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Quick Ion Injection and Acceleration at Parallel Shocks

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Abstract

Although particle acceleration processes at quasi-parallel shocks have been widely discussed, the very initial injection from thermal to suprathermal energies is still controversial. Here we show that the non-linear wave-particle interaction at quasi-parallel shocks results in quick injection and quick further acceleration of non-thermal (NT) ions. Instead of an ensemble small amplitude random waves, a large-amplitude monochromatic upstream wave is set to propagate into the shock transition layer, and test particle orbits are deterministically calculated. The conversion of the wave at the shock front brings about quick injection of selected thermal ions into NT energies. Some of the NT ions leaving the shock front are quickly scattered back to the shock by the wave and experience repeated acceleration in relatively short interval. The resultant energy spectrum has the power-law index of $\sim$ -1 upto $\sim$ 20 times the upstream bulk flow energy.

1 Introduction:

Many investigations have been made to understand ion accelerations at the collisionless shock waves. The diffusive acceleration theory has been the main frame work for the studies, and stochastic scattering processes have been investigated mainly by Monte-Carlo simulations. (e.g. Ellison et al., 1990). These results have been compared with in-situ observations at the terrestrial bow shock and at interplanetary traveling shocks, and the power-law slope of the energy spectra are shown to agree well. A possible problem, on the other hand, appears when one recognizes that, at the terrestrial bow shock, the NT ions must be quickly produced because the time available for acceleration is quite limited ($200\Omega_i{}^{-1}$). Furthermore, upstream waves are usually dominated by a single mode excited by the upstream ions themselves (e.g. Winske and Leroy 1984), which might make the quasi-linear approach less convincing.

Here we assume a large-amplitude monochromatic wave to propagate into the shock front. By following test particle trajectories deterministically in the wave-field, it is shown that selected ions are quickly injected into NT energies. Some of them get further accelerated by multiple interactions at the shock within relatively short interval. All these are made possible because of the non-linear phase-trapping in the large amplitude wave (e.g. Matsumoto et al., 1974).

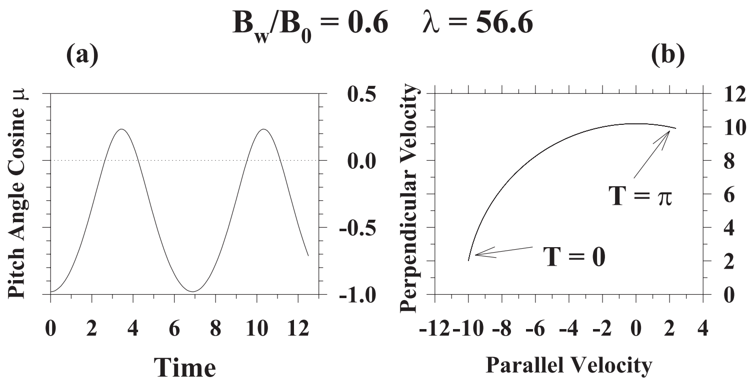

Figure 1: An example of ion motions in a large-amplitude monochromatic wave. (a) Pitch angle modulation. (b) Trajectory in the velocity space. The cyclotron resonance condition at $V_{||} \sim 9$ has little effect.

2 Ion Motion in a Large Amplitude Monochromatic Wave:

First we show the ion motion in a large amplitude parallel propagating Alfvén wave. It is noted that the ion's velocity components change in time but its energy is conserved in the wave-rest frame. When the amplitude wave is small, only cyclotron resonant ions are affected and change their pitch angles slightly. In a large amplitude case, on the other hand, non-resonant particles are also affected significantly. Figure 1 shows an example of the ion trajectories in right-hand polarized wave field. Hereafter, the magnetic field is normalized by the background value B_0: velocity, time, and length, by Alfvén velocity V_A, inverse proton gyro-frequency Ω_i^{-1}, and ion inertia length λ_i, where these are calculated with the background density and B_0. Plotted are time profile of pitch angle (μ: pitch angle cosine) in panel (a) and the trajectory in velocity space in panel (b). These are in the rest frame of the wave, whose amplitude and wavelength are 0.6 and 56.6, respectively. These are expected in the upstream of the parallel shock with $\mathrm{M_A} \sim 5$ and are actually detected by in-situ measurements. It can be seen that the pitch angle modulates over a wide range in as short as one gyro-period (2π).

