Anisotropic evolution of highly-oblique Alfvén waves in the presence of hot drifting ions

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Plasma heating and cooling in the solar wind is a dynamic process, which can occur sporadically at various heliocentric distances. Simultaneously the magnetic field power spectra is observed to be anisotropic with different spectral slopes in directions parallel and perpendicular with respect to the background magnetic field. Observational analysis shows compelling evidence for in situ ion heating via wave-particle interactions, as well as plasma cooling regulated by linear or non-linear kinetic micro-instabilities. However which types of waves and related plasma instabilities are most efficient in scattering the ions and contribute most to the evolution of the observed anisotopric turbulence remain open questions, which requires further investigations. In this theoretical study we perform 2.5D hyrbid simulations to investigate the anisotropic evolution of highly oblique ion-cyclotron waves, sometimes known as kinetic Alfvén waves, in the presence of drifting hot protons and alpha particles. The current model applies to two ion species – protons and alpha particles. Results from previous studies including the effect of other minor ions such as Oxygen 5^+, or the effect of solar wind expansion for the evolution of two-stream instability has been presented in [8, 7]. In all fore-mentioned studies the electron dynamics within the current hybrid model is not resolved and they are treated as an isothermal massless fluid, used for charge neutrality and current conservation. To model the initial input waves for the simulations we perform linear instability analysis and calculate the magnetic field and the plasma fluctuations, corresponding to obliquely propagating dispersive Alfvén waves at various propagation angles. The reconstruction of the magnetic field follows the approach given in [4]. We consider hot initially isotropic drifting multi-species plasma with $V_{\alpha p} = 0.44 V_{\mathrm{A}}$, $\beta_p = \beta_a = 0.33$, and select initial parameters to describe the in situ observed undisturbed solar wind conditions as shown in [6]. In previous studies we have found strong anisotropic heating of He^{++} by monochromatic and broad-band parallel dispersive Alfvén waves [1, 2, 3, 5]. Furthermore the ion beam formations and minor ion heating by oblique waves at different angles have been compared to the corresponding plasma heating by parallel Alfvén-cyclotron waves [6]. The generation of oblique waves from initially strictly parallel Alfvén waves has been shown in [5]. In this study we extend our previous findings by focusing on the evolution of the magnetic field fluctuations and their spectral properties.

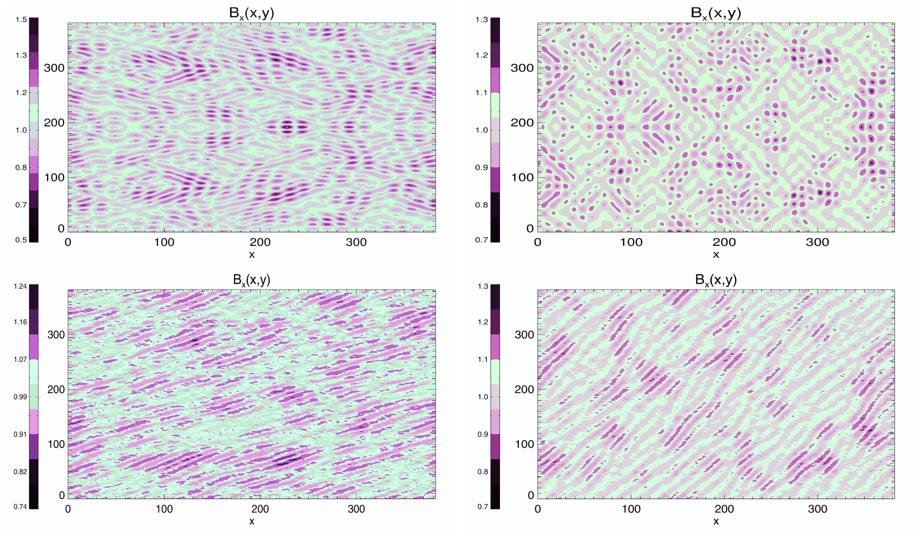

Figure 1: *The initial and final stages of the normalized parallel component of the magnetic field fluctuations $\delta B_x/B_0$ in real space for 2 initial propagation angles (see text for details).*

The interplanetary magnetic field sets a preferential direction in which often additional heating and acceleration take place. The power spectra of magnetic fluctuations in the solar wind typically follow a turbulent power law whose slope depends on the observed frequencies and corresponding wave-numbers. The solar wind plasma temperature and the turbulent magnetic fluctuations at ion scales simultaneously show anisotropic features, with different temperature components and fluctuation power in parallel and perpendicular direction with respect to the orientation of the background magnetic field. At the same time the evolution of the solar wind turbulence at the ion and electron scales in return is influenced by the plasma properties through micro-instabilities and wave-particle interactions. The current work aims to perform simulation analysis of the temporal variation of the magnetic field power spectral slopes and discuss their dependence on the parallel and perpendicular wave-numbers.

