

INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE

3 - Avenue Circulaire
B - 1180 BRUXELLES

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A computer simulation study of the microscopic structure
of a typical current sheet in the solar wind

by

M.A. ROTH

BELGISCH INSTITUUT VOOR RUIMTE-AERONOMIE

3 - Ringlaan
B - 1180 BRUSSEL

FOREWORD

This text has been presented at the 19th ESLAB Symposium on The Sun and the Heliosphere in three dimensions (4-6 June 1985, Les Diablerets, Switzerland). It will be published in a volume of the series "Astrophysics and Space Science Library" (D. Reidel Publishing Company. Dordrecht-Holland).

AVANT-PROPOS

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VOORWOORD

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VORWORT

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A COMPUTER SIMULATION STUDY OF THE MICROSCOPIC STRUCTURE OF A
TYPICAL CURRENT SHEET IN THE SOLAR WIND

by

M.A. ROTH

Abstract

It is shown that the internal structure of a typical current sheet in the solar wind can be simulated numerically by means of a computer program based on the well-known Vlasov theory of tangential discontinuities in collisionless plasma with multiple species. For each plasma species, moments of the velocity distribution function up to the third order have been computed and are illustrated, together with the magnetic field, the electric potential, the electric field and the charge density. It is shown that the thickness of the current layer is about 20 proton gyro-radii. This means that, in order to resolve such layers, the time resolution of plasma measurements should not exceed 1s.

Résumé

On montre que l'on peut simuler numériquement la structure interne d'une couche de courant typique au vent solaire au moyen d'un programme d'ordinateur basé sur la théorie bien connue de Vlasov des discontinuités tangentielles dans un plasma sans collisions à plusieurs constituants. Pour chacun de ces constituants, les moments de la fonction de distribution des vitesses jusqu'au troisième ordre ont été calculés et sont illustrés, ainsi que le champ magnétique, le potentiel électrique, le champ électrique et la densité de charge. On montre que l'épaisseur de la couche de courant est d'environ 20 rayons de gyration de Larmor des protons. Cela signifie que la résolution temporelle des mesures de plasma ne devrait pas dépasser 1s si l'on veut résoudre de telles couches.

Samenvatting

Er wordt aangetoond dat de interne structuur van een typische stroomlaag in de zonnewind numeriek kan nagebootst worden door middel van een computerprogramma gebaseerd op de bekende Vlasovtheorie van de tangentiële discontinuïteiten in een botsingvrije plasma met meerdere bestanddelen. Voor elk van deze bestanddelen werden de momenten van de snelheidsverdelingsfuncties tot de 3e graad berekend en geïllustreerd, alsook het magnetisch veld, de elektrische potentiaal, het elektrisch veld en de ladingsdichtheid. Er wordt getoond dat de dikte van de stroomlaag ongeveer 20 proton gyrostralen bedraagt. Dat betekent dat de tijdelijke resolutie van de plasmametingen de 1s niet mag overschrijden als men dergelijke lagen wil oplossen.

Zusammenfassung

Es wird gezeigt das die innere Struktur einer typischen Stromschicht im Sonnewind numerisch kann simuliert werden mit einem Computerprogramm basiert auf der bekannten Vlasovtheorie der tangentialen Unterbrechungen in einem stossfreien Plasma mit mehreren Bestandteilen. Für jeden Bestandteil wurden die Momenten der Geschwindigkeitsverteilungsfunktionen zum dritten Grad berechnet und illustriert, wie auch das Magnetfeld, das elektrische Potential, das elektrische Feld und die Ladungsdichtigkeit. Es wird gezeigt das die Dicke der Stromschicht ungefähr 20 proton "Gyroradius" ist. Das bedeutet das die zeitweilige Resolution der Plasmamessungen 1s nicht mag überschreiten wenn man solche Lagen will auflösen.

1. INTRODUCTION

Kinetic theories of tangential discontinuities (TD) in space plasmas have been discussed by a number of authors (e.g., Alpers, 1969; Roth, 1978; 1979; 1980; and 1983; Lee and Kan, 1979). These theories consider unidimensional plane current layers and the determination of their microscopic structure is based on both Vlasov and Maxwell's equations for plasma and fields. It is outside the scope of this paper to give a detailed account of these theories, but the interested reader can refer to Roth (1980, 1983) for the theoretical aspect sustaining the numerical results given in this note.

