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ELECTROSTATIC, SHORT-WAVELENGTH, TURBULENCE AS THE SOURCE OF ION HEATING IN THE SOLAR WIND

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ABSTRACT

We propose a mechanism for the nonthermal ion heating observed in the solar wind at 1A.U. based on an electrostatic, short wavelength, instability between the ions in the observed colliding plasma streams. The modes lying on a plane perpendicular to the magnetic field thermalize most of the differential energy. The model suggests local electrostatic turbulence, that α-particles are heated more than protons $(T_\alpha \sim 4T_p)$, a maximum proton temperature $T_p \lesssim 10^6 k$ and for the bulk speed U possibly a $T_p^{1/2} = aU + b$ relationship. These predictions are consistent with observations.

I. INTRODUCTION

Direct satellite observations during the last 9 years have led to a remarkably detailed and reasonably complete knowledge of the interplanetary plasma (e.g. Strong et al 1966; Neugebauer and Snyder 1966; Hundhausen 1968; Burlaga and Ogilvie 1969; Parker 1969). Equilibrium hydrodynamic models of the coronal expansion while fairly successful in predicting the ovserved mass flow properties underestimate the proton temperatures in the active wind by more than one order of magnitude (Sturrock and Hartle (1966)). In addition, the distribution of the internal energy among the various ion species indicates clearly the existence of non-thermal heating mechanisms. Proper identification of these mechanisms seems to be the key in understanding the observed thermal properties of the interplanetary plasma.

Sturrock and Hartle (1966) first suggested that the required energy for ion heating may be contained either in magnetohydrodynamic waves originating near the Sun and propagating outward through the solar wind plasma or in the differential motion of solar wind streams. In the latter case the Kelvin-Helmholtz instability is the mechanism by which the differential energy is converted into long wavelength turbulence. Following this Coleman (1968) argued that regardless of the source of the waves, it is likely that they cascade down into shorter wavelengths by non-linear processes, much as in hydrodynamic turbulence, till they transfer their energy to the ions by ion cyclotron damping. Jokipii and Davis (1969) argue that if the waves were of solar origin they would damp out before reaching the earth's orbit as shown by Barnes (1967). Subsequently assuming that such waves are generated by the colliding plasma streams, suggest that they heat the plasma directly by resonant interactions and most of the wave energy does not cascade to smaller eddies, as proposed by Coleman.

The colliding stream structure of the wind, was discovered by Snyder et al (1963) and is at times associated with the magnetic sector structure of Ness and Wilcox (1966). Sarabhai (1963) noted that as solar rotation brings a sector of higher wind velocity beneath one of lower velocity, the fast stream overtakes the slower one. Jokipii and Davis (1969) argue that it is the collision between such streams that generates the waves, rather than the shear between them (Coleman 1968). However in either view the observed low frequency and large wave-length fluctuations are associated with the "anomalous" ion heating, which should therefore be a large scale phenomenon (Parker 1969).

The recent observational analysis of the Explorer 34 data by Burlaga and Ogilvie (1969) seems to contradict various aspects of the proposed above non-thermal ion heating mechanisms.

Lack of correlation between negative velocity gradients (as viewed from the earth) with the observed non-thermal ion heating seems to rule out the hypothesis of the Kelvin-Helmholz instability.

The observed turbulence, as opposed to fluctuations, occurs only in "patches" and is well correlated with local proton heating. This is consistent with the interpretation of data from Mariner 2 by Neugebauer and Snyder (1966) and from the Vela by Hundhausen et al (1967), who placed an upper limit on the wavelength of the observed turbulence of the order 5-50 km (Hundhausen, 1968). Such a limit implies that the magnetic field does not participate in the turbulent or collective motions, which should therefore be electrostatic in nature.

Finally strong correlation of local proton heating with large positive velocity gradients, is consistent with the idea that heat is generated by the collision of fast streams with slower moving plasma.

