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Perpendicular Ion Acceleration in Anisotropic Whistler Turbulence
非等方的ホイッスラー乱流によるイオン垂直加速

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Whistler turbulence has an anisotropic property in wavenumber at electron scales. These waves have electrostatic components perpendicular to the background magnetic field. In this study, a full kinetic, two-dimensional particle-in-cell simulation has been done, and shows that whistler turbulence can accelerate ions in the direction perpendicular to the background magnetic field. When the ions resonate with electrostatic fluctuations of quasi-perpendicularly propagating whistler waves, the ions are effectively accelerated in the perpendicular direction. The simulation results suggest that whistler turbulence contributes to the perpendicular heating of ions observed in the solar wind.

1. Introduction

Solar wind plasma often has anisotropic velocity distribution of ions. Marsch *et al.* (1982) [1] showed that temperature anisotropy $T_{\|}>T_{\perp}$ is a persistent feature of high-speed solar wind, where $T_{\|}$ and $T_{\perp}$ are ion temperature parallel and perpendicular to the background magnetic field, respectively. Ion cyclotron wave, which is the left-hand polarized wave, is a plausible candidate to explain the anisotropic heating [2].

As the ion cyclotron wave is dissipated at the ion scale through the cyclotron resonance, a right-hand polarized whistler wave could remain at the kinetic scales (ion and electron spatial scales) [3]. A reduced magnetic helicity in ion scale observed in the solar wind suggests that the magnetic fluctuations are predominantly right-hand polarized if the fluctuations are assumed to propagate outward from the Sun [4]. While recent theoretical and observational studies emphasize that kinetic Alfvén turbulence is essential for the dissipation of the solar wind turbulence, the whistler turbulence is also used to explain the property of the turbulence in ion and electron kinetic scales. We expect that whistler turbulence as well as kinetic Alfvén turbulence would play a key role in the dissipation of the energy of solar wind turbulence.

Here we investigate the wave-particle interaction of ions with decaying whistler turbulence by using a particle-in-cell simulation. We find that the ions are accelerated preferentially perpendicular to the background magnetic field by the electrostatic fluctuations of quasi-perpendicularly propagating whistler waves. See detail explanation shown in a paper published in *Physics of Plasmas*, **21**, 042303 (2014) [5].

2. Simulation model

We use a two-dimensional, particle-in-cell simulation code modified from the TRISTAN code [6]. We use a GPU (Graphics Processing Unit: K20c) to accelerate the calculation in the simulation, using the zigzag method to calculate the electric current associated with the charged-particle motion [7]. We consider the plasma behavior in two spatial dimensions and a fully three-dimensional velocity space. Initial parameters used here are as follows: the ion to electron mass ratio is $m_i/m_e=400$; the temperature ratio is $T_i/T_e=1$, the ratio of the electron plasma to the electron cyclotron frequency is 1.58; the electron plasma beta value is $\beta=0.05$; and the ratio of the electron thermal speed to the light speed is $v_{t,e}/c=0.1$. Note that we assume a relatively hot plasma and relatively small mass ratio (<1836) in order to reduce the computational cost. The background magnetic field $\mathbf{B}_0$ is along the x direction. As in previous studies [8,9], we impose 42 whistler-mode waves at t=0. The imposed fluctuation energy is $|\delta\mathbf{B}|^2=0.1|\mathbf{B}_0|^2$.

3. Simulation results

Figure 1 shows the time evolution of the wavenumber spectra of the whistler turbulence. The initial whistler turbulence cascades its magnetic fluctuation energy into larger wavenumbers as seen in the panels labeled (a). The magnetic energy spectrum is preferentially extended in the k_y direction, which is perpendicular to the background magnetic field. The panels labeled (b) also show that E_y spectra extend to larger k_y. Whistler waves at electron scales with wavenumber vector toward

