Particle Acceleration at Fluid Compressions and What That Teaches Us about Shock Acceleration

Kittipat Malakit,[1] Kamonporn Klappong,[1,2] Kanokporn Leerungnavarat,[1] Piyanate Chuychai,[1] Nuanwan Sanguansak,[3,4] and David Ruffolo[1]

(1) Department of Physics, Chulalongkorn University, Bangkok 10330, Thailand
(2) Present address: Department of Physical Science, Huachiew Chalermprakiat University, Bangplee, Samut Prakarn 10540, Thailand
(3) Department of Physics, Chiang Mai University, Chiang Mai 50200, Thailand
(4) Present address: National Synchrotron Research Center, Nakorn Ratchasima 30000, Thailand

Abstract

Particle acceleration at shocks and fluid compressions is examined by numerically solving pitch angle transport equations for various magnetic field angles. The recently discovered jump in the steady-state particle density just upstream of an oblique shock is much stronger for lower energy particles or greater shock obliquity. For narrow, oblique compressions the analogous feature is a peak in particle density in the compression region. We refer to both as "mirroring peaks" because for a compression we clearly see that the peak arises from magnetic mirroring and reflection of particles. Steady-state spectra of particles accelerated at an oblique shock or compression are hardened at low energy in association with the mirroring peak; magnetic mirroring leads to more effective acceleration. The spectral index at a given particle energy increases approximately linearly with compression width. Steady-state spectra from compression regions can also harden at high energy.

1. Introduction

It is commonly believed that most cosmic rays are accelerated at astrophysical shocks. In addition to research on the acceleration of relativistic particles, there are also many open questions about the acceleration of low energy particles. Much theoretical work neglects effects of order (U/v), where U is the fluid speed relative to the shock and v is the particle speed, which are especially important for oblique shocks with a general field-shock angle [1]. For example, [3,10] have reported a jump of order (U/v) in the particle density at a shock.

The study of particle acceleration at a shock discontinuity raises the question of acceleration at continuous fluid compressions that have not yet developed into shocks. This has previously been examined for a magnetic field parallel to

pp. 3677–3680

the shock normal [6]. Particle acceleration was examined in a general, steady-state context in a preliminary report by [5], while [2,4] examined the problem for the situation of corotating interaction regions and were able to explain observed time-intensity profiles.

The present work examines steady-state particle acceleration at continuous fluid compressions of varying width in comparison with that at a discontinuous shock for various shock-field angles. The configurations are shown in Fig. 1; in the compression case, magnetic field lines have a hyperbolic shape and width (semi-conjugate axis) b along the field. In comparison with shocks, the narrow compressions exhibit quantitatively similar particle acceleration, leading smoothly to the shock results as the width is reduced. However, compressions do not naturally yield a power-law particle spectrum; rather, the resulting spectrum is sensitive to the velocity dependence of the scattering mean free path. The study of acceleration at compression leads to better understanding of shock acceleration, especially regarding the effect of magnetic mirroring on the distribution function and hardening of the particle spectrum.

2. Numerical Simulations

The transport and acceleration of energetic charged particles near a fluid compression is studied by numerically solving a time-dependent pitch angle transport equation for a general, static magnetic field [11]. The numerical methods are based on those of [9,10].

For a shock the transport equation is greatly simplified, but care is required when treating particles crossing the shock. We now consider particle orbits as they cross the shock, using a transfer matrix to assign the distribution function to the appropriate μ and z cells after the shock encounter. In a stringent test of the accuracy of the pitch-angle treatment, our simulations have been able to explain observed loss-cone precursors to Forbush decreases [8].

Although the key results of this work are derived from a more fundamental treatment of pitch angle (PA) transport, we also make use of an approximate diffusion-convection (DC) treatment. The DC transport equation for the plane-parallel configuration is an ordinary differential equation, which can be solved analytically for a shock, and can readily be solved numerically for a compression. In this paper approximate DC results are shown specifically to highlight the role of magnetic mirroring, which is neglected by DC included in the full PA treatment.

3. Results

In the results, we found that particle spectra from shocks, as predicted by PA, are not exactly power laws as predicted by DC [7]. The spectra are hardened at low energy, especially for the quasi-perpendicular (Q-Perp) case (upstream

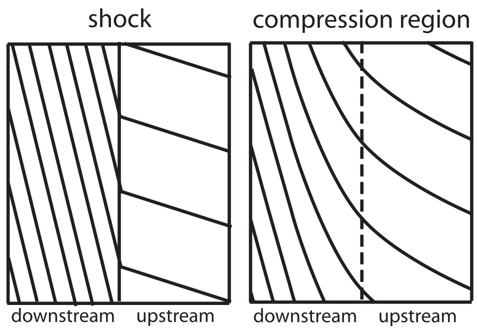

Fig. 1. Sample mean magnetic field configurations for a shock (left) and a compression region (right)

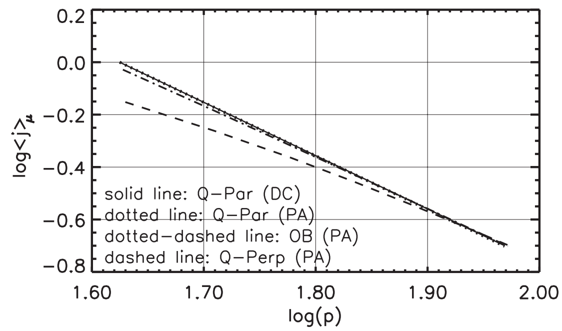

Fig. 2. Particle spectra for cases of shocks obtained by PA compared with a power-law spectrum obtained by DC

shock-field angle $\theta_1 = 75.96°$). However, the particle spectrum in the case of a quasi-parallel (Q-Par) shock ($\theta_1 = 0.57°$), predicted by PA, is still a power-law (see Fig. 2). Similarly, the particle-density jump can be predicted by PA only. The jump is highest in the Q-Perp case, intermediate for the oblique (OB) case ($\theta_1 = 45°$), and disappears for a Q-Par shock (see Fig. 3).

