AIP | Physics of Plasmas

Ion temperature in plasmas with intrinsic Alfven waves

C. S. Wu, P. H. Yoon, and C. B. Wang

Citation: Physics of Plasmas (1994-present) **21**, 104507 (2014); doi: 10.1063/1.4897376
View online: http://dx.doi.org/10.1063/1.4897376
View Table of Contents: http://scitation.aip.org/content/aip/journal/pop/21/10?ver=pdfcov
Published by the AIP Publishing

PHYSICS OF PLASMAS **21**, 104507 (2014)

Ion temperature in plasmas with intrinsic Alfven waves

C. S. Wu,[1,2] P. H. Yoon,[2,3] and C. B. Wang[1]
[1]*CAS Key Laboratory of Geospace Environment, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China*
[2]*Institute for Physical Science and Technology, University of Maryland, College Park, Maryland 20742, USA*
[3]*School of Space Research, Kyung Hee University, Yongin, Gyeonggi 446-701, Korea*

(Received 27 August 2014; accepted 24 September 2014; published online 10 October 2014)

This Brief Communication clarifies the physics of non-resonant heating of protons by low-frequency Alfvenic turbulence. On the basis of general definition for wave energy density in plasmas, it is shown that the wave magnetic field energy is equivalent to the kinetic energy density of the ions, whose motion is induced by the wave magnetic field, thus providing a self-consistent description of the non-resonant heating by Alfvenic turbulence. Although the study is motivated by the research on the solar corona, the present discussion is only concerned with the plasma physics of the heating process. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4897376]

The purpose of this brief communication is two fold: to discuss a fundamental issue and to point out an important implication that may be significant for the study of solar physics. The present study actually grew out of some earlier works.[1–3] The previous as well as the present research is motivated by the fact that Alfven waves pervade almost the entire solar atmosphere and the solar wind.[4–8] Although the physical origins of these waves are still not fully understood, from the viewpoint of plasma physics, it is anticipated that these waves may result in significant effects on many basic kinetic processes in the region. Two seemingly simple but fundamental questions need to be addressed: first, can ions maintain thermal equilibrium in the presence of the intrinsic turbulence and, second, if yes, what is the relevant "temperature"? We expect that in general the thermodynamic state of the plasma should be affected, one way or the other, by the preexisting Alfven waves. To look into this issue, we make use of the quasilinear approach in plasma physics.[9–12] In order to make the discussion self-contained, we first briefly review the discussion in Ref. 1 in the following.

We pay attention to protons (because the analysis is mass-dependent in general) and we presume that the protons are in thermal equilibrium with a Maxwellian velocity distribution function when the Alfven waves are absent,

$$F_p(v_z, v_\perp) = \frac{m_p^{3/2}}{(\pi T_{0\perp} T_{0z})^{3/2}} \exp\left(-\frac{m_p v_\perp^2}{2T_{0\perp}} - \frac{m_p v_z^2}{2T_{0z}}\right), \tag{1}$$

where m_p denotes proton mass; T_0 is that proton temperature; and subscripts z and $\perp$ denote directions parallel and perpendicular to the ambient field. It is anticipated from the viewpoint of statistical physics that the presence of Alfvenic turbulence the distribution function should be affected. To study this issue, we invoke a non-resonant quasilinear theory[1] which considers weak Alfvenic turbulence (i.e., the energy density of the Alfven waves is much lower than that of the ambient magnetic field). It is found that the intrinsic waves then modify the proton distribution function[1] to the following form:

$$F_p(v_z, v_\perp) = \frac{m_p^{3/2}}{(\pi T_{p\perp} T_{0z})^{3/2}} \exp\left(-\frac{m_p v_\perp^2}{2T_{p\perp}} - \frac{m_p v_z^2}{2T_{0z}}\right), \tag{2}$$

