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QUASI-EXOSPHERIC HEAT FLUX OF SOLAR-WIND ELECTRONS

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Aerospace Corporation

ADA011764

Quasi-Exospheric Heat Flux
of Solar-Wind Electrons

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15 May 1975

Interim Report

Prepared for

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SAMSO-TR-75-139	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD-AO11 764
4. TITLE (and Subtitle) QUASI-EXOSPHERIC HEAT FLUX OF SOLAR-WIND ELECTRONS		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER TR-0075(5260-20)-5
7. AUTHOR(s) Aharon Eviatar and Michael Schulz		8. CONTRACT OR GRANT NUMBER(s) F04701-74-C-0075
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space and Missile Systems Organization Air Force Systems Command Los Angeles, Calif. 90045		12. REPORT DATE 15 May 1975
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Exospheric Heat Flux

Solar Wind Electrons

PRICES SUBJECT TO CHANGE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Density, bulk-velocity, and heat-flow moments are calculated for truncated Maxwellian distributions representing the cool and hot populations of solar-wind electrons, as realized at the base of a hypothetical exosphere. The electrostatic potential is thus calculated by requiring charge quasi-neutrality and the absence of electrical current. Plasma-kinetic coupling of the cool-electron and proton bulk velocities leads to an increase in the electrostatic potential and a decrease in the heat-flow moment. If the velocities differ

19. KEY WORDS (Continued)

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 2.72×10^{-2} erg/cm^{2}sec. In each case the heat flux is carried mainly by the quasi-exospheric _hot_ electrons.

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PREFACE

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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 $\underset{\sim}{B}$ (the interplanetary magnetic field) is profoundly affected by an electrostatic field that arises in order to assure charge quasineutrality 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 φ, 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 φ is thereby related to the proton bulk speed u along $\underset{\sim}{B}$ by means of exponential and error functions of $-q_e\varphi/\kappa T_e$, where κ 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 $v_\| \approx u \sec \chi - c_A$ (where χ is the local spiral angle, $\cos \chi = \underset{\sim}{\hat{r}} \cdot \underset{\sim}{\hat{B}}$, and c_A is the Alfvén speed) rather than about $v_\| = 0$

(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 φ required to enforce charge quasi-neutrality. Such a change in φ 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 φ locally for the hypothetical (but unstable) electron exosphere. Second, by treating only the minor (hotter) component exospherically, we hope to estimate the increased φ 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 $\varphi = \varphi_0$ 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

$$m_e v^2 + 2q_e \varphi_0 < 0 \tag{1}$$

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

$$f(v_{\parallel}, v_{\perp}; r_0) = \sum_{j=1}^{2} f_j(v_{\parallel}, v_{\perp}; r_0)$$

$$= 2[\theta(v_{\parallel}) + \theta(-v_{\parallel})\theta(-m_e v^2 - 2q_e \varphi_0)]$$

$$\times \sum_{j=1}^{2} N_j (m_e/2\pi\varkappa T_j)^{3/2} \exp(-m_e v^2/2\varkappa T_j)$$

$$\times [1 + \mathrm{erf}((-q_e \varphi_0/\varkappa T_j)^{1/2})$$

$$- 2(-q_e \varphi_0/\pi\varkappa T_j)^{1/2} \exp(q_e \varphi_0/\varkappa T_j)]^{-1}, \tag{2}$$

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

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

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

$$(2\pi m_e u^2 / \varkappa T_1)^{1/2} \sec \chi =$$

$$2 \sum_{j=1}^{2} (N_j / N_p)(T_j / T_1)^{1/2} [1 - (q_e \varphi_0 / \varkappa T_j)] \exp(q_e \varphi_0 / \varkappa T_j)$$

$$\times [1 + \mathrm{erf}((-q_e \varphi_0 / \varkappa T_j)^{1/2})$$

$$- 2(-q_e \varphi_0 / \pi \varkappa T_j)^{1/2} \exp(q_e \varphi_0 / \varkappa T_j)]^{-1}. \tag{4}$$

This equation determines $(-q_e \varphi_0 / \varkappa T_1)$ as a function of $(2\pi m_e u^2 / \varkappa T_1)^{1/2} \sec \chi$ 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

