Adv. Space Res. Vol. 8, No. 1, pp. (1)35–(1)38, 1988
Printed in Great Britain.

0273–1177/88 $0.00 + .50

SIMULATION AND NON-LINEAR STAGE OF THE ELECTROSTATIC WAVES OBSERVED DURING THE AMPTE LITHIUM RELEASE IN THE SOLAR WIND

N. Omidi,* T. Z. Ma,** K. Quest,*** M. Ashour-Abdalla,*
D. Gurnett** and R. Sydora*

*I.G.P.P., U.C.L.A., Los Angeles, CA 90024, U.S.A.
**Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242, U.S.A.
***Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.

ABSTRACT

During the AMPTE lithium releases in the solar wind intense electrostatic waves with frequencies between a few tens of Hz to several kHz were observed outside the diamagnetic cavity. The results of linear Vlasov theory have suggested that these waves may be generated through two types of instabilities. One is the ion-ion instability associated with the relative drift between the lithium ions and the solar wind protons, and the other is the ion-acoustic instability due to the relative drift between the electrons and the ions. In order to look at the non-linear behavior of the wave-particle interactions, and discern the effect of waves on the particles, full particle electrostatic simulations have been performed, and the results are presented here. It is shown that the ion-ion instability whose phase velocity is oblique to the solar wind velocity can cause considerable anisotropic "heating" of both the lithium ions and the solar wind protons.

INTRODUCTION

In the recent Active Magnetospheric Particle Tracer Experiments (AMPTE), lithium gas was twice released in the solar wind by the Ion Release Module (IRM) spacecraft. Subsequent to these releases, intense and broadbanded electrostatic waves with frequencies from tens of Hz to several KHz were observed /1,2/. This noise whose peak integrated electric field strength was as high as 40 mV/m was generated outside the diamagnetic cavity where the lithium ion density could have varied from about fifty times larger than the solar wind density to fifty times smaller.

Initial analysis of the electrostatic waves, and linear Vlasov theory was conducted by Gurnett et al. /1/, where it was shown that streaming type instabilities associated with the relative drift between the solar wind and the lithium ions were probably responsible for the generation of these waves. Specifically a plasma model was considered where the lithium ions formed a non-drifting Maxwellian with a temperature $T_{Li}+ = 2 \times 10^3$ °K; protons were represented by a drifting Maxwellian with $T_p = 10^5$ °K and a drift speed $V_{sw} = 460$ km/s; solar wind electrons had a temperature $T_e^h = 5 \times 10^5$ °K; and a colder photo-electron population associated with the lithium ionization with $T_e^c = 5 \times 10^4$ °K was also considered. The electrons were assumed to drift with a speed such that the net current was zero. The linear analysis by Gurnett et al. /1/ was performed for various ratios of the proton to lithium density ($N_p/N_{Li}+$) with, and without the cold electrons to represent the initial, and the subsequent phase of the cloud expansion. The results were in general agreement with the wave observations. More recently the initial linear analysis by Gurnett et al. /1/ was extended by looking at the instability of the waves whose wave vector $\vec{K}$ is oblique to the solar wind direction /3,4/. It was found that the waves are unstable over a wide range of directions. To demonstrate this, in Figure 1 the maximum growth rate γ_{max} is plotted versus the angle θ between $\vec{k}$, and the solar wind direction for the parameters stated in that Figure (c.f., Ma et al. /3/). As can be seen γ_{max} is appreciable for a wide range of θ. In addition, γ_{max} initially decreases with increasing θ, however, when θ becomes large, γ_{max} increases with θ. This change is due to the fact that two instabilities are present. One is the ion-acoustic instability whose growth rate is maximum at $\theta = 0$. The other is the ion-ion instability with maximum growth at $\theta \sim 80°$. The ion-acoustic instability which is due to the relative drift between the lithium ions and the electrons grows through Landau resonance with the electrons. On the other hand, the ion-ion instability is a fluid-type instability (for the parameters considered here) and is due to the drift between the protons and the lithium ions. Before proceeding further, it should be mentioned that the above-mentioned linear analyses /1,3,4/ were performed assuming an unmagnetized plasma. This assumption is well-justified since both the ion-acoustic, and the ion-ion instabilities are insensitive to the presence of a magnetic field independent of whether the beam propagates along or across the field /5,6/. Because the ion-ion and the ion acoustic instabilities seem like good candidates for the generation of AMPTE electrostatic waves, in the following we look at the non-linear behavior of these waves.

