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Injection and Acceleration at Non-Parallel Shocks

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We discuss new results in the physics of charged-particle acceleration by shock waves propagating at an arbitrary angle to the magnetic field. For the usually discussed case of a parallel shock acceleration by a supernova blast wave up to the knee in the cosmic-ray spectrum requires very special assumptions such as a strong increase in the magnetic field, perhaps due to excitation from the streaming cosmic rays. We show that no such special circumstances are required when one considers acceleration at nearly perpendicular shocks.

1. Introduction

Diffusive acceleration of charged particles at collisionless shocks, at which particles are accelerated by the converging flows and plasma compressions, naturally explains the observed universal power law of cosmic rays up to the knee in the spectrum at about 10^{15} eV (see, e.g., the reviews by Drury [1], Blandford and Eichler [2]; and Jones & Ellison [3]). The acute angle between the shock-normal direction and the incident magnetic fields (θ_{Bn}) plays an important role in determining the resulting accelerated-particle spectrum. It was shown by Jokipii [4, 5] that the acceleration rate depends strongly on θ_{Bn} and is the highest when the shock is perpendicular ($\theta_{Bn} = 90°$). Thus, given a particular time interval over which to accelerate particles, those with highest energy will originate from the perpendicular shock.

An important issue in diffusive shock acceleration at nearly perpendicular shocks has been the well-known injection threshold problem. The problem arises because, until recently, it was assumed that particles move essentially along the lines of force which are convecting through the shock. Therefore, it was thought that there was no means by which low-energy particles could encounter the shock several times, which is required for efficient particle acceleration.

Here we show that there is actually no such injection problem and, in fact, the injection does not depend strongly on the shock-normal angle. This can be understood in terms of the increased cross-field transport arising from so-called field-line random walk due to the large-scale (order of a parsec) turbulent interstellar magnetic field.

2. Analytical Considerations

The main assumption in diffusive shock acceleration is that the pitch-angle distribution is nearly isotropic. By requiring the diffusive streaming anisotropy to be small, one can readily derive an expression for the "injection velocity," w_{inj} (c.f. [6]). The most general expression is given by:

$$w_{inj} = 3U_1 \left[1 + \frac{\kappa_A^2 \sin^2\theta_{Bn} + (\kappa_\parallel - \kappa_\perp)^2 \sin^2\theta_{Bn}\cos^2\theta_{Bn}}{\left(\kappa_\perp \sin^2\theta_{Bn} + \kappa_\parallel \cos^2\theta_{Bn}\right)^2} \right]^{1/2} \quad (1)$$

where $\kappa_\perp$, and $\kappa_\parallel$, are the components of the diffusion tensor perpendicular and parallel to the mean magnetic field, respectively, and the antisymmetric component of the diffusion tensor is $\kappa_A = vr_g/3$.

For the case in which the correlation scale of the turbulent magnetic field is much larger than the gyroradius of

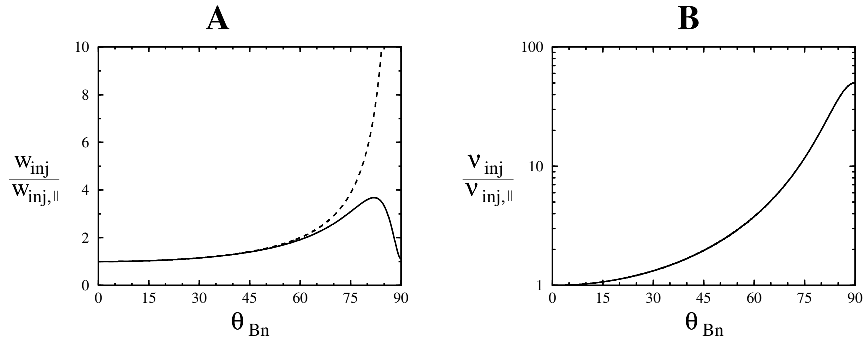

Figure 1. (A) The injection velocity derived from the diffusive streaming anisotropy for the case of field-line random walk (solid line) normalized to that at a parallel shock. The dashed curve assumes the scatter-free approximation. See text for details. The right panel (B) is the acceleration rate, normalized to that at a parallel shock, as a function of θ_{Bn}.

