# The Interaction of Alfvén Waves and Perpendicular Shocks

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**Abstract.** Two-dimensional (2-D) hybrid simulations are performed to investigate the interaction between Alfvén waves and a perpendicular shock self-consistently. The shock is formed by reflecting particles at the right boundary, and Alfvén waves are injected from the left boundary. Some upstream ions can be reflected by the perpendicular shock, to be energized by the motional electric field in the shock. Therefore, these ions have a large temperature anisotropy immediately downstream of the shock, which can excite ion cyclotron waves. We discuss the transmission and enhancement of upstream Alfvén waves through the shock, and their influence on the downstream ion cyclotron waves. Their possible effects on particle acceleration by the shock are also investigated.

**Keywords:** Alfvén waves, perpendicular shock, hybrid simulations, ion cyclotron waves.
**PACS:** 52.35.Tc, 52.35Bj, 52.65.Ww

## INTRODUCTION

Particle acceleration is ubiquitous at shock waves, ranging from supernova remnants to interplanetary shocks. Diffusive shock acceleration is the mechanism thought to be responsible for the observed power-law spectra of energetic particles from cosmic rays to solar energetic particles (SEPs). The theory of diffusive shock acceleration is successful in explaining observed energetic particles at quasi-parallel shocks. At quasi-parallel shocks, upstream ions reflected by the shock can propagate far upstream along the magnetic field, and excite low-frequency plasma waves. These waves scatter ions that then cross the shock back and forth several times and the particles can be accelerated to very high energies [1-3]. However, a similar theory cannot work directly at quasi-perpendicular shocks. At quasi-perpendicular shock, the reflected upstream ions return to the shock almost immediately due to the gyromotion of the particles in the magnetic field. Furthermore, a quasi-perpendicular shock cannot generate upstream plasma waves to scatter the particles, making it difficult to accelerate particles to high energy.

Recently, cross field diffusion by large-amplitude in situ magnetic turbulence was identified as playing an important role in particle acceleration at quasi-perpendicular shock. When particles follow these irregular magnetic fields, they can also cross the shock several times. In this way, the particles can also be accelerated to high energy. This mechanism is considered to be responsible for the observed power-law spectrum of energetic particles at a perpendicular shock [4,5]. Therefore, the interaction

CP1039, *Particle Acceleration and Transport in the Heliosphere and Beyond— 7th Annual Astrophysics Conference*
edited by G. Li, Q. Hu, O. Verkhoglyadova, G. P. Zank, R. P. Lin, and J. Luhmann

between upstream Alfvén waves (as a proxy of solar wind turbulence) and quasi-perpendicular shock plays an important role in particle acceleration at quasi-perpendicular shocks. The theoretical analysis has been developed by several authors to describe the interaction between Alfvén waves and quasi-perpendicular shock [6,7]. In these works, the profiles of the shocks were fixed, and not affected by the waves. In this paper, using 2-dimensional (2-D) hybrid simulations, we investigate the interaction of Alfvén waves and a perpendicular shock self-consistently.

The next section describes the 2-D hybrid simulation results. We then summarize and discuss relevant observational evidence in the last section.

## SIMULATION RESULTS

In our hybrid simulations, the ions are treated kinetically while the electrons are considered as massless fluid [8]. The plasma consists of two ion components (proton and $He^{2+}$) and an electron component. The simulations are performed in the *x*-*y* plane. Initially, both proton and $He^{2+}$ particles satisfy a bi-Maxwellian velocity distribution with same thermal velocity, and they flow in the *x* direction. The background magnetic field is assumed to be along the *y* direction. The particles are injected from the left boundary with speed $V_b = 4.0V_A$, and the plasma beta $\beta_p = 1.0$. The number of the grid cells is $n_x \times n_y = 700 \times 256$, and the grid sizes are $\Delta x = 0.4c/\omega_{pp}$, $\Delta y = 1.0c/\omega_{pp}$ (where $c/\omega_{pp}$ is the proton inertial length). The time step is $\Omega_p t = 0.02$ (where $\Omega_p$ is the proton gyro-frequency). The shock is formed by reflecting the particles at a rigid wall to the right. Periodic boundary conditions for the particles and fields are used in the *y* direction. In what follows, we present three case studies with different properties of the injected Alfvén waves.

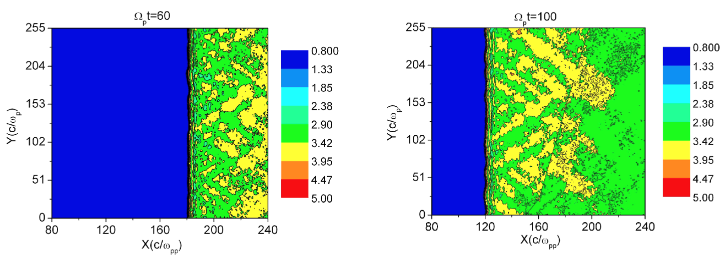


**FIGURE 1**. The distribution of the magnetic field component $B_y$ at $\Omega_p t = 60$, and 100 for the case without Alfvén waves (scales given by the colorbar to the right).

