocks in a scattering medium.

This attractive mechanism must have been in the air a few years ago, as it has been discovered simultaneously by astrophysicists all over the world (3, 4). This is somewhat surprising, as the tools used in the various derivations, and the motivation, have been around for a much longer time.

Let us consider a strong shock, propagating at a velocity V in the direction of the magnetic field lines. We assume that $V \gg v_A$, where v_A is the Alfven velocity ($v_A^2 = B^2/4\pi\rho^*$, where ρ^* is the density of ionized particles). In the shock frame, the gas is flowing in at a velocity $u_1 = V$. At the shock, the gas is compressed by a factor r, so that the velocity downstream, relative to the shock, is $u_2 = V/r$.

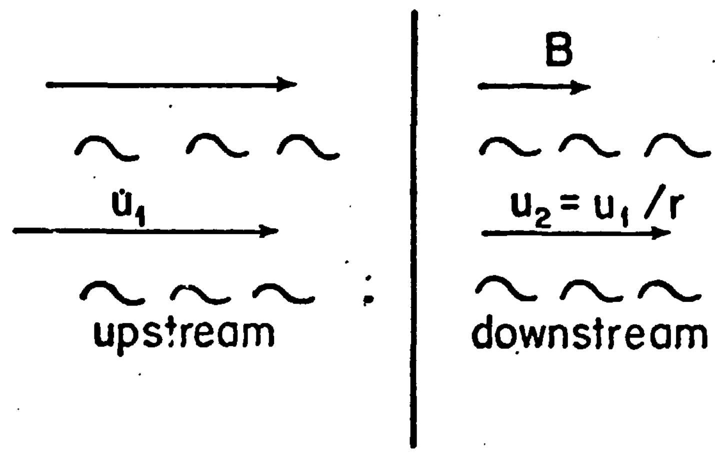

Figure 2

Parallel shock in a scattering medium

The presence of scattering centers of cosmic rays is postulated, so that cosmic rays diffuse on both sides of the shock; the diffusion coefficient is, in general, a function of space, of particle momentum, and of time. In any case, the scattering centers act as cosmic ray traps, ensuring that the particles will be reflected back and forth across the shock a large number of times. Every passage through the shock is equivalent to running head on into a "magnetic wall" of velocity $V = u_1 - u_2 = V(1-1/r)$; averaging over incidence angles, we obtain the mean gain per passage:

$$E = (4/3)(V/c)(1-1/r)E \quad (7)$$

Assume that particles of energy E_o are continuously fed to the shock. To complete a picture "a la Fermi," we need to know the mean probability of escaping the system. Bell (4) has put forward the simplest derivation of this probability. His argument goes as follows: the diffusion mean free path of cosmic rays, λ, is much larger than the width of the shock. Consequently, the cosmic ray density is continuous across the shock. The scattering ensures that, far from the shock, the distribution of the momentum vectors of cosmic ray is isotropic in the frame of the gas. The shock generates anisotropies of order V/c; but, to zero order in V/c, the distribution at the shock is isotropic. Thus, the flux of cosmic rays crossing the shock, at any given time, is simply (1/4) n(o) v, where n(o) is the cosmic ray density at the shock, and v the c.r. velocity. The numbers of particles swept back downstream, and thus escaping the system every second, is n(o) u_2. Thus, the escape probability per cycle is:

$$\eta = \frac{n(o)u_2}{n(o)v/4} = \frac{4u_2}{v}$$

After ℓ passages through the shock, the cosmic ray energy is:

$$E_\ell = E_o \exp\{\frac{4}{3}\,\ell\,\frac{V}{c}\,(1 - 1/r)\} \tag{9}$$

The probability of completing at least ℓ passages is:

$$P_\ell = (1 - \eta)^\ell \tag{10}$$

Folding E_ℓ and P_ℓ, we obtain the time independent spectrum:

$$N(E) \propto E^{-\mu}\ ,\ \mu = (2+r)/(r-1) \tag{11}$$

For strong shocks, r=4 and μ=2. Weaker shocks generate steeper spectra.

The remarkable property of this mechanism is that, in the time-independent limit, the slope of the power law it generates depends only on the shock, and not at all on the diffusion coefficient (assumed "small enough") or the dimensions of the scattering region (assumed "large enough"). This is a consequence of eq. (8).

