Diffusive Compression Acceleration of Charged Particles

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Abstract

We consider the acceleration of fast charged particles by smooth compressions and expansions in a collisionless fluid, using the diffusion approximation. If the diffusion length κ/U is of the order of the fluid scale or larger, efficient acceleration occurs which has similarities with both 2nd-order Fermi acceleration and diffusive shock acceleration, but is different from both. A simple, one-dimensional sinusoidal flow is analysed. We show that the acceleration dominates, even with equal amounts of compression and expansion. The acceleration time is $\approx \kappa/U^2$. We suggest that this mechanism may be an important accelerator in regions where there are large-scale compressive disturbances, but few shocks. The mechanism provides a natural explanation of observations in the heliosphere near CIR compressions. It may contribute to the acceleration of cosmic rays elsewhere in the Heliosphere and the galaxy. We suggest the name "diffusive compression acceleration" for this mechanism.

1. Introduction

Understanding the acceleration of cosmic rays or energetic charged particles is one of the most fundamental goals of astrophysics. A number of general mechanisms have been suggested. The most successful of these has been the acceleration by collisionless shocks [1,2,3,4,6,7]. However, there are important situations where energetic particles are accelerated with no shocks present. One recent and particularly clear example consists of the energetic ions observed in interplanetary co-rotating interaction regions near 1 AU, well inside the radius where the associated co-rotating shocks form [8]. Giacalone et al [5] found that compression acceleration provided a natural and compelling interpretation of the observations. It is our purpose in this paper to explore the properties of this compressive acceleration in the diffusion limit.

2. Charged Particle Acceleration in the Diffusion Approximation.

We consider the transport of cosmic rays in the diffusion approximation, where the (nearly-isotropic) distribution function $f(\mathbf{r}, p, t)$ as a function of posi-

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tion **r**, momentum magnitude p and time t satisfies the Parker equation [9]

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] - U_i\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial \ell n(p)} + Q - L \qquad (1)$$

where κ_{ij} is the diffusion tensor, U_i is the flow velocity of the background plasma, and Q and L represent any additional sources and losses. This equation applies if there is enough scattering that the distribution function remains nearly isotropic, even at discontinuities such as current sheets and shock waves. Particle acceleration is contained in the term $\partial U_i/\partial x_i$.

Application of equation (1) to a one-dimensional system having a planar shock, where the flow velocity changes discontinuously, yields all of the results of diffusive shock acceleration mentioned above. If the disturbance is not a discontinuity, but instead is a more-gradual compression having a characteristic length scale L_c, one can show that in the limit where the ratio of the diffusive skin depth $L_d = \kappa_{xx}/U_x$ to the length scale L_c is large, or, equivalently, $\xi = \kappa_{xx}/(U_x L_c) \gg 1$, the solution for the cosmic-ray distribution f goes over to the standard diffusive shock solution. In the opposite limit $\xi \ll 1$, the cosmic rays are closely tied to the convecting fluid, and simply compress adiabatically.

2.1. Diffusive-Compression Acceleration

Consider the case $L_d \tilde{>} L_c$, but where the flow varies smoothly. Note that the scattering mean free path λ_{sc} does not appear explicitly in this inequality. So it is possible to have λ_{sc} small compared with the compression length scales L_c (so that the diffusion approximation applies) but where the diffusive skin depth L_d is of the order of L_c or larger. We find that such non-shock compressions may be efficient accelerators, even if there are associated expansions.

The physical basis of the acceleration is the interplay between a) the energy change caused by the compression or expansion of the fluid and b) the diffusion into or away from the region of compression or expansion. Rapid diffusion leads to the particle being able to diffuse away from a region of compression or expansion before the compensating expansion or compression can occur. Hence, statistically, some few particles will be fortunate enough to gain energy in several compression regions. In this process, for large κ, the accelerations dominate the particle energy change, even in those cases where the compressions and expansions are equally present in the fluid flow. This is because, statistically, some particles can reach very high energies, but they cannot be decelerated to energies lower than zero.

Note also that this acceleration can take place for any orientation of the magnetic field. Gradient and curvature drifts can in general significantly affect the particle trajectories as they are accelerated.