In section 2 we will briefly describe the theoretical model, while section 3 will give numerical results for the internal structure of a typical current sheet in the solar wind. Finally, the time resolution of plasma measurements across such a layer will be discussed in section 4 in the frame of an Interdisciplinary Study of Directional Discontinuities in the Solar Wind with the Ulysses Mission (Lemaire et al., 1983).

2. THE MODEL

In a cartesian coordinate system, the plane of a "discontinuity" is parallel to the (Y, Z) plane and all the variables are assumed to depend on the X coordinate, normal to the discontinuity. Since there is no mass flow across the transition and since the parallel conductivity is very large, the electric field is everywhere oriented along the X-axis. Furthermore, the normal component of the magnetic field (B_x) is assumed to vanish since this model applies to the description of tangential discontinuities (TD).

Kinetic models for the description of TD are all based on Vlasov-Maxwell's equations. Indeed for TD the Vlasov equation can be solved easily because it is possible to find a sufficient number of true constants for the motion of a particle. These are the energy H and the p_y

and p_z components of the canonical momentum. These constants can then be used to construct a solution for the velocity distribution functions. In the theory developed by Roth (e.g. Roth, 1983), any velocity distribution function (F) is a suitable linear combination of two Maxwellians n_1 and n_2 ; each of these Maxwellians being weighted by a coefficient g , function of p_y and p_z . It is this functional dependence of g on p_y and p_z which makes that, at large distances from the center of the transition, the distribution F tends towards n_1 or n_2 (the indices 1 and 2 refer respectively to regions of large negative and large positive values of X). The first moments of these Maxwellians are in fact given parameters equivalent to observed boundary conditions. Moments of F , of arbitrary order, can also be determined analytically in terms of the electric potential and in terms of the tangential components of the magnetic vector potential. As these quantities can be obtained from a numerical integration of the Maxwell's equations, a complete description of the internal structure of the transition can then be made. The theory is self-consistent in that the electric potential and the electric field are obtained from the charge-neutral approximation which is verified a posteriori. Indeed, in most cases, the relative charge density obtained by computing the second derivative of the potential remains very small as assumed.

3. THE INTERNAL STRUCTURE OF A TYPICAL CURRENT SHEET

Plasma boundary conditions for a typical current sheet in the solar wind are given in table I. On the left hand side of the transition, or side 1, i.e. for large negative values of X , there is a "hot" plasma of hydrogen and helium (e_1^- , H_1^+ and He_1^{++}), while on the right hand side or side 2, i.e. for large positive values of X , there is a "cold" plasma of hydrogen and helium (e_2^- , H_2^+ and He_2^{++}). Notice that on side 1, each plasma component (e_1^- , H_1^+ and He_1^{++}) has a distinct mean velocity. Note also that the "hot" plasma species have a vanishing number density on side 2 while the "cold" ones have a vanishing number density on side 1. The transition itself will be a region where these two plasmas of different characteristics are interpenetrated. The plasma in the transi-

PLASMA BOUNDARY CONDITIONS

	N_1	N_2	T_1	T_2	V_{y1}	V_{z1}	V_{y2}	V_{z2}
e^-_1	5	0	15		219	-311	.	
e^-_2	0	3		10			175	-285
H^+_1	4.5	0	6		223	-315		
H^+_2	0	2.7		4			175	-285
He^{++}_1	0.25	0	16		180	-272		
He^{++}_2	0	0.15		12			175	-285
	cm^{-3}		eV		km/s		km/s	

Table 1 : The indices 1 and 2 refer respectively to sides 1 and 2, i.e., to large negative and large positive values of X , the distance along the normal to the current sheet. The "hot" plasma (e^-_1 , H^+_1 and He^{++}_1) is confined to side 1 while the "cold" one (e^-_2 , H^+_2 and He^{++}_2) is confined to side 2.

tion will therefore be considered as a three-components plasma (e^- , H^+ and H_e^{++}), an admixture of the two adjacent plasmas. The magnetic field on side 1 is assumed to be uniform and its components are $B_{y_1} = -3.5$ nT and $B_{z_1} = +3.5$ nT. Its intensity on side 2 is, of course, predetermined from the pressure balance condition. On each side of the transition, the plasma boundary values satisfy the charge neutrality and the zero current density conditions.

