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QUASI-EXOSPHERIC HEAT FLUX OF SOLAR-WIND ELECTRONS

Aharon Eviatar, et al

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# Quasi-Exospheric Heat Flux of Solar-Wind Electrons

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## 20. ABSTRACT (Continued)

by the Alfvén speed along the magnetic field, for example, the potential rises to 72.6 V and the heat flux falls to  $2.72 \times 10^{-2}$  erg/cm<sup>2</sup>sec. In each case the heat flux is carried mainly by the quasi-exospheric hot electrons.

## PREFACE

Aharon Eviatar is on sabbatical leave from the Department of Environmental Sciences, Tel-Aviv University, Ramat-Aviv, Israel.

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## 1. INTRODUCTION

In the exospheric description of solar-wind plasma (Eviatar and Schulz, 1968; Perkins and Spight, 1970), individual electrons and protons execute trajectories that conserve both total energy (kinetic plus potential) and first adiabatic invariant (magnetic moment). The motion of these particles along  $\underline{\underline{B}}$  (the interplanetary magnetic field) is profoundly affected by an electrostatic field that arises in order to assure charge quasi-neutrality of the plasma, i.e., to equalize the escaping fluxes of protons and electrons in the presence of the Sun's gravitational field (Jockers, 1968; 1970).

Calculation of the corresponding electrostatic potential  $\phi$ , at a point where the electron flux is locally isotropic and Maxwellian except for the escape trajectories, has been described by Schulz and Eviatar (1972). The local potential  $\phi$  is thereby related to the proton bulk speed  $u$  along  $\underline{\underline{B}}$  by means of exponential and error functions of  $-q_e\phi/kT_e$ , where  $k$  is Boltzmann's constant,  $T_e$  is the electron temperature, and  $q_e$  ( $<0$ ) is the electronic charge. Observations by Feldman et al. (1974a), however, suggest that the solar-wind electron distribution at the Earth's orbit is more nearly a superposition of two quasi-Maxwellian distributions, related in temperature such that  $T_2 \sim 6T_1$  and in density such that  $N_2 \sim 0.06N_1$ . Moreover, the major electron component seems to have a velocity distribution that is symmetric about  $v_{\parallel} \approx u \sec \chi - c_A$  (where  $\chi$  is the local spiral angle,  $\cos \chi = \hat{\underline{\underline{r}}} \cdot \hat{\underline{\underline{B}}}$ , and  $c_A$  is the Alfvén speed) rather than about  $v_{\parallel} = 0$



(as exospheric theory would predict).

These new observational findings require that the exospheric theory be updated, but not necessarily discarded. In view of the plasma-kinetic instabilities (Forslund, 1970) to which an electron exosphere is subject (Schulz and Eviatar, 1972; Perkins, 1973), it was not really expected that the observed distribution would be symmetric about  $v_{\parallel} = 0$  (Hollweg, 1974). Moreover, much can still be learned about the consequences of such plasma instabilities by treating the minor (hotter) electron component exospherically. By increasing the outward bulk velocity of the major (cooler) electron component, for example, the unstable interplanetary-plasma waves may increase the local electrostatic potential  $\phi$  required to enforce charge quasi-neutrality. Such a change in  $\phi$  would profoundly, although indirectly, affect the heat-flow moment of the entire electron distribution.

It is the purpose of this work to examine such plasma effects in detail. First, by treating both electron components exospherically, we hope to estimate  $\phi$  locally for the hypothetical (but unstable) electron exosphere. Second, by treating only the minor (hotter) component exospherically, we hope to estimate the increased  $\phi$  that is empirically compatible with the effects of the inevitable plasma turbulence. The analytical evaluation of heat-flow moments in both cases will serve to distinguish the two cases in a dynamically interesting way.

## 2. TWO-COMPONENT ELECTRON EXOSPHERE

The first step in constructing a properly normalized exospheric distribution function  $f(v_{\parallel}, v_{\perp}; r)$  is to select a closed surface  $r = r_0$  (not necessarily a sphere, since  $r_0$  could be a function of solar latitude) on which  $\phi = \phi_0$  and beyond which collisions are considered negligible. Since gravity is negligible for electrons, the function  $f(v_{\parallel}, v_{\perp}; r)$  must be even with respect to  $v_{\parallel}$  for electrons satisfying the condition

$$m_e v^2 + 2q_e \phi_0 < 0 \quad (1)$$

and must vanish for  $v_{\parallel} < 0$  for values of  $v^2$  not satisfying (1). An acceptable choice (cf. Schulz and Eviatar, 1972) turns out to be