where

$$T_{p\perp} = T_{0\perp} + \frac{\delta B_w^2}{8\pi n_p}, \tag{3}$$

and n_p is the proton density; $\delta B_w^2/(8\pi) \equiv \int d^3k \langle \delta B_k^2 \rangle/(8\pi)$ denotes the Alfven wave energy density while $\langle \delta B_k^2 \rangle$ represents the spectral energy of the turbulent wave magnetic field of wave $\mathbf{k}$. The distribution function described by Eq. (2) includes the effect of the preexisting Alfven waves on the distribution function expressed by Eq. (1). Moreover, Eq. (3) implicates a heating process normal to the ambient magnetic field. Since no energy transfer from the Alfven waves to the protons is considered in the theory, there is no dissipation. An issue arises thereby: how can "heating" take place without dissipation? This issue makes some readers feel uncomfortable. The theory is further studied in two subsequent publications[2,3] whereas the issue is not settled. In this report, we explain why the heating process[3] occurs without dissipation.

Let us begin the discussion by considering the general expression for the wave energy density. If it is denoted by W, it may be expressed as[13,14]

$$W = \int d^3k \left\{ \frac{1}{\omega_k} \frac{\partial}{\partial \omega_k} [\omega_k^2 a_i \varepsilon_{ij}(\mathbf{k}, \omega_k) a_j^*] \frac{\langle \delta E_k^2 \rangle}{8\pi} \right\}, \tag{4}$$

where $\varepsilon_{ij}(\mathbf{k}, \omega_k)$ is the ij component of dielectric tensor relevant to the wave mode of interest; $\mathbf{a}$ is the unit polarization vector and $\mathbf{a}^*$ denotes its complex conjugate; $\langle \delta E_k^2 \rangle/(8\pi)$ represents the spectral energy of the turbulent wave electric field; ω_k is the wave frequency and $\mathbf{k}$ is the wave vector. Clearly in general the wave energy density depends not only upon the energy of the wave field but also on the plasma response to the wave field. If we denote the latter by W_{plasma}, it may be written as

$$W_{\text{plasma}} = \int d^3k \left\{ \frac{1}{\omega_k}\frac{\partial}{\partial \omega_k}[\omega_k^2 a_i \varepsilon_{ij}(\mathbf{k},\omega_k) a_j^*] - 1 \right\} \frac{\langle \delta E_k^2 \rangle}{8\pi}. \tag{5}$$

Indeed, it is well known in MHD theory that coherent Alfven wave may induce a fluid motion[15] by which the plasma can attain a significant amount of kinetic energy. However, it is not useful to compare the MHD finding with the present theory in which not only kinetic theory of ions but also turbulent Alfvén waves are under consideration. Hence, the issue should be considered self-consistently on the basis of Eq. (2). Thus, a discussion is given as follows.

Let us consider the convention of the coordinate system $\mathbf{k} = (k_\perp\ \mathbf{i}_x,\ 0,\ k_z\ \mathbf{i}_z)$, which is widely used in the literature of plasma physics. On the basis of such a coordinate system, the perturbation current and the polarization vector of the Alfven wave are both parallel to the x axis[16,17] such that the dispersion equation of the standard Alfven wave may be in general written as

$$\frac{k_z^2 c^2}{\omega_k^2} = \varepsilon_{xx}(\mathbf{k}, \omega_k). \tag{6}$$

Furthermore for Alfven waves, we can show

$$\varepsilon_{xx} \approx -\frac{\omega_p^2}{\Omega_p^2}\int d^3v \frac{1}{\omega_k^2}\left\{(\omega_k - k_z v_z)^2 - \frac{k_z^2 v_\perp^2}{2}\right\} F_p, \tag{7}$$

where the proton velocity distribution function of protons F_p so far is supposed to be arbitrary. We now return to Eq. (5) and make use of Eqs. (2) and (7). It is found that

$$W_{\text{plasma}} = \int d^3k \left\{ \frac{\langle \delta B_k^2 \rangle}{8\pi} \right\} \equiv \frac{\delta B_w^2}{8\pi}. \tag{8}$$

It is important to keep in mind that $W_{\text{plasma}} (= \delta B_w^2/8\pi)$ actually represents an amount of kinetic energy of the ions due to motion induced by the wave magnetic field. The motion is actually reflected in the distribution function by Eq. (2). This finding has resolved the puzzling "riddle" and explains the heating process peculiar to the case of Alfvenic turbulence. The heating process is reversible and has no dissipation.

