Particle acceleration at the interaction of shocks and discontinuities

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Abstract: A theoretical model of particle acceleration by the interaction of a magnetic field directional discontinuity and a collisionless shock is presented. The geometry of the interaction region, the relative angles of the shock, discontinuity, and magnetic field highly influences the acceleration process. In certain geometries the particles can re-enter the acceleration region again and again, which leads to more effective acceleration and higher final energies. This mechanism can contribute to the generation of energetic particles in Hot Flow Anomalies, and can play an important role in the pre-acceleration of anomalous cosmic rays.

PRELIMINARY VERSION

Introduction

It is widely accepted that the high energy ion and electron distributions of astrophysical plasmas originate in regions where particles interact with shock waves. In most environments where energetic populations are observed, shocks can also be seen. Shocks are associated with most energetic particle populations in space.

The three dominant processes of shock acceleration are the shock drift acceleration [1], the diffusive shock acceleration [1] (first order Fermi process) and the stochastic shock acceleration [1] (second order Fermi process). In shock drift acceleration, particles gain energy by drifting in the induced electric field along the shock surface. This drift is a kind of gradient drift induced by the different field magnitudes upstream and downstream of the shock. In the Fermi processes particles interact with moving scattering centers. The energy source in the first order mechanism is the different upstream and downstream plasma speed. The particle bouncing back and forth across the shock can gain more energy in an upstream interaction than that it loses by interacting with a downstream scattering center. In stochastic acceleration, the particles interact with randomly moving scattering centers. The ”scattering centers” in these processes are mostly MHD waves.

In this paper we study various aspects of the drift acceleration. Our main objective is to investigate the influence of a magnetic field directional discontinuity, but at first we examine the limitations of the shock drift acceleration to show the necessity of an additional mechanism in an effective acceleration process. After this we present one such mechanism, which enable the particles to re-enter the acceleration region again and again, which leads to more effective acceleration and higher final energies.

Maximal energy gain

There are various results about the maximal energy gain in a simple drift acceleration event, in which the particle's gyrocenter crosses the shock surface only once. The simplest [1] is calculated using the assumption that the first adiabatic invariant is conserved during the transition $p_\perp^2/B = const$ (here $p_\perp$ is that component of the particle's momentum, which is perpendicular to the magnetic field, and B is the magnetic field magnitude). In this case the energy gain can be written as:

$$\Delta\mathcal{E} = \left(\frac{B_2}{B_1} - 1\right)\frac{p_{\perp 1}^2}{2m} < 3\,\mathcal{E}_1, \qquad (1)$$

where the 1 and 2 subscripts denote the upstream and downstream regions, respectively. (The last inequality holds because the magnetic field compression ratio $r = B_2/B_1 < 4$ for a non-relativistic monoatomic gas.)

The validity of the adiabatic approximation is not apparent, because in a shock the scale length of the magnetic field variation is usually smaller than the gyroradius of the particles. Although it is proven that the first adiabatic invariant is nearly conserved when the path of the particle crosses the shock many times, this approach hides the microphysics of the shock-crossing, and possibly hides several interesting effects as well. Hence we calculate the maximal energy gain based on the detailed investigation of the shock-crossing.

Doing this we can separate two highly different regimes. If the scale length of the magnetic field variation is larger than the gyroradius of the particles (and the conservation of the adiabatic invariant is a very good approximation) the microphysics shows a fairly high energy gain, roughly speaking the acceleration is unbounded. On the other hand when the magnetic field variation is abrupt, its scale length is much smaller than the gyroradius (shock case) the energy has a very strong upper bound.

The simplest way to find the maximum of the energy gain is to compute the length of time interval in which the gyrating particle completely passes the shock, the maximal distance (z_m) it can drift in the direction of the electric field in that time, and the energy change is given by

$$\Delta\mathcal{E} = eEz_m. \quad (2)$$

But the acceleration makes the calculation somewhat more difficult. The gyroradius continously changes during the drift, even such extremity is possible that the particle never leaves the shock completely, because the gyroradius grows more rapidly than the gyrocenter moves away from the shock. In that case the acceleration continues ”forever” and the energy grows unboundedly.

We can find the simple differential equation, which governs the motion of the gyrocenter in this problem. Its general form is $\frac{dz}{dt} = v_D(z)$, where $v_D(z)$ is the (z component of the) z dependent drift velocity.

In a slowly changing magnetic field, the drift velocity is proportional to the square of the particle speed perpendicular to the field direction $v_D(z) \sim v_\perp^2(z)$. But $v_\perp^2(z) \sim p\perp^2 \sim const + eEz$, which means that $\frac{dz}{dt} \sim const + z$. The solution of this differential equation has the form $z \sim t + exp(c \cdot t)$. Using Eq. (2) we can see that the acceleration can be much more effective than that predicted by the approximation used in Eq. (1).

For the shock case we can find the time interval Δt between two consecutive shock-crossing using simple geometrical considerations

$$\Delta t = \frac{m}{e}\left(\frac{\alpha}{B_1} + \frac{2\pi - \alpha}{B_2}\right),$$

where m and e are the mass and charge of the particle, B_1 and B_2 are the magnetic field magnitude upstream and downstream respectively, and alpha is the ”viewing angle” of the upstream part of the circular path as seen from the gyrocenter. It is changing as the gyrocenter moves across the shock, a good approximation for Δt is $\Delta t = \frac{m\pi}{e}\left(\frac{1}{B_1} + \frac{1}{B_2}\right)$.