$$\begin{aligned} f(v_{\parallel}, v_{\perp}; r_0) &= \sum_{j=1}^2 f_j(v_{\parallel}, v_{\perp}; r_0) \\ &= 2[\theta(v_{\parallel}) + \theta(-v_{\parallel})\theta(-m_e v^2 - 2q_e \phi_0)] \\ &\quad \times \sum_{j=1}^2 N_j (m_e / 2\pi\kappa T_j)^{3/2} \exp(-m_e v^2 / 2\kappa T_j) \\ &\quad \times [1 + \operatorname{erf}((-q_e \phi_0 / \kappa T_j)^{1/2}) \\ &\quad - 2(-q_e \phi_0 / \pi\kappa T_j)^{1/2} \exp(q_e \phi_0 / \kappa T_j)]^{-1}, \quad (2) \end{aligned}$$

where  $\theta(x)$  is the unit step function [ $\theta(x) = 1$  for  $x \geq 0$  and  $\theta(x) = 0$  for  $x < 0$ ]. If  $N_p$  is the proton density and alpha particles are neglected, quasi-neutrality thus requires that  $N_p = N_1 + N_2$  and that

$$N_p u \sec \chi = 2\pi \int_{-\infty}^{+\infty} \int_0^{\infty} v_{\parallel} f v_{\perp} dv_{\perp} dv_{\parallel}. \quad (3)$$

The integral in (3) is most easily evaluated in spherical coordinates, and the result is that

$$\begin{aligned} (2\pi m_e u^2 / \kappa T_1)^{1/2} \sec \chi = & \\ & 2 \sum_{j=1}^2 (N_j / N_p) (T_j / T_1)^{1/2} [1 - (q_e \phi_0 / \kappa T_j)] \exp(q_e \phi_0 / \kappa T_j) \\ & \times [1 + \operatorname{erf}((-q_e \phi_0 / \kappa T_j)^{1/2}) \\ & - 2(-q_e \phi_0 / \pi \kappa T_j)^{1/2} \exp(q_e \phi_0 / \kappa T_j)]^{-1}. \quad (4) \end{aligned}$$

This equation determines  $(-q_e \phi_0 / \kappa T_1)$  as a function of  $(2\pi m_e u^2 / \kappa T_1)^{1/2} \sec \chi$  for fixed values of  $N_2 / N_p$  and  $T_2 / T_1$ . Representative contours are plotted in Figure 1. The contour  $N_2 / N_p = 0$  corresponds to the case treated by Schulz and Eviatar (1972), who also made a minor normalization error that is corrected here.

It is instructive to define partial heat-flow moments

$$Q_{\parallel}^{(j)} = 2\pi \int_{-\infty}^{+\infty} \int_0^{\infty} (m_e / 2) (v_{\parallel} - u \sec \chi)^3 f_j v_{\perp} dv_{\perp} dv_{\parallel} \quad (5a)$$