3 Ion Injection at a Shock Front:

Now we consider how ions behave at the shock front while a large amplitude upstream wave propagates into it. In the 1D system where a shock is at rest, X directs from upstream to downstream region and an exactly parallel shock is located at $X = 0$. The shock Mach number is $M_A = 5$. We superpose a monochromatic Alfvén wave $B_w = (0, B_y(x), B_z(x))$, on the background magnetic field $(1, 0, 0)$. At $X < 0$, the wave is propagating upstream-wise in the fluid-rest frame. The transmitted waves at $X > 0$ are determined using shock jump conditions. The upstream monochromatic wave is chosen to be right-hand polarized with the amplitude of 0.6 (amplified to about 1.8 in the downstream). Figure 2a and 2b show how a selected ion is injected at the shock front. At time $T = 0$, the ion starts from $X = -1$ with $V_{||} = 4.2$ (shock normal velocity) and $V_{\perp} = 2.0$ (shock tangential velocity). Since the shock Mach number is 5, this ion belongs to the tail of the thermal population. At the end (as short as $T = 6\pi$), the velocity is increased up to 10.8, that is, in the NT energy range. Figure 2b shows that acceleration is mainly in $V_{\perp}$.

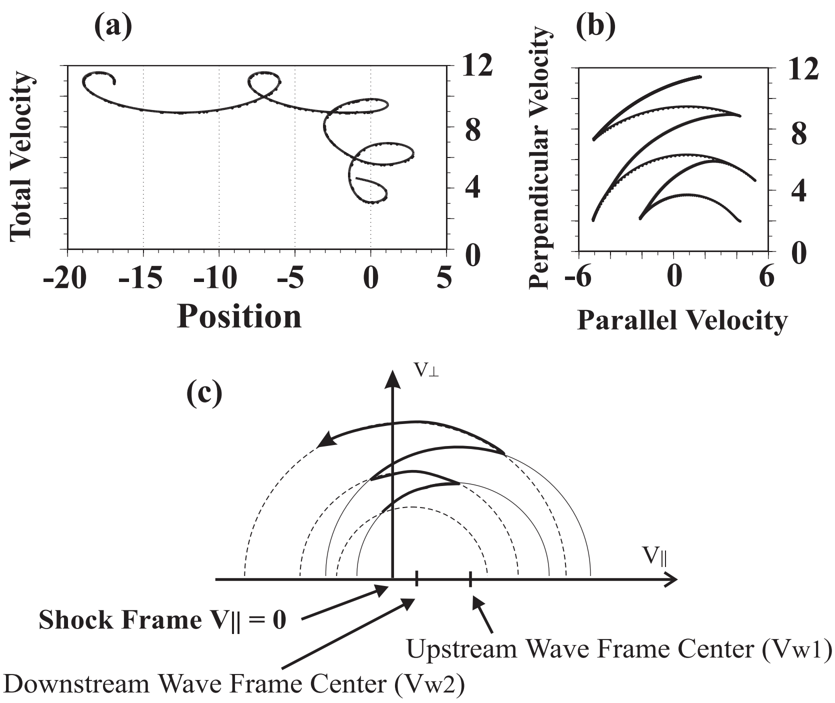

Figure 2: Ion injection at a parallel shock with a large amplitude upstream wave. (a) total velocity versus position and (b) velocity space trajectory. The trajectory in (b) is explained by repeated transfers from one wave to the other at the shock front ((c), see text).

The above injection mechanism is as follows: The reduction in fluid velocity at the shock also reduces the wave phase velocity in the shock-rest frame from V_{w1} (upstream) to V_{w2} (downstream). Consider an ion in the upstream region interacting with the wave and moving on the thin solid circle whose center is V_{w1} in Fig. 2c. When this ion is gaining energy in the shock frame, its $V_{||}$ increases and it eventually crosses the shock front (Note that a positive parallel velocity directs from upstream to downstream). To come back to the upstream region, this ion must have a negative $V_{||}$ while it interacts with the downstream wave (moving along dashed curves centered at V_{w2}). This is also an energy gaining process. This trajectory is shown by the thick curved arrow in Figure 2c. In contrast to the well-known second-order Fermi acceleration, energy is always increasing. For a thermal ion to be selected for injection as above, its phase angle is around π at the shock surface.

