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Pseudoheating of protons in the presence of Alfvénic turbulence

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The possibility of heating of protons via Alfvén waves is a topic that stimulates much discussion in both plasma physics and astrophysics. Conventional thinking is that dissipation is essential for heating. In two recent discussions it is shown that turbulent Alfvén waves can enhance stochastic particle motion via scattering. This process can lead to a higher proton temperature. In this Letter two essential points are stressed: First, there is no dissipation; second, physically the temperature increment is "apparent" rather than genuine, and consequently the heating is spurious. If the turbulent wave field should diminish, the proton temperature returns to its original value. The purpose of this communication is to elucidate and explain the above points. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3068472]

All known heating processes occurring in neutral gases or plasmas are either due to dissipation of kinetic energy of orderly motion or at the expense of energy supplied by external sources. In layman's language heating means that the random motion of particles at microscopic level is significantly enhanced so that the temperature of a given species is increased. For a neutral gas interparticle collisions, in general, play the essential role. For instance, compression of a gas in a shock wave can result in enhanced collisions in the shock layer so that part of the kinetic energy associated with the upstream motion is converted into that of random motion of particles. As a result, the temperature of the downstream gas is increased. Physically such an energy conversion process is irreversible and it implies "dissipation" of the orderly motion.

However, it is well known that in high temperature plasmas such as the solar and stellar coronae, collisions are infrequent and cannot lead to the observed high temperature. Thus, the origins of hot solar and stellar coronae[1–3] are longstanding issues that are still not fully understood. Solar physicists have conjectured for many years that Alfvén waves may be important for the creation of the solar corona.[4,5] Generally these studies are mostly based on the notion that resonant wave-particle interactions may convert part of the wave field energy to particle thermal energy.[6–11] However, it is well known that no thermal protons can be resonant with Alfvén waves in low beta plasmas such as the solar corona since the condition of cyclotron resonance is not satisfied. This difficulty motivates us to search for some kind of wave-proton interaction process that can enhance microscopic random motion of protons but not based on resonant wave-particle interactions so that there is no dissipation of the wave field. Indeed this is a conjecture. The rationale is that, in principle, if Alfvén waves are turbulent waves, the wave magnetic field could result in enhanced stochastic particle motion via scattering. It is shown in the two preceding discussions[12,13] that our conjecture is verified. In these discussions two fundamentally different approaches are used and yet we are able to show the similar conclusion. Since the heating process discussed in Refs. 12 and 13 does not require dissipation, one may ask whether this "heating" makes sense. The main purpose of this Letter is to clarify this important and essential question.

First of all, as shown in Ref. 13, based on a quasilinear theory it is found that in the presence of Alfvénic turbulence the proton temperature is enhanced. This is indicated by the following relation:

$$T_p \approx T_0 + \frac{W}{n_0}, \tag{1}$$

where T_0 denotes the plasma temperature in the absence of the turbulent Alfvén waves, W is the energy density of turbulent Alfvén wave field, and n_0 is the plasma density. One may view the above result from a different angle: The "heat" energy is actually associated with the induced particle motion that tends to enhance the total wave energy (as discussed in plasma kinetic theory for Langmuir waves[14,15]).

Here we reiterate two points: (i) In the derivation of expression (1) only nonresonant quasilinear wave-particle scattering is considered and, therefore, there is no dissipation, and (ii) expression (1) indicates explicitly that if W should diminish the temperature returns to its initial value. The second point implies that this rather special heating process is physically reversible. The reason is that the enhanced stochastic motion is actually parasitic to the turbulent wave field (the stochasticity is manifested by the Maxwellian distribution shown in Ref. 13). If the waves should subside the heating is expected to disappear. It is in this sense that the heating is spurious and different from that defined conventionally. Therefore we name such a process as "pseudoheating." Similarly the temperature T_p in expression (1) should