The first three panels of figure 1 illustrate the number densities. The second panel displays the total number density of electrons (e^-), protons (H^+) and helium particles (He^{++}), i.e. the sum of the number densities of e_1^- and e_2^- , H_1^+ and H_2^+ and He_1^{++} and He_2^{++} , illustrated on the first and third panels. Also in figure 1 are displayed the temperatures : 4th panel for the "hot" plasma species, 6th panel for the "cold" plasma species and 5th panel for the average temperatures of the admixture. Notice that the electron temperatures (e_1^- and e_2^-) do not change throughout the transition. This is a consequence of a particular choice for the parameters of the electron velocity distribution functions. Indeed, for the two electron species, it has been assumed that the velocity distribution functions remain isotropic about their mean velocity. Computation of the temperature (and also of moments of higher order) becomes meaningless, of course, when the corresponding number density becomes vanishingly small, as shown in the 4th and the 6th panels. The last three panels of figure 1 illustrate, respectively, the bulk velocity components and the components of the energy flow in the admixture. The thickness of the transition in unit of the proton gyro-radius, $R(H^+)$, can be deduced from the scale shown in the upper part of the panels. It can be seen that the variation in the H^+ number density occurs in about $20 R(H^+)$, i.e., in about 800 km.

The 12 panels of figure 2 illustrate the electric potential (1st panel), the electric field (5th panel), the relative charge density (9th panel), the current density components (2nd panel), the magnetic field components (6th panel) and hodogram (10th panel), the contribution of each plasma species to the current density (3rd, 4th, 7th and 8th panels)