the particles of interest, it has been shown from numerical simulations that $\kappa_\perp/\kappa_\|$ is independent of energy [6]. Thus, taking $\epsilon = \kappa_\perp/\kappa_\| \ll 1$ and $\eta = (1/3)\lambda_\| r_g$, where $\lambda_\|$ is the parallel mean-free path and r_g is the Larmor radius, (1) can be rewritten as:

$$w_{inj} = w_{inj,\|}\left[1 + \frac{(1/\eta)^2 \sin^2\theta_{Bn} + \sin^2\theta_{Bn}\cos^2\theta_{Bn}}{\left(\epsilon\sin^2\theta_{Bn} + \cos^2\theta_{Bn}\right)^2}\right] \tag{2}$$

where $w_{inj,\|} = 3U_1$ is the injection velocity for a parallel shock.

Shown in left panel of Figure 1 (A) is the solution to (2) for $\eta = 100$ and$\epsilon = 0.02$. The dashed curve is $\sec\theta_{Bn}$, which is the scatter-free approximation which is clearly invalid for the case of a turbulent magnetic field. Note that at low-energies, the injection velocity at a perpendicular shock approaches $3U_1$, which is the same as that obtained for a parallel shock [7].

Thus, we can conclude that enhanced motion normal to mean field by field-line random walk significantly decreases the injection velocity threshold for acceleration. Thus, the theory predicts that there should not be an injection problem at nearly perpendicular shocks.

The acceleration rate, ν_{acc}, in diffusive shock acceleration is given by

$$\nu_{acc} = \frac{1}{\tau_{acc}} \sim \frac{U_1^2}{\kappa_\|\cos^2\theta_{Bn} + \kappa_\perp\sin^2\theta_{Bn}} \tag{3}$$

Thus, taking $\nu_{acc,\|}$, and to be the acceleration rate at a parallel shock ($\theta_{Bn} = 0$), and $\epsilon = \kappa_\perp/\kappa_\|$ (as before), we obtain

$$\frac{\nu_{acc}}{\nu_{acc,\|}} = \frac{1}{\cos^2\theta_{Bn} + \epsilon\sin^2\theta_{Bn}} \tag{4}$$

Equation (4) is plotted as a function of θ_{Bn} for the case of $\epsilon = 0.02$. in the right panel of Figure 1 (B). Clearly the acceleration rate is a maximum at perpendicular shocks. Therefore, we conclude that perpendicular shocks are both efficient and rapid accelerators of charged particles are most important in producing high-energy cosmic rays in a wide variety of astrophysical plasmas.

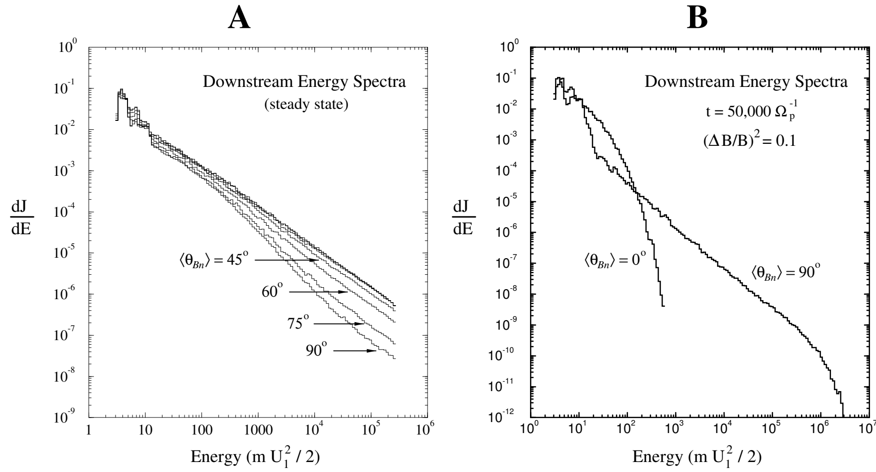

Figure 2. Downstream energy spectra for test-particle numerical simulations. (A) Steady-state spectra obtained from simulations using different values of the shock-normal angle. (B) Time-dependent spectra for two different shock-normal angles and weaker turbulence. These figures are from Giacalone [8].

