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ION THERMALIZATION IN THE EARTH'S BOW SHOCK

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THE INSTITUTE FOR FLUID DYNAMICS *and* APPLIED MATHEMATICS

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ABSTRACT

The role of the counterstreaming ion instability in thermalizing the solar wind ions in the earth's bow shock is discussed. It is shown that the interplanetary magnetic field plays an important role in the development of this instability. Comparison with recent experimental data shows that it can be the dominant mechanism of ion thermalization.

I. INTRODUCTION

Recent satellite measurements in the bow shock region of the earth (Fredricks et al 1970, Montgomery et al 1970) demonstrate the existence of strong low frequency electrostatic turbulence followed by intensive ion heating. Fredricks et al (1970) propose the electron-ion streaming instability (Buneman 1958, Fried and Gould 1961, Davidson et al 1970) as the main ion dissipation mechanism. The source of the electron drifts is the diamagnetic electron current in the large magnetic field gradients. However recent theoretical and computer simulation work has shown that while this instability may account for the observed electron heating in the shock front, it is not very effective in thermalizing the ions (Davidson et al 1970; McKee 1970). Moreover, theoretical work (Tidman and Krall 1970, Crevier and Tidman 1970) has shown that resistive dissipation is inadequate to support oblique shocks above a critical Mach number $(M_A^{cr} \sim 2,3)$ since wave breaking occurs. These authors point out that the consequence of such wave breaking is a multistreaming situation for the protons which might lead to a two ion stream instability, but they did not include the effect of the magnetic field on the instability in their discussion. This instability and the resulting ion thermalization has been recently studied theoretically and with computer simulation by Papadopoulos et al (1970). These latter studies included the magnetic field which has an important effect on the electron dynamics. It is the purpose of the present note to demonstrate that the turbulence generated by the counterstreaming ion instability across the compressed magnetic field in the earth's bow shock can account for the experimentally observed ion heating.

II. COUNTERSTREAMING ION INSTABILITY

In this section we summarize the basic results of the time development for the counterstreaming ion instability across a magnetic field. A detailed theory of the instability can be found in Papadopoulos et al (1970). The system shown in Fig. 1 is linearly unstable for

$$\frac{\omega_{pe}^2}{\Omega_e^2} \frac{m_i}{m_e} \frac{u^2}{c^2} < 4(1 + \beta_e) \tag{1}$$

where $u = 2V_d$ is the relative velocity of the ion stream. In linear theory the dispersion for this system predicts the following growth rate and wave number for the most unstable mode

$$\gamma_m = \frac{1}{2} \omega_o \qquad\qquad k_m^2 = \frac{3}{4} \frac{\omega_o^2}{V_d^2} \tag{2}$$

where

$$\omega_o^2 = \frac{\omega_{pi}^2}{2\left(1 + \dfrac{\omega_{pe}^2}{\Omega_e^2}\right)} \tag{3}$$

The range of unstable wave-numbers is

$$0 < k^2 < \frac{2\omega_o^2}{V_d^2} \tag{4}$$

In deriving these results it was assumed that the electrons are bound to field lines $(kr_e \ll 1 \, , \; |\omega| \ll \Omega_e)$, while the ions follow straight orbits $(kr_i \gg 1 \, , \; |\omega| \gg \Omega_i)$.

In general these unstable oscillations are mixed (electrostatic-electromagnetic), but the electrostatic character is dominant in the smaller wave-lengths ($k \sim \omega_{pe}/c$). The instability develops in a quasilinear fashion as described by Papadopoulos et al (1970) and is stabilized by ion trapping when the electrostatic field energy reaches

$$\varepsilon_{Fmax} = \frac{.23}{1 + \frac{\omega_{pe}^2}{\Omega_{ce}^2}} \frac{1}{2} n m_i V_d^2 , \quad (5)$$

by which time a large fraction of the ion drift energy has been converted into ion heating. Computer simulation confirmed these results.

