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Relativistic surfing acceleration of ions at oblique shocks

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Abstract

It was shown in [M.A. Lee, V.D. Shapiro, R.Z. Sagdeev, J. Geophys. Res. 101 (1996) 4777] that one of the limits to the shock surfing acceleration of ions at quasiperpendicular shocks is because of the obliqueness of the shock wave. In this Letter, a critical obliqueness is found for the relativistic shock wave, below which the energy gain of the particle due to the shock surfing acceleration is not limited by the obliqueness of the shock wave.

Keywords: Shock surfing; Ion acceleration; Oblique shocks; Relativistic energies

Shock surfing acceleration, which was proposed by Sagdeev [1] has proven to be an efficient acceleration mechanism especially for slow pick-up ions at the perpendicular shock waves [2,3].

With a *strictly* perpendicular shock wave, the surfing ion's motion can be considered a combination of bouncing motion, which is normal to the shock front, and acceleration in the plane of the shock front. Bouncing motion occurs because the ion is trapped in front of the shock between two turning points. The ion is reflected at the shock front by the shock potential, which is a characteristic of the quasiperpendicular shock wave. The second turning point is due to the upstream magnetic field. The Lorentz force pushes the ion back to the shock front. The ion is accelerated under the influence of the convective electric field of the plasma flow as long as it is trapped between these two turning points.

The constraints on this acceleration mechanism can be summarized as follows:

(1) The ion escapes from the acceleration region if the Lorentz force, which pushes the particle toward the shock front, exceeds the electric force normal to the shock front.

$$E_x < \frac{v_y}{c} B_z.$$

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That is, it is crucial to have E_x/B_z ratios close to 1 in order to keep the relativistic particle in the acceleration region. Such large E_x/B_z ratios are expected at high Mach number supercritical shocks. In this Letter, we assume that the electric field normal to the shock front is sufficiently large to render this constraint irrelevant. However, in order to verify this assumption, further investigation is needed using numerical simulations of quasiperpendicular shock waves in the high Mach number regime. Quest [4] performed such simulations with a hybrid code that treats ions as macroparticles and electrons as a massless fluid. For such analysis, shocks are wide and the electric field is small because the only space scale is the ion inertial length. Therefore, we point out here that further analysis is needed using PIC simulations that include kinetic electrons.

(2) The ion escapes from the acceleration region if the ion's bounce kinetic energy exceeds the potential barrier at the shock front.

In the nonrelativistic case, the bounce energy of the ion increases during acceleration. This constrains surfing acceleration significantly. Üçer and Shapiro [5] showed that for a *relativistic* particle, bounce kinetic energy decreases during acceleration, which allowed this constraint to be eliminated. This earlier work also found that if the surfing particle stays in the acceleration region until it reaches a critical energy, its bounce kinetic energy would never exceed the potential barrier at the shock front.

(3) For efficient acceleration, the width of the shock front should be small compared to the ion gyroradius.

The amplitude of the bounce motion in front of the shock is comparable to the ion gyroradius. If the width of the shock front is small compared to the ion gyroradius, this leads to a simple picture of an accelerated particle bouncing between the two turning points where the shock potential does not affect the upstream turning point. This is crucial for the efficiency of the acceleration. Narrow ramp widths also lead to large cross-shock electric fields, thus this condition is also closely related to the first constraint explained above. Observations reveal the existence of thin shocks where the ramp with is of the order of several electron skin depths [6].

(4) At oblique shocks, another limitation to shock surfing appears due to the presence of a magnetic field component in the direction of the shock normal [2]. This component of the magnetic field causes cycloidal motion of the ion in the shock plane. Due to this motion, the particle is untrapped from the acceleration region after a certain time.

This Letter will examine the possible elimination of this particular constraint with the introduction of relativistic shock waves.

Examination of the structure of the shock and the surfing ion's trajectory allows us to understand this constraint qualitatively. The shock is moving in the $+x$ direction with a velocity $\mathbf{v}_s = u\hat{x}$, thus the bulk plasma flow in the shock frame has a velocity $-u\hat{x}$. Since quasiperpendicular shocks are mainly propagating perpendicular to the ambient magnetic field, there is a convective electric field at the shock frame:

$$\mathbf{E} = \frac{1}{c}\mathbf{v}_s \times \mathbf{B}_0 = -\frac{u}{c}B_{z0}\hat{y}, \qquad (1)$$

where $\mathbf{B}_0$ is the *upstream* magnetic field and $B_{y0} = 0$. The noncoplanar magnetic field B_y is nonzero only in the shock transition layer [7], and its significance will be discussed later.

Fig. 1 shows the trajectory of an ion incident on the shock plane, which is located at $x = 0$. The trajectory is shown in the frame of the shock wave, therefore vector $\mathbf{u}$ indicates the direction of the upstream plasma flow. Ion is incident on the shock wave from upstream. The figure is generated for two different orientations of the magnetic field with respect to the shock propagation direction.

Trajectory (1) is when the shock is moving strictly perpendicular to the ambient magnetic field, thus ($\mathbf{B} = B_z\hat{z}$). For this case, there are two types of motion: bounce motion in the x direction and the acceleration imparted by the convective electric field in the $-y$ direction. The bouncing motion is between two turning points. One turning point is due to the shock potential at the shock front, and the other is due to the upstream Lorentz force.

Trajectory (2) is when the magnetic field is not strictly perpendicular to the propagation direction. In other words, the component of the magnetic field normal to the shock front is not zero. The existence of B_x changes the trajectory such that, in addition to the bounce motion and the acceleration, there is a cycloidal motion of the ion on the yz plane. Fig. 1 shows that the motion on the yz plane is no longer restricted