METHODOLOGY AND RESULTS OF THE SIMULATIONS

In order to study the non-linear behavior of the wave-particle interactions full particle one-dimensional (along the x-axis) electrostatic simulations are performed for the case where no photo-electrons are present. As is evident in Figure 1 the two instabilities have maximum growth rates at different directions of $\vec{K}$, and thus in order to account for both instabilities simultaneously use must be made of a two-dimensional model. However, the advantage of using a one-dimensional system is that each instability can be studied separately and thus its effect on the particles can more clearly be discerned. As will be shown later the use of a one-dimensional system for the present study imposes little or no constraint on the conclusions. The length of the simulation box is 32 electron Debye lengths (λ_e) and periodic boundary conditions are used. The plasma model considered is similar to that used by Gurnett et al. and Ma et al. /1,3/ where the lithium ions are at rest, the protons drift along the x-direction with a speed $v_{dx} = V_{sw}\cos\theta$, and the electron drift speed is such that the current along the x-axis is zero. Note that by varying v_{dx}, various angles of propagation θ can be considered. The simulations are carried out as an initial value problem where the system is allowed to evolve in time without a constant refurbishing of new particles. The thermal velocities are such that $v_p = 0.01\ v_e$, and $v_{Li} = 0.26 \times 10^{-2}\ v_e$ where v_g is the thermal velocity of the g species.

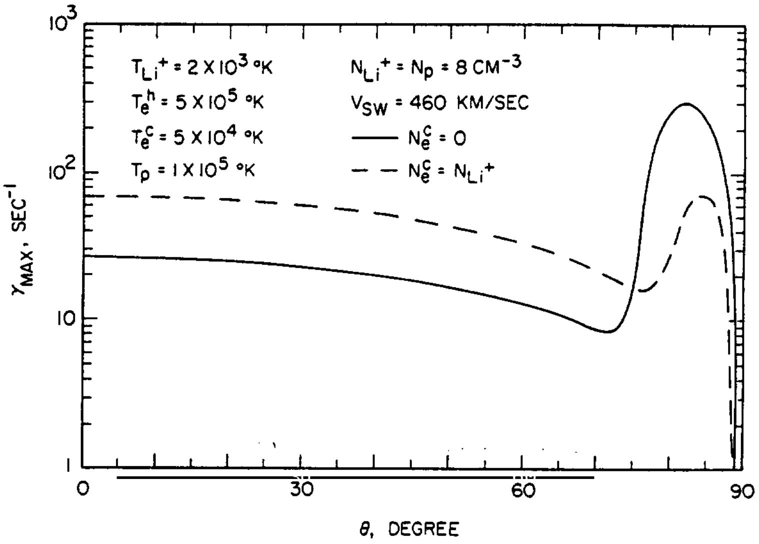

Fig. 1. Maximum growth rate γ_{max} is plotted vs. θ the angle between $\vec{K}$ and the solar wind velocity. Growth rates at $\theta \lesssim 70°$ are due to the ion-acoustic, and those at $\theta \gtrsim 70°$ are due to the ion-ion instability (from Ma et al. /3/).

Using the simulation model described above, a number of cases with $\theta = 0°$ and $\theta = 85°$ for various lithium to proton density ratios were examined. Figures 2, 3, and 4 show the results for the case where $N_{Li} = N_p$, and $\theta = 85°$ which corresponds to the ion-ion instability. It has been shown by Ma et al. /3/ that the growth rates are maximized when $N_{Li} = N_p$. In Figure 2, the total energy in the electrostatic field and the kinetic energy of the electrons, protons, and lithium ions plotted versus time are shown from top to bottom panels, respectively. Time is normalized to the electron plasma period (ω_{pe}^{-1}). As can be seen, the electric field energy initially grows with time due to the ion-ion instability, until it saturates and begins to lose some of its energy back to the particles specifically the lithium ions. The electrons also gain some energy with time, however, this energy gain is for all practical purposes negligible. In fact throughout this run the electrons remained more or less unaffected by the waves. Protons, on the other hand, lost considerable energy because they were the source of free energy for the wave excitation. As can be seen in the bottom panel of Figure 2, lithium ions gained energy due to interaction with the waves. In order to better understand the effects of the waves on the protons and the lithium ions, the phase space density plots of these particles at three different times are shown in Figures 3 and 4. Note that the velocity of each species is normalized to its initial thermal velocity. The two top panels in Figures 3 and 4 show the phase space density of the ions at $t = 300\ \omega_{pe}^{-1}$. At this stage the ions are somewhat modified by the waves but the instability is still in its linear growth phase. The middle panel in Figure 3 shows the protons at $t = 600\ \omega_{pe}^{-1}$ where