Fig. 2 shows the time development of the ion distribution function and the ion phase space for a typical simulation run. Most of the directed ion beam energy is converted into random ion energy. These results apply to a one dimensional system.

For a two dimensional system the condition for instability as given in Eq. (1) should be interpreted as the condition for all k directions in the x-y plane (Fig. 1.b) to be unstable. One can relax this condition substantially and still have unstable waves with $\underline{k}$ in the x-y plane but at angle to $\underline{V}_d$. However, as it will be shown for the shock parameters Eq. (1) is satisfied in the turbulent transition region so that the one dimensional theory can be applied to the problem under consideration. One should add that for unequal beam densities the basic features in the development of the instability remain the same while the linear growth rate is reduced by the density ratio.

III. COMPARISON WITH EXPERIMENT

The excellent series of data presented by Montgomery et al (1970) and Fredricks et al (1970) provide us with the highest time resolved and most complete shock structure measurements to date. Montgomery et al (1970) present mainly particle data, including both proton and electron velocity distribution functions. The Vela 4 spacecraft did not carry any field experiments. However, the particle measurements are easily reconciled with the fields and particle data from OGO-5 presented by Fredricks et al (1970). We summarize here the main results presented in the above papers:

(1) Large magnetic field compressions (e.g. from 7 γ to 30-40γ) were observed with scale lengths c/ω_{pe} .

(2) Electrostatic turbulence builds to high level in regions of high magnetic field ($|B| > 20\gamma$) [1], then decays rapidly downstream.

(3) The electrostatic waves increase in intensity with depth and saturate at $E^2/8\pi nT_e \lesssim 10^{-2}$.

(4) Proton randomization appears to correlate in every case with the region of saturation of electrostatic turbulence and the jump in proton temperature is 2-4 times greater than the jump in electron temperature.

(5) T_e/T_p upstream varies between .6 and .4 .

(6) Electron thermalization occurs in a thin region (150-600 m), upstream from the region of the ion thermalization which occurs in a distance of 40-100 km.

(7) The particle measurements show a single humped distribution function for the electrons and a double humped for the ions in the transition region. Downstream the proton distribution function takes on a flat-topped appearance. Further downstream the distribution becomes more rounded near the peak and only fluctuating ripples remain on the high energy tail. The electron distribution function becomes flat topped almost immediately (150-600 m).

Table I shows the upstream and downstream shock parameters for a particular transition. These can be considered as rather typical experimental values.

The most striking characteristic of these observations is the intense ion heating. Resistive heating due to electron-ion instabilities cannot explain the observed ion temperatures downstream and an anomalous ion viscosity is required. The counterstreaming ion-ion instability operating in the region of compressed magnetic field can provide such an anomalous dissipation.

Most of the observations summarized above, arise in a natural way during the development of the instability. The ion distribution functions as reported by Montgomery et al (1970) appear to develop in a similar way with Fig. 2(a-c). The necessary condition for instability given by Eq. (1) is satisfied for the observed values in the regions of turbulence. The ion heating is independent from the electron heating, which is resistive, so that ion temperatures higher than electron are a natural consequence of the mechanism. The proton thermalization occurs in the region of saturation of the electrostatic turbulence, in agreement with Fig. 2(d,f,g).

The length scale predicted for ion thermalization can be estimated easily from Eqs. (2) and (3), by taking the thermalization time as 5-10 γ_m^{-1} , consistent with the simulation results. Then for the plasma parameters in the compressed magnetic field region given by Table I and for drift velocity $u \sim 4 \times 10^7$ cm/sec, the ion thermalization distance is

$$L \sim 5\text{-}10 \frac{u}{\gamma_m} \sim 5\text{-}10\ 2\sqrt{2} \frac{\Omega_e}{\omega_{pe}} \frac{u}{\omega_{pi}} \sim (5\text{-}10)\ 10^2 \frac{u}{\omega_{pi}} \sim 40\text{-}80 \text{ km}$$