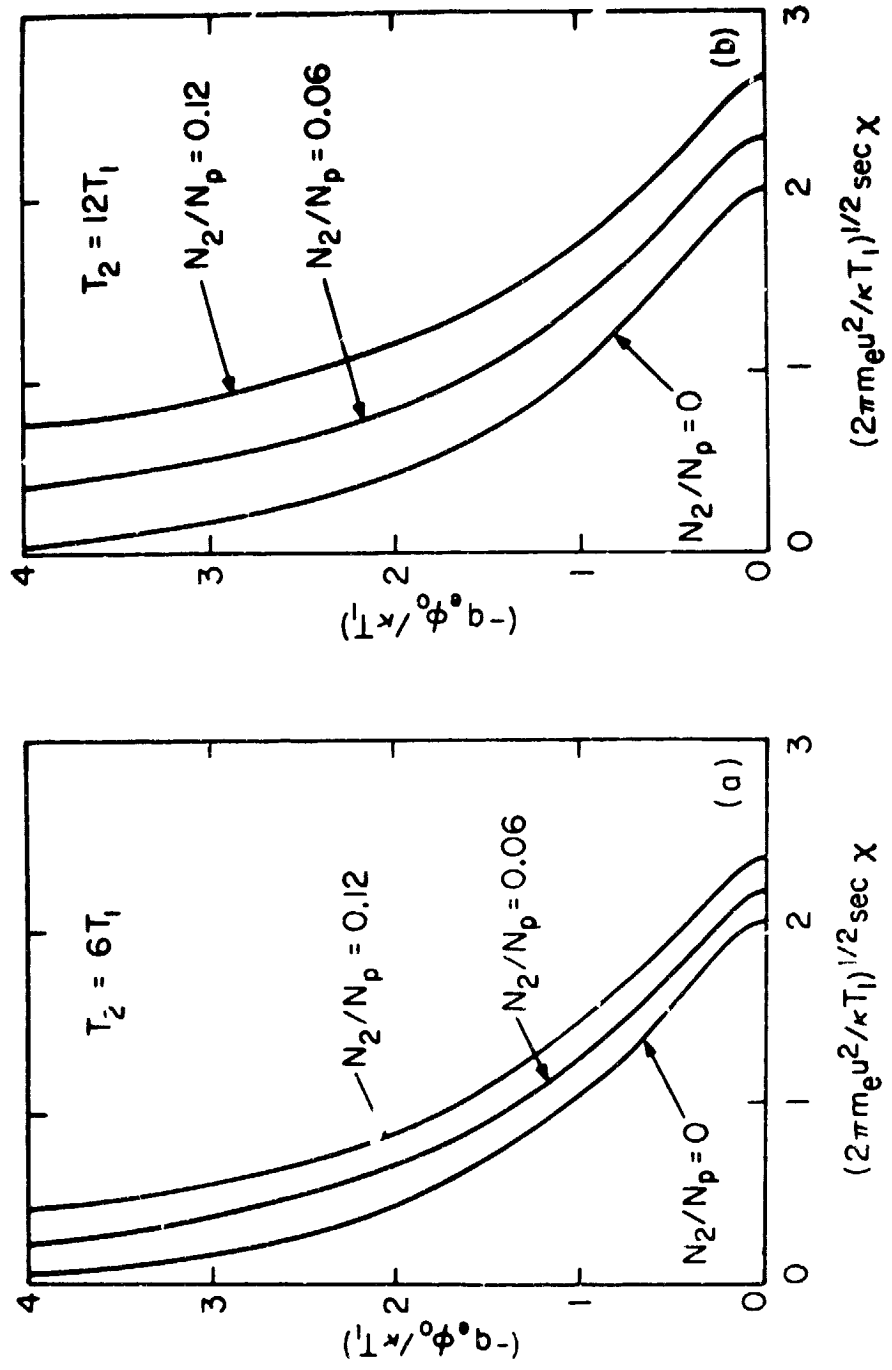


Figure 1. Dependence of electrostatic potential ( $\phi_0$ ) on proton bulk velocity (u) for selected values of  $N_2/N_p$  and  $T_2/T_1$  at the base of an ideal solar exosphere.

and

$$Q_{\perp}^{(j)} = 2\pi \int_{-\infty}^{+\infty} \int_0^{\pi} (m_e/2) v_{\perp}^2 (v_{\parallel} - u \sec \chi) f_j v_{\perp} dv_{\perp} dv_{\parallel} \quad (5b)$$

for the "conduction of thermal energy" along  $\hat{B}$ . For Maxwellian distributions truncated as in (2), the moment integrals are most easily evaluated in spherical velocity coordinates. The results are given by

$$\begin{aligned} (m_e/kT_j)^{3/2} (Q_{\parallel}^{(j)}/N_j m_e) = & \\ & - \frac{1}{2} (m_e u^2/kT_j)^{1/2} [3 + (m_e u^2/kT_j) \sec^2 \chi] \sec \chi \\ & + (2\pi)^{-1/2} [1 - 2(-q_e \phi_0/\pi kT_j)^{1/2} \exp(q_e \phi_0/kT_j) \\ & \quad + \operatorname{erf}((-q_e \phi_0/kT_j)^{1/2})]^{-1} \\ & \times \{ (q_e \phi_0/kT_j)^2 - 2(q_e \phi_0/kT_j) + 2 \\ & \quad + (-2q_e \phi_0/kT_j)^{3/2} (m_e u^2/kT_j)^{1/2} \sec \chi \\ & \quad + 3[1 - (q_e \phi_0/kT_j)] (m_e u^2/kT_j) \sec^2 \chi \} \exp(q_e \phi_0/kT_j) \end{aligned} \quad (6a)$$

and

$$(m_e/\kappa T_j)^{3/2} (Q_{\perp}^{(j)}/N_j m_e) =$$

$$(2\pi)^{-1/2} [1 - 2(-q_e \phi_0/\pi \kappa T_j)^{1/2} \exp(q_e \phi_0/\kappa T_j)$$

$$+ \operatorname{erf}((-q_e \phi_0/\kappa T_j)^{1/2})]^{-1}$$

$$\times [(2/3)(-2q_e \phi_0/\kappa T_j)^{3/2} (m_e u^2/\kappa T_j)^{1/2} \sec \chi$$

$$+ (q_e \phi_0/\kappa T_j)^2 - 2(q_e \phi_0/\kappa T_j) + 2] \exp(q_e \phi_0/\kappa T_j)$$

$$- (m_e u^2/\kappa T_j)^{1/2} \sec \chi.$$

(6b)

