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Response to "Comment on 'Heating of ions by low-frequency Alfvén waves in partially ionized plasmas'" [Phys. Plasmas 18, 084703 (2011)]

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The calculation of temperature in a plasma system that is not in thermal equilibrium remains a topic of debate. In our article [Dong and Paty, Phys. Plasmas **18**, 030702 (2011)] we use the average kinetic energy to calculate the "*kinetic temperature*" in a non-equilibrium system to quantify the heating of ions by low-frequency Alfvén waves in a partially ionized plasma (i.e., where collisions with neutrals can not be ignored). We implement a method previously used by Wang, Wu and Yoon [Wang, Wu and Yoon, Phys. Rev. Lett. **96**, 125001 (2006)] and several others studying the effects of low frequency Alfvén waves in collisionless plasmas. This method is appropriate for several reasons discussed in this response. Most notably, we implement it to investigate heating of the plasma population since the bulk velocity of the particle ensemble perpendicular to the ambient magnetic field remains zero during the numerical experiment. © *2011 American Institute of Physics*. [doi:10.1063/1.3626548]

In the preceding Comment,[1] Lu, Gao, and Li discuss two primary points, and we welcome this opportunity to clarify. The first question relates to the method used to calculate anisotropic temperatures in a non-equilibrium system, while the second question is with regard to the duration of the neutral-ion collisional coupling.

Recently, several papers have been published that discuss the heating of ions by low-frequency Alfvén waves in a collisionless environment.[3–12] In these works, the authors calculated the temperature by slightly different methods. In the thermodynamic sense, the temperature can only be calculated for plasmas in or close to thermal equilibrium. As to the calculation of kinetic temperature in our article,[2] we implement the same method as that in Refs. 6–12, calculating the average kinetic energy over different spatial coordinates z; while the temperature in the work by Lu and Li[1,3,4] is defined in terms of the random kinetic energy in the particles' mean-velocity frame. Here, one thing that should be pointed out is that their bulk velocity depends on the spatial coordinate z.[1,3,4] In other words, their bulk motion is not a global behavior based on the statistics of particles with different spatial coordinates z. As stated in their Comment,[1] the temperatures they defined are a function of both the time t and spatial coordinate z, thus the temperatures calculated by the analytic approach in their work are actually the local temperatures of particles with same spatial coordinate z in a non-equilibrium system. However, the temperature plots in the authors own work (Refs. 3–5) show the dependence of temperature on time only, which indicates that they still simulate the temperature based on the statistics of ions with different spatial coordinates z; otherwise their heating results will depend on the specified spatial coordinate z and this is especially true for the situation of Alfvén waves with a spectrum (refer to Fig. 2 in Ref. 5). Therefore, their temperatures are based on two types of averages; resulting in a description of the temperature that is only a function of time t.

In our article,[2] as there was no detectable bulk velocity in the perpendicular direction in the velocity phase space (i.e., $\langle v_x \rangle = \langle v_y \rangle = 0$, where the bracket $\langle \cdot \rangle$ denotes an average over particles with different spatial coordinates z), we used the average kinetic energy to illustrate the heating, thus referring to it as "*kinetic temperature*". The reasons are as follows:

(1) In our calculation there is no bulk motion in the velocity phase space, where particles have different spatial coordinates z, in the perpendicular direction with respect to the ambient magnetic field B_0. (2) Even in fully ionized plasmas, the heating process is irreversible due to the initial pitch angle scattering.[9] Therefore, it is definitely irreversible in the collisional and partially ionized environment examined in our work. (3) As shown by Refs. 3 and 5, the kinetic behavior of particles under a wave spectrum versus particles experiencing a monochromatic dispersionless wave is different; our work implements a spectrum of waves. (4) The characteristic spatial scale of our system is much larger than typical Alfvén wavelength. (5) Our calculation of the kinetic temperature is based on the statistical average of the particles' kinetic energy over different spatial coordinates z. The number of particles, N, is much greater than one in our paper (see the sentence above Eq. (11) in Ref. 2). The kinetic temperature is NEVER defined for a single particle within the paper. (6) The temperature calculated in our paper[2] is independent of a coordinate transformation since there is no bulk motion based on the statistics of all the ions. Based on the points mentioned above, it is reasonable to use the average kinetic energy to calculate the kinetic temperature given the environment investigated in our article.[2] The real question arises in the meaning of temperature for nonthermal equilibrium cases. Since our work builds upon the foundation of previous

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research, it is necessary to implement validatable methods to ensure that comparisons are reasonable. To this end, the model developed in our work was validated for a collision free and fully ionized scenario against the previously published work[6] before implementing the physical effects of collisions in a partially ionized plasma.

The particles motion in the context of our paper[2] and Refs. 6–11 is random due to the pitch-angle scattering, the corresponding physical pictures are shown in Ref. 8 (refer to Figs. 1 and 3). Further, as stated in Ref. 8, "*The concept of random particle motion is perhaps best described by phase space 'mixing'*."; therefore, the heating mechanism described in our paper[2] is exactly the same as that described in the Comment.[1]

