Hybrid Simulations of Preferential Heating of Heavy Ions in the Solar Wind

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Abstract. We present results from the first fully self-consistent 1D hybrid (kinetic ions/fluid electrons) simulations of the preferential heating of alphas and heavier minor ions by a flat spectrum of Alfvén-ion cyclotron waves in a collisionless plasma. We find that the simulations reproduce the observed solar wind scaling $T \propto M$ for alphas and heavier minor ions when the alphas and the minor ions have equal charge to mass ratios, q/M, and equal initial thermal velocities, $V_{th}=(T/M)^{1/2}$. This scaling is interpreted as a result of the basic physics: the time evolution of the Vlasov/Maxwell system without collisions depends only on the ratio q/M and not q or M separately. Because this result follows from the basic nature of the physical model, the $T \propto M$ scaling would be obtained for any spectrum of waves. For minor ions with q/M different from the alphas but equal initial thermal velocities, the final thermal velocity is seen to vary by ±50% from that of the alphas in the simulations presented here.

INTRODUCTION

It has long been observed that, in the solar wind, the alpha particles and heavier minor ions have higher temperatures than the protons (1,2). In coronal hole associated solar wind, the heavy ion temperatures are found to be proportional to the heavy ion mass, $T \propto M$, resulting in equal thermal velocities (3,4). Recently von Steiger et al. (5) extended this result to more ion species using SWICS/Ulysses data. Wave-particle interactions between the ions and Alfvén/ion cyclotron waves are generally considered to be the cause of the preferential heavy ion heating.

Quasilinear models (6 and references therein) have successfully shown that the alphas can be heated and accelerated relative to the protons. More recently, a non-linear hybrid simulation model which includes the effects of solar wind expansion on the evolution of the wave spectrum and frequencies has also reproduced preferential heating and acceleration of the alphas relative to the protons (7).

This paper focuses on the heating of multiple heavy ion species. Quasilinear models of the heating of minor ions have not been able to reproduce the $T \propto M$ scaling for alphas and heavier ions (8). Based on an analysis of the linear dispersion relation for a multi-ion plasma, Gomberoff and Astudillo (9) have suggested a scenario that could lead to the $T \propto M$ scaling, but a non-linear analysis is needed to verify this suggestion.

Here we present results of self-consistent 1D hybrid (kinetic ions/fluid electrons) simulations of the interaction of alpha particles and heavy ions with a spectrum of Alfvén-ion cyclotron waves. In these simulations, the heavy ions, alpha particles and protons, are all treated self-consistently and thus the linear and non-linear effects of the heavy ions on the waves are included. These effects include, for example, the introduction of the frequency gap at the alpha cyclotron frequency by the 4% alpha population (linear effect) and the damping of the waves by resonant ions of all 3 species (non-linear effect). We believe these are the first simulations of minor ion heating by Alfvén waves in which the alphas and other minor ions, as well as the protons, are treated self-consistently with the wave fields. The simulations are initialized with a spectrum of circularly polarized Alfvén-ion cyclotron waves. For the results presented here, the initial spectrum of waves was flat out to wave numbers $kV_A=1.5\Omega_P$ where $\Omega_P (= eB/M_Pc)$ is the proton gyro- frequency. The waves heat and accelerate the ions and the ions damp the waves.

We find that the simulations reproduce the observed scaling $T \propto M$ for alphas and heavier minor ions when the minor ions and the alphas have the same q/M and the same initial *thermal velocities* $V_{th}=(T/M)^{1/2}$. This result is explained as a consequence of the dependence of the Lorenz force solely on the ratio of q/M and not q or M independently and would be obtained for any wave spectrum. For minor ions with q/M different from the alphas but with the same initial

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thermal velocities, we find that the final thermal velocity may vary by ±50% from that of the alphas in our simulations. For minor ions with same q/M and equal initial *temperatures*, the heavier ions have a higher final temperature, but the $T \propto M$ scaling is not strictly observed.

THE MODEL

The plasma simulation model used is the 1D hybrid code of Winske and Leroy (10), modified to include multiple ion species. All three ion species – protons, alphas and the minor ions– are treated as particles and the code updates the ions at each time cycle using

$$\frac{d\vec{x}}{dt}=\vec{v} \quad \text{and} \quad \frac{d\vec{v}}{dt}=\frac{q}{M}\left(\vec{E}+\vec{v}\times\vec{B}\right) \tag{1}$$

where the electric and magnetic fields are computed self-consistently from the particle positions and velocities (10). Thus all ion species are treated in a fully self-consistent manner. The electrons are treated as a neutralizing fluid. This model has also been extended to include the effects of solar wind expansion on ion cyclotron heating (7), but that capability has not yet been used in this study.