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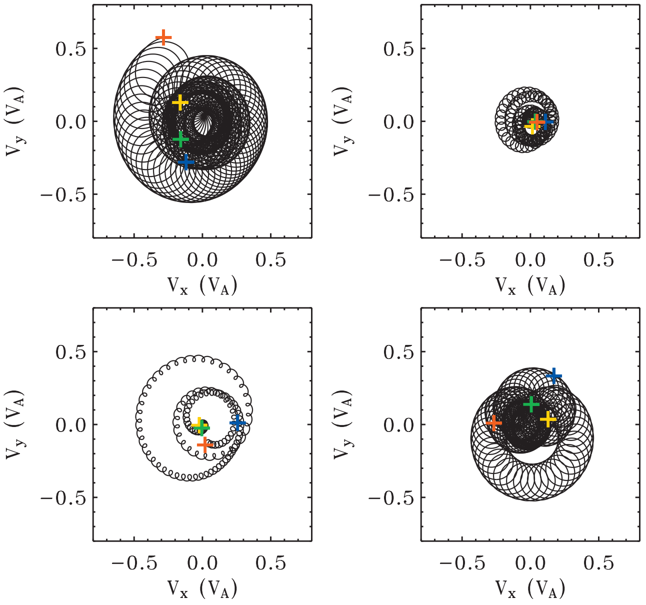

FIG. 1. (Color) The orbits of four arbitrarily picked protons with almost equal initial velocities are shown in four panels. The purpose of these plots is to show that protons with slightly different initial velocities can have substantially different orbits. In each panel the times are marked by colored crosses: The yellow is the particle position at $\Omega_p t=0$, the green is at $\Omega_p t=250$, the blue is at $\Omega_p t=500$, and the red is at $\Omega_p t=1000$. The numerical scheme is similar to that described in Ref. 12. Fifty-one Alfvén waves are used in the simulation in which frequencies are uniformly distributed in the range $0.01\Omega_p<\omega<0.05\Omega_p$. The amplitude of each wave mode is considered to be equal but changes gradually with time such that $\delta B^2=\Sigma_k B_k^2=\epsilon(t)B_0^2$, where $\epsilon(t)=\epsilon_0\exp[-(t-t_1)^2/\tau^2]$ for $t<t_1$, and $\epsilon(t)=\epsilon_0$ for $t_1\le t\le t_2$, $\epsilon(t)=\epsilon_0\exp[-(t-t_2)^2/\tau^2]$ for $t>t_2$. We suppose $t_1=500\Omega_p^{-1}$, $t_2=1000\Omega_p^{-1}$, $\tau=100\Omega_p^{-1}$, and $\epsilon_0=0.1$, where Ω_p is the proton gyrofrequency. The initial velocities of test particles are randomly distributed and possess a Maxwellian distribution with thermal speed about $0.1v_A$.

also be distinguished from that associated with a real heating process. Thus, we call it "apparent temperature." Here it should be emphasized that astrophysical observations based on spectroscopic data cannot discriminate apparent temperature and real temperature. It is entirely possible that in many remote cosmic environments of interest pseudoheating rather than genuine heating might prevail.

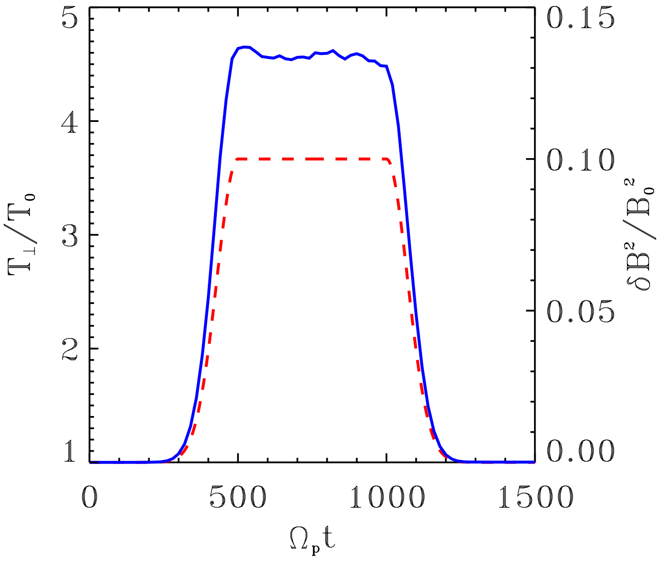

FIG. 2. (Color online) Temperature (solid line) and wave field strength (dashed line) acquired with numerical simulation are displayed. Profiles are plotted vs time.