Typical values of normalized exospheric heat fluxes are plotted in Figure 2a, which includes the individual components  $Q_{\parallel}^{(j)}$  and  $Q_{\perp}^{(j)}$ , the consolidated elements  $Q_{\parallel} \equiv \sum Q_{\parallel}^{(j)}$  and  $Q_{\perp} \equiv \sum Q_{\perp}^{(j)}$ , and the total  $Q \equiv Q_{\parallel} + Q_{\perp}$  for conditions ( $N_2 = 0.06 N_p$ ,  $T_2 = 6T_1$ ) described as typical by Feldman et al. (1974a). Figure 2b provides normalized plots of the total  $Q$  for other values of  $T_2/T_1$  and  $N_2/N_p$ .

A numerical example would help to illustrate the use of Figures 1 and 2. For parameters (Lundhausen, 1970) characteristic of the quiet solar wind ( $u = 320$  km/sec,  $T_1 = 1.2 \times 10^5$  °K) one obtains  $\sec \chi = 1.61$  and thus  $(2\pi m_e u^2/\kappa T_1)^{1/2} \sec \chi = 0.957$ . It follows from Figure 1a that  $(-q_e \phi_0/\kappa T_1) = 1.484$ , which is to say that  $\phi_0 \approx 15.4$  V for  $N_2 = 0.06 N_p$  and  $T_2/T_1 = 6$ . Locating this value of  $(-q_e \phi_0/\kappa T_1)$  in Figure 2, one obtains (for example) the result that  $(m_e/\kappa T_1)^{3/2} (Q/N_p m_e) = 2.257$ , which is