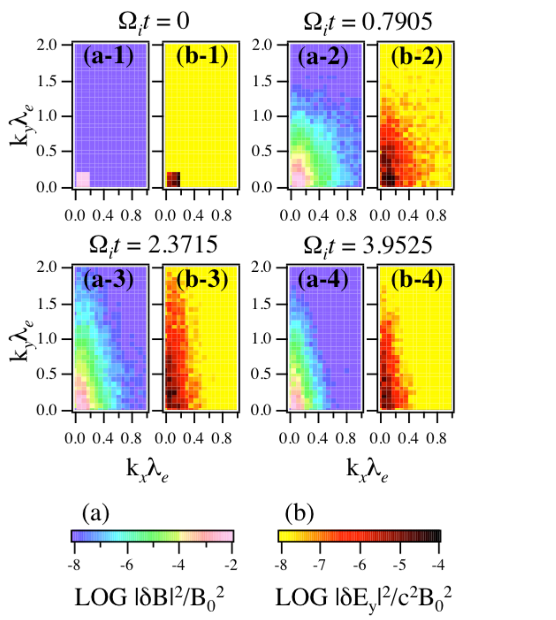

Figure 1: An overview of the perpendicular ion acceleration during the development of the anisotropic whistler turbulence. The panels labeled (a) in the top line show the magnetic wavenumber spectra $|\delta \mathbf{B}|^2=|\delta B_x|^2+|\delta B_y|^2+|\delta B_z|^2$. The panels labeled (b) show the electric wavenumber spectra $|\delta E_y|^2$. This figure has been published as the top line of FIG. 1 in [5].

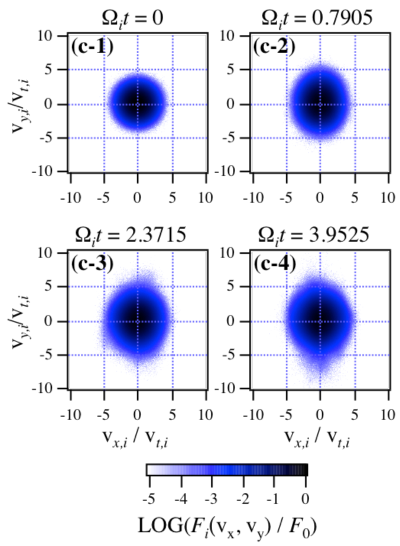

Figure 2: The reduced ion velocity distribution function $F_i(v_x,v_y)$, which is the integration of $f_i(v_x,v_y,v_z)$ in the v_z direction. Here F_0 is $F_i(v_x=0, v_y=0)$ at t=0. This figure has been published as the bottom line of FIG. 1 in [5].

to the quasi-perpendicular direction tend to be electrostatic, meaning that these waves predominantly contain the electrostatic component.

Figure 2 shows time evolution of reduced ion velocity distribution. The initial state is isotropic because the ion bulk component associated with the initial whistler turbulence is neglected in order to simplify the initial condition. At $\Omega_i t=0.79$, the distribution becomes broader than the initial distribution because of the response to the whistler turbulence. The ion bulk component is self-consistently created at a relatively early stage in this simulation. After the whistler turbulence is well developed, high-energy ions are gradually produced in the perpendicular direction at later times. Several ions reach at a velocity of approximately $>8v_{t,i}$, where $v_{t,i}$ is the ion thermal speed.

4. Conclusion

We have performed a two-dimensional, particle-in-cell simulation and shown that whistler turbulence can accelerate ions in a direction perpendicular to the background magnetic field. Quasi-perpendicularly propagating whistler waves in whistler turbulence have electrostatic fluctuations as described in linear theory. Ions are almost unmagnetized in the electron time and spatial scales. Thus the electrostatic fluctuations of the whistler waves with wavenumber vector toward to the quasi-perpendicular direction can resonate with ions through Landau resonance as the resonance condition $\omega-\mathbf{k}\cdot\mathbf{v}=0$ is satisfied. We expect that more ions can satisfy the wave-particle resonance condition at higher beta values (at which the wave phase speed normalized to the ion thermal speed becomes smaller); thus, we propose that whistler turbulence contributes to the perpendicular heating of ions observed in the solar wind at a distance of 1 AU. Further discussion is in a paper published in *Physics of Plasmas*, **21**, 042303 (2014) [5].

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