The code is initialized with a spectrum of outward propagating left-hand circularly polarized Alfvén-ion cyclotron waves. For the results presented here, the initial spectrum of waves was flat out to wave numbers $kV_A=1.5\Omega_P$ where $\Omega_P(= eB/M_Pc)$ is the proton gyro-frequency. Various fluctuations levels were used, $|\delta B/B|^2=0.16 - 0.55$. The alpha particles can resonate with and damp waves with wave numbers $kV_A\sim\Omega_{He}=0.5\Omega_P$ and higher and likewise for heavier minor ions with $q_{MI}/M_{MI}\sim q_{He}/M_{He}< q_p/M_p =1$ (in our units). Only wave numbers, not wave frequencies, are specified in hybrid simulation codes; the time evolution of the waves is determined by the self-consistent time integration of the particle and field equations. Thus the alpha minor ion effects on the linear dispersion relation are correctly treated in our simulation model. The longest wave length modes, those with $kV_A<<\Omega_P$, satisfy $\omega= kV_A$. In a pure proton plasma, as k increases the left-hand circularly polarized branch approaches $\omega = \Omega_P$ asymptotically. In cold plasmas with an alpha density typical of the solar wind (~4%), the low frequency LHCP branch asymptotes to $\omega=\Omega_{He}$ and a gap appears between this low frequency branch and the proton cyclotron frequency branch at $\omega\sim\Omega_P$. The gap can disappear as the alphas are heated and accelerated (see, e.g. Ref. 9).

SIMULATION RESULTS

In the results presented here, each simulation run had three ions species: protons (p), alphas (He) and one minor ion specie (MI); separate runs were made to determine the dependence of the heating on the particular minor ion. The alphas contributed 4% of the number density, the minor ion 0.1% with protons making up the remaining 95.9%. The parameters for these runs were as follows: time step $\Delta t\ \Omega_P=0.001$, $\omega_{pi}/\Omega_P = 100$, grid size $L_x = 128\ V_A/\Omega_P$, number of grid cells $N_x = 256$ with 40,240 particles for each for the three species. The protons were initialized with $\beta_P = 0.05$. Results are presented here for two initializations of the alpha and heavy ion temperatures. In the first set of runs, the protons, alphas and minor ions were initialized with equal thermal velocities $V_{th}=(T/M)^{1/2}$; runs were made for cases with various minor ion species (Carbon, Oxygen, Neon, Magnesium and Iron) in various charge states. The initial level of turbulence was $\delta B/B=0.4$.

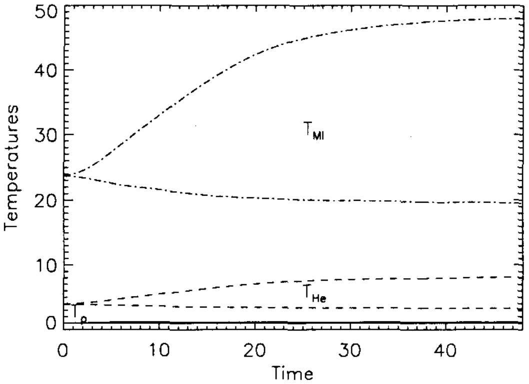

Figure 1. Proton (__), He^{++} (---) and Mg^{12+} (._._) perpendicular and parallel temperatures as a function of time in the simulation. The upper of the two curves for each species is the perpendicular temperature and the lower the parallel temperature. Note that the Mg^{12+} temperature is 6 times the He^{++} temperature for all times in the simulation, giving $T \propto M$. Very little proton heating is seen (~10%).

Figure 1 shows the time history of the perpendicular and parallel temperatures for a case with Mg^{12+}. To obtain the V_{th} for each species, each species mean velocity is first calculated at each grid point. The thermal velocity is then the square root of the sum over all ions of a species of the squares of each ion's relative velocity, as determined by interpolation of the mean velocity to the particle's position. In the simulations, most of the heating of the ions occurred by $t\Omega_P \approx 30$. Very little proton heating (~10%) occurred. In the figure, it can be seen that the alphas are heated more than the protons and the minor ions are heated more than the alphas; the heating is all perpendicular with a slight cooling in the parallel direction as expected from cyclotron damping. The alphas and Mg^{12+} ions can resonate with waves $kV_A \geq \Omega_{He} = \Omega_{Mg12+} = 0.5\Omega_p$, and thus have access to more of the spectral energy than the protons. For a case with the same parameters but no alphas or minor ions, the protons are heated somewhat more than in this case (15% increase in temperature vs. the 10% seen in the Figure 1 case).