These observations indicate that non-thermal ion heating is a localized rather than large scale phenomenon, electrostatic in nature, consistent with the hypothesis of electrostatic instabilities in colliding streams and not connected directly with the large scale hydromagnetic turbulence.

It is the purpose of the present note to propose an ion heating model consistent with the above picture. The thermalization mechanism is a short wavelength electrostatic instability between the counterstreaming ions in the colliding streams. Under some local conditions specified in the next section modes with wave vectors (k) on a plane perpendicular to the magnetic field are unstable, and non-linear theory indicates that they result in thermalizing the differential energy perpendicular to the direction of the magnetic field. An extensive account of the linear and non-linear theory of the instability supported by computer experiments has been published recently by Papadopoulos et al (1971) and Wagner et al (1971). Below, following a brief summary of the instability theory, we present arguments which suggest that the proposed model is consistent with the various observational characteristics.

II. THEORETICAL BACKROUND

Several studies of ion instabilities between plasma streams appeared lately in the literature due to their importance in high Mach number (M_A) shocks and controlled thermonuclear research (Papadopoulos et al 1971; Wagner et al 1971; Landau 1971). We present here a short review of the results pertaining to unstable modes on a plane perpendicular to a magnetic field, which appear to be important in the problem under consideration. For a detailed account we refer the interested reader to Papadopoulos et al (1971) and Wagner et al (1971).

The system shown in fig.1a is linearly unstable if

$$u_r \leq 2.5 \sqrt{1+\beta}\, V_A \tag{1}$$

where V_A is the local Alfvén spead ($V_A = B/[4\pi nM]^{1/2}$) and β the ratio of the electron to the magnetic pressure ($\beta = nk_B T_e/B^2/8\pi$). The growth rate and the wavenumber for the most unstable <u>electrostatic</u> mode is

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

where $\omega_o^2 = \omega_i^2/2[1 + \omega_e^2/\Omega_e^2]$, $\omega_e(\omega_i)$ the electron (ion) plasma frequency and Ω_e the electron cyclotron frequency. The range of the electrostatically unstable wavenumbers k is given by

$$0 < k^2 < \frac{2\omega_o^2}{u_r^2} \tag{3}$$

subject to the condition $k^2c^2/\omega_e^2\,(1+\beta) \geq 1$. Electromagnetic instabilities do not result in ion thermalization and can therefore be neglected for the present case.

Non-linear theory shows that the instability results in thermalizing the relative ion streaming energy producing a single-humped ion distribution function moving with the velocity of the center of mass of the system (fig. 1b) and temperature

$$\frac{T_i}{1/2\ Mu_r^2} \sim .3 \qquad . \tag{4}$$

The stabilization mechanism is ion trapping in the large amplitude electrostatic ion turbulence which occurs at a fluctuation energy level ε_F such

$$\varepsilon_F \sim 5 \times 10^{-2} \frac{\frac{1}{2} n M u_r^2}{1 + \frac{\omega_e^2}{\Omega_e^2}} \qquad . \tag{5}$$

These thoretical results have been confirmed by computer simulation using a code which follows the orbits of 2×10^4 electrons and ions. Fig. 1 (a,b) shows the evolution of the ion distribution function and ion phase space for a typical numerical experiment, with parameters relevant to the solar wind.

In the discussion presented above we assumed equidensity ion beam streaming perpendicular to the direction of the magnetic field B . One can generalize the results for cases of oblique streaming by replacing the relative streaming speed u_r by its projection $u_r \sin\theta$ in the direction perpendicular to the magnetic field. This can relax the instability condition so that streams with relative velocity $u_r \lesssim 2V_A\sqrt{1+\beta}/\sin\theta$ can be unstable. However the temperatures achieved will be lower than given by eq. (4) by a factor $\sin^2\theta$. Therefore streamers along the magnetic field lines will not be heated. The effects of unequal stream densities were discussed in Papadopoulos et al (1971). The essential conclusion is that while for density ratios close to unity the ion temperatures will be of the order of magnitude given by eq. (4). For large density ratios only the low density stream will be thermalized and will thus form a hot ion tail in the main ion distribution function. In all cases the average ion heating is related to the increase in the bulk velocity (Δu) over that of the slow plasma with a relation of the form

$$\sqrt{T_i} = a\Delta u \qquad (6)$$

where a will be a function of the density ratio and the angle θ .