4 Further Acceleration by Multiple Interaction:

When only the right-hand polarized wave is present in the upstream region, upstream escaping ions' ($\mu < 0$ in Fig. 1) pitch-angle modulations are not such that would return the ions to the shock front (Fig. 1). When a large amplitude left-hand polarized wave co-exist, deterministic chaos sets in and ion trajectories cover the full μ range: Some of them are returned back to the shock front within a short time. These ions may be trapped around the shock surface again and get further accelerated. The energy spectra resulting from such a multiple interaction are shown in Figure 3a. In this calculation, both polarity waves have the same amplitude and the same wavelength of 0.6 and 56.6, respectively at upstream (linearly polarized). The energy is normalized by the upstream bulk flow energy (E_0: $M_A = 5$). The spectra are sampled from a upstream region at four different times $T = 4\pi$(gray), 12π(black thin), 44π(black thin), and 76π(black thick). Dotted line represents the power-law spectrum with index -1. The spectrum at 4 π shows freshly injected ions. Spectra at 44 and 76 π are nearly same, that is, the spectrum shape becomes stationary within a relatively short time interval. These energy spectra seem to have cut-off energy around 20 E_0. Below this energy, power-law spectrum of the index -1 is formed, which indicates that the mechanism considered here has the ability of quick injection and of highly efficient further acceleration of NT ions. The process is so quick that significant NT ions can be produced even within the limited time available at the terrestrial bow shock.

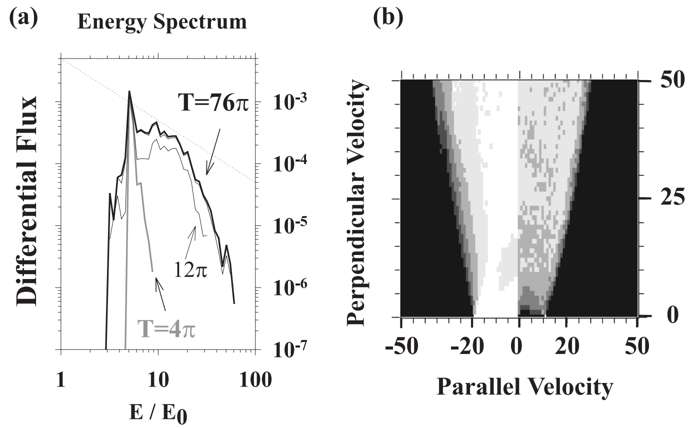

Figure 3: (a) Energy spectrum at four different times: 4, 12, 44, and 76 π. Freshly injected NT ions ($T = 4\pi$) are further accelerated rather quickly. Spectra at 44 and 76 π are nearly identical, implying a stationary shape. Below the cut-off energy around the $E/E_0 \sim 20$, the spectrum has a very hard index of $\sim$ -1 (dotted line). (b) The contour showing returning probabilities of injected ions. Ions starting from the shock front with velocities in white (black) regions (don't) return to the shock front within 76 π time interval. The demarcation around $V_{||} \sim \pm 20$ explains the cut-off energy in Panel (a).

The existence of a cut-off energy suggests that this mechanism is highly effective only upto a certain energy range. Figure 3b shows the returning probability of ions injected from the shock front. Ions starting with velocities in white (black) regions (don't) return to the shock front within 76 π time interval. Dependence on their initial phase angles causes gradation in the plot. It can be seen that it gets hard for ions with high parallel speed to return to the shock. The demarcation around $V_{||} \sim \pm 20$ results in less chance for repeated acceleration for ions with $E/E_0 > 16$, corresponding to the cut-off energy $E/E_0 \sim 20$ in the spectrum. An analysis utilizing a Poincaré plot suggests that the demarcation line will not shift much even we expand the time interval. This indicates that the high energy cut-off is an inherent property of the present mechanism.

5 Discussion:

By deterministic test particle calculations, we have shown that quick injection and further acceleration of non-thermal ions are possible at (quasi-) parallel shocks. These are possible as long as there are large amplitude monochromatic upstream waves of both polarities propagating into the shock front. While we have simply assumed their presence, there are theoretical and observational supports that this is not an unrealistic assumption, at least for the terrestrial bow shock (e.g. Omidi and Winske 1990). Indeed, consideration on the requirement for dissipation makes it quite likely that large amplitude monochromatic upstream waves are inherently associated with (quasi-) parallel shocks in general, suggesting that the present mechanism should be operating universally. Another support for the present test particle study is that the injection process is observed in self-consistent hybrid simulations (*Sugiyama, 1998*).

The present mechanism seems to have an upper energy limit upto which the efficiency is quite high. For ions above this energy, much slower diffusive action by longer wavelength turbulence may set in. How the transition occurs is an interesting topic that should be pursued in the future.

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