The mean value of the displacement of the gyrocenter in one “circle” can be written as $\Delta z = 2(r_1 - r_2)\langle sin(\alpha)\rangle = \frac{\pi}{2}(r_1 - r_2)$. Now we can calculate the drift speed:

$$v_D(z) \approx \frac{\Delta z}{\Delta t} = Kv_\perp(z), \quad K = \frac{1}{2}\frac{1 - \frac{B_1}{B_2}}{1 + \frac{B_1}{B_2}} \quad (3)$$

It yields that

$$\frac{dz}{dt} = K\sqrt{\frac{2eE}{m}}\sqrt{\frac{v_{\perp 0}^2 m}{2eE} + z}. \quad (4)$$

The solution of this equation is a second order polynomial of t. The last shock-crossing happens when the distance of the gyrocenter from the shock just equals to the z dependent gyroradius $u_2 t = r(z) = r_0 + mv_D/KeB = r_0 + Ku_2 t$. Here u_2 is the downstream solar wind speed, and we used the $E = u \times B$ relation. Thus the “one-pass acceleration time” is $t = r_0/(1 - K)u_2$. Using this, the maximal distance, what the particle can drift along the direction of the induced electric field can be written as:

$$z_{\max} = \frac{\frac{1}{2}mv_{\perp 0}^2}{eE}\left(\left(1 + \frac{K}{1 - K}\right)^2 - 1\right), \quad (5)$$

and the one-pass energy gain is:

$$\Delta\mathcal{E} = \frac{1}{2}mv_{\perp 0}^2\left(\left(1+\frac{K}{1-K}\right)^2-1\right). \quad (6)$$

Fig. 1 shows this energy gain as a function of the magnetic field compression ratio (r) in $\frac{1}{2}mv_{\perp 0}^2$ units.

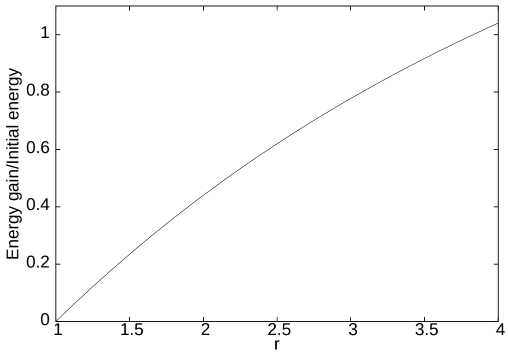

Figure 1: The ratio of the energy gain ($\Delta\mathcal{E}$) and the initial perpendicular energy ($\frac{1}{2}mv_{\perp 0}^2$) as a function of the magnetic field compression ratio (r)

We can see, that it is a growing function of r, and reaches the maximum at $r = 4$ (strong shock case). But this maximum is hardly more than 1, which means a very strong constraint on the maximum of the "one-pass" energy gain. This constraint is much stronger than that in Eq. (1), and other constraints in the literature. This means that a particle can win even less energy in a single drift acceleration event, than it was expected earlier.

The "conveyor belt"

Let's suppose that a tangential discontinuity crosses the shock in the interaction region. On one side of the discontinuity, the shock is quasi-perpendicular, and drift acceleration pumps up the energy of the particles, up to the above calculated limit. On the other side of the discontinuity the shock may be quasi-perpendicular or quasi-parallel. In these environment, the accelerated particles may escape into the upstream region [1] inside the low-field current sheet, or (on the quasi-parallel side) along the field lines. The accelerating electric field must point towards the discontinuity, because otherwise the escaping particles are not accelerated but decelerated by the shock. If the magnetic field has no fluctuating component, the escaping particles cannot pass the discontinuity again, and has little probability to re-enter the interaction region. (This is because in a constant field the motion of the particle perpendicular to the discontinuity is symmetric, if it diverges from the discontinuity it has to approach it again.)

In the presence of a little magnetic field fluctuation this symmetry is broken, and the field lines of the quasi-perpendicular side can pick up the escaped ions. This also is an acceleration process even in itself. The perpendicular energy of the picked up particle is $\frac{1}{4}m\left(v_\perp^2+(v_\perp+u)^2\right)$. What is more, this particle will be transported back to the shock, for another pass of drift acceleration.

Certainly this is useless, if the particle remain in the direct vicinity of the discontinuity, because than the acceleration distance is even more limited, and the particle cannot gain energy drifting on the shock (or if it travels a higher distance along the shock, it leaves the discontinuity and cannot escape). But with fluctuating field, the so-called compound diffusion [1] (field-line mixing + parallel diffusion) can transfer the particles further into the quasi-perpendicular side. What is more, in this proccess, the particles always move perpendicular to the *local* electric field, which means, that they will not been decelerated, although they move against the *mean* electric field. In that way the particles can re-enter the acceleration region, gain energy by drift acceleration and the pick-up process again and again.

Multiple acceleration in details

Conclusions

In this paper we investigated the limits of the drift acceleration process, and a mechanism, which can amplify the acceleration by feeding back the accelerated particles into the acceleration region.

We found, that in a slowly changing field, the particles can reach fairly high energies in a one pass drift acceleration event, but for shock drift acceleration the energy gain is limited by the inequality

$$\Delta\mathcal{E} < 1.04\,\frac{1}{2}mv_{\perp 0}^2$$

This result emphasizes the necessity of the feed-back process.

The feed-back is possible in the presence of a discontinuity, when the magnetic field has a fluctuating component. In that case the field lines of the quasi-perpendicular side can pick up the escaped ions accelerating and transferring back them to the shock in the same time. The particles can move away from the discontinuity by compound diffusion, without losing their energy. These particles can drift back to the discontinuity along the shock, gaining more energy and entering into the feed-back process again.

This mechanism can play an important role in the generation of energetic particles in Hot Flow Anomalies, and in the pre-acceleration of anomalous cosmic rays.

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References

[1] Citation needed.