In closing this section we mention that the instability has been recently identified as producing ion heating in two laboratory experiments (Davis et al 1971; Dean et al 1971).

Solar Wind Ion Heating

We examine next whether the implications of the proposed model are consistent with the observations of the non-thermal properties in the solar wind. We concentrate on observations related to the turbulence and overall ion heating, rather than the anisotropic features such as the ratios $T_{\parallel}/T_{\perp}$ of the parallel to perpendicular temperatures which should be accounted for in terms of internal instabilities of electromagnetic nature (Parker 1963; Scarf et al 1967) and are independent of the electrostatic mechanism producing local ion heating. These observations, as reported in an excellent review article by Hundhausen (1968), and a later paper by Burlaga and Ogilvie (1969), are:

(1) Proton temperatures: The observed proton temperatures in the active wind are of the order of 3×10^5 °K with an upper limit of 9×10^5 °K (Hundhausen 1968). These are more than one order of magnitude higher than

the 10^4 °K expected from the two fluid model (Sturrock and Hartle 1966). The proposed mechanism can explain both the observed temperatures and the upper limit by independent considerations. As indicated by eq. (4) in order to achieve temperatures of the order of 3×10^5 °K one needs relative speeds between the streamers of the order of 140 km/sec, which definitely falls in the range of relative speeds expected and observed. The maximum temperature of the ions due to the proposed thermalization mechanism can be found by combyning eqs. (1) and (4) and is given by $(T_p)_{max} \sim 1/4\ 6.25\ (1 + \beta)\ 1/2\ M_P V_A^2$. Such temperatures of course would appear only if $u_r = 2.5\sqrt{1 + \beta}\ V_A$ which is the largest relative velocity for the system to be unstable. Since for the active wind at 1AU $\beta \sim .5$ and $V_A \sim 80$ km/sec, we find that $(T_P)_{max} \sim 10^6$ °K . It is remarkable that his upper limit set by the values of magnetic field and the density as measured in the active wind rather than by speculations about the differential energy of the stream, is in such a good agreement with the proton temperature observations.

(2) Temperature distribution among the various ion species: It has been observed that while in the quiet wind the temperatures of the various ion species present are almost the same, in the active wind they are greatly different and tend to be proportional to their masses (e.g., the helium to proton temperature is $T_{HE}/T_P \sim 4$) indicating equality of their thermal velocities. This seems to be one of the strongest arguments in favor of a two stream electrostatic instability. From eq. (4) we find that the stabilization temperature T_j of the ion species j with mass M_j follows the law

$$\frac{T_j}{M_j} = \text{const.}$$

Notice that the constant depends only on the relative streaming u_r, which is presumably the same for all species. The observed distribution of internal energy among the various ion species is an absolutely natural consequence of the proposed mechanism.

(3) Scale and wavelengths of the turbulence: Measurements of flux vs. angle or energy per change peaks show a substantial spread which might be the result of turbulent or collective motions. Such an interpretation of the data as discussed by Neugebauer and Snyder (1966) places an upper limit of 50 km on the wavelength of the turbulent motions as seen in a reference frame moving with the plasma flow. Similar considerations on the data transmitted by the Vela satellite lower the wavelength limit to 5 km (Hundhausen et al 1967). This is consistent with the Explorer 34 observations (Burlaga and Ogilvie 1969) which indicate that turbulence occurs only in "patches" and should be distinguished from fluctuations which are a large scale effect. As was discussed in the previous section the electrostatically unstable wavenumbers are such that $k^2c^2/\omega_e^2 \geq 1$. Since in the active wind at 1A.U $c/\omega_e \sim 1$ km, we would expect the maximum wavelength to be $\lambda \sim 2\pi/k \sim 6$ km, which seems to be consistent with the observations. In the proposed model we would expect the electrostatic ionic turbulence to be imbedded within the large scale hydromagnetic fluctuations produced either by the colliding streams in regions where they are electrostatically stable ($u_r > 2.5\sqrt{1+\beta}V_A$) or by internal instabilities due to anisotropies in temperature.

