

Interactive comment on “On heating of solar wind protons by the breaking of large amplitude Alfvén waves” by Horia Comișel et al.

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Reply to referee comments

On heating of solar wind protons by the breaking of large amplitude Alfvén waves

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Thank you very much for reading the manuscript and raising helpful comments and suggestions.

C1

- *This manuscript describes a hybrid kinetic simulation study of a parametric instability in which two counter-propagating Alfvén waves couple with a spectrum of ion acoustic modes to transfer fluctuation energy from the former into the latter. This is an interesting configuration to examine, but the manuscript is incomplete because it does not clearly discuss the physical consequences of the computation.*

The central problem here is that Figure 3 and the associated discussion is not clearly defined. I do not agree that Figure 3 shows that the velocity distributions are “different for the three analyzed systems”; to my eye the six panels of Figure 3 are qualitatively all the same.”

Reply:

Figure 3 has been updated by including a missing term ($1/v_{\perp}$) used to properly compute the velocity distribution function in cylindrical coordinates. The velocity distribution function f is computed by counting the number of particles $dN = f(v_{\perp}, v_{\parallel}, \Phi)dV$ in the volume element $dV = v_{\perp}dv_{\perp}dv_{\parallel}d\Phi$, and by integrating over the azimuthal Φ angle. Here, $v_{\perp} = \sqrt{v_{\perp 1}^2 + v_{\perp 2}^2}$ is the velocity component perpendicular to the mean magnetic field, v_{\parallel} is the parallel velocity, and the angle $\Phi = \arctan v_{\perp 1}/v_{\perp 2}$ gives the sign of v_{\perp} . At times ($t\Omega_p=300$; $t\Omega_p=600$), the updated plots are slightly different from those shown in former Fig. 3.

We accept the referee criticism that there are no obvious differences between the velocity distributions shown in Fig. 3 (or in new Fig.3). However, one can notice a distinct trend of evolution for the distributions between the intermediate ($t\Omega_p=300$) and the final time of simulation ($t\Omega_p=600$). At the final time, the contour levels in the 3D simulation are moderately enlarging both in the parallel and perpendicular directions by following the contour levels of energy conservation

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driven by the pitch-angle scattering of protons. The contour levels in 1D and 2D runs, in contrast, are developing mainly towards parallel direction while their initial perpendicular displacement is removing with time elapsing.

Changes in the manuscript:

- Page 5: Line 6 to Line 10:
 "The velocity distribution function f is computed by counting the number of particles $dN = f(v_{\perp}, v_{\parallel}, \Phi)dV$ in the volume element $dV = v_{\perp}dv_{\perp}dv_{\parallel}d\Phi$, and by integrating over the azimuthal Φ angle. Here, $v_{\perp} = \sqrt{v_{\perp 1}^2 + v_{\perp 2}^2}$ is the velocity component perpendicular to the mean magnetic field, v_{\parallel} is the parallel velocity, and the angle $\Phi = \arctan v_{\perp 1}/v_{\perp 2}$ gives the sign of v_{\perp} ."
- Page 5: Line 11 to Line 14:
 "Due to the transversal wave field imposed at the initial condition, the velocity distribution functions are rigid shifted towards the initial bulk velocity $\pm u_{\perp}$, see e.g., Verscharen2011, Nariyuki2011. The two symmetrical sets of contour levels with respect to the $v_{\perp} = 0$ axis are slowly merging with the time evolution and at time $t\Omega_p=300$ there are no remnants of the rigid displacement observed at the initial time."
- Former manuscript, Page 5: Line 1 to Line 3 - deleted.
- Page 6: Line 6 to Line 11:
 "Although there are no obvious differences between the velocity distributions in the three different setups, one can notice a distinct trend of evolution for the distributions between the intermediate ($t\Omega_p=300$) and the final time of simulation ($t\Omega_p=600$). At the final time, the contour levels in the 3D simulation are moderately enlarging both in the parallel and perpendicular direc-

C3

tions by following the contour levels of energy conservation driven by the pitch-angle scattering of protons. The contour levels in 1D and 2D runs, in contrast, are developing mainly towards parallel direction while their initial perpendicular displacement is removing with time elapsing."

- *I disagree that "the final distribution functions for the 3D system ... report a larger perpendicular acceleration. To substantiate this claim, the authors should do the velocity integrations to compute T_{\parallel} and T_{\perp} as functions of time through the simulation.*

Reply:

The time evolutions of T_{\parallel} and T_{\perp} determined during the simulation runs are shown in new Figure 4. Figure 4 reports that the perpendicular temperature (normalized to its initial value) achieved in the 3D system at the final time ($t\Omega_p=600$) is about two times larger than that one from the 2D system.

