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Self-consistent simulation of field-aligned ion beams and upstream waves in quasi-parallel collisionless shock

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A collisionless shock is thought to be an efficient accelerator of charged particles in space. At a quasi-parallel Earth's bow shock, spacecraft directly measure the so-called diffuse ions, which are quasi-isotropic non-thermal ion component. Diffusive shock acceleration (DSA) is expected to produce the diffuse ions. In the model particles gain a high energy due to the shock compression via many times of the shock crossing, through scatterings by electromagnetic waves upstream and downstream of the shock. However, it remains unclear how and where the diffuse ions are produced escaping from the thermal pool of the solar wind plasma. In this presentation, we perform a self-consistent full particle-in-cell (PIC) simulation of a quasi-parallel collisionless shock to investigate the processes such as upstream wave excitation and resultant particle scattering and acceleration.

In the PIC simulation, the plasma and electromagnetic field evolve self-consistently in one-dimensional space along x axis. Plasma consists of ions and electrons and both are treated as particles. The plasma is continuously injected from the left boundary of the system, and the incoming plasma is reflected at the right boundary. A mixture of the incoming and reflected plasmas results in the plasma in the downstream. Hence, the simulation is in the downstream rest frame. Background magnetic field lies in x-z plane, and is inclined at an angle of 20 degrees from the shock normal direction along the x axis. The plasma parameters are ion and electron betas of 0.5, electron plasma frequency of $\omega_{pe}=12.5\Omega_e$, electron gyrofrequency of $\Omega_e=64\,\Omega_i$, and Alfven velocity of $V_A=0.01c$, where Ω_i and c are the ion gyrofrequency and the light speed, respectively.

Image of Figure 1(a) shows the evolution of magnetic field fluctuation along y direction in space and time. The wave magnetic field is traveling from the left side with the velocity slightly smaller than the incoming plasma flow velocity, $0.05c$, which is indicated by the slope of the dashed line for the reference. This represents the excited wave, traveling toward the upstream in the plasma rest frame, is convected by the plasma flow. The convected wave is discontinuously slow down with its increased wave amplitude. The wave discontinuity shown by the white dashed line corresponds to the shock front, which is traveling to the negative x direction, with the shock speed of $-0.016c$. Thus, the Alfven Mach number of M_A is 6.6 in the present simulation.

Figure 1(b) shows the two components (B_y and B_z) of wave magnetic field indicated the red and blue lines, respectively, at $\omega_{pe}t=120000$. At far upstream ($1700<x\,\Omega_i/V_A<1900$), the wave is almost monochromatic with the wavelength of $58V_A/\Omega_i$. The beam ions along the upstream magnetic field generate the Alfvenic wave via the right-hand resonant ion-ion instability[1]. The resonance condition predicts the wave length of $75V_A/\Omega_i$, using a specularly reflected velocity in the plasma frame of $2M_AV_A=13V_A$. The simulation result roughly matches with the theory. The quasi-monochromatic wave is amplified and compressed during the plasma convection.

In Figure 1(a), the trajectory of a highly accelerated ion sampled from the macro-particles is superimposed on the B_y fluctuation. The ion speed, v, corresponding to the trajectory in the x-t space is shown in Figure 1(c), and is evaluated in the upstream rest frame. The ion injected into the shock as a part of the incoming ions follows the four steps: (1) reflection at the shock, (2) scattering toward the shock by the excited upstream waves, (3) gain of the energy during the interaction with the shock, and (4) escaping far upstream as a highly accelerated ion without the scattering by the upstream waves. The acceleration mechanism is similar to the quick acceleration around the quasi-parallel shock proposed by Sugiyama et al (2001)[2].

In this presentation, we will discuss the spatial and temporal evolution of the upstream waves related with the backstreaming ion properties. Interaction between electrons and high-frequency waves is also presented. Our results have important implications in understanding the injection process for the DSA upstream of the Earth's bow shock.

References
[1] Gary et al., *J. Geophys. Res.*, 86, 6691, 1981
[2] Sugiyama et al., *J. Geophys. Res.*, 106, 21657, 2001

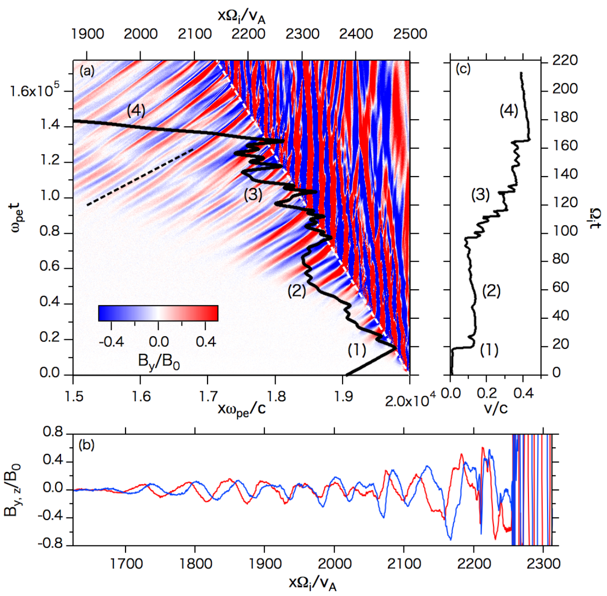

Figure 1: (a) Evolution of the wave magnetic field and trajectory of an accelerated ion, (b) wave magnetic field profile at $\omega_{pe}t=1.2\times10^5$, and (c) the ion speed vs. time.