in good agreement with the measured value of 40-100 km. Finally the saturation wave energy of the instability is given by Eq. (5). For the values of Table I and with proton flow energy 800 ev we find

$$\frac{E^2}{8\pi} \sim .3 \text{ ev}$$

which is consistent with the observation

$$\frac{E^2}{8\pi n T_e} \lesssim 10^{-2}$$

We will not attempt here to enter a detailed discussion of the magnetic compression with scale lengths c/ω_e or the electron heating. Fredricks et al (1970) gave a good description of these. The magnetic field compression is basically a laminar Adlam-Allen (1958) wave. In the front of the wave the $(\nabla \times B)$ currents are carried mainly by electrons. These electron drifts trigger an electron-ion instability with growth rate (Buneman 1958)

$$\gamma \sim \frac{\sqrt{3}}{2} \left(\frac{m_e}{m_i}\right)^{1/3} \omega_{pe}$$

This instability holds down the current and heats the electrons till their thermal velocity approaches the value of the drift velocity. This mechanism accounts for keeping the electron $\beta \sim 1$, with thermalization distance

$$L \sim (5\text{-}10)\ \frac{u}{\gamma} \sim 200\text{-}400\ \text{m}$$

as observed in the experiment.

SUMMARY

We have discussed the role of the counterstreaming ion-ion instability in the ion thermalization process for the earth's bow shock. Observations of the ion distribution functions, the spectrum of turbulence, and the scale elength and location of the ion thermalization seem to support the thesis that this instability plays a dominant role in the ion thermalization.

ACKNOWLEDGMENTS

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REFERENCES

Adlam, J.H. and J.G. Allen, The structure of steady colllisionless-free hydromagnetic waves, Phil. May. 3, 448-455, 1958

Boris, J.P. J.M. Dawson, J.H. Orens and K.V. Roberts, Computations on anomalous resistance, Phys. Rev. Lett. 25, 706-710, 1970

Buneman, O.D., Dissipation of currents in ionized media, Phys. Rev. Lett. 115, 503-518, 1959

Crevier, W.F. and D.A. Tidman, Oblique shocks in finite-beta plasmas, Phys. Fluids 13, 2275-2287, 1970

Davidson, R.C., N.A. Krall, K. Papadopoulos and R. Shanny, Electron heating by electron-ion beam instability, Phys. Rev. Lett. 24, 579-582, 1970

Fredricks, R.W., G.M. Crook, C.F. Kennel, I.M. Green, F.L. Scarf, P.J. Coleman and C.T. Russel, Electrostatic turbulence in bow shock magnetic structures. OGO-5 observations, J. Geophys. Res., 1970

Fried, B.D. and R.W. Gould, Longitudinal ion oscillations in a hot plasma, Phys. Fluids 4, 139-147, 1961

McKee, C.F., Simulation of counterstreaming plasmas with application to collisionless electrostatic shocks, Phys. Rev. Lett. 24, 990-994, 1970

Montgomery, M.D., J.R. Asbridge and S.J. Bame, Vela 4 plasma observations near the Earth's bow shock, J. Geophys. Res. 75, 1217-1231, 1970

Papadopoulos, K., R.C. Davidson, J.M. Dawson, I. Haber, D.A. Hammer, N.A. Krall and R. Shanny, Heating of counterstreaming ion beams in an external magnetic field, Phys. Fluids (to published, 1970)

Tidman, D.A. and N.A. Krall, Shock Waves in Collisionless Plasmas Chapter IV, John Wiley & Sons, Inc. New York, 1970