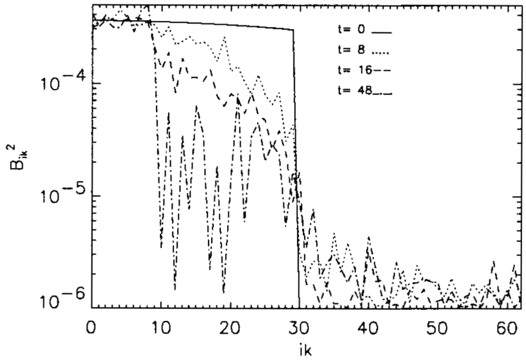

Figure 2. Power spectrum of the waves at 4 times from the same simulation as in Figure 1. Waves in the region ik > 10, corresponding to $kV_A > \Omega_{He} = \Omega_{Mg12+}$, have been damped by the ions.

Figure 2 shows the wave spectrum at four times in the same simulation. It can be seen that waves in the region ik>10, corresponding to $kV_A > \Omega_{He} = \Omega_{Mg12+}$, have been damped by the ions. Presumably the protons are responsible for some of the damping in the region ik>20, corresponding to $k = kV_A > \Omega_P$. The spikes seen in the spectrum are statistical fluctuations as the wave energy fluctuates between the various k modes; time-averaging the spectrum would smooth these out.

Figure 3 plots the thermal velocities of the heavy ions relative to the thermal velocity of the alphas from the various simulations with equal heavy ion initial temperatures at $t\Omega_P = 0$. Ions with the same q/M as alphas (O^{8+}, Ne^{10+}, $Mg12^+$, plotted as ◊) have the same thermal velocities for all times (all the points fall on top of each other). The velocities of ions with different q/M are plotted at $t\Omega_P = 50$ (Δ) and 100 (❑). By $t\Omega_P = 100$, the rate of change of the temperatures is small. The thermal velocities observed for ions of different q/M vary by about ±50% from that of the alphas and other q/M=0.5 ions. Thus we are able to reproduce the observation $T \propto M$ exactly, but only for alphas and heavy ions which have the same q/M as the alphas and the same initial thermal velocities.

The variations in the thermal velocity with q/M are not presently understood. Numerical experiments have shown that the results are not dependent on the spatial resolution, and thus k-space density, of the simulations. We plan to investigate how these deviations depend on the spectrum of the waves and other parameters.

The result that $T \propto M$ for heavy ions that start with the same thermal velocities and have the same q/M as the alphas can be understood from the basic physical system. In a collisionless plasma, the particle distribution functions evolve under the influence of the Lorenz force that depends only on the *ratio* of q/M, and not on either separately:

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{x}} + \frac{q}{M}\left(\vec{E} + \vec{v} \times \vec{B}\right)\frac{\partial f}{\partial \vec{v}} = 0 \qquad (2)$$

If the alphas and heavy ions have the same f(x,v,t) initially and the same q/M, the distribution functions, and hence the thermal velocities, will remain the same for all times. The hybrid code uses instead equation (1), but the physical argument is the same. Moreover, because the scaling $T \propto M$ for ions with equal initial thermal velocities and q/M is a result of the nature of the physical system, this scaling would be obtained for any wave spectrum. Note that including the Sun's gravitational force would not add any dependence on mass alone and the physical argument is unchanged.

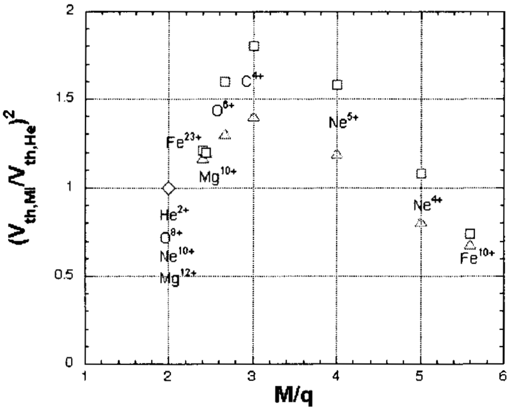

Figure 3. Square of thermal velocities of the heavier minor ions relative to the thermal velocity of the alphas from the various simulations with equal heavy ion initial temperatures. Minor ions with the q/M of alphas (◊) all fall on top of each other for all times; for these ions, we reproduce the $T \propto M$ scaling. The thermal velocities of minor ions of other q/M's (Δ for $t\Omega_P = 50$; ❑ for $t\Omega_P = 100$) vary by about ±50%.

In the second set of simulation runs, the three species (proton, alpha and the minor ion), all with $q_{MI}/M_{MI} = q_{He}/M_{He} = 0.5$) were initialized with equal temperatures ($T_P = T_{He} = T_{MI}$). Cases were run with two levels of turbulence ($|\delta B/B|^2 = 0.16$ and 0.55) and two minor ions [O^{8+} ($M_{MI} = 16$) and Mg^{12+} ($M_{MI} = 24$)]. Results are shown in Figure 4 again at time $t\Omega_P = 100$.