Let us now move on to the other purpose of this communication: we suggest that the proton temperature $T_{p\perp}$ defined in Eq. (3) should in principle represent observed proton temperature, assuming that we are technically capable to measure it. In this sense, the theoretical prediction may have important implications. At least, it leads to a physical picture very different from what we have conjectured and supposed before. A comparative discussion of the theory and available observations is beyond the scope of this paper in which the discussion mainly focuses on issue of interest to the basic plasma physics. However, we shall comment on some elementary considerations.

First of all, past research efforts discussed in the solar physics literature have shown that it is exceedingly difficult, if not impossible, to explain of the origin of the hot solar corona on the basis of the traditional perception of heating. However, the new finding gives us a hope to find a way out. The hot coronal plasma might be attributed to intrinsic Alfvenic turbulence. We agree that much research is needed to prove this point. There are some encouraging clues. For instance, if the quasilinear approach is used to study minor ions in the solar corona, we find that the temperature of heavy ions is much higher than that of the protons if they are affected under the same level of turbulence. It may be readily shown

$$T_{s\perp} - T_{s0} = \frac{\delta B_w^2}{8\pi n_p}\left(\frac{m_s}{m_p}\right) = \left(\frac{m_s}{m_p}\right)(T_{p\perp} - T_{0\perp}). \tag{9}$$

Here subscript s denotes a minor ion species; T_{s0} is the temperature while the Alfven waves are absent; m_s and m_p are the minor ion mass and proton mass, respectively. The above theoretical prediction is consistent with observations[18–22] which show (i) in general, almost all ion species have anisotropic temperatures such that $T_\perp > T_z$, and (ii) the heavier the ion species, the higher the anisotropy. However, since the local turbulence level is not known, a quantitative discussion along this line is difficult. Maybe the observed anisotropy can help us infer the local turbulence level.

Finally, we summarize that the present theory may lead to several achievements. First, we may explain the hot corona without recourse to the traditional perception of heating due to dissipation. Second, the scenario may enable us to understand the temperature gradient and structure inside the solar transition region. Third, it might also enable us to discuss the issue of "non-thermal motion" of minor ions in the corona, a topic that has attracted much attention in solar physics community and is briefly reviewed in Ref. 23.

Indeed, human understanding of the solar atmosphere is still very primitive even after many years research. On the observational and theoretical fronts there are still many unresolved issues. We agree that before we can understand the pervasively and continuously generated Alfven waves in the solar atmosphere, the present theory is still incomplete.

C.S.W. wants to thank the University of Science and Technology of China in Hefei, China for hospitality during his recent visit. We enjoyed fruitful discussions with D. J. Wu and G. Q, Zhao at the Purple Mountain Observatory of Chinese Academy of Sciences, in Nanjing, China. P.H.Y. acknowledges the support by the BK21 plus program through the National Research Foundation (NRF) funded by the Ministry of Education of Korea, and NSF grant AGS1242331 to the University of Maryland. Research by C.B.W. was supported by the NSFC under Grant Nos. 41174123 and 41121003, and by the CAS under Grant No. KZZD-EW-01.

[1] C. S. Wu and P. H. Yoon, Phys. Rev. Lett. **99**, 075001 (2007).
[2] P. H. Yoon, C. B. Wang, and C. S. Wu, Phys. Plasmas **16**, 102102 (2009).
[3] C. B. Wang and C. S. Wu, Phys. Plasmas **16**, 020703 (2009).
[4] L. F. Burlaga, Space Sci. Rev. **12**, 600 (1971).
[5] J. V. Hollweg, Rev. Geophys. Space Sci. **13**, 263 (1975).
[6] R. Erdeyi and V. Fedun, Science **318**, 1572 (2007) and references therein.
[7] E. Marsch, Living Rev. Sol. Phys. **3**, 1–100 (2006).