The idea raised by Lu, Gao, and Li in their Comment[1] that the neutral particles are "riding" the Alfvén waves is interesting to consider, however it is inappropriate in the context of our work. In their Comment,[1] they explain that ions and neutrals can be strongly coupled, indicating that both the neutrals and ions will be "riding" the Alfvén waves within "*a collisional period*". However, they did not mention explicitly what type of collision period, e.g., ion-neutral collision period or neutral-ion collision period, which is an important distinction. The neutral-ion coupling time depends on ν_{ni}^{-1}, not ν_{in}^{-1}, where ν_{ni} and ν_{in} are the neutral-ion collision frequency and ion-neutral collision frequency, respectively.[13,14] The ion-neutral collision frequency (ν_{in}) is much larger than the neutral-ion collision frequency (ν_{ni}) in the region discussed in our article,[2] i.e., 800–1500 km above the photosphere in solar chromosphere, according to VAL C model.[16] For example, $\nu_{in} \sim 3\times10^4$ Hz and $\nu_{ni} \sim 5\times10^2$ Hz at 1200 km above the photosphere.[16] The reason can be explained simply as follows. The collision frequency (ν_{ij}) between species (i and j) is directly proportional to the number of density of species j. When the colliding particles have the same mass, as is the case for our study where the ions and neutrals are predominantly hydrogen, Eq. (2) in Ref. 13 reduces to

$$\nu_{ij} = \frac{m_j}{m_i + m_j} n_j \left[\frac{8kT}{\pi m_{ij}}\right]^{\frac{1}{2}} \sigma_{ij} = 2n_j \left[\frac{kT}{\pi m_H}\right]^{\frac{1}{2}} \sigma_{ij} \qquad (1)$$

where $m_i = m_j = m_H$; σ_{ij} is the collisional cross section between two species, and therefore $\sigma_{ij} = \sigma_{ji}$. In order to conserve the momentum transferred between ion and neutral species via collisions, we see via Eq. (3) in Ref. 13 that for particles of the same mass

$$n_n \nu_{ni} = n_i \nu_{in} \qquad (2)$$

In the region of 800–1500 km above the photosphere in solar chromosphere, the number density of neutral hydrogen (n_n) is much larger than the proton number density (n_i),[16] thus it necessarily results in $\nu_{ni} \ll \nu_{in}$. In our paper, ions and neutrals are both cold initially, and the ion-neutral collision frequency (ν_{in}) is smaller than the ion gyrofrequency (Ω_0), e.g., $\Omega_0 \sim 2\times10^5$ Hz ($\nu_{in}/\Omega_0 = 0.15$) at 1200 km above the photosphere,[17] indicating that the neutral-ion collision frequency (ν_{ni}) is *much* smaller than the ion gyrofrequency. Therefore, the timescale of a neutral-ion collision period is much larger than one ion cyclotron period, which in turn reveals that neutrals cannot "ride" on the Alfvén waves during the initial several ion cyclotron periods.

As stated in the original paper,[2] in our calculations particles are deployed continuously over the duration of one gyroperiod. New ions are constantly created by processes such as photoionization, charge exchange, or impact ionization. The heating process saturates in one ion gyroperiod and no heating can be observed after one ion gyroperiod,[4,6] thus the heating time scale is related to the inverse of the ion gyrofrequency Ω_0^{-1}, instead of the inverse of the wave frequency ω^{-1} as indicated in the Comment.[1] The short heating time for the continuous creation of ions is due to the resulting continuous phase shift in the ion gyrospeed. This accelerates the phase mixing of the particles and in turn reduces the heating time.[4] Hence the argument made in the Comment,[1] that the coupling between neutrals and ions via elastic collisions will result in zero heating of newly created ions by the Alfvén waves, is not valid to our article.[2] Further, the heating efficiency depends on the plasma beta value; the smaller the β, the more efficient the heating. The plasma β can reach as small as 10^{-4} in the solar chromosphere[18] which is much smaller than the β value we used in our article for the case study,[2] indicating it can produce more heating than the scenario considered. Fig. 4 in Ref. 8 illustrates the dependence of heating efficiency on the proton β_p value, showing that $\beta_p = 10^{-4}$ and $\delta B_w^2/B_0^2 = 0.1$ can achieve $T_{proton}/T_{initial} = 1000$ in the collisionless environment. While not explored in our original work due to the relatively short time scales considered in our article,[2] both the ions and the neutrals can be heated given the energy conservation between neutrals and ions during elastic collisions. This could lead to a slightly higher temperature achieved by the ion population. However, the neutral population as a whole will heat much more slowly than the ions as indicated in our article[2] as well as in this response. Moreover, in reality other Alfvén-wave related heating mechanisms also exist, such as ion-neutral collisional damping of Alfvén waves with frequencies over 0.01 Hz.[13–15] Thus we stress that we determine a lower limit for the amount of ion heating from low-frequency Alfvén waves in our article.[2] It is noteworthy that the solar chromosphere temperature is several orders lower than the solar corona. Hence, we think the heating mechanism presented in our article[2] provides an important source of heating in the solar chromosphere not previously considered.[13–15] This is especially true in the upper solar chromosphere where $n_i \gtrsim n_n$,[16] indicating it is necessary for us to consider the energy feedback between neutral and ion populations via elastic collisions during the heating process.

In conclusion, the definition of temperature in a non-equilibrium system remains a topic of debate, thus it is imperative to calculate the temperature in a self-consistent way throughout the work. Since there is no bulk motion in the velocity phase space perpendicular to the magnetic field B_0, we use the average kinetic energy for the plasma population to calculate the kinetic temperature and assess the heating. Implementing this approach places this work in the context of the existing body of literature examining the role of low frequency Alfvén waves in heating the system.[6–11] Newly created ions are deployed continuously over the course of one ion gyroperiod in our work, representing source terms such as photoionization, charge exchange and impact ionization. The neutral population will not collisionally couple to the ions, and hence will not couple to the Alfvén waves, since the neutral-ion collision frequency is several orders of magnitude smaller than the ion gyrofrequency. This results in a coupling timescale much longer than the timescale for heating of the plasma (which occurs within one gyroperiod). In a partially ionized plasma, which includes collisions with neutrals, low frequency Alfvén waves can cause an increase in the perpendicular kinetic energy. Hence the waves contribute to the overall energization of the plasma. The total amount depends on the plasma β value, and the collisions with the cold neutral population.[2]

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