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Comment on "Heating of ions by low-frequency Alfvén waves in partially ionized plasmas" [Phys. Plasmas 18, 030702 (2011)]

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In their paper, Dong and Paty[1] investigated the nonresonant ion heating by low-frequency parallel propagating Alfven waves in partially ionized plasmas. The heating efficiency was found to be lower in partially ionized plasmas than that in plasmas without ion-neutral collision. Here we point out that ion heating process is different from the descriptions by Dong and Paty.[1] Their conclusions are based on the following basic equation, which describes the perpendicular velocity component of one single ion in a spectrum of Alfven waves, whose dispersion relation is $\omega = kv_A$ (v_A: Alfven speed; ω: wave angular frequency; k: wave number). The equation is

$$v_\perp = v_\perp(0)e^{-(i\Omega_0+\nu_{in})t} + \frac{\nu_{in}u_\perp(\nu_{in} - i\Omega_0)}{\Omega_0^2+\nu_{in}^2}[1 - e^{-i\Omega_0 t}e^{-\nu_{in}t}] - \frac{\sum_k \Omega_k[v_A - v_\parallel(0)](\Omega_0 + i\nu_{in})}{\Omega_0^2+\nu_{in}^2} \times \{e^{-ik(v_A t - z) - i\varphi_k} - e^{i[kz(0)-\varphi_k]}e^{-(i\Omega_0+\nu_{in})t}\}. \quad (1)$$

In this comment, we use the same notations for the variables and parameters as in their paper,[1] so here we do not explain them in detail. With the same assumptions as in their paper: the bulk velocity of the cold neutrals $u_\perp \approx 0$ and $|v_\parallel(0)| \ll v_A$ for the ions because of $\beta \ll 1$, Eq. (1) can be simplified to

$$v_\perp = v_\perp(0)e^{-(i\Omega_0+\nu_{in})t} - v_A\frac{\sum_k \Omega_k(\Omega_0 + i\nu_{in})}{\Omega_0^2+\nu_{in}^2} \times \{e^{-ik(v_A t - z) - i\varphi_k} - e^{i[kz(0)-\varphi_k]}e^{-(i\Omega_0+\nu_{in})t}\}. \quad (2)$$

In their paper, the kinetic temperatures are defined as in the follows:

$$T_\perp(t) = \frac{1}{2}\sum_{i=1}^{N}\frac{m_i v_\perp^2(t)}{N}; \quad T_\parallel(t) = \sum_{i=1}^{N}\frac{m_i v_\parallel^2(t)}{N}, \quad (3)$$

where $T_\perp(T_\parallel)$ is the perpendicular (parallel) kinetic temperature and N denotes the total number of the ions. However, whether their definition can be called temperature is questionable. The reasons are described as follows: according to their definition, even a single particle can have temperatures, and the temperatures may be changed after a coordinate transformation. Simultaneously, the temperatures they defined are only the function of the time t, and independent of the spatial coordinate z. These concepts conflict with our general understanding of temperature. Actually, they are ion kinetic energy, instead of ion kinetic temperatures. The kinetic temperature in plasma physics is usually based on a statistical particle ensemble and defined in terms of the random kinetic energy in the particles' mean-velocity frame. The kinetic temperatures at the spatial coordinate z should be then defined as

$$T_\perp(z,t) = \frac{m_i}{2}\langle(v_x - \langle v_x\rangle)^2 + (v_y - \langle v_y\rangle)^2\rangle; \quad T_\parallel(z,t) = m_i\langle(v_z - \langle v_z\rangle)^2\rangle, \quad (4)$$

where $\langle\cdot\rangle$ means an average of the ions in the phase space at the spatial coordinate z. In the follows, we focus on the perpendicular temperature $T_\perp(z,t)$.

Let's at first consider two cases: Case 1, ions have zero bulk velocity. Case 2: ions initially have bulk velocities that satisfy the condition of the coherent particle motion that is necessary to maintain the waves in a self-consistent way. In the first case, with the same method used by Lu *et al.*,[2,3] we can calculate the perpendicular bulk velocity at the spatial coordinate z and time t is

$$V_\perp(z,t) = -v_A\frac{\sum_k \Omega_k(\Omega_0 + i\nu_{in})}{\Omega_0^2+\nu_{in}^2} \times [e^{-ik(v_A t - z) - i\varphi_k} - A_k e^{ikz - i\varphi_k}e^{-(i\Omega_0+\nu_{in})t}], \quad (5)$$

where $A_k = e^{-k^2 v_{th}^2 t^2/4}$, and $v_{th} = (2T_0/m_i)^{1/2}$ is the initial ion thermal speed (where T_0 is the initial ion temperature).

Therefore, the perpendicular temperature can be calculated as

$$T_\perp(z,t) = T_0\left[1 + \frac{1}{\beta}\sum\nolimits_k \frac{\Omega_k^2}{\Omega_0^2+\nu_{in}^2}(1 - A_k^2)\right]e^{-2\nu_{in}t}. \quad (6)$$

If $\nu_{in} \ll \omega$, the ions can be significantly heated, and the time scale is related to the inverse of the wave frequencies. The heating mechanism is due to the phase difference randomization between ions produced by the parallel thermal motions of ions, which is valid for both a monochromatic Alfven wave and a spectrum of Alfven waves.[3] The randomization or heating process saturates when phase differences are sufficiently large.[2,3] The heating mechanism is not related to as a

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randomization of the particle motion (or stochastic motion) as described in their paper. From Eq. (2), we can know that only the gyrofrequency Ω_0 and the wave frequencies ω are involved in the particle motion. Only when the Alfven waves have a continuous spectrum or when the Alfven waves propagate obliquely,[4,5] the motion is stochastic, otherwise, it is quasi-periodic. However, the temperature tends to be zero rapidly in a time scale of the ion-neutral collision period if $\nu_{in} \gg \omega$.

