Ann. Geophys. Discuss.,
https://doi.org/10.5194/angeo-2018-14-AC2, 2018

Annales Geophysicae Discussions

Interactive comment on "On heating of solar wind protons by the breaking of large amplitude Alfvén waves" *by* Horia Comişel et al.

Horia Comişel et al.

h.comisel@tu-braunschweig.de

Received and published: 16 April 2018

Reply to referee comments

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

Manuscript ID: angeo-2018-14 (AngeoComm)
H. Comişel, Y. Nariyuki, Y. Narita, and U. Motschmann

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

- *The manuscript #angeo-2018-14 by ComiÂÿsel et al. discusses heating of protons during the course of nonlinear evolution of a large amplitude Alfven wave in the solar wind. The author used a hybrid code to conduct 1D, 2D, and 3D simulations all started with a circularly polarized pump Alfven wave imposed at the initial condition. The simulation results showed that an efficient proton heating in the perpendicular direction occurs in 3D, but not in 1D and 2D. I think the finding itself is interesting and the paper is potentially worth for publication. However, the authors' discussion does not explain how the discrepancy arises between the different simulations. Also, there is a plenty of room for improvement in the quality of presentation. Therefore, I believe that substantial revisions need to be made on the manuscript before the publication.*

  Major Issues

  The simulation results suggested that pitch-angle scattering by both the pump and daughter Alfven waves are more important than the heating in the parallel direction via damping of ion sound waves in 3D. In contrast, 1D and 2D results suggested that the pitch-angle scattering are less important compared to 3D. It is not entirely clear how the difference arises. If you look at Figure 1, you can clearly see that the ion sound wave amplitudes do not change much between 2D and 3D. On the other hand, the amplitude of the daughter Alfven wave in 3D is much less than that in 2D. Apparently, this contradicts with the behavior seen in the distribution function. The 3D simulation presented in the paper is quite large and should contain a lot of information. My impression is that the authors did not make use of the benefits of the large-scale simulation. I would encourage the authors to conduct more detailed analysis and draw more physically sound and grounded conclusions based on the data.

Reply:

Figure 1 shows indeed 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 $\delta\vec{B}^2(k_\|)$ is obtained by the Fourier transformation of the averaged magnetic field,

$$\delta\tilde{\vec{B}}(r_\|) = \int \delta\vec{B}(r_{\perp 1}, r_{\perp 2}, r_\|)dr_{\perp 1}dr_{\perp 2},$$

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 reason 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.

The velocity distribution functions have been updated (please see our answer concerning Fig. 3 below). Although there are no obvious differences in the three analyzed 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 directions 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. The more efficient heating of plasma in the 3D system is consistent with the time evolution of the ion temperature shown in the new added Figure 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.

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.

Changes in the manuscript:

- Former manuscript, Page 6: Line 10 to Line Line 14 - deleted.
- Page 6: Line 19 to Line 29
  "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 $\delta\vec{B}^2(k_\|)$ is obtained by the Fourier transformation of the averaged magnetic field, $\delta\tilde{\vec{B}}(r_\|) = \int \delta\vec{B}(r_{\perp 1}, r_{\perp 2}, r_\|)dr_{\perp 1}dr_{\perp 2}$, 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 reason remains unclear within the simulation work here and needs further in-

vestigations. 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."

- Page 6: Line 6 to Line 18
  "Although there are no obvious differences in the three analyzed 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 directions 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. The more efficient heating of plasma in the 3D system is consistent with the time evolution of the ion temperature shown in Figure 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.

  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."

- *The authors used beta = 0.01, which is very small in comparison with the solar wind at 1 AU. Please consider to state the motivation for adopting this particular value. Also, the author may think it better to include discussion on the dependence of the plasma beta.*

  Reply:
  We agree and accept the referee's criticism. It is true that we are aiming at the simulations for a higher value of beta (ideally a beta value of unity for the solar wind at 1 AU) but the numerical costs become increasingly higher at higher values of beta and in a three-dimensional setup. The reason for this is the fact that a considerably large number of particles needs to be used for high-beta plasmas and also the number of cells or mesh grids increases in three dimensions.

  The value of beta value 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.

  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."

- *P.2, L. 23: "the conditions of beta plasmas" does not make sense.*

  Reply:
  We specify now low-beta plasmas.

  Changes in the manuscript:

  - Page 2: Line 23
    " ... the conditions of low-beta plasmas".

- *P.3, L. 29: The sentence ending with "due to most probably the small value of electron beta used in simulation" needs more clarification.*

  Reply:
  We delete "most probably" and add the sentences below.

  Changes in the manuscript:

  - Page: 4 Line 13 to Line 16
    "This is a consequence of the low values for the electron beta (β=0.01)

and ion beta (β=0.01) used in the simulation. At 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.".

- *P.4, L. 25: What the authors meant by the sentence "We see that these arcs..." is not clear. I can guess what you wanted to mention, but in general, it is not a good idea to let the readers guess the meanings.*

  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 18).

- *Figure 2: Are the color scales linear or logarithmic? Are they the same or different between the four panels? It is difficult for me to see behaviors in the low-energy part of the distribution function. Is this the authors' intention?*

  Reply:
  The color code is given in logarithmic scales. The color code bars are now added to each panel in new Figure 2. The purpose of using the color code representation is to identify the occurrence of vortices in the velocity phase space.

  Changes in the manuscript:

– Figure 2 is updated.
– 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."

- *Figure 3: It would be better to add a description for the dashed lines in the caption. The authors' definition of v_perp should never become negative. You need a more clear description what the distribution functions in Figure 3 represent.*

Reply:
Done.
Figure 3 has been updated by including a missing term $(1/v_\perp)$ used to properly compute the velocity distribution functions 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 $v_\perp$. The updated plots are slightly different from those shown in former Fig. 3. The distribution functions at the initial time are also introduced.

Changes in the manuscript:

– The caption of Fig. 3
"... The dashed lines describe the locus $(v_\parallel, v_\perp)$ of the particle velocities

$v = \sqrt{(v_\parallel - V_{ph})^2 + v_\perp^2}$ where their energy is conserved in the wave frame. Here V_{ph} is the phase speed of the Alfvén wave."
– Page 5: Line 7 to Line 9
"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 $v_\perp$ in Fig. 3."
– 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 tΩ_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.

Other changes in the manuscript:

– Title of the paper: Instead "breaking of ..." we introduced "parametric decay of ..." in order to avoid any confusion.
– Abstract Page 1: Line 3 to Line 7
"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. 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."

- Page 6: Line 32 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 pitch-angle scattering is the mechanism able to describe the perpendicular broadening observed in the particle velocity distribution functions."