QUASI-LINEAR DYNAMICS OF A HOT MAXWELLIAN ELECTRON DISTRIBUTION RELEASED FROM A LOCALIZED REGION IN A HOMOGENEOUS PLASMA

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ABSTRACT

To investigate by numerical analysis the transition towards the asymptotic regime postulated by Ryutov and Sagdeev (1970) in their study of the expansion of a hot electron cloud through a plasma, a physically consistent system of one-dimensional quasi-linear equations has been solved on a Cyber 7600. The results obtained for various conditions of injection were all found in qualitative agreement with the simple analytic description of Ryutov and Sagdeev, in spite of the serious deficiencies of their analysis. Although the aims and techniques of the present study are quite distinct from published numerical works by Takakura and Shibahashi (1976) and Magelssen (1976), all the results point towards the same conclusion: plasmon emission, due to advective instability at the front of the electronic disturbance, is followed by strong reabsorption through a reverse advective process at the rear. In the present note, only the case of a localized hot electronic distribution (initially Maxwellian with $T_e = 10^8$ K) is considered. The effect of plasmon-plasmon scattering, which can also be included in the programmes, is mentioned in the conclusion.

INTRODUCTION

In their pioneering work on the quasi-linear dynamics of 'hot electron clouds' spreading in a homogeneous plasma, Ryutov and Sagdeev (1970) postulated a priori the existence of an asymptotic regime which could be studied analytically without solving explicitly the complex non-linear equations of evolution provided by the quasi-linear theory. The obvious deficiencies of their global techniques were pointed out in a former publication (Grognard, 1975). In particular, it was not clear that such an asymptotic regime could ever be reached and then maintained. To investigate the transition from given initial data towards this hypothetical regime, a system of one-dimensional, discrete quasi-linear equations was constructed on the basis of the equations of Harris (1969), thereby providing general conservation and entropy theorems. Further,

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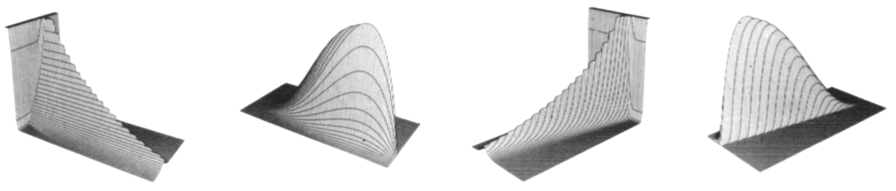
to make the discrete system fully physically consistent, time and space coordinates were discretized to yield a semi-implicit system for which the proof of positiveness can be established and which possesses a stable thermodynamical state, which is equivalent to the usual one in the limit where the variables become continuous. This system was eventually solved on a Cyber 7600 for various initial and boundary conditions, up to the stage where the asymptotic regime was clearly established. Our aims and techniques were therefore sufficiently distinct from published works of a similar nature to warrant an independent publication. The method has been also extended to cover the case of plasmon-plasmon scattering. In this note, we present a single case, illustrating (Fig. 1a-d) the onset of the asymptotic



(a) (b) (c) (d)

Fig. 1 - ASYMPTOTIC REGIME
$t \gtrsim 1$ s if the background plasma is such that ω_p = 100 MHz.
(a) Front view in true perspective of the electron distribution. The 'wall' at left represents the background plasma distribution, truncated at about 500 electrons per Debye length. The space coordinate runs parallel to it, increasing from right to left (range ~200000 km). The velocity coordinate runs perpendicular to it from 2 to 35 thermal velocities.
(b) Front view of the plasmon distribution (same perspective as for (a)). The peak is at about 10^5 times the background level.
(c) Rear view of 1(a).
(d) Rear view of 1(b). The straight cut-off line, of equation: $x = \frac{1}{2}vt$, is obvious in this view.

regime for the instantaneous injection of a hot Maxwellian ($T_e = 10^8$ K), spread initially in space as a Gaussian 'cloud'. A movie, presented at the Symposium (see Wild, this volume), illustrates yet another case where a hot Maxwellian, at the same temperature, is injected at a single point but following a finite time profile. Both results are substantially the same in the asymptotic regime. In all programmes, the space-time frame work is Minkowskian, permitting consideration of much higher temperatures while remaining in agreement with relativistic kinematics (as in Zaitsev et al., 1972 and Zaitsev et al., 1974). However, it should be pointed out that no relativistic plasma kinetics is involved in this exercise.