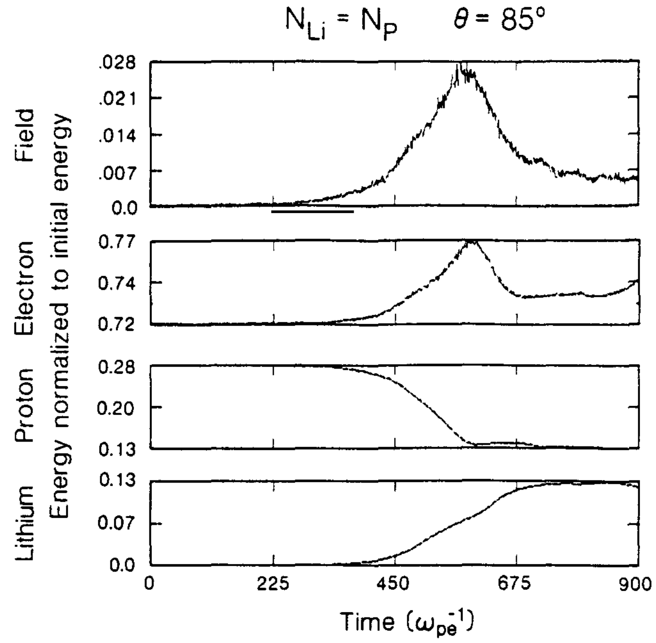

Fig. 2. Time history of the electrostatic and particle energies normalized to the initial kinetic energy in the system.

the non-linear stage of the wave particle interaction is evident and the waves have reached a saturation level. As can be seen, the protons have become trapped in the waves and the so-called trapping vortices are clearly evident. Similarly, the middle panel in Figure 4 shows the trapping of the lithium ions at t = 500 ω_{pe}^{-1}. In the case of the lithium ions, some of the particles gain velocities beyond 5 v_{Li}, and thus are not shown in the middle and the bottom panels. Finally, the bottom panels in Figure 3 and 4 show the coalescence of the trapping vortices and the mixing of the particles in phase space which will eventually lead to their thermalization. Thus it is evident from Figures 3 and 4 that the ion-ion instability can greatly modify and heat both the protons, and the lithium ions through trapping by the waves. It is interesting to note that even though the phase velocity of the waves is smaller than the proton drift speed, the wave amplitude grows to sufficiently large values so that the protons become trapped. It should also be noted that because the ion-ion instability grows at large θ the heating shown here would predominantly occur in the direction nearly perpendicular to the solar wind direction.

The results of simulations at θ = 0° show quite a different result. In this case no waves are appreciably amplified before t ~ 3000 ω_{pe}^{-1} which is expected from the linear theory since the ion-acoustic mode has a maximum growth rate which is an order of magnitude smaller than the ion-ion mode (see Figure 1). On the other hand, we have seen that both the lithium ions and the protons are greatly modified by the ion-ion instability as early as t = 500 ω_{pe}^{-1}. Because the ion-acoustic instability is due to the interaction between the lithium ions and the electrons it seems reasonable to assume that even in a two-dimensional simulation model the only excited waves would be the ion-ion mode.

SUMMARY AND CONCLUSIONS

By performing full-particle electrostatic simulations it has been shown that the ion-ion instability which grows at oblique angles can lead to considerable anisotropic heating of both the solar wind protons and the lithium ions. It has also been shown that in an initial-value type simulation among the two possible instabilities, the ion-ion mode is the dominant one (in the absence of cold photo-electrons) and the ion-acoustic waves will probably not grow. This, however, does not necessarily mean that in the actual lithium releases ion-acoustic waves were not excited. This is because both protons and lithium ions were continuously refurbished for a while and thus the ion-acoustic waves might have indeed been amplified. Because the ion-acoustic waves grow due to Landau resonance with the electrons the saturation mechanism for this instability is the quasi-linear heating of the electrons. Since this heating can take place on a rapid time scale, one might expect these waves not to greatly affect the protons or the lithium ions. Similarly in the presence of cold electrons, the ion-acoustic instability may have growth rates comparable or larger than the ion-ion waves. In this case one might expect heating of the cold electrons without a substantial change in