It can be seen that the heavy ion temperature increases with mass, but the scaling $T \propto M$ is not strictly obeyed. However, as the fluctuation level increases, the initial condition becomes less important and the scaling is approached. We suspect that if there was a source of wave energy to continue the heating, then the $T \propto M$ would again be obtained.

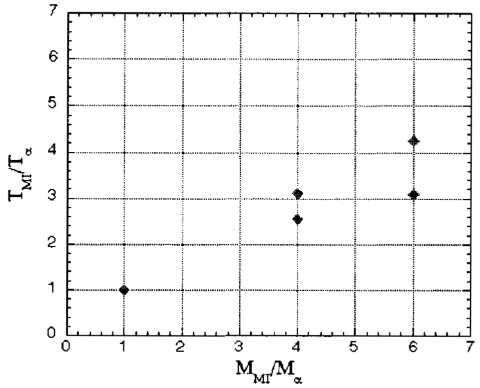

FIGURE 4. Temperature versus mass from simulations with equal initial temperatures and heavier ions with $q_{MI}/M_{MI}=q_{He}/M_{He}=0.5$. For each mass, upper (lower) point is for initial fluctuation level $|\delta B/B|^2= 0.55$ (0.16).

DISCUSSION

We have presented simulation results showing that a spectrum of waves heats alpha particles and heavier minor ions to temperatures $T \propto M$ for minor ions with the same q/M as the alphas and the same initial thermal velocities. This result stems from the basic nature of the physical model governing the evolution of the system: the Lorenz forces depends only on the ratio q/M. Thus this result would be obtained for any level of turbulence and any wave spectrum. This result only holds in collisionless plasmas. The Coulomb collision frequency depends on q^2/M, and the temporal evolution no longer depends only on the ratio q/M.

How does this relate to the observations (1-3,5)? The solar wind observations of von Steiger et al. (5) showed that $T \propto M$ in fast solar wind where collisions are not important and there is a large flux of Alfvén waves. The M/q of the ions in Ref. 5 was not identical to that of the alphas, but the range was not very great: $M/q = 2$ for O^{8+} to $M/q=3$ for C^{4+}. Deviations from $T \propto M$ of the size seen in our simulations (Figure 3) were within the error bars on the temperatures in Ref. 5.

We have not addressed here the question of how the wave power reaches the high frequencies used in the simulation spectrum. However, in related work using a hybrid code with the effects of solar wind expansion included (7), we have shown that a spectrum of waves below the alpha and proton cyclotron frequencies becomes resonant first with the alphas as the solar wind expands and the mode frequencies decrease (~1/R) less rapidly than the cyclotron frequencies (~$1/R^2$). We plan to continue these studies with minor ions included. The minor ion with the lowest q/M will come into resonance first as the solar wind expands (cf. Ref. 9).

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REFERENCES

1. Neugebauer, M., *Fund. of Cosmic Physics* **7**,131-1099 (1981).
2. Zurbuchen, T. H., Fisk, L. A., Schwadron, N. A., and Gloeckler, G., this proceedings.
3. Schmidt, W. K. H., Rosenbauer, H., Shelley, E. G., Sharp, R. D., Johnson, R. G., and Geiss, J., *Geophys. Res. Lett.* **7**, 697-700 (1980).
4. Ogilvie, K. W., Bochsler, P., Geiss, J., and Coplan, M. *J. Geophys. Res.* A **85**, 6069-6074 (1980).
5. Von Steiger, R., Geiss, J., Gloeckler, G., and Galvin, A. B., *Space Science Reviews* **72**, 71-76 (1995).
6. Marsch, E., Goertz, C. K., and Richter, K., *J. Geophys. Res.* A **87**, 5030-5044 (1982).
7. Liewer, P., Velli, M. and Goldstein, B., in *Solar Wind Nine*, edited by S. Habbal, R. Esser, J. V. Hollweg and P. A. Isenberg (AIP Conference Proceedings 471) 449 (1999).
8. Isenberg, P. A., and Hollweg, J. V., *J. Geophys. Res.* A **88**, 3923-3935 (1983).
9. Gomberoff, L., and Astudillo, H. F., in Solar *Wind Nine*, edited by S. Habbal, R. Esser, J. V. Hollweg and P. A. Isenberg (AIP Conference Proceedings 471) 461 (1999).
10. Winske, D., and Leroy, M. M., in *Computer Simulation of Space Plasmas – Selected Lectures at the First ISSS*, edited by H. Matsumoto and T. Sata, D. Reidel, Norwell, MA (1985).