TABLE I

Shock Transition Parameter

	Upstream	Downstream[2]
B	5.2 γ	35 γ
n	5 cm	15 cm^{-3}
u	4.15×10^7 cm sec^{-1}	3.3×10^7 cm sec^{-1}
T_e	1.5×10^5 °K	7×10^5 °K
T_i	6×10^4 °K	2×10^6 °K
β	1.4	1.0
ω_{pe}	1.2×10^5 sec^{-1}	2×10^5 sec^{-1}
ω_{ce}	8.8×10^2 sec^{-1}	5×10^3 sec^{-1}
M_A	6 - 10	

FOOTNOTES

1. Fredricks et al note that electrostatic noise occurs in regions of high $|B|$-gradients. However in some cases, e.g. Fig. 2 at $0^h\ 43^m\ 51^s$ of Fredricks et al (1970), it appears that high level noise occurs without any field gradients, but only compressed fields. For this reason we prefer, consistently with the proposed picture, to correlate the electrostatic turbulence with high $|B|$-fields, which is the case in all data presented.

2. Since there were no magnetic probes on the Vela we assume a magnetic field value of $35\ \gamma$ on the basis of Fredricks et al (1970) data.

FIGURE CAPTIONS

Fig. 1a. Initial velocity space configuration of ion streams and electron background

Fig. 1 b. Geometry of system

Fig. 2. [From K. Papadopoulos et al (1970)]

a–c: Time sequence of electron and ion distribution functions

d: Time development of field energy (ε_F), Ion temperature (K_i) and Electron y-drift energy (K_{ye}) $(\alpha^2 = 1 + \omega_{pe}^2/\Omega_e^2)$.

e–h: Time sequence of ion phase space.