(4) Flow speed to proton temperature correlation: High bulk velocities in the solar wind have been found to correlate well with large proton temperatures (Neugebauer and Snyder 1966). In particular Burlaga and Ogilvie find an empirical relation of the form $T_p^{1/2} = aU + b$ to be valid over a wide

variety of solar wind conditions. The Sturrock-Hartke model predicts quite accurately the observed T_P-U relation for the quiet wind. Thus if this remarkable relation is actually a fundamental property of the solar wind flow, the increase in temperature $(\Delta T_P \sim T_P)$ should be accompanied by an increase in the bulk speed ΔU of a functional form $T_P^{1/2} \alpha \Delta U$. This also is a consequence of the proposed mechanism since as one can see from the theory of the instability part of the relative streaming energy goes to random energy and part to increase the bulk speed over that of the slower stream. As explained in Papadopoulos et al (1971) the proportionality constant a in the $T_P^{1/2} = a\Delta u$ relationship is a function of the density ratio of the interacting streams and the angle θ. Although the exact numerical T_P-U relationship cannot be found from our simple model, we believe that the property of the instability to increase the bulk speed proportionally to the thermal speed is a positive indication.

(5) Ion tails: We mention finally that tails in the proton distribution function such as expected when low density streamers collide with high density streamers, are observed regularly in the wind (Hundhausen 1968). In addition the fact that electrons and protons are heated by different mechanisms (Burlaga and Ogilvie 1969) is consistent with the proposed model.

As mentioned at the beginning of the section besides the properties discussed above, the proton temperature exhibits an anisotropy $T_{P\parallel}/T_{P\perp} \sim 2$. We feel that this is not connected with the electrostatic non-thermal heating mechanism which occurs over such short distances that the direction of the magnetic field over the interaction times depends more on the local fluctuations than in equilibrium field considerations. This is more so since in regions of colliding streams magnetic flux conservation requires a temporary and local enhancement of the field in the direction perpendicular to the streams. Thus if the ratio $T_{P\parallel}/T_{P\perp}$ is controlled by internal electromagnetic instabilities (Parker 1963; Scarf et al 1967) would therefore expect such instabilities which thend to restore isotropy, to follow the local proton heating, producing long wavelength fluctuations, such as observed.

Before closing this section we mention that one can apply similar considerations to the thermalization of the differential motions described by Coleman (1968) which are due to large scale fluctuations in the magnetic field and the streaming velocity. This can provide an ion heat source even in the quiet wind.

Summary and discussion:

In the foregoing the hypothesis that the non-thermal proton heating and turbulence in the solar wind is due to a short wavelength, electrostatic instability between the counterstreaming ions in colliding plasma streams has been tested. It has been shown that the dominant non-thermal properties of the solar wind are consistent with the predictions of the proposed mechanism. The picture emerging is that of localized proton heating and short wavelength electrostatic turbulence embedded within large scale magnetohydrodynamic fluctuations. It was pointed out that following the proton heating, instability related to the emerging temperature anisotropies might create long wavelength fluctuations. Additional proton heating might arise from thermalizing differential motions due to the large scale fluctuations.

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Figure Captions

Fig. 1a Initial ion phase space and distribution function

Fig. 1b Ion phase space distribution function at thermalization.