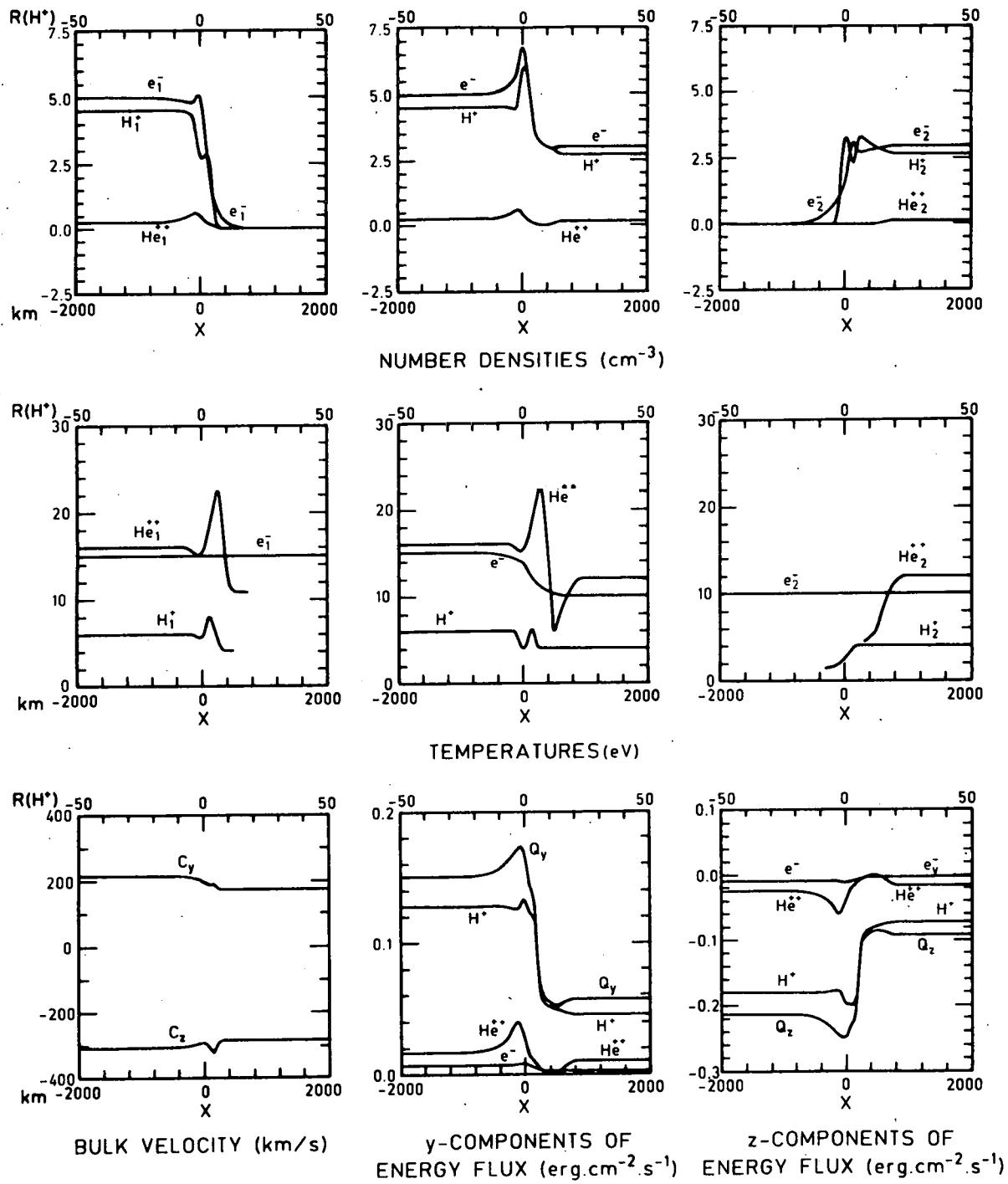


Fig. 1.— Plasma characteristics across a TD whose boundary conditions are given in table 1. The X-axis is along the normal to the discontinuity.