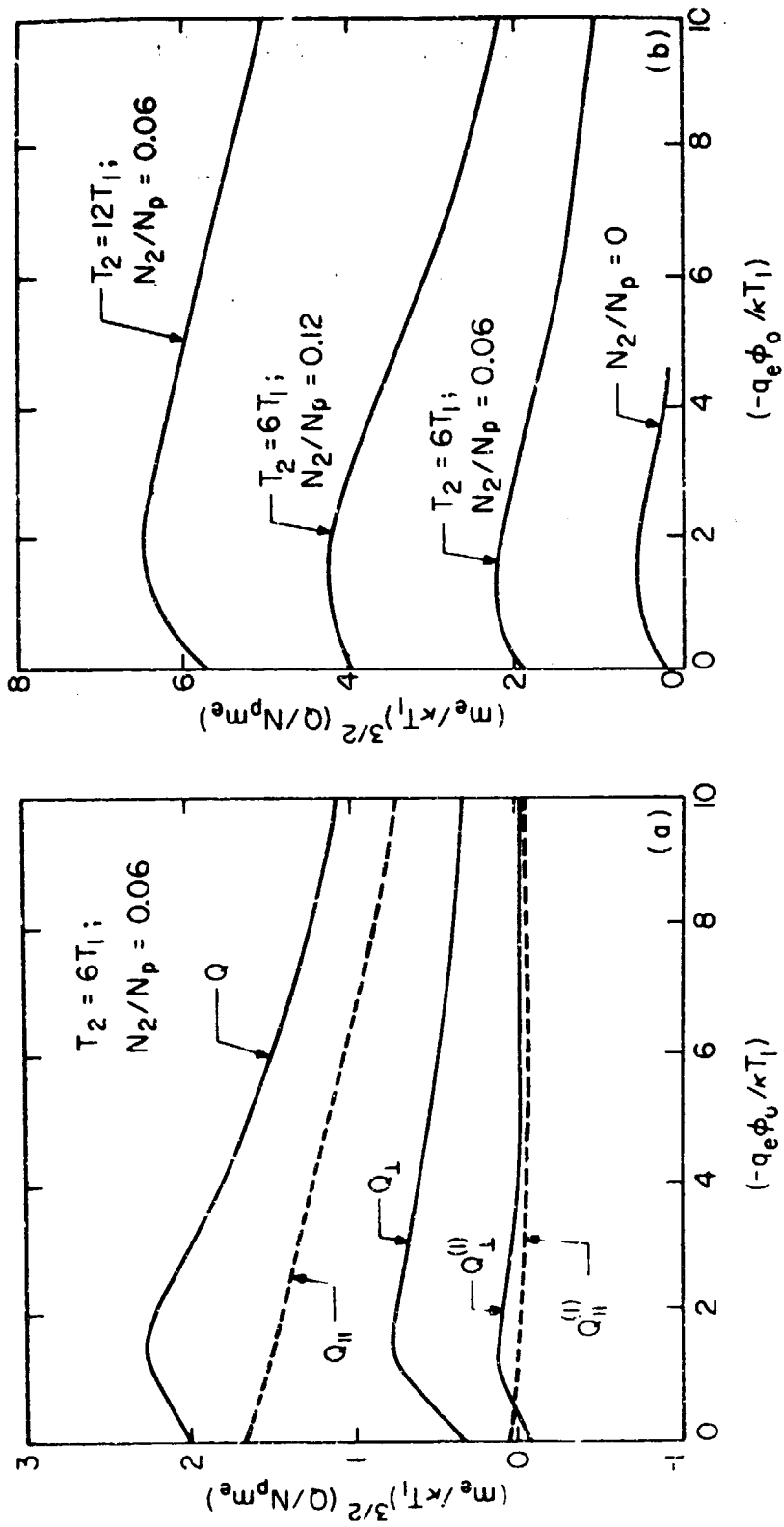


Figure 2. Dependence of heat flux ( $Q$ ) along the magnetic field on electrostatic potential ( $\phi_0$ ) for selected values of  $N_2/N_p$  and  $T_2/T_1$  at the base of an ideal solar exosphere. In the left panel (a), various contributions to  $Q$  are indicated separately.

to say that  $Q = 4.04 \times 10^{-2}$  erg/cm<sup>2</sup>sec for  $N_p = 8$  cm<sup>-3</sup>, the proton density recommended by Hundhausen (1970). This heat flux should be compared with the corrected value ( $Q \sim 1-3 \times 10^{-2}$  erg/cm<sup>2</sup>sec) obtained observationally by Montgomery et al. (1968). However, using the  $N_2/N_p = 0$  contour in Figure 1, one would have obtained  $(-q_e \phi_0 / \kappa T_1) = 1.094$  or  $\phi_0 \approx 11.3$  V (cf. Schulz and Eviatar, 1972). Using (6) to evaluate  $Q$  in this case (which is included in Figure 2b) one obtains  $(m_e / \kappa T_1)^{3/2} (Q / N_p m_e) = 0.271$  or  $Q \approx 0.72 \times 10^{-2}$  erg/cm<sup>2</sup>sec for  $N_p = 8$  cm<sup>-3</sup> and  $T_1 = 1.2 \times 10^5$  °K. The hot component ( $j = 2$ ) thus contributes most of the electron heat flux at  $r = r_0$  in this fully exospheric model.



### 3. EXOSPHERIC TREATMENT OF HOT COMPONENT ONLY

The ideal electron exosphere described above is unstable to a variety of plasma wave modes (Forslund, 1970; Schulz and Eviatar, 1972; Perkins, 1973). Specific predictions have been muddled because of an unwillingness of authors (e.g., Schulz and Eviatar, 1972) to do high-beta calculations for all of the relevant wave modes, but current opinion (e.g., Hollweg, 1974) favors the obliquely propagating electromagnetic proton-cyclotron mode as the dominant instability, operative wherever the peaks (maxima) of the proton and electron distribution functions are separated by  $\sim c_A$  (the Alfvén speed) or more, in velocity space. For the quiet solar-wind parameters proposed by Hundhausen (1970) one obtains  $u \sec \chi \approx 515$  km/sec and  $c_A \approx 38.7$  km/sec.

Hollweg (1974) conjectures that the resulting instability reduces the velocity-space separation between the electron and proton peaks to a value  $v_1 \approx 0.23 \beta_p^{-1/3} \beta_e^{1/2} c_A$ , where  $\beta_j \equiv 8\pi N_j k T_j / B^2$  for protons ( $j = p$ ) and electrons ( $j = e$ ), essentially by adding  $u \sec \chi - v_1$  to the parallel velocity of each electron in the distribution. Various arguments have been given for and against this conjecture. However, the observations of Feldman et al. (1974a) seem to bear it out, as applied to the major (cooler) electron component. In other words, the majority of solar-wind electrons belong to a distribution having the form

$$f_1(v_{\parallel}, v_{\perp}; r) \approx (m_e / 2\pi k T_1)^{3/2} N_1 \exp(-m_e v_{\perp}^2 / 2k T_1) \\ \times \exp[-(m_e / 2k T_1)(v_{\parallel} - u \sec \chi + \eta c_A)^2], \quad (7)$$

(with  $\eta \sim 1$ ) as an empirical fit to the observational data.

This distribution is not exospheric, since it is not an even function of  $v_{\parallel}$  for electrons satisfying (1), nor does it vanish exactly for electrons failing to satisfy (1) at negative  $v_{\parallel}$ .

However, it may still make sense to treat the minor (hot) electron component exospherically, as a first approximation.