THE TRANSITION TOWARDS THE ASYMPTOTIC REGIME

It is essential to note that Ryutov and Sagdeev's (1970) results make sense only if the injected distribution, f_0, is such that $\partial f_0/\partial v \leqslant 0$ everywhere; otherwise non-physical negative solutions are found. It rules out injections of 'beams' centred on a velocity $V_0 \neq 0$. In the case of such beams it is found by numerical analysis that the first stage of evolution leads to plasmon pile-up in the domain of injection. This accumulation of plasma waves acts as a censor, letting out only relaxed distributions with $\partial f/\partial v \leqslant 0$. In this stage, a considerable amount of energy is left behind. Therefore, we investigated more extensively the evolution of localized electron distributions which are initially thermal but hotter than the surrounding medium (typically at 100 times the background temperature). Then it is found that the growth of plasmons produced by advection is much smoother than for beams (as pointed out in fact by Zheleznyakov and Zaitsev (1970)). Ahead of the bulk of the electronic disturbance a runaway electron distribution of small amplitude ($n_e \lesssim 10$ electrons per Debye length) escapes and raises the plasmon temperature to just below the threshold of induced mechanisms. Given the linearity of the vertical scales in Figure 1 this mechanism is not conspicuous, but it can be seen in the foreground of Figures 1a-b, where relaxation is almost complete. On the other hand, it is clearly seen on Magelssen and Smith's (1977) logarithmic plots. At the front of the bulk of the distribution, induced emission, still sustained by advection (i.e. ultimately by the spatial gradient of the plateau heights), raises the plasmon level to 10^5-10^6 times the background temperature (and at this level plasmon-plasmon scattering should be very active). In these conditions, relaxation is quasi-instantaneous and the flat electron distributions are maintained in spite of advection but the spatial gradient of the plateau heights does not increase. On the other hand, at the high negative slopes appearing at the rear of the electron cloud (Fig. 1c), strong reabsorption of plasmons takes place and consequently electrons are accelerated until almost no plasmon is left behind. The reverse advective process at the rear maintains the upper cut-off line in both electron and plasmon distributions on a curve which goes asymptotically to the straight line of equation: $x = \frac{1}{2}vt$, quite obvious on Figure 1c (t is the time of the image).

In the case of a continuous injection at a point, similar agreement with Ryutov and Sagdeev's (1970) results is obtained.

An interesting new result is obtained with repeated injections a short time apart. The initially distinct electron disturbances merge rapidly with one another and yield only transiently distinct plasmon emissions. Asymptotically, the emission at the front of the first disturbance is the only one sustained.

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CONCLUSION

Programmes specifically designed to investigate the emergence of the asymptotic regime postulated by Ryutov and Sagdeev (1970) yielded results in complete qualitative agreement with their hypothesis. Thereby a question raised in the second part of Grognard (1975) is eventually answered. Our independent results are also in accord with earlier numerical works aimed directly at realistic modelling of the dynamics of the electron cloud responsible for solar Type III bursts. It must be pointed out however that the high plasmon levels reached lead to active plasmon-plasmon scattering. In the one-dimensional models at least, this entails a significant loss of energy from the electron cloud. Careful investigations of this question are still needed before one can consider this fascinating problem as definitely solved.

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DISCUSSION

Papadapoulos: It is well known that ion dynamics cannot be neglected in beam plasma interactions, unless $\frac{W}{nt} \ll (K\lambda_D)^2$. Were these conditions satisfied in the simulations? [Note that particle simulations (Rowland and Papadopoulos Phys. Rev. Lett. 20, 1276, 1977) clearly demonstrated the role of collapse and ion dynamics in such situations].

McLean (for Grognard): Unfortunately, as I am reporting for Grognard, I do not have the data to answer your question.

Bradford: How do you reconcile the electron exciter stream velocity distributions with long plateaus that theoreticians discuss, with the "scatter free" electron event velocity distributions observed at 1 AU? The observed instantaneous velocity appear more like spikes with a high velocity tail, which might be due to interplanetary scattering, and a sharp low velocity cutoff corresponding to the propagation time along a spiral path from the sun.

McLean (for Grognard): The distributions to which you refer are recorded near 1 AU. Perhaps the work which I describe is relevant much closer to the sun, e.g. when the plasma frequency is $\sim$ 100 MHz.

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