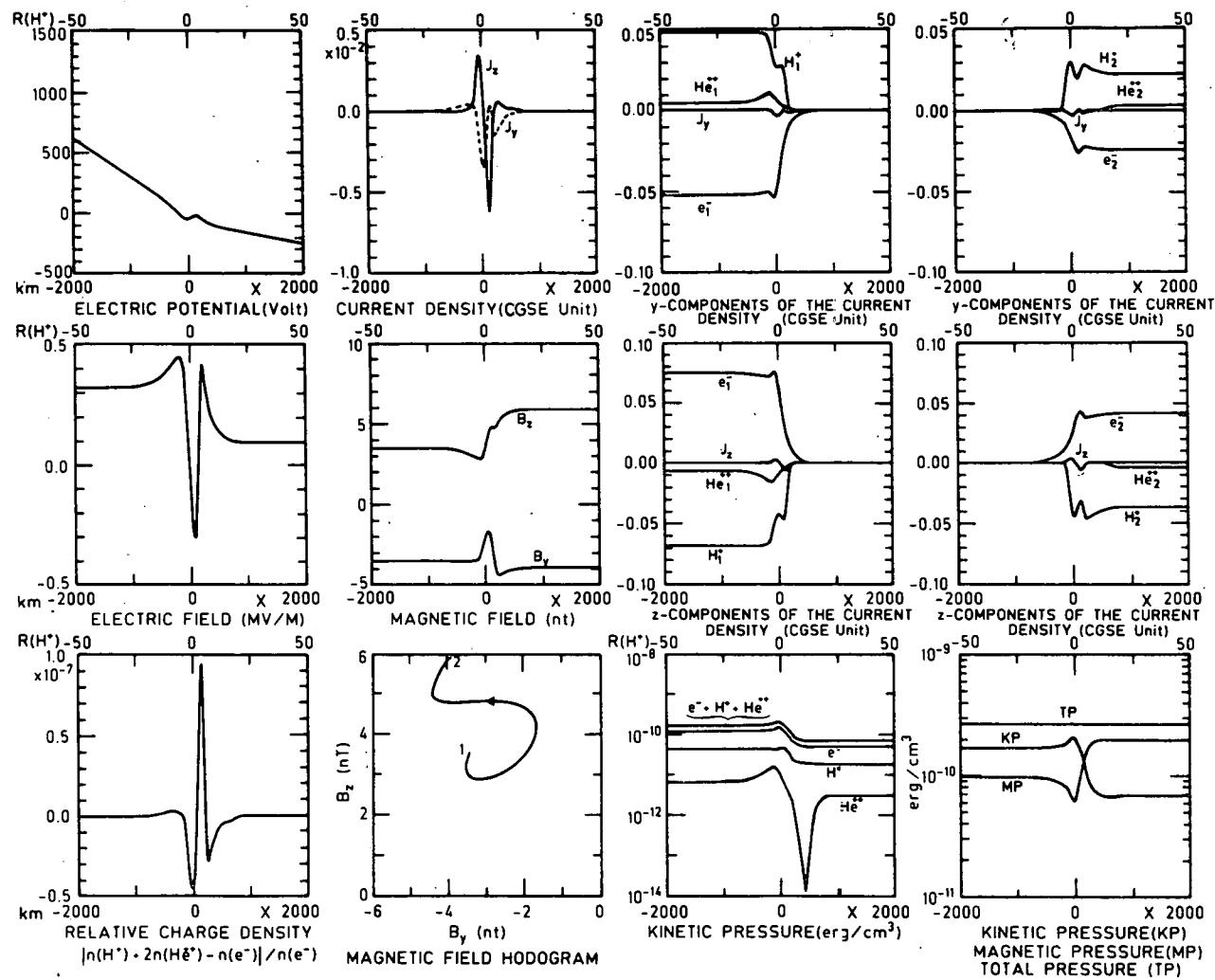


Fig. 2.- Fields and current characteristics across a TD whose boundary conditions are given in table 1. The X-axis is along the normal to the discontinuity.

and to the plasma kinetic pressure (11th panel) and finally (12th panel) the pressure balance condition.

Figure 3 shows how each plasma species contributes to the bulk velocity of the plasma. Panels 1-2-3, 4-5-6 and 7-8-9 illustrate respectively the mean velocity of electron, proton and helium species. The hodograms illustrated in panels 10 and 12 show that the protons carry most of the bulk velocity of the plasma, as can also be seen from panels 5 and 11.

Moments of the third order have also been computed and are illustrated in figure 4, for the electrons (e^-), protons (H^+) and helium (He^{++}) in the admixture. In this figure, the tangential energy flow, Q , has been separated into three separated parts (Longmire, 1963) : the energy flow of macroscopic energy (Q_1), the flow of internal energy carried by convection (Q_2) and the flow of internal energy carried by conduction, i.e., the heat flow (Q_3). From this figure and from panels 8 and 11 of figure 1, it can be seen that most of the energy flow is carried by the macroscopic plasma flow, while the heat flow is nearly three order of magnitude smaller ($Q_1 \sim 10^{-1} \text{ erg. cm}^{-2} \cdot s^{-1}$; $Q_3 \sim 10^{-4} \text{ erg. cm}^{-2} \cdot s^{-1}$).

4. CONCLUSIONS

The results shown in this paper indicate how to model a tangential discontinuity in the solar wind. This modeling of current sheets is one aspect of the Interdisciplinary Study of Directional Discontinuities in the Solar Wind with the Ulysses Mission (Lemaire et al., 1983). One of the objective of this Interdisciplinary Study is a detailed comparison of theoretical calculations with magnetic-field and particle-flux measurements. As shown in this paper, the theoretical thickness for current sheets in the solar wind is expected to be of the order of 20 $R(H^+)$ or less. The time resolution of present-day magnetic-field measurements in space is usually high enough to determine the fine structure of such sharp magnetic-field "discontinuities", but the best time resolution