Changes in the manuscript:

- Page 6: Line 11 to Line 14:
 "The more efficient heating of plasma in the 3D system is consistent with the time evolution of the ion temperature shown in Fig. 4. The particles experience a similar parallel heating while the perpendicular temperature achieved in the 3D system (solid line) dominates by a factor of two or more the corresponding values obtained in the 1D (dotted line) and 2D (dashed line) simulations. "

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- *The sentence “... these arcs coincide with the most obliquely parts of contour lines while the outer contours are better overlapped than the inner ones” is confusing, and I find the subsequent discussion through page 6 difficult to follow.*

Reply:

This sentence and the following ones (Page 5, Line 16 to Page 6, Line 9 in the former manuscript) have been deleted. Instead, we introduced a new comment discussed above (Page 6, Line 6 to Line 11). The next paragraph in the former manuscript (Page 6, Line 10 to Line 14) was replaced by the following comment.

Changes in the manuscript:

- Page 6: Line 15 to Line 29:

“These results suggest that the damping of the ion sound waves excited by the field aligned parametric decay is the main mechanism of plasma heating in the 1D and 2D systems. In the 3D system, the protons are also heated in the perpendicular direction by the cyclotron damping of waves. The ions are perpendicular scattered by the field aligned and the oblique developed Alfvén daughter waves.

Figure 1 shows that the amplitude of the anti-parallel propagating Alfvén daughter wave decreases with increasing spatial dimension, while the level of the density fluctuation is similar. The power spectrum $\delta\vec{B}^2(k_{\parallel})$ is obtained by the Fourier transformation of the averaged magnetic field, $\delta\vec{B}(r_{\parallel}) = \int \delta\vec{B}(r_{\perp 1}, r_{\perp 2}, r_{\parallel}) dr_{\perp 1} dr_{\perp 2}$, in the assumption of strictly parallel wave propagation. Any deviation from the parallel direction will conduct to a reduction of the E^D amplitude of the daughter mode. A slight obliquity (several degrees) of the daughter wave mode is noticed in the 3D system but the rea-

C5

son remains unclear within the simulation work here and needs further investigations. The pitch-angle scattering and the perpendicular temperature increase observed in the time evolutions of the velocity distribution functions and temperatures, respectively, suggest that the Alfvén daughter waves are in cyclotron resonance with protons and the wave-particle interaction could explain the deviation in the propagation angle and the stronger damping of the daughter waves in the 3D system. A detailed spectral analyzing of the oblique wave modes developed in the decay process based on the 2D reduced magnetic field spectrum will be subject for a further study.”

- *Add the $t=0$ contours to Figure 3, and compute the T_{\parallel} and T_{\perp} values as functions of time to quantify the statements in the discussion.*

Reply:

Done.

Changes in the manuscript:

- Fig. 3 is updated with time $t=0$.
- New Fig. 4 shows the time evolution of temperatures.

- *A central point of this manuscript is that the 3D simulations yield better results than the corresponding 1D and 2D results. This point should be made in the Abstract and repeated in the Conclusion section.*

C6

Reply:
We thank the referee for this suggestion.

Changes in the manuscript:

- Abstract, Page 1: Line 3 to Line 6:
“The comparison made among different spatial dimensions proves that the three-dimensional simulation exhibits more efficient heating. Plasma is heated parallel to the mean magnetic field by the damping of the ion acoustic waves while being heated perpendicular by the cyclotron resonance and damping of protons by Alfvén daughter waves.”
 - Conclusion, Page 6: Line 33 to Page 7 Line 4:
“By comparing the wave modes and proton velocity distribution functions in 1D, 2D, and 3D systems, we conclude that the plasma is heated more efficient in the 3D system, thus proving that the 3D simulations yield better results than the corresponding 1D and 2D results. Parallel heating of plasma is provided by the damping of ion sound waves while perpendicular heating is given by the perpendicular scattering of protons by the field aligned and the oblique developed Alfvén daughter waves.”
- *The proton velocity distributions measured from spacecraft in the fast solar wind often show a beam component and a core component with different relative densities and relative flow velocities parallel to the background magnetic field. Figure 3 of this manuscript shows two proton components of equal densities with relative flow velocities perpendicular to B_0 . The Abstract claims the results of the simulations are in agreement with in situ measurements; to justify this claim, the authors need to explain these differences.*

C7

Reply:
We reformulated the sentence as follows: “In the solar wind context, the antisunward part of the core component of the proton velocity distributions is controlled by the sunward-propagating waves driven by the parametric decay.”