In the first case, no Alfvén waves were injected from the left boundary. Fig. 1 shows the distributions of the magnetic field $B_y$ at $\Omega_p t = 60$ and 100. The shock is formed at an earlier time, and it propagates from the right boundary to the left with a speed of about $1.6V_A$. At the same time, some upstream ions are reflected by the shock, and these particles are accelerated in the direction perpendicular to the magnetic field by the motional electric field. The ions therefore have a larger perpendicular temperature than parallel temperature immediately downstream. Such ion temperature anisotropy can excite ion cyclotron waves or mirror waves. The mirror mode, a compressive wave mode propagating obliquely to the magnetic field, should dominate the ion cyclotron waves for high-beta ( $\beta_{\parallel p} > 1$ , where $\beta_{\parallel p}$ is the parallel proton plasma beta), low-anisotropy conditions ($T_{\perp p} / T_{\parallel p} < 2$, where $T_{\perp p}$ and $T_{\parallel p}$ denote the proton temperatures perpendicular and parallel to the magnetic field, respectively) [9,10]. Ion cyclotron waves, a transverse wave mode with maximum growth rate along the magnetic field, should dominate for low-beta, high-anisotropy conditions. In this case, because the ions immediate downstream of the shock have high temperature anisotropy, ion cyclotron waves are excited downstream [11]. Ion cyclotron waves with a dominant wavelength of about $35c / \omega_{pp}$ exist just downstream of the shock, as confirmed by a Fourier analysis (not shown) of a cut along the $y$ direction.

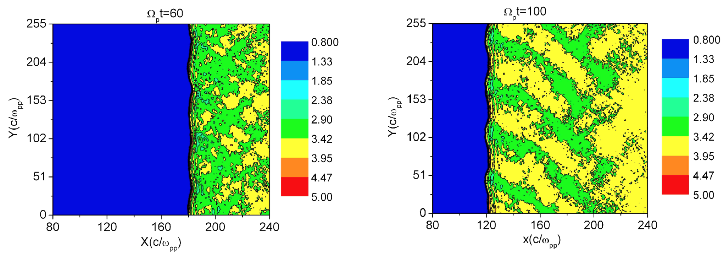


**FIGURE 2**. The same format as Fig.1 but for the case with a monochromatic Alfvén wave.

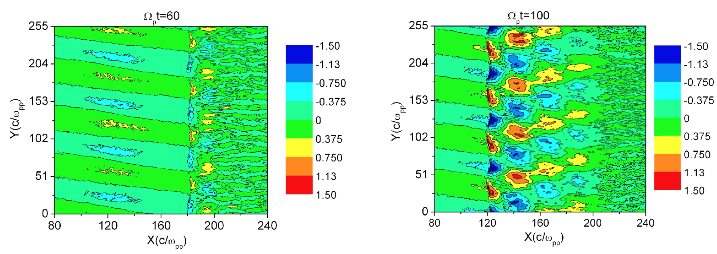


**FIGURE 3**. The distribution of the magnetic field component $B_z$ at $\Omega_p t = 60$ , and 100 for the case with monochromatic wave (scales given by the colorbar to the right).

In the second case, a monochromatic Alfvén wave was injected from the left boundary. The amplitude and wavelength of the Alfvén wave are $\delta B_{\perp} / B_0 = 0.6$ and $64c / \omega_{pp}$ , respectively. Fig. 2 shows the distribution of the magnetic field component $B_y$ at $\Omega_p t = 60$ and 100, respectively. While the shock propagates from the right boundary along the $-x$ direction, the Alfvén wave is convected to the $+x$ direction. At about $\Omega_p t = 55$ , the Alfvén wave begins to interact with the shock, and large amplitude ripples form at the shock front. Fig. 3 shows the corresponding $B_z$ component. From the figure, we find that after the Alfvén wave transmits the shock, the amplitude of the fluctuating magnetic field is enhanced by about 3-4 times. At the same time, the transmitted Alfvén wave propagates along the ambient magnetic field in the *y*-direction, while being convected away from the shock. The propagation speed is the local downstream Alfvén speed, which is larger than that upstream. For this case, the magnetic field power spectrum downstream shows that the amplitude of the ion cyclotron waves is much depressed compared with the previous case, whereas a peak corresponding to the transmitted Alfvén wave dominates.