On doing so, one obtains

$$\begin{aligned}
 & (2\pi m_e u^2 / \kappa T_2)^{1/2} \sec \chi + (2\pi m_e \eta^2 c_A^2 / \kappa T_2)^{1/2} (N_1 / N_2) \\
 & = 2 [1 - (q_e \phi_0 / \kappa T_2)] \exp(q_e \phi_0 / \kappa T_2) \\
 & \quad \times [1 + \operatorname{erf}((-q_e \phi_0 / \kappa T_2)^{1/2}) \\
 & \quad - 2(-q_e \phi_0 / \pi \kappa T_2)^{1/2} \exp(q_e \phi_0 / \kappa T_2)]^{-1} \quad (8)
 \end{aligned}$$

instead of (4). Comparison of (4) and (8) reveals that  $(-q_e \phi_0 / \kappa T_2)$  is the same function of  $(2\pi m_e u^2 / \kappa T_2)^{1/2} \sec \chi + (2\pi m_e \eta^2 c_A^2 / \kappa T_2)^{1/2} (N_1 / N_2)$  in (8) as  $(-q_e \phi_0 / \kappa T_1)$  is of  $(2\pi m_e u^2 / \kappa T_1)^{1/2} \sec \chi$  for  $N_2 / N_p = 0$  in (4). Thus, the potential  $\phi_0$  given by (8) can be read from the contour  $N_2 / N_p = 0$  in Figure 1 if the ordinate and abscissa are appropriately relabeled. Continuing the numerical example of the previous section ( $N_2 = 0.06 N_p$ ,  $T_2 = 6 T_1 = 7.2 \times 10^5$  °K,  $u = 320$  km/sec,  $c_A = 38.7$  km/sec), one obtains a value of 0.9037 on the abscissa for  $\eta = 1$ . The corresponding value of  $(-q_e \phi_0 / \kappa T_2)$

on the ordinate is 1.169, which is to say that  $\phi_0 \approx 72.6$  V.

The electrostatic potential  $\phi_0$  is significantly larger in this case than for the purely exospheric treatment of both electron components.

The exospheric heat fluxes  $Q_{\parallel}^{(2)}$  and  $Q_{\perp}^{(2)}$  remain as given algebraically by (6), but the relation between  $(-q_e \phi_0 / \kappa T_2)$  and  $(m_e u^2 / \kappa T_2)^{1/2} \sec \chi$  therein must be obtained from (8) rather than from (4). Moreover, the heat fluxes carried by  $f_1(v_{\parallel}, v_{\perp}; r_0)$  are now given by

$$\begin{aligned} & (m_e / \kappa T_1)^{3/2} (Q_{\parallel}^{(1)} / N_1 m_e) \\ & = - (1/2) [3 + (m_e \eta^2 c_A^2 / \kappa T_1)] (m_e \eta^2 c_A^2 / \kappa T_1)^{1/2} \end{aligned} \quad (9a)$$

and

$$(m_e / \kappa T_1)^{3/2} (Q_{\perp}^{(1)} / N_1 m_e) = - (m_e \eta^2 c_A^2 / \kappa T_1)^{1/2} \quad (9b)$$

rather than by (6). The various contributions to  $(m_e / \kappa T_1)^{3/2} (Q / N_p m_e)$  have been plotted (using  $\eta \approx 1$ ) in Figure 3a for comparison with Figure 2a. Inserting  $\phi_0 = 72.6$  V and  $N_p = 8 \text{ cm}^{-3}$ , one obtains  $(m_e / \kappa T_1)^{3/2} (Q / N_p m_e) = 1.519$  or  $Q \approx 2.72 \times 10^{-2} \text{ erg/cm}^2 \text{ sec}$ . This heat flux is considerably smaller than that obtained above in the purely exospheric two-component model. Moreover, the total electron heat flux is essentially that of the hot component, as Feldman et al. (1974a) have found by analyzing the observed distribution function  $f(v_{\parallel}, v_{\perp}; r)$  at  $r \sim 1$  AU.