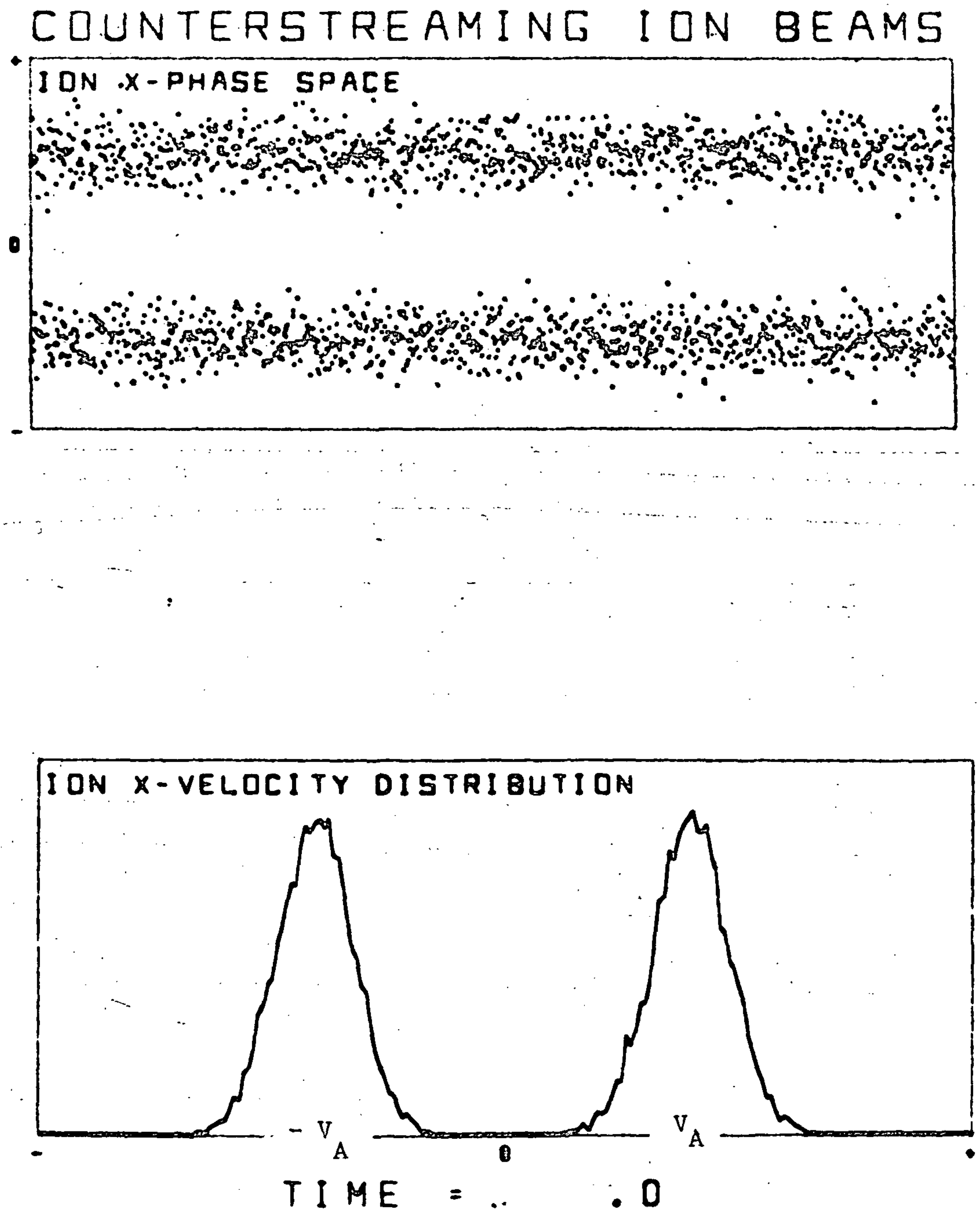
COUNTERSTREAMING ION BEAMS
ION X-PHASE SPACE
0
ION X-VELOCITY DISTRIBUTION
$-V_A$
0
V_A
TIME = .0

Figure 1a.