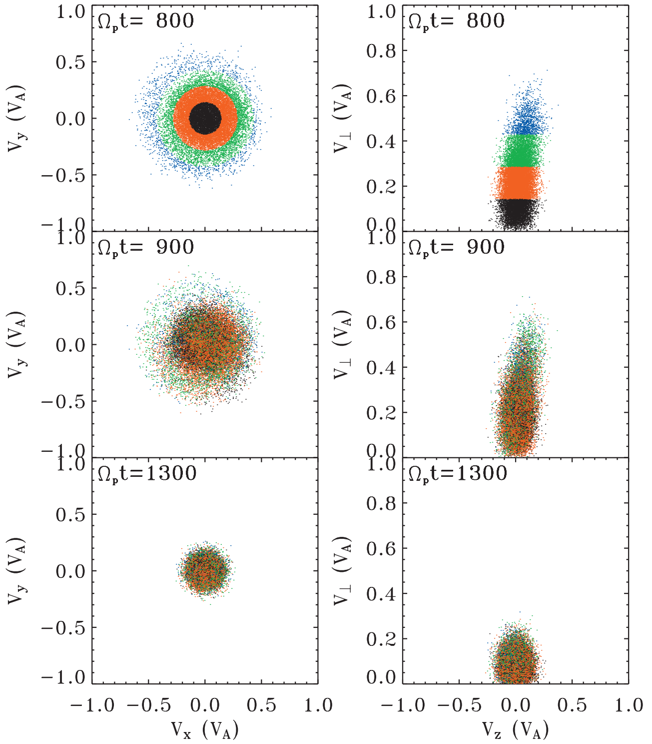

FIG. 3. (Color) Scatter plots of the test particle velocities in the v_x-v_y and $v_\perp-v_z$ planes at time $\Omega_p t=800$, $\Omega_p t=900$, and $\Omega_p t=1300$, where $v_\perp=\sqrt{v_x^2+v_y^2}$ and v_z are the velocity components perpendicular and parallel to the ambient magnetic field. At $\Omega_p t=800$ the "heated" protons with perpendicular speeds in the ranges $[0\text{–}1/7)v_A$, $[1/7\text{–}2/7)v_A$, $[2/7\text{–}3/7)v_A$, and $(\ge 3/7)v_A$ are painted with black, red, green, and blue colors, respectively. We see their "mixing" and randomization in the subsequent moments. This result confirms the stochasticity of the proton motion. As shown, the heating diminishes eventually when the turbulent Alfvén waves subside at $\Omega_p t=1300$. This point is also reflected in Fig. 2.

The underlying physics why turbulent Alfvén waves can "randomize" proton motion is actually described in Refs. 12 and 16. Pitch-angle scattering plays the key role. This point can be conveniently discussed if we work in the wave frame. In the wave frame the thermal protons have a bulk speed equal to the Alfvén speed. The turbulent Alfvén waves scatter the incident protons in a stochastic manner so that the protons are randomly accelerated (in the transverse directions) via scattering (at the expense of their initial motion in the parallel direction). As a result, the initial unidirectional motion of protons (in the wave frame) is thereby transformed into random motion in directions normal to the ambient field. To further discuss the physics we carry out a series of numerical study. The numerical scheme is similar to that described in Ref. 12. In the simulation the turbulent waves are imposed and withdrew slowly and adiabatically. However for simplicity we assume that there are no newly created ions during the emergence of the intrinsic waves.