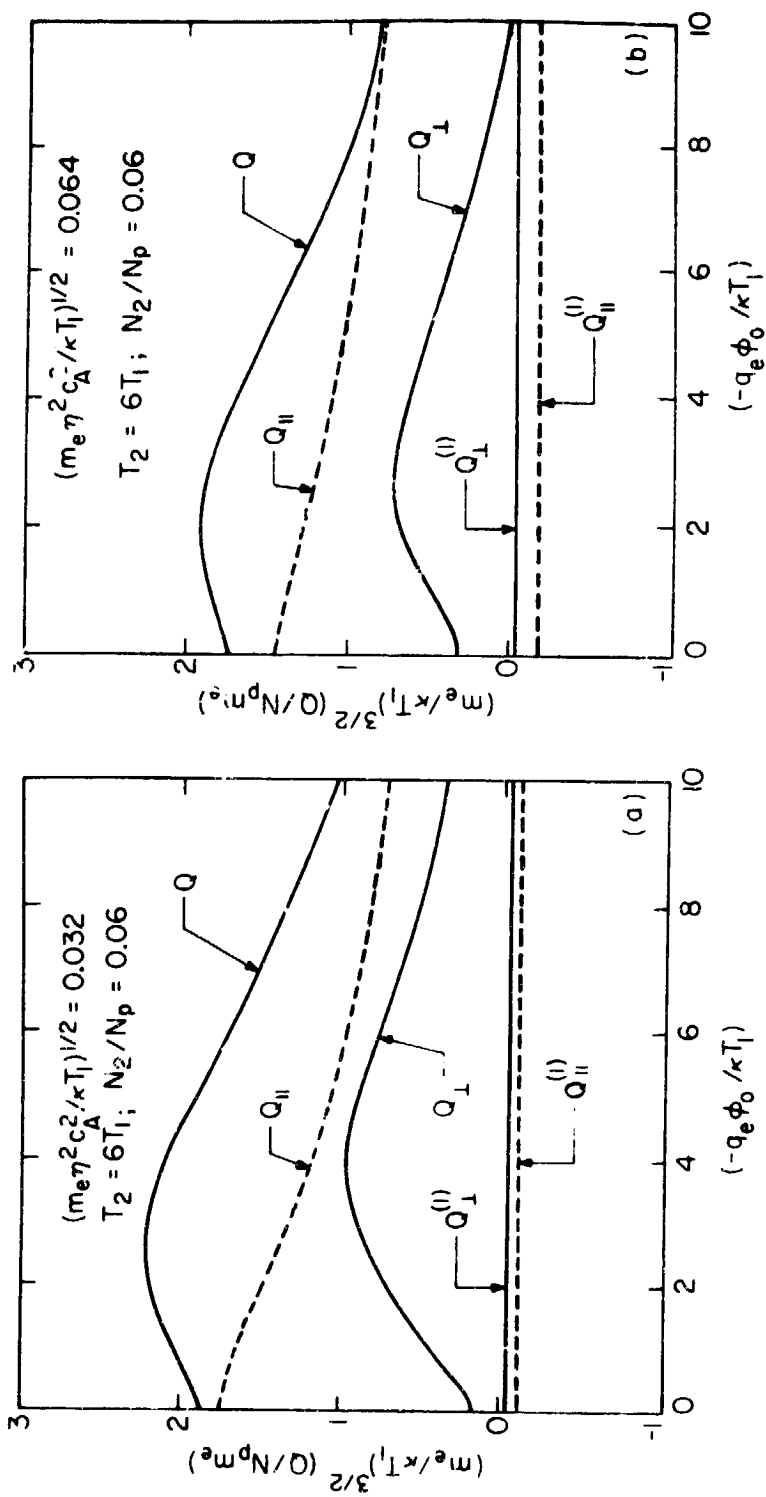


Figure 3. Dependence of field-aligned heat flux ( $Q$ ) and its constituent parts on electrostatic potential ( $\phi_0$ ) for selected values of  $N_2/N_p$ ,  $T_2/T_1$ , and  $(m_e \eta^2 c_A^2 / \kappa T_1)^{1/2}$  at the base of an ideal hot-electron exosphere. Cooler electrons ( $j = 1$ ) here belong to isotropic Maxwellian with bulk velocity  $u \sec \chi - \eta_{CA}$  along  $B$  in the frame of reference that corotates with the Sun.

The contours plotted in Figure 3b correspond more nearly to  $\eta \approx 2$ , as would be required (Schulz and Eviatar, 1972) for magnetosonic instability at  $r \sim 1$  AU. For the solar-wind parameters used above, this choice of  $\eta$  corresponds to an abscissa of 1.417 (and therefore an ordinate of 0.6122) on the  $N_2/N_p = 0$  contour in Figure 1a. This value on the ordinate indicates an electrostatic potential  $\varphi_0 \approx 38.0$  V and (in Figure 3b) a normalized heat flux  $(m_e/\kappa T_1)^{3/2}(Q/N_p m_e) = 1.765$ ; for  $N_p = 8 \text{ cm}^{-3}$ , the corresponding physical heat flux is  $Q \approx 3.16 \times 10^{-2} \text{ erg/cm}^2 \text{ sec}$ . This lies between the value for  $\eta \approx 1$  ( $Q \approx 2.72 \times 10^{-2} \text{ erg/cm}^2 \text{ sec}$ , as shown above) and the exospheric value ( $Q \approx 4.04 \times 10^{-2} \text{ erg/cm}^2 \text{ sec}$ ). Similarly, the electrostatic potential obtained for  $\eta \approx 2$  ( $\varphi_0 \approx 38.0$  V) lies between that obtained for  $\eta \approx 1$  ( $\varphi_0 \approx 72.6$  V) and that obtained for the exospheric case ( $\varphi_0 \approx 15.4$  V).