The study of shock acceleration of cosmic rays is now an active area of research. A recent, detailed review of the subject as it stands can be found in reference (5). A detailed application of the linear, time independent mechanism I have just described to the acceleration of galactic cosmic rays is given in reference (6). Here, we just mention some of the problem areas:

a) If cosmic rays extract so much energy from the shock, their pressure can become the dominant one. For instance, this will inevitably occur if cosmic rays are getting accelerated by a strong shock, to a spectrum E^{-2} for a sufficiently long time. Even if the shock is not so strong ($r<4$), the cosmic ray pressure can become dominant if the rate of injection of particles in the system is sufficiently rapid. The expectation is that, eventually, the cosmic rays broaden the shock, making it a less efficient particle accelerator; if the shock becomes wider than the particle mean free path λ, particles only get a small amount of adiabatic acceleration as they traverse the compressed regions, but a power law tail does not develop. While some progress has been made, (5,6) the full problem of non-linear shocks, as well as the distinct, but coupled problem of particle injection into the acceleration mechanism, still poses many intriguing puzzles.

b) This problem has always been treated in the framework of the quasi-linear theory, which assumes that the turbulent energy in the hydromagnetic waves acting as particle scatterers is much less than the energy density of the magnetic field. However, the anisotropies induced by supernova shocks in the pre-existing population of galactic cosmic rays are sufficient to render these waves extremely unstable; the wave amplitudes predicted by the quasi-linear theory are too high to be fully consistent with this theory.

c) Finally, this acceleration process is slow; consequently, when applied to realistic shocks, which have a finite lifetime, the theory predicts a high energy cut-off. In the case of supernova shocks, it seems impossible to attain the highest energies generally attributed to galactic cosmic rays, 10^{15} eV (see contribution by P.O. Lagage).

<u>Hydrodynamic acceleration</u>

The possibility of impulsive cosmic ray acceleration by supernova shocks right after the supernova explosion has been emphasized, these last twenty years, by Stirling Colgate and his collaborators (7).

Supernova explosions are due to a gravitational or thermonuclear instability occuring in the interior of a star at the end of its evolution. A strong shock wave is emitted, which "blows up" the envelope. If the envelope is compact, the shock accelerates as it propagates outwards, until it attains a relativistic velocity. (Type II pre-supernova stars are known to have extended envelopes, but the details of the structure of Type I pre-supernova stars are uncertain.) Type I supernovae are believed to arise from the explosion of white dwarfs which are slowly accreting matter from a more massive companion. For the pre-supernova model adopted by Colgate, with a radiative envelope obeying a polytropic equation of state, the outer (2.10^{-5}) fraction of the star is accelerated to a relativistic velocity; the differential particle spectrum obtained is proportional to E^{-3} in the plane approximation, and $E^{-3.5}$ in the case of a expansion (8).

This theory also predicts a high energy cut off in the spectrum, as the shock must terminate when the range of the particles exceeds the scale-height of the atmosphere. In fact, the final cosmic ray spectrum, and even more, the maximum energy, are very dependent on details of the structure of the outer layers of the pre-supernova star; this is one of the main weaknesses of this theory. Other problems which it encountered have been overcome; for instance, it was feared that spallation reactions would destroy most of the heavy nuclei during acceleration. Recently, Colgate and Petschek (8) have shown that the temperature behind the shock is so high that positron-electron pairs, in equilibrium with the radiation, are 10^4 times more numerous than the nucleons. The pairs cushion the particles against collisions among themselves, and spallation reactions do not occur. The material heated by the shock expands and cools down very rapidly, so that the hydrogen nuclei ejected at less than GeV/n recombine. At the same time: unstable nuclei like ^{57}Co and ^{56}Ni acquire K-shell electrons, and can decay by electron-capture even after acceleration; thus, the objection to prompt cosmic ray acceleration derived from the iron peak abundances in cosmic rays (9) can be circumvented by this model. In any case, the matter accelerated here is not freshly synthetized material, but the outer layers of an accreting white dwarf; the corresponding composition is extremely difficult to guess. (10)

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References

1) Fermi, E: 1943, Phys. Rev. 75, p. 1169.

2) Syrovatskii, S.I.: 1961, Soviet Physics - JETP 13, p. 1257.

3) Krymsky, G.F.: 1977, Dok. Akad. Nauk. S.S.S.R. 234, p. 1306.

Axford, W.I., Leer, E., Skadron, G.: 1977, 15th Int. Cosmic Ray Conf. 11, p. 132.

Blandford, R.D., Ostriker, J.P.: 1978, Ap. J. (Lett.) 221, p. 129.

4) Bell, A.R.: 1978, M.N.R.A.S. 182, p. 147.

5) Axford, W.I.: 1981, "Plasma Astrophysics", Varenna, ESA SP-161, p. 425.

6) Eichler, D.: 1979, Ap. J. 229, p. 419.

Drury, L.O.C., Volk, H.J.: 1981, Ap. J. 248, p. 344.

Ellison, D.C., et al.: 1982, J.G.R., in press.

7) Colgate, S.A., Johnson, N.H.: 1960, Phys. Rev. Lett. 5, p. 235.

8) Colgate, S.A., Petscheck, A.G.: 1978, Ap. J. 229, p. 682.

9) Soutoul, A., Cassé, M., Juliusson, E.: 1978, Ap. J. 219, p. 753.

10) Epstein, R.: 1980, seminar at CENS- Saclay.