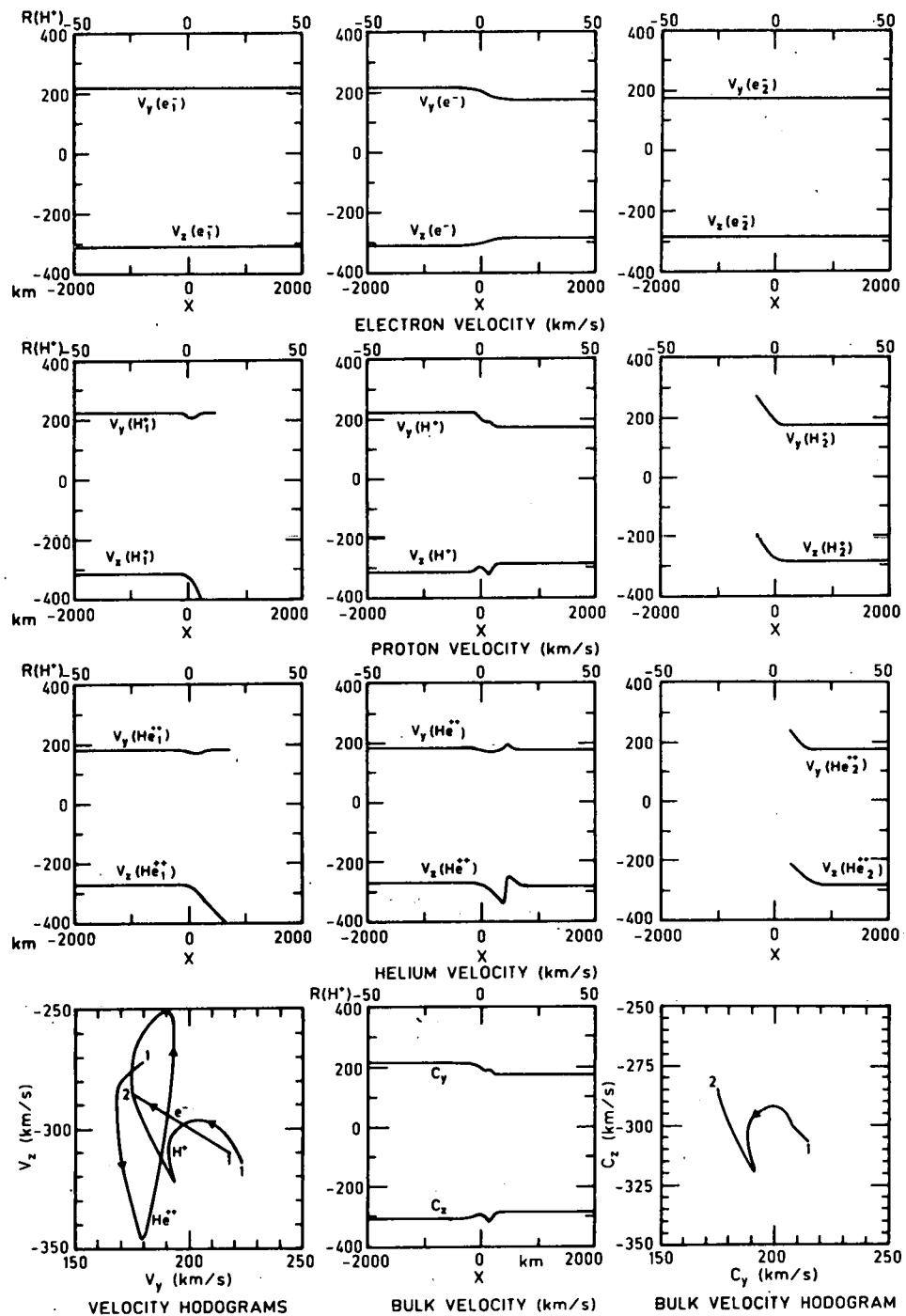


Fig. 3.- Flow characteristics across a TD whose boundary conditions are given in table 1. The X-axis is along the normal to the discontinuity.