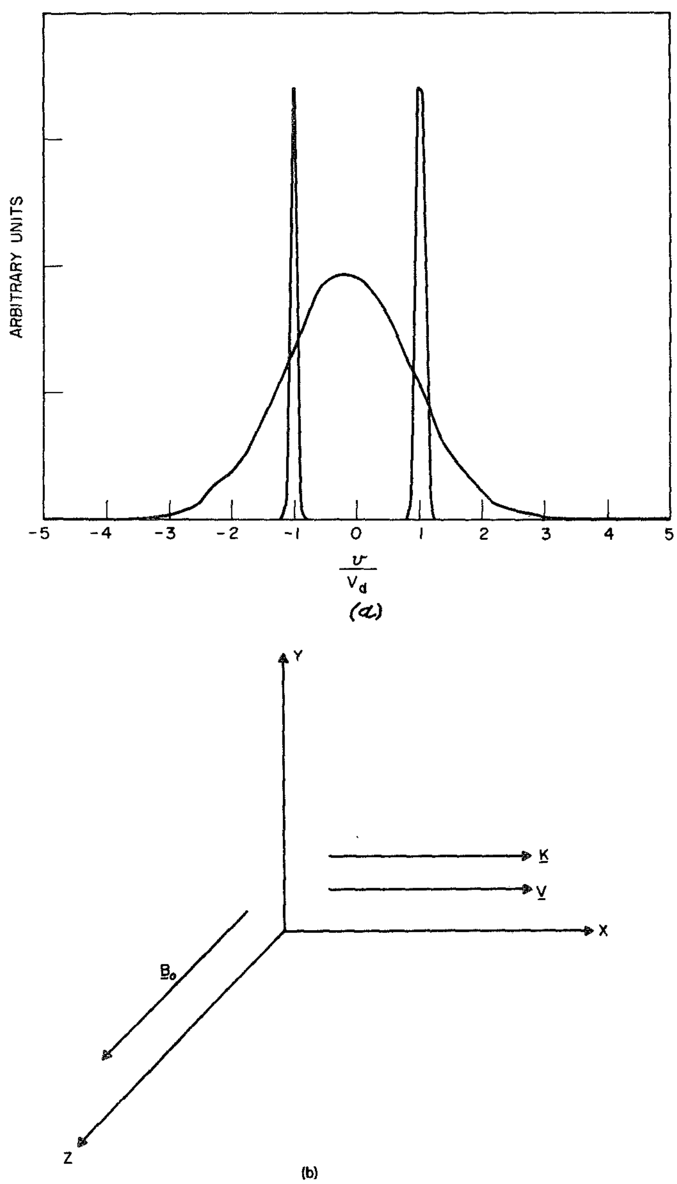
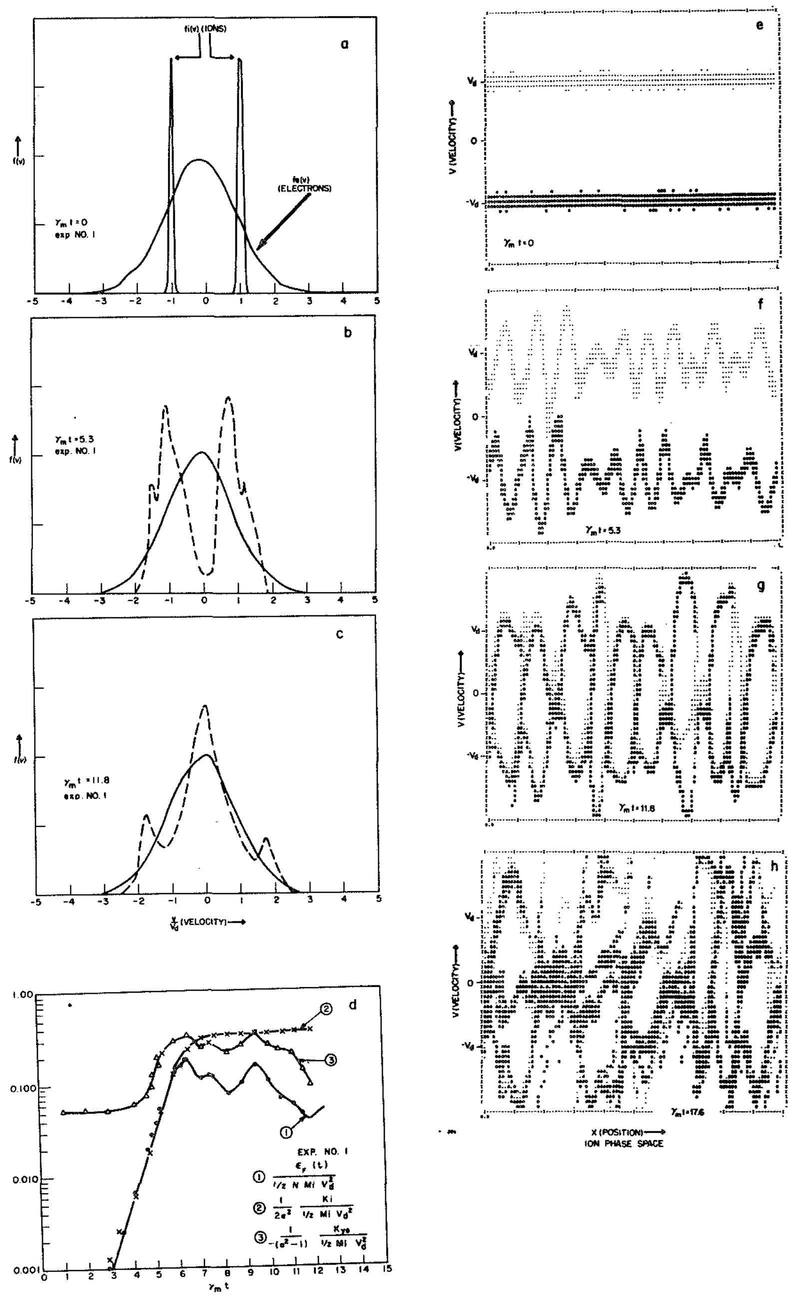


FIG. 1 a) INITIAL VELOCITY SPACE CONFIGURATION OF ION STREAMS AND ELECTRON BACKGROUND. b) GEOMETRY OF THE SYSTEM.



<u>Figure 2</u>