In Fig. 1 we present the orbits of four arbitrarily picked protons, which have similar initial velocities. We consider a time interval of $1000\Omega_p^{-1}$ and pay attention to the motion in v_x-v_y plane, which is perpendicular to the ambient magnetic

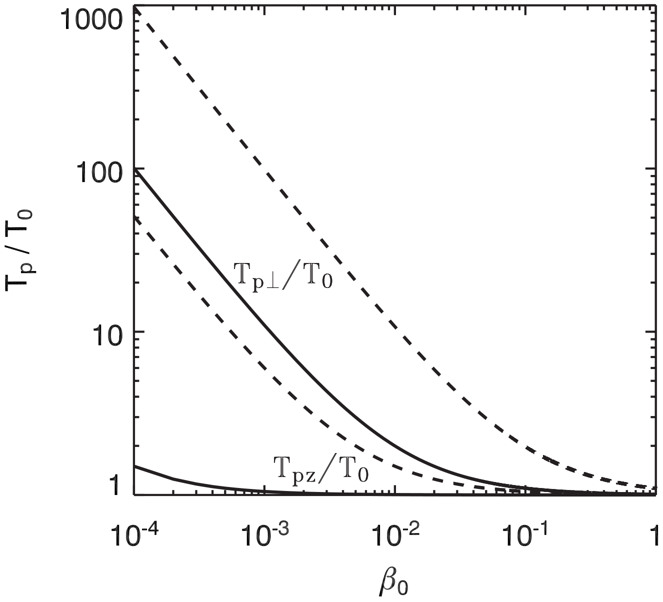

FIG. 4. Results of a generalized calculation of proton apparent temperatures versus proton beta $\beta_0=8\pi n_0 T_0/B_0^2$ based on Eq. (11) in Ref. 13. Note that the proton beta is defined with the temperature T_0 without Alfvénic turbulence. The dashed and solid lines show the results for the cases of $\delta B^2/B_0^2=0.1$ and 0.01, respectively.

field. It is found that although the motion of an individual particle is regular, particles with slightly different initial velocities, the subsequent orbits are qualitatively different, implicating that their relative motions are random and unpredictable. We can calculate the kinetic temperature of these particles with time-dependent turbulence level. In Fig. 2 we present the time variation of the apparent temperature and wave field strength. One can see that the heating process is parasitic with the waves. After the waves are diminished, the heated temperature will return to its initial value. It is in this sense that the heating is reversible. The concept of random particle motion is perhaps best described by phase space "mixing." To demonstrate the mixing process we then paint the hot protons with four distinctly different colors in velocity space. Then we let the system run. As shown in Fig. 3, the colored particles indeed mix themselves randomly and quickly. Before closing we reiterate the essential assumptions used in the above study. It is considered that within the simulation system the spectral density of the turbulent wave field, which has a broad spectrum, is spatially homogeneous and slowly varying in time. The apparent temperature is a statistical quantity that depends upon the ensemble averaged kinetic energies of the particles within the system, which has a dimension many times the wavelength. In astrophysics measurement of temperature is based on spectroscopic data collected from the source region of interest. Due to the restriction of spatial resolution of the measuring instruments the observed temperature is meaningful only in the coarse-grained sense. We agree that one should be cautious when the present theory is applied to a specific physical situation. It is also interesting to remark that in the study of nonlinear particle dynamics that reversible particle motion can occur when the wave amplitude is not sufficiently large.[17,18] Such a result is compatible with what we have found.

Figure 4 shows the results of a generalized calculation of proton apparent temperatures versus proton beta. The result is based on the numerical solution of Eq. (11) in Ref. 13. It is found that for the case of low beta coronal plasma, eventually proton heating with $T_p/T_0 \approx 10^2$ is theoretically obtainable. It is also clear that the apparent temperature decreases with increasing value of plasma beta value.

In summary in this communication we have introduced two new concepts: One is pseudoheating and the other is apparent temperature. Although the heating is "pseudo" and the corresponding temperature is "apparent," they represent interesting and significant physical consequences. They may help us produce hot plasmas in laboratory experiments without dissipation. It might also enable us to explain the physical origins of hot plasmas observed in astrophysics because Alfvén waves are believed to be pervasive in cosmic environments. Finally we remark that from the viewpoint of plasma physics, the process is of interest in its own right. It is the first time that a heating process without dissipation is proposed.

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