3. Numerical Calculations

3.1 Test-Particle Simulations

We now consider non-diffusive test-particle numerical simulations to better address the physics of acceleration at low energies. This work has recently appeared in the *Astrophysical Journal* ([8]). In these calculations, the trajectories of an ensemble of test particles are integrated by numerically solving the Lorentz force on each particle using pre-specified electric and magnetic fields. The mean magnetic field makes an angle θ_{Bn} with respect to the shock-normal direction. Superimposed on this is a fluctuating component that is determined from a pre-specified power spectrum that resembles the usual Kolmorov spectrum. The correlation scale of the turbulent magnetic field is taken to be 2000 U_1/Ω_i, where U_1 is the upstream flow speed and Ω_i is the ion cyclotron frequency. Both components satisfy Maxwell's equations. Test particles (protons) are released with an energy of 3 times the plasma-ram energy in the local fluid frame just behind the shock front. Each particle's trajectory is integrated until it escapes downstream by convection (based on a probability of return criterion), or reaches an arbitrary high-energy cutoff (taken to be 2×10^5 times the plasma-ram energy).

Figure 2 is from Giacalone [8]. The left panel (A) shows the stead-state energy spectra downstream of the shock for 7 numerical simulations in which the only varying parameter is θ_{Bn}. Note that the spectra for the cases of $\theta_{Bn} = 0°, 15°, 30°$ all lie on top of one another indicating that there is no dependence on this parameter at all for quasi-parallel shocks. The right panel (B) is for the case of a time-dependent acceleration process. Here, weaker turbulence was used and two different shock-normal angles are considered (as indicated).

The results shown in Figure 2 indicate the injection energy, and therefore, the acceleration efficiency does not have a strong dependence on the shock-normal angle. However, as shown in the right panel of Figure 2, for any given time interval to accelerate the particles, perpendicular shocks produce the highest-energy particles. This is because, as we discussed above, the acceleration rate is strongly dependent on the shock normal angle, provided $\kappa_\perp \ll \kappa_\parallel$. This is discussed further in Giacalone [8].

3.2 Self-Consistent Hybrid Simulations

Recently, Giacalone [10] performed massive-scale two-dimensional hybrid simulations of perpendicular shocks propagating into a turbulent upstream magnetic field. It was shown that a fraction of thermal particles encountering the shock are accelerated to high energies. The physics of this process is similar to that which we have already described above. However, the source of the high-energy particles comes directly from the thermal population, which had not been seen in previous self-consistent plasma simulations. It has been long known that a fraction of thermal ions are specularly reflected by the shock and begin to gyrate within the shock ramp before becoming thermalized downstream. For the case in which the shock moves into an upstream region containing large-scale magnetic fluctuations, some of these ions can move upstream along these lines of force before returning to the shock. These ions can gain considerable energy because they can achieve multiple interactions with the shock.

The efficiency for the acceleration in these large-scale hybrid simulations is difficult to estimate because the spatial domain is still rather limited by computation resources. However, it was estimated that the efficiency is probably comparable to that obtained for a parallel shock, or about 10-20% [11].

4. Summary

We have addressed the physics of charged-particle acceleration by shocks. We have shown that the perpendicular shocks are as efficient as parallel shocks in accelerating particles to high energies using reasonable parameters. For these same parameters, perpendicular shocks are much more rapid accelerators. Thus, we conclude that perpendicular shocks are important sites of acceleration and can produce high-energy cosmic rays in a wide variety of astrophysical plasmas.

5. Acknowledgements

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