For compression regions, there is also a peak near the compression plane that is analogous with the jump in the case of shocks. This peak is not as high as the shock jump and the peak height decreases when the compression is wider (see Fig. 4). Note that, here, compression width is expressed in terms of the ratio of b to the parallel mean free path.

We conclude that the peak (or jump) should be due to magnetic mirroring, which is neglected in the DC approach. As further evidence, Fig. 5 shows isodensity contours in the μ-z plane, with a density peak near the compression plane for particles mirroring back upstream. Moreover, we conclude that the mirroring effect leads to more effective acceleration, especially at low energy, evidenced by the hardened spectrum.

Another result is that spectra of particles accelerated by compression regions are generally not power laws but rather are hardened at high energy (see Fig. 6). Furthermore, we also found that the spectral index at a given particle energy increases approximately linearly with the compression width for wide compressions.

This work was partially supported by a Basic Research Grant and a Royal Golden Jubilee Fellowship from the Thailand Research Fund.

4. References

1. Drury L.O'C. 1983, Rep. Prog. Phys. 46, 973

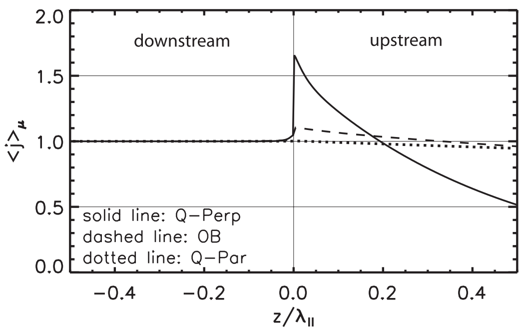

Fig. 3. Particle density vs. position, obtained by PA, with a higher jump for a more perpendicular shock-field angle

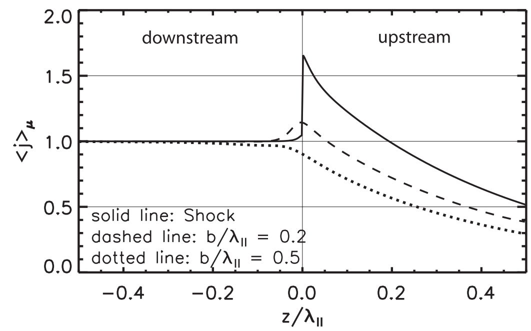

Fig. 4. Particle density vs. position, obtained by PA, for the Q-Perp case, with a higher peak (or jump) for a narrower compression

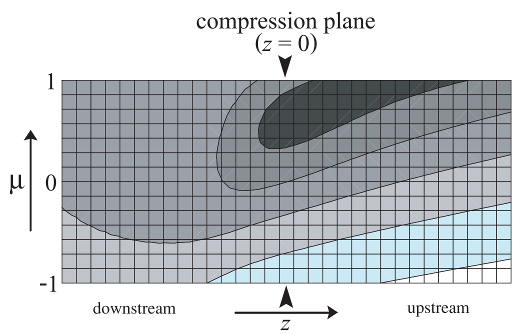

Fig. 5. Contour plot of the distribution function at a Q-Perp compression region with $b/\lambda_{\|} = 0.2$ (darker regions have a higher particle density)

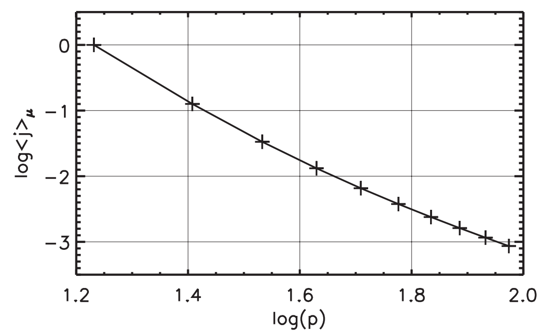

Fig. 6. Particle spectrum for a compression region with $b/\lambda_{\|} = 2.0$

2. Giacalone J., Jokipii J.R., Kóta J. 2002, ApJ 573, 845
3. Gieseler U.D.J., Kirk J.G., Gallant Y.A., Achterberg A. 1999, A&A 345, 298
4. Jokipii J.R., Giacalone J., Kóta J. 2001, Proc. 27th ICRC 9, 3581
5. Klappong K., Leerungnavarat K., Chuychai P., Ruffolo D. 2001, Proc. 27th ICRC 8, 3461
6. Krülls W.M., Achterberg A. 1994, A&A 286, 314
7. Krymskii G.F. 1977, Sov. Phys. Dokl. 23, 327
8. Leerungnavarat K., Ruffolo D., Bieber J. 2003, ApJ (in press)
9. Nutaro T., Riyavong S., Ruffolo D. 2001, Comp. Phys. Comm. 134, 209
10. Ruffolo D. 1999, ApJ 515, 787
11. Ruffolo D., Chuychai P. 1999, Proc. 26th ICRC 6, 552