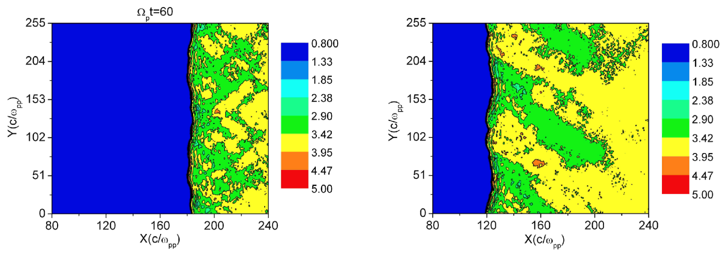


**FIGURE 4**. The same format as Fig.1 for the case with a superposition of Alfvén waves upstream.

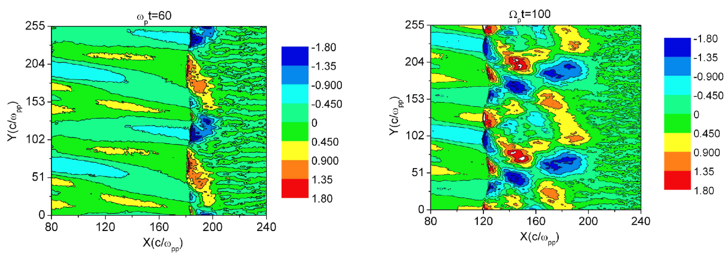


**FIGURE 5**. The same format as Fig.3 for the case with a superposition of Alfvén waves upstream.

For the third case, a superposition of Alfvén waves composed of sinusoidal waves of wavelength, $82\,c/\omega_{pp}$ , $64\,c/\omega_{pp}$ and $51.2\,c/\omega_{pp}$ , was injected from the left boundary. The corresponding power spectrum has a power-law index 1.667. Their total amplitude is $\delta B_{\perp} / B_0 = 0.6$. Fig. 4 shows the distribution of $B_y$ at $\Omega_p t = 60$ and 100, and Fig. 5 shows the corresponding $B_z$. Similar to the case of a monochromatic Alfvén wave, there are ripples at the shock front due to its interactions with Alfvén waves. Again, we find that the amplitude of the fluctuating magnetic field is enhanced by about 3-4 times after transmitting the shock.

Fig. 6 shows the spectra of energetic protons at $\Omega_p t = 100$ for the three cases described above. Clearly, the efficiency of particle acceleration was enhanced by the presence of Alfvén waves at the shock. Specifically, for the cases with injected Alfvén waves, the particle density per energy is greater than the case without Alfvén waves. More diagnostic measures, assessing particle energization/acceleration in these cases, such as test-particle calculations, are being undertaken.

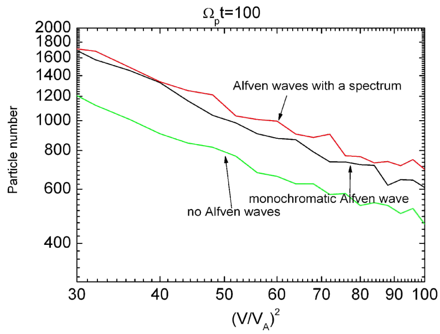


**FIGURE 6**. The spectra of energetic protons for the three cases.

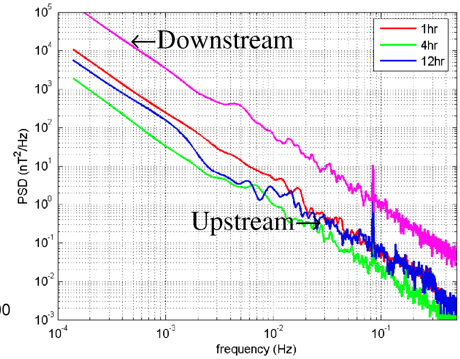


**FIGURE 7**. The PSDs of magnetic field upstream and downstream of a perpendicular shock.

## CONCLUSIONS AND DISCUSSION

In this paper, we have investigated the interaction of Alfvén waves and perpendicular shocks, using 2D hybrid simulations. In the absence of upstream Alfvén waves, the temperature anisotropy downstream of a perpendicular shock can excite ion cyclotron waves. However, in the presence of upstream Alfvén waves, the ion cyclotron waves are depressed by the Alfvén waves transmitted through the shock. The amplitude of the Alfvén waves is enhanced by about 3-4 times as they transmit the shock, consistent with prior theoretical work [6,7]. At the same time, the efficiency of particle acceleration by the shock appears to be enhanced when we inject Alfvén waves from the left boundary.

Observations have shown that at interplanetary perpendicular shocks, energetic ions can also be accelerated efficiently, presumably via the diffusive shock acceleration mechanism [5]. Fig. 7 shows the magnetic field Power Spectral Density (PSD) upstream (red, green, and blue lines) and downstream (pink line) of such a shock, adapted from [5], where the upstream PSDs were calculated for three intervals located at increasing distances from the shock. The PSD downstream was calculated for an interval immediately after the shock. The shock normal forms an angle of 92±4° with ambient upstream magnetic field. No apparent enhancement of magnetic field fluctuations, often indicative of wave activity, with distances approaching the shock upstream exists, whereas such an enhancement is often observed at quasi-parallel shocks [5]. However, the power of downstream fluctuations is enhanced by about an order of magnitude, consistent with our simulation results presented above.

## ACKNOWLEDGMENTS

We thank Garry Webb at University of California, Riverside for valuable discussions. Q. M. Lu was partly supported by the National Science Foundation of China (NSFC) under Grants Nos. 40725013 and 40674093.

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