#### 4. DISCUSSION

The foregoing results suggest the subtle manner in which plasma instabilities may reduce the heat flux carried by solar-wind electrons belonging to the hot ( $j = 2$ ) component. Although (in this model) only the cooler ( $j = 1$ ) electron population interacts with the unstable waves, the consequently required increase in  $\phi_0$  makes the quasi-exospheric hot component less skewed in velocity space. The result is a diminished heat flow moment, as given by (6). This interpretation emphasizes the macroscopic (non-local) character of the phenomenon.

In the case of a uniform plasma, it might be argued that only a small portion of even the cooler electron velocity distribution could participate in the resonant wave-particle interactions. Thus, it would be difficult to understand how the cooler distribution as a whole could acquire a mean velocity  $\sim u \sec \chi - \eta c_A$ . In the interplanetary medium, however, the unperturbed motion of the typical electron is a bounded oscillation between a magnetic mirror point ( $r = r_1$ ) and an electrostatic mirror point ( $r = r_2 > r_1$ ). The particle goes through resonance twice in traveling from  $r_1$  to  $r_2$ , and receives an impulse from the unstable waves on each occasion. Involvement of the entire cooler electron distribution becomes plausible when viewed in this way. Hollweg (1974) conjectures that the distribution thus acquires a mean velocity  $\sim u \sec \chi - \eta c_A$  in the frame of reference that corotates with the Sun. The observations of Feldman et al. (1974a) confirm this conjecture.

The present model does not quite account for the observed

form (Feldman et al., 1974a) of the hot-electron distribution  $f_2(v_{\parallel}, v_{\perp}; r)$ . This is not a major cause for concern. A model that realistically incorporates collisions and wave-particle interactions will presumably yield a more nearly Maxwellian  $f_2(v_{\parallel}, v_{\perp}; r)$  as observed, without drastically modifying the electrostatic potential  $\phi_0$ . The vigilant critic might ask why the base of the exosphere ( $r = r_0$ ) should happen to coincide with the position of the observer ( $r \sim 1$  AU), as is tacitly assumed in applying (1)-(9) to local plasma conditions. This question serves to emphasize the quasi-exospheric spirit of the present work and similar past works (e.g., Perkins, 1973; Hollweg, 1974). The plasma is being treated locally as if it were at the base of a true exosphere. However, the exosphere itself plays the role of a "straw man", corresponding to the role of Vlasov equilibria in simpler plasma-kinetic problems.

In the limiting case  $N_2/N_p = 0$ , the results summarized by (4) and (6) reduce to the expressions obtained by Hollweg (1974). The present results for  $\phi_0$  bear a close resemblance to those obtained by Feldman et al. (1974b) from a more nearly hydrodynamical analysis. The quasi-exospheric treatment offered here should be considered as a viable alternative to the fluid philosophy.

The electrostatic potential  $\phi_0 \sim 40-70$  V, obtained by inserting local solar-wind parameters in (8), corresponds to only a modest increase ( $< 2$  km/sec) in the proton bulk velocity  $u$  between  $r \sim 1$  AU and  $r = \infty$ . However, the gravitational potential of the Sun amounts to only  $-9.4$  eV/nucleon at  $r \sim 1$  AU. If the

electrostatic potential scales as  $1/r$ , at least back to  $r \sim 10-20 r_{\odot}$  (solar radii), then the corresponding radial electric field is ample to overcome gravity and accelerate solar-wind protons to the observed bulk speed  $u \sim 320$  km/sec. Such exospheric acceleration would correspond qualitatively to the observed outward proton heat-flow moment (Schulz and Eviatar, 1973). Alpha particles in the same electric field would experience a smaller acceleration of the same sign, since the charge/mass ratio is half that of protons. It is difficult to understand, in this context, the occasional observations by Asbridge et al. (1974) that alpha particles have slightly larger bulk velocities than protons in the solar wind.

In summary, quasi-exospheric models help to clarify certain observable properties of the interplanetary plasma and serve as a point of departure for the Vlasov analysis of plasma turbulence in the solar wind. Such models are strikingly incomplete, however, and leave many important questions unanswered. If the method of quasilinear theory could be adapted to the geometry of this inhomogeneous and almost collisionless medium, the role of wavelike turbulence in the interplanetary plasma might be ascertained in quantitative detail.



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