[8] A. Keiling, Space Sci. Rev. **142**, 73 (2009).
[9] A. A. Galeev and R. Z. Sadgeev, in *Review of Plasma Physics*, edited by M. A. Leontovich (Consultant Bureau, New York 1965), Vol. 7.
[10] R. C. Davidson, *Methods in Nonlinear Plasma Theory* (Academic, New York, 1972).
[11] A. I. Akhiezer, I. A. Akhiezer, R. V. Polovin, A. G. Sitenko, and K. N. Stepanov, *Plasma Electrodynamics, Nonlinear Theory and Fluctuations* (Pergamon, New York, 1975), Vol. 2.
[12] T. Stix, *Waves in Plasmas* (AIP, New York, 1992).
[13] Yu. L. Klimontovich, *The Statistical Theory of Non-Equilibrium Processes in a Plasma* (MIT Press, Cambridge, MA, 1967).
[14] D. B. Melrose, *Plasma Astrophysics* (Gordon and Breach, New York, 1980), Vol. I.
[15] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Pergamon Press, Oxford, 1960).
[16] V. D. Shafranov, in *Review of Plasma Physics*, edited by M. A. Leontovich (Consultant Bureau, New York 1967), Vol. 3.
[17] A. Hasegawa, *Plasma Instabilities and Nonlinear Effects* (Springer-Verlag, New York, 1975).
[18] J. L. Kohl, G. Noci, E. Antonucci, G. Tondello, M. C. E. Huber, L. D. Gardner, N. Nicolosi, L. Strachan, S. Fineschi, J. C. Raymond, M. Romoli, D. Spadaro, A. Panasyuk, O. H. W. Siegmund, C. Benna, A. Ciaravella, S. R. Cranmer, S. Giodano, M. Karavska, R. Martin, J. Michels, A. Modigliani, G. Naletto, C. Pernechele, G. Poletto, and P. L. Smith, Solar Phys. **175**, 613 (1997).
[19] J. L. Kohl, G. Noci, E. Antonucci, G. Tondello, M. C. E. Huber, S. R. Crammer, L. Strachan, A. V. Panasyuk, L. D. Gardner, M. Romoli, S. Fineschi, D. Dobrzycka, J. C. Raymond, P. Nicolosi, O. H. W. Siegmund, D. Spadaro, C. Benna, A. Ciaravella, S. Giordano, S. R. Habbal, M. Karovska, X. Li, R. Martin, J. M. Michels, A. Modigliani, G. Naletto, R. H. O'Neal, C. Pernechele, G. Poletto, P. L. Smith, and R. M. Suleiman, Astrophys. J. **501**, L127 (1998).
[20] S. R. Cranmer, J. L. Kohl, G. Noci, E. Antonucci, G. Tondello, M. C. E. Huber, L. Strachan, A. V. Panasyuk, L. D. Gardner, M. Romoli, S. Fineschi, D. Dobrzycka, J. C. Raymond, P. Nicolosi, O. H. W. Siegmund, D. Spadaro, C. Benna, A. Ciaravella, S. Giordano, S. R. Habbal, M. Karovska, X. Li, R. Martin, J. G. Michels, A. Modigliani, G. Naletto, R. H. O'Neal, C. Pernechele, G. Poletto, P. L. Smith, and R. M. Suleiman, Astrophys. J. **511**, 481 (1999).
[21] S. R. Cranmer, G. B. Field, and J. L. Kohl, Astrophys. J. **518**, 937 (1999).
[22] E. Marsch, Space Sci. Rev. **87**, 1 (1999).
[23] G. A. Doschek, J. T. Mariska, H. P. Warren, C. M. Brown, J. L. Culhane, H. Hara, T. Watanabe, P. R. Young, and H. E. Mason, Astrophys. J. **667**, L109 (2007).