Figure 1 describes the variation of the magnetic field fluctuations during the nonlinear evolution of the system. The figure describes two cases corresponding to initial oblique Alfvén waves at different propagation angles. The top panels show the initial profiles of the magnetic field fluctuations as a function of the simulation box coordinates x and y, normalized to the proton inertial length d_i. The bottom panels show the late-stage evolution at $\omega_{pc}t = 800$, where ω_{pc} is the proton gyro-frequency. The upper and lower left panels describe fluctuations, initially propagating at around 30°, whereas the right panels correspond to highly oblique fluctuations with propagation angles close to 60°. The end stage of the simulations show formation of coherent structures, which co-exist with the developed ion temperature anisotropies as described in [6]. The following Figure 2 describes the evolution of the corresponding spectral slopes of

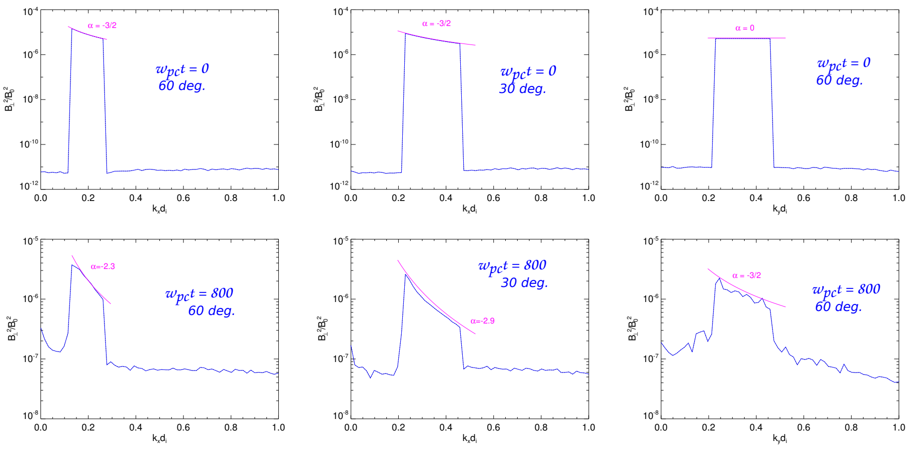

Figure 2: *Initial and final PSD of the magnetic field fluctuations at* 30° *and* 60° *as a function of parallel* $k_x d_i$ *and perpendicular* $k_y d_i$ *normalized wave numbers.*

the magnetic field in parallel and perpendicular direction in Fourier space. The upper panels show the initial spectral slopes. The bottom panel show the late-stage evolution at $\omega_{pc}t = 800$. From left panels shows the power spectra density (PSD) of the magnetic fields as a function of the parallel wave-number for highly oblique propagation angles close to 60°. The middle panels show the PSD as a function of the parallel wave-number for the case of initial oblique waves with angles around 30°. The right panels show the evolution of the PSD for the same case shown in the left panels, but as a function of the perpendicular wave-numbers. The results show steeper spectral slopes as function of the parallel wave-number k_x. Nevertheless, we should note that in this case the initial turbulence was already anisotropic with different slopes in k_x and k_y. To generalize and re-validate our results further studies with initially isotropic turbulence are being performed, which will be presented in an upcoming publication.

Figure 3 shows the evolution in Fourier space of the PSD of the magnetic field fluctuations initially propagating at highly oblique angle $\geq 60°$. From left to the right (top and bottom) the figure shows snapshots with the PSD in Fourier space at $\omega_{pc}t = 1, 10, 595$ and 800. The first panel represents the input magnetic field power. The right panel on the top shows beating of daughter waves excited by nonlinear wave-wave interactions at the early stage of the evolution at $\omega_{pc}t = 10$. At this stage simultaneous cascade in k_x and k_y is observed with generation of strictly perpendicular kinetic Alfvén waves. At the late stages $\omega_{pc}t = 595$ and $\omega_{pc}t = 800$ shown at the bottom, the initial power is further transferred in k_x and k_y, and some strictly parallel waves are being generated, which remain present until the end of the simulations.

From the plots above we can draw several conclusions about the evolution of the magnetic field fluctuations in the presence of hot drifting proton-alpha ion species. The first conclusion

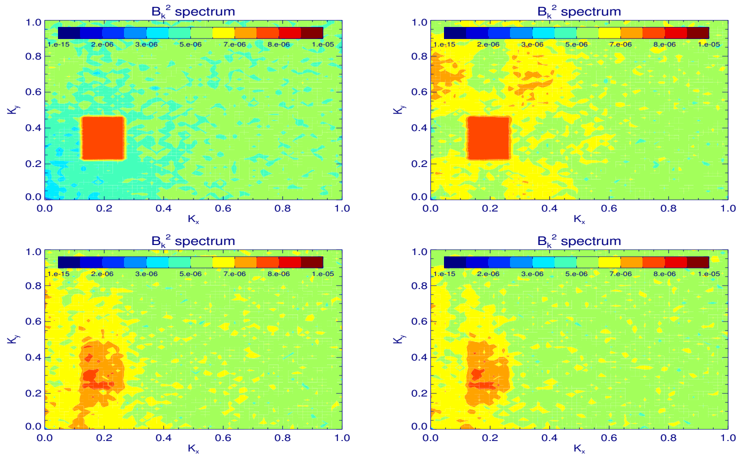

Figure 3: *Evolution of the two-dimensional PSD of the magnetic field fluctuations in Fourier space.*

is that the initially choatic magnetic fields tend to get more organized and develop coherent structures. The second conclusion is that the perpendicular component of the magnetic field power spectral density evolves in an anisotropic manner as a function of the parallel k_x and perpendicular k_y wave numbers. Furthermore the spectral slopes of the PSD depend on the angle of propagation. The parallel and quasi-parallel waves propagating around 30° exhibit steeper slopes in k_x than the highly oblique waves. In addition the spectral slopes in k_x appear steeper than the spectral slopes in k_y. This means that during the evolution of the solar wind turbulence most of the observed power is expected to remain in perpendicular direction, as observed in situ at $1AU$. Lastly, the third Figure 3 shows the presence of beating with nonlinear cascade towards strictly perpendicular wave numbers. This process could contribute to the generation of highly-oblique kinetic Alfvén waves as observed in the undisturbed solar wind near the Earth.

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