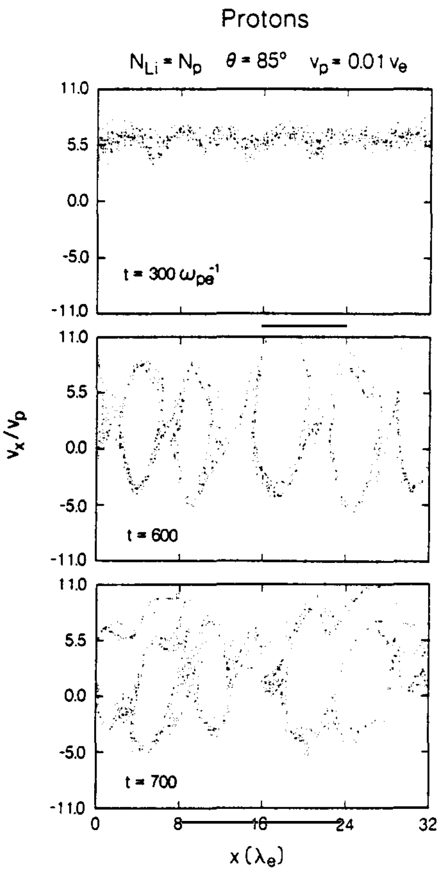

Fig. 3. Phase space density plot of the protons.

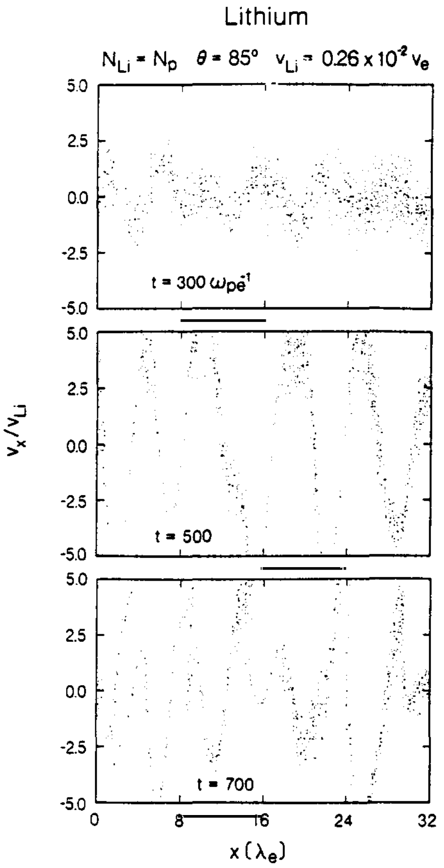

Fig. 4. Phase space density plot of the lithium ions.

the proton and lithium ions. These issues are currently under investigation and the results will be presented in the future.

ACKNOWLEDGEMENT

This research was supported by NASA STTP NAGW-78, National Science Foundation ATM85-12512 and Air Force F19628-85-K-0027 grants.

REFERENCES

1. D.A. Gurnett, T.Z. Ma, R.R. Anderson, O.H. Bauer, G. Haerendel, B. Häusler, G. Paschmann, R.A. Treumann, H.C. Koons, R. Holzworth, and H. Lühr, Analysis and interpretation of the shocklike electrostatic noise observed during the AMPTE solar wind lithium releases, J. Geophys. Res., 91, 1301, 1986.

2. B. Häusler, L.J. Woolliscroft, R.R. Anderson, D.A. Gurnett, R. Holzworth, H.C. Koons, O.H. Bauer, G. Haerendel, R.A. Treumann, P.J. Christiansen, A.G. Darbyshire, M.P. Gough, S.R. Jones, A.J. Norris, H. Lühr, and N. Klöcker, Plasma waves observed by the IRM and UKS spacecraft during the AMPTE solar wind lithium releases: overview, J. Geophys. Res., 91, 1283, 1986.

3. T.Z. Ma, D.A. Gurnett, and N. Omidi, Shock-like noises in the AMPTE solar wind ion releases, J. Geophys. Res., submitted, 1986.

4. A.L. Brinca, A.A. Moreira, F.M. Serra, G. Haerendel, and G. Paschmann, Complementary analysis and interpretation of the shock-like electrostatic noise observed during the AMPTE solar wind lithium releases, J. Geophys. Res., 91, 1283, 1986.

5. K. Akimoto and N. Omidi, The generation of broadband electrostatic noise by an ion beam in the magnetotail, Geophys. Res. Lett., 13, 97, 1986.

6. S.P. Gary and N. Omidi, The Ion/ion-acoustic instability, J. Plasma Phys., submitted, 1986.