Changes in the manuscript:

- Page 1: Line 6 to Line 7
“In the solar wind context, the antisunward part of the core component of the proton velocity distributions is controlled by the sunward-propagating waves driven by the parametric decay.”
- *Title: There is no discussion or demonstration of wave “breaking” here, this word should be deleted from the title.*

Changes in the manuscript:

- Title: We replaced “breaking” by “parametric decay”.
- *Page 2, Line 9: Delete “so”.*

Reply:
Done.

Changes in the manuscript:

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- Page 2: Line 9.

- Page 2, Line 23: "Low-beta"?

Reply:
Done.

Changes in the manuscript:

- Page: 2, Line 23: "low-beta plasmas."

- Page 2, Line 31: "in directions perpendicular" ...

Reply:
Done.

Changes in the manuscript:

- Page: 2, Line: 31.
"... in directions perpendicular to the mean magnetic field."

- Page 3, Line 12: Replace "circularly" with "circular".

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Reply:
Done.

Changes in the manuscript:

- Page 3, Line 16.

- Page 3, Line 15: Replace "transversal" with "fluctuating".

Reply:
Done.

Changes in the manuscript:

- Page 3: Line 19
"The initial fluctuating magnetic field ..."

- Page 3, Lines 18-19: "The parametric decay modeled here is a 3-wave process involving a large-amplitude monochromatic Alfvén pump wave propagating parallel to B_0 , a spectrum of electrostatic ion acoustic waves also at parallel propagation, and a spectrum of Alfvén daughter waves at anti-parallel propagation."

Reply:
Done.

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Changes in the manuscript:

- Page 3: Line 23 - 25

"The parametric decay modeled here is a three-wave process involving a large-amplitude monochromatic Alfvén pump wave propagating parallel to B_0 , a spectrum of electrostatic ion acoustic waves also at parallel propagation, and a spectrum of Alfvén daughter waves at anti-parallel propagation."

- Page 3, Line 22: Delete "linear" (saturation is a nonlinear process).

Reply:
Done.

Changes in the manuscript:

- Page 3: Line 28.

- Page 3, Line 23: Delete "nonlinear"; it is unnecessary.

Reply:
Done.

Changes in the manuscript:

C11

- Page 3: Line 29.

- Page 3, Line 33: "... and the lower panels correspond to the end of the simulation ($t \Omega_{cp} = 600$)."

Reply:
Done.

Changes in the manuscript:

- Page 4: Line 7

"... and the lower panels correspond to the end of the simulation ($t \Omega_p = 600$)."

- Page 6: Insert the definitions of the solid lines and the dashed lines in the caption to Figure 3.

Reply:
Done.

Changes in the manuscript:

- Caption of Fig. 3:

"... The dashed lines describe the locus $(v_{\parallel}, v_{\perp})$ of the particle velocities

C12

$v = \sqrt{(v_{\parallel} - V_{ph})^2 + v_{\perp}^2}$ where their energy is conserved in the wave frame. Here V_{ph} is the phase speed of the Alfvén wave.”

Other changes in the manuscript:

- Page: 3, Line 11 to line 15
“The value of beta parameter 0.01 is set in order to keep the same value of beta in all the 1-D, 2-D, and 3-D setups for the purpose of comparison, and moreover, a lower value of beta (such as 0.01) is not irrelevant from the solar wind studies. In fact, the solar wind plasma originates in the corona and the low-beta plasmas are more representative in the inner heliosphere. Therefore, we regard our numerical studies not only for understanding the solar wind but also for understanding the solar corona.”
- Page 4: Line 4 to Line 6
“The time evolution of the velocity distribution functions is usually helpful to emphasize the role of the kinetic regime on the saturation of the instability via particle trapping and wave particle interactions.”
- Page 4: Line 13 to Line 16
“This is a consequence of the low values for the electron beta ($\beta=0.01$) and ion beta ($\beta=0.01$) used in the simulation. At very low electron temperatures, the contribution of the electron pressure term to the electric field ($\nabla P_e = \nabla n k_B T_e$) is small and the particle density fluctuations n are less efficient in coupling to the electric field fluctuations.”