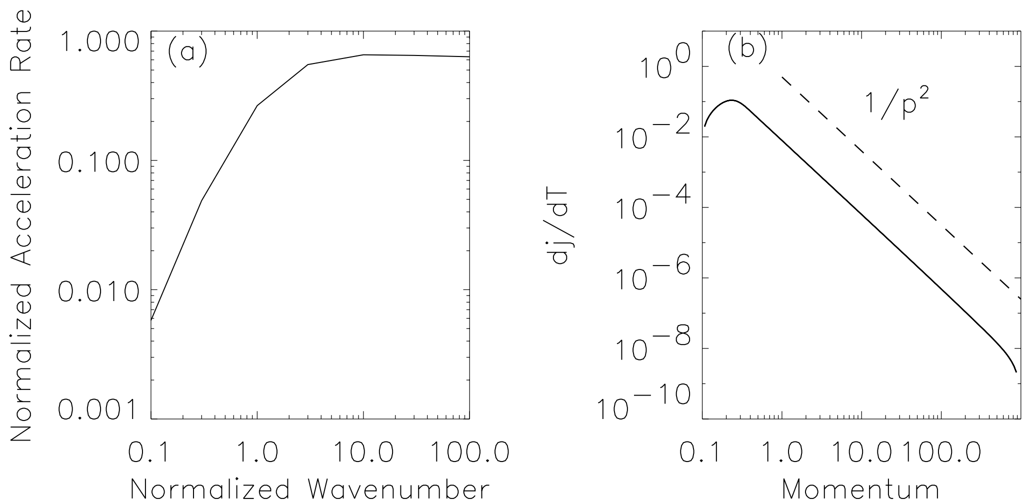

Fig. 1. Illustration of the acceleration times (a), and resulting energy spectrum (b).

3. Acceleration Rates and Energy Spectrum

To illustrate this process, consider the simple, periodic one-dimensional velocity profile $U_x(x) = U_0(1 + a\ sin(kx))$ and κ_{xx} independent of x or p. We have not been able to solve this analytically for general parameters, but it is simple to solve numerically, and the solutions depend only on the dimensionless parameters $\chi = [U_0/\kappa_{xx}]x$, $\tau = [U_0^2/\kappa_{xx}]t$ and $\eta = [\kappa xx/U_0]k$ and the amplitude a. The solutions are clearly periodic in χ with a period $2\pi/\eta$.

Illustrated in figure 1(a) is the initial rate of acceleration $d\ell n(p)/d\tau$ (in units of $1/\tau$), averaged over x and plotted as a function of normalized wavenumber η, for the case where the parameter $a = .6$, which corresponds to a ratio of maximum density (or velocity) to minimum density (or velocity) of 4. It is apparent from the figure that the average acceleration rate decreases rapidly for wavenumber much less than 1 (diffusion too slow), and asymptotically approaches a constant which is about unity for larger wavenumbers (when the diffusion becomes more important). A net acceleration occurs in spite of the balancing of compression and expansion for the reasons given previously.

3.1. Energy Spectrum for a Simple Confinement Model

Consider next the solution to equation (2) for the case where the system is not strictly periodic, but there are diffusive loss boundaries at $x = +15$ and for $\eta = 2$. The velocity is of the form $U(x,t) = asin(\eta x - t)$, where a = .6, which is essentially the same as the periodic system used above, but is a propagating wave. The particles are injected continuously and uniformly in x at a momentum $p_0 = 1$, so the source term $Q(x, p, t) = R_0\delta(p - p_0)$. Figure 1(b) illustrates the energy spectrum obtained for this model system.

4. Discussion and Conclusions

Significant acceleration by non-shock compressions, even in the present of comparable expansions, is possible, as long as the diffusion scale is comparable to the scale of the fluid variations, or larger. This diffusive compression acceleration has some similarities with 2nd-order Fermi acceleration and with shock acceleration, but is different from both. It appears to produce naturally a power-law-like spectrum, similar to that in shock acceleration, over a broad range of parameters. Note also that this problem has been linearized and subjected to a multi-scale analysis by Webb, et al [10], in which case some analytic results have been obtained.

This acceleration can occur in a number of circumstances. For example, in the inner heliosphere near 1 AU, for ≈ 1 MeV galactic cosmic rays where $\kappa_{par} \approx 10^{20}$ cm^2/sec, and where compressive velocities should be of the order of $V_a \approx 50$ km/sec, we have $\xi \tilde{>} 1$ for scales $L_c \tilde{<}$ 1 AU. Observations suggest that there may be significant compressive fluctuations over these scales. In the interstellar medium, where the diffusion coefficient is typically $\tilde{>} 10^{26}$ cm^2/sec, and typical fluid velocities are ≈ 100 km/sec or so, scales of several parsecs to tens of parscec can correspond to $\xi \tilde{>} 1$. Again, we expect significant compressive fluid fluctuations on these scales. We conclude that compressive variations may contribute to the acceleration of energetic particles in many places.

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