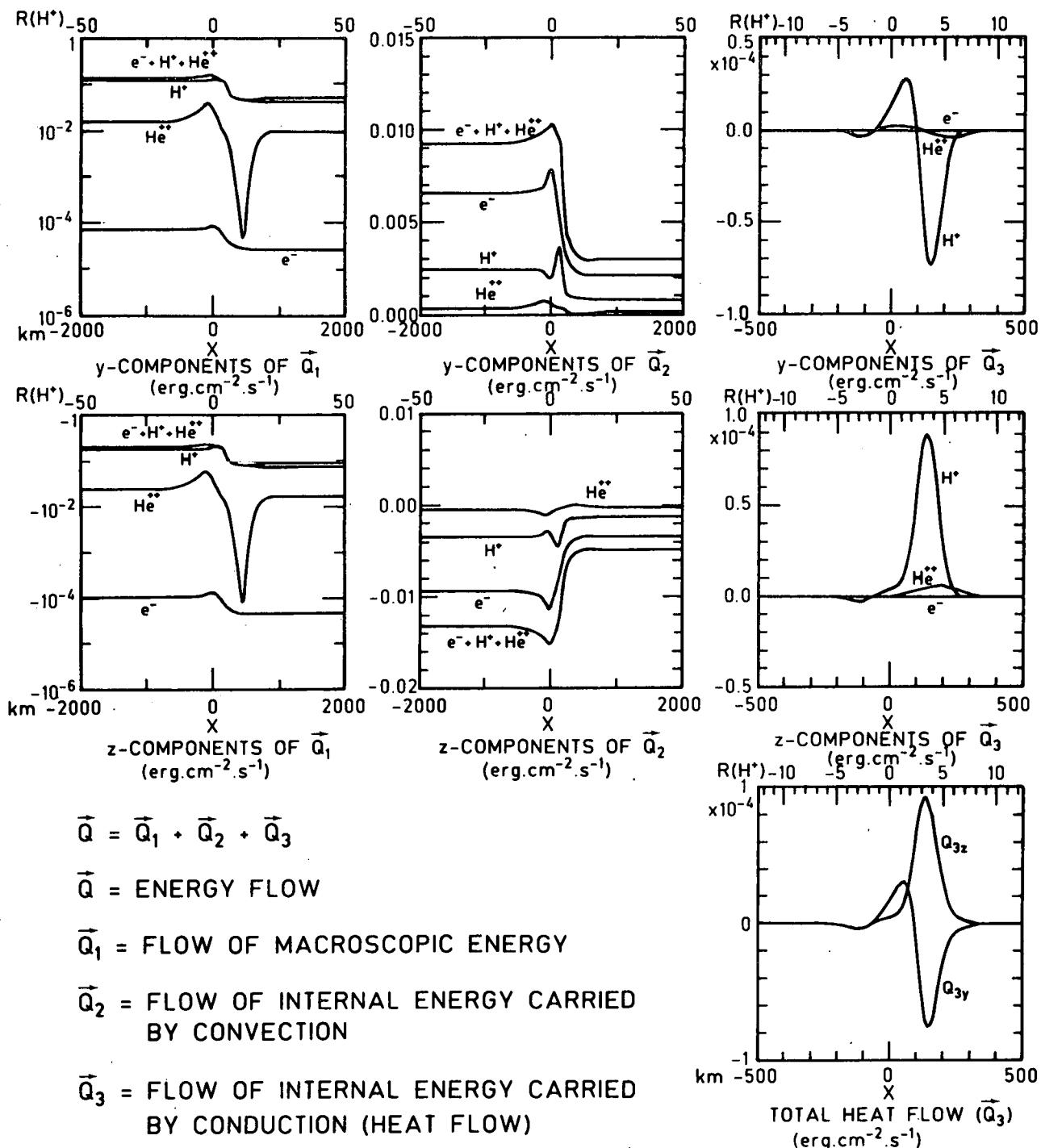


Fig. 4.- Energy flow characteristics across a TD whose boundary conditions are given in table 1. The X-axis is along the normal to the discontinuity.

for direct plasma measurements is generally much lower. A time of at least 10 s is required to sample particles in all energy ranges and in all velocity directions. Over such a long period, a spacecraft has travelled a distance of 4000 km in the frame of the supersonic solar wind plasma. Since the actual time resolution of solar wind plasma instruments will be much larger than the time (~ 1-5 s) required for an interplanetary vehicle to pass through a thin current sheet, the particle fluxes measured in successive energy channels and successive solid angles must be compared directly with the corresponding values deduced from theoretical distributions calculated at different depths in the current sheet.

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