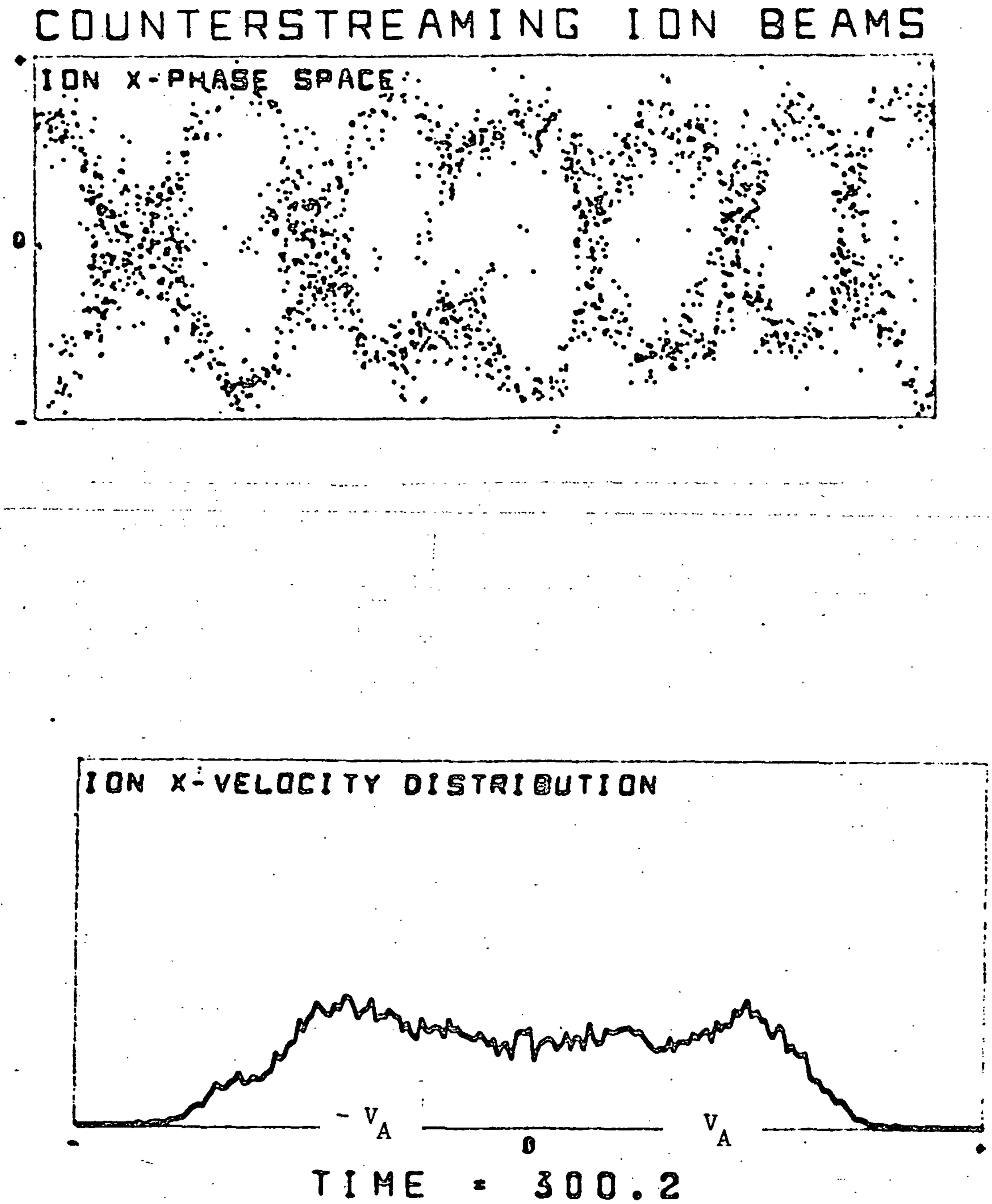
COUNTERSTREAMING ION BEAMS
ION X-PHASE SPACE
0
ION X-VELOCITY DISTRIBUTION
- V
A
0
V
A
TIME = 300.2

Figure 1b.