In the second case, ions initially have a sloshing perpendicular bulk velocity dictated by the Alfven waves

$$V_\perp(0) = -v_A \frac{\sum_k \Omega_k(\Omega_0 + i\nu_{in})}{\Omega_0^2 + \nu_{in}^2} e^{i[kz(0)-\varphi_k]} \tag{7}$$

and then

$$v_\perp(0) = V_\perp(0) + v'_\perp(0) \tag{8}$$

where $v'_\perp(0)$ is the initial perpendicular thermal velocity. Therefore, Eq. (2) can be reduced to

$$v_\perp = v'_\perp(0)e^{-(i\Omega_0+\nu_{in})t} - v_A \frac{\sum_k \Omega_k(\Omega_0 + i\nu_{in})}{\Omega_0^2 + \nu_{in}^2} e^{-ik(v_A t - z) - i\varphi_k}. \tag{9}$$

The perpendicular bulk velocity will be

$$V_\perp(z,t) = -v_A \frac{\sum_k \Omega_k(\Omega_0 + i\nu_{in})}{\Omega_0^2 + \nu_{in}^2} e^{-ik(v_A t - z) - i\varphi_k} \tag{10}$$

and the perpendicular temperature will be $T_0 e^{-2\nu_{in} t}$, which is only the function of time t and independent on the spatial coordinate z.

In the first case, ions initially do not follow the coherent particle motion of Alfven waves. They are pickup ions.[2,6] These particles may be originated from the ionization of neutral particles from various processes (e.g., charge exchange, photonization). However, non-pickup ions are not supposed to break the condition of the coherent particle motion (described by Eq. (7)) that is necessary to maintain the Alfven waves in a self-consistent way. These ions correspond to the second case and cannot be heated.[2,6]

Now let's consider the situation in Dong and Paty,[1] where pickup ions are deployed continuously over the duration of one gyroperiod. The heating mechanism is similar to Case 1, which are due to the phase difference randomization between pickup ions. In Case 1, the phase difference randomization is produced by the parallel thermal motions of the pickup ions. In Dong and Paty,[1] the phase difference randomization is produced by the phase difference of the pickup ions generated continuously over the duration of one gyroperiod.[6] Therefore, the heating process is very rapid, which is about one gyroperiod. However, in partially ionized plasma, such as solar chromosphere, both the neutral-ion and ion-neutral collision frequencies are much higher than the wave frequency. The ions and neutral particles are coupled together strongly, and both of them will be riding on the Alfven waves to maintain the Alfven waves in a time scale of a collision period (the smaller one of the neutral-ion collision frequency and ion-neutral collision frequency).[7] Then the pickup ions from the neutral particles are already riding on the Alfven waves, and cannot be heated, as described in Case 2. Even if the bulk velocity of the cold neutral particles is kept as zero (as in Dong and Paty,[1] the situation may be reasonable if the density of the neutral particles is much larger than that of the ions riding on the Alfven waves), the temperature of the pickup ions from the neutral particles will tend to be zero in a time scale of an ion-neutral collision periods, as described in Eq. (6). Therefore, the pickup ions ionized from the neutral particles may be heated by the Alfven waves only in a time scale of a collision period (comparable to the ion gyroperiod in solar chromospheres, and much shorter than the period of the Alfven waves), and then they cannot be heated. Its importance in solar chromosphere is questionable.

In summary, ions, which initially are already riding on the Alfven waves (the second case), cannot be heated by parallel propagating Alfven waves. Parallel propagating Alfven waves can only heat pickup ions, which initially do not follow the coherent particle motion dictated by these Alfven waves.[2,6] The heating is due to phase differences randomization between pickup ions. The randomization or heating process saturates when phase differences are sufficiently large. However, in partially ionized plasma, such as chromosphere, both the neutral-ion and ion-neutral collision frequencies are much higher than the wave frequency. The neutral particles and ions are coupled together strongly, and both of them will be riding on the Alfven waves to maintain the Alfven waves in a time scale of a collision period (the smaller one of the neutral-ion collision frequency and ion-neutral collision frequency). Then, the pickup ions ionized from the neutral particles, as well as the neutral particles, are also riding on the Alfven waves, and cannot be heated. Even if the bulk velocity of the cold neutral particles is considered to be zero, as in Dong and Paty,[1] the temperature of the pickup ions will tend to be zero in a time scale of an ion-neutral collision period.

Therefore, in partially ionized plasma, such as solar chromosphere, the pickup ions ionized from the neutral particles may be heated by the Alfven waves only in a time scale of a collision period (the smaller one of the neutral-ion collision frequency and ion-neutral collision frequency), which is comparable to the ion gyroperiod in chromospheres and much shorter than the period of the Alfven waves. After this period, the pickup ions are already riding on the Alfven waves, and cannot be heated further. Its importance in solar chromosphere is negligible.

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