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

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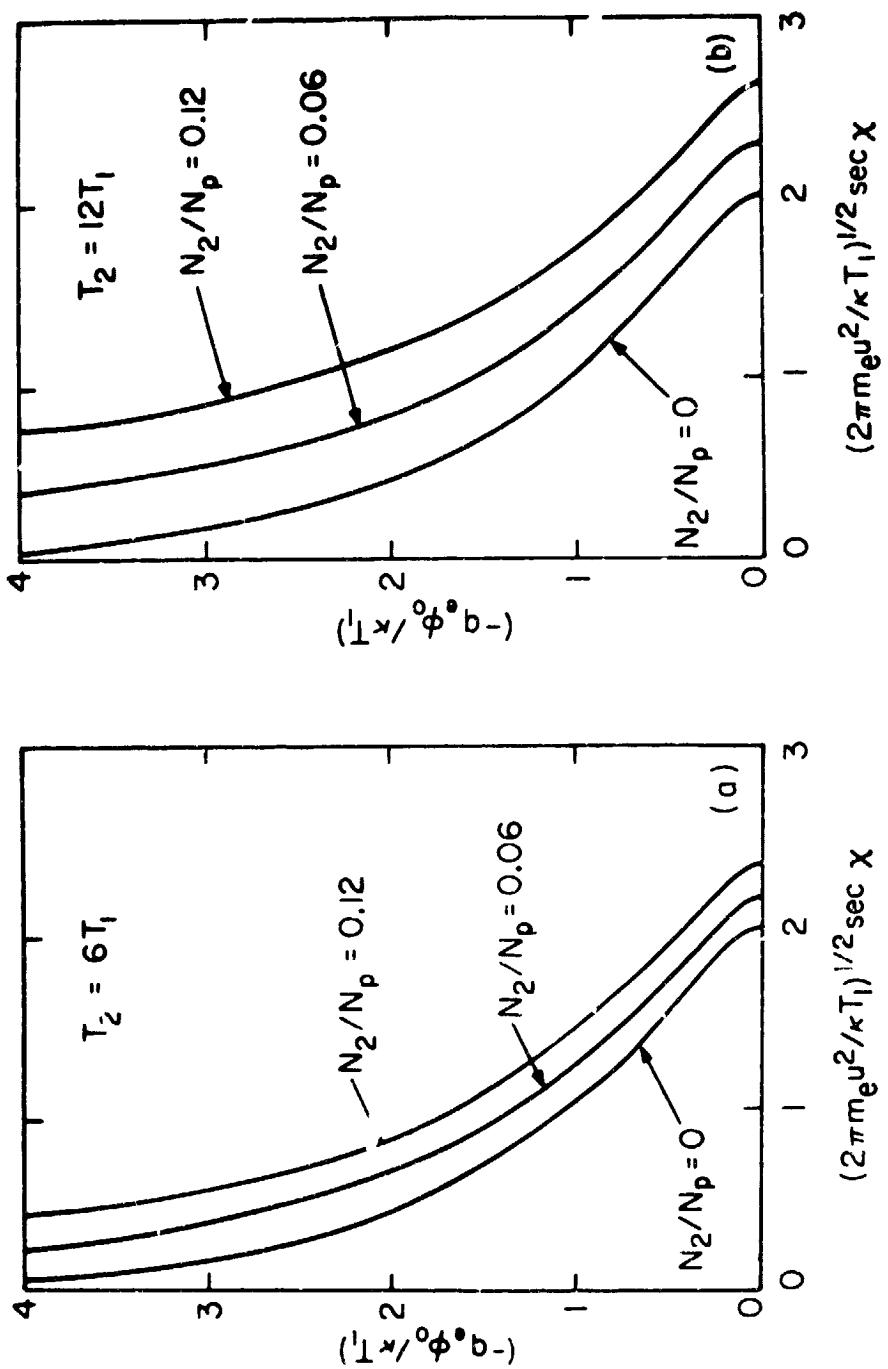
Figure 1. Dependence of electrostatic potential (φ_0) on proton bulk velocity (u) for selected values of N_2/N_p and T_2/T_1 at the base of an ideal solar exosphere.

and

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

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

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

$$-\tfrac{1}{2}(m_e u^2/\kappa T_j)^{1/2} [3 + (m_e u^2/\kappa T_j) \sec^2 \chi] \sec \chi$$

$$+ (2\pi)^{-1/2} [1 - 2(-q_e \varphi_0/\pi\kappa T_j)^{1/2} \exp(q_e \varphi_0/\kappa T_j)$$

$$+ \operatorname{erf}((- q_e \varphi_0/\kappa T_j)^{1/2})]^{-1}$$

$$\times \{(q_e \varphi_0/\kappa T_j)^2 - 2(q_e \varphi_0/\kappa T_j) + 2$$

$$+ (-2 q_e \varphi_0/\kappa T_j)^{3/2} (m_e u^2/\kappa T_j)^{1/2} \sec \chi$$

$$+ 3[1 - (q_e \varphi_0/\kappa T_j)](m_e u^2/\kappa T_j) \sec^2 \chi\} \exp(q_e \varphi_0/\kappa T_j)$$

$$(6a)$$

and

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

$$(2\pi)^{-1/2}\left[1 - 2\left(-q_e\varphi_0/\pi\varkappa T_j\right)^{1/2}\exp\left(q_e\varphi_0/\varkappa T_j\right)\right.$$

$$+ \left.\mathrm{erf}\left(\left(-q_e\varphi_0/\varkappa T_j\right)^{1/2}\right)\right]^{-1}$$

$$\times \left[(2/3)\left(-2q_e\varphi_0/\varkappa T_j\right)^{3/2}\left(m_e u^2/\varkappa T_j\right)^{1/2}\sec\chi\right.$$

$$+ \left(q_e\varphi_0/\varkappa T_j\right)^2 - 2\left(q_e\varphi_0/\varkappa T_j\right) + 2\Big]\exp\left(q_e\varphi_0/\varkappa T_j\right)$$

$$- \left(m_e u^2/\varkappa T_j\right)^{1/2}\sec\chi. \tag{6b}$$

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 $Q_\parallel \equiv \Sigma Q_\parallel^{(j)}$ and $Q_\perp \equiv \Sigma Q_\perp^{(j)}$, 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 (Hundhausen, 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 $(2\pi m_e u^2/\varkappa T_1)^{1/2}\sec\chi = 0.957$. It follows from Figure 1a that $(-q_e\varphi_0/\varkappa T_1) = 1.484$, which is to say that $\varphi_0 \approx 15.4$ V for $N_2 = 0.06 N_p$ and $T_2/T_1 = 6$. Locating this value of $(-q_e\varphi_0/\varkappa T_1)$ in Figure 2, one obtains (for example) the result that $(m_e/\varkappa T_1)^{3/2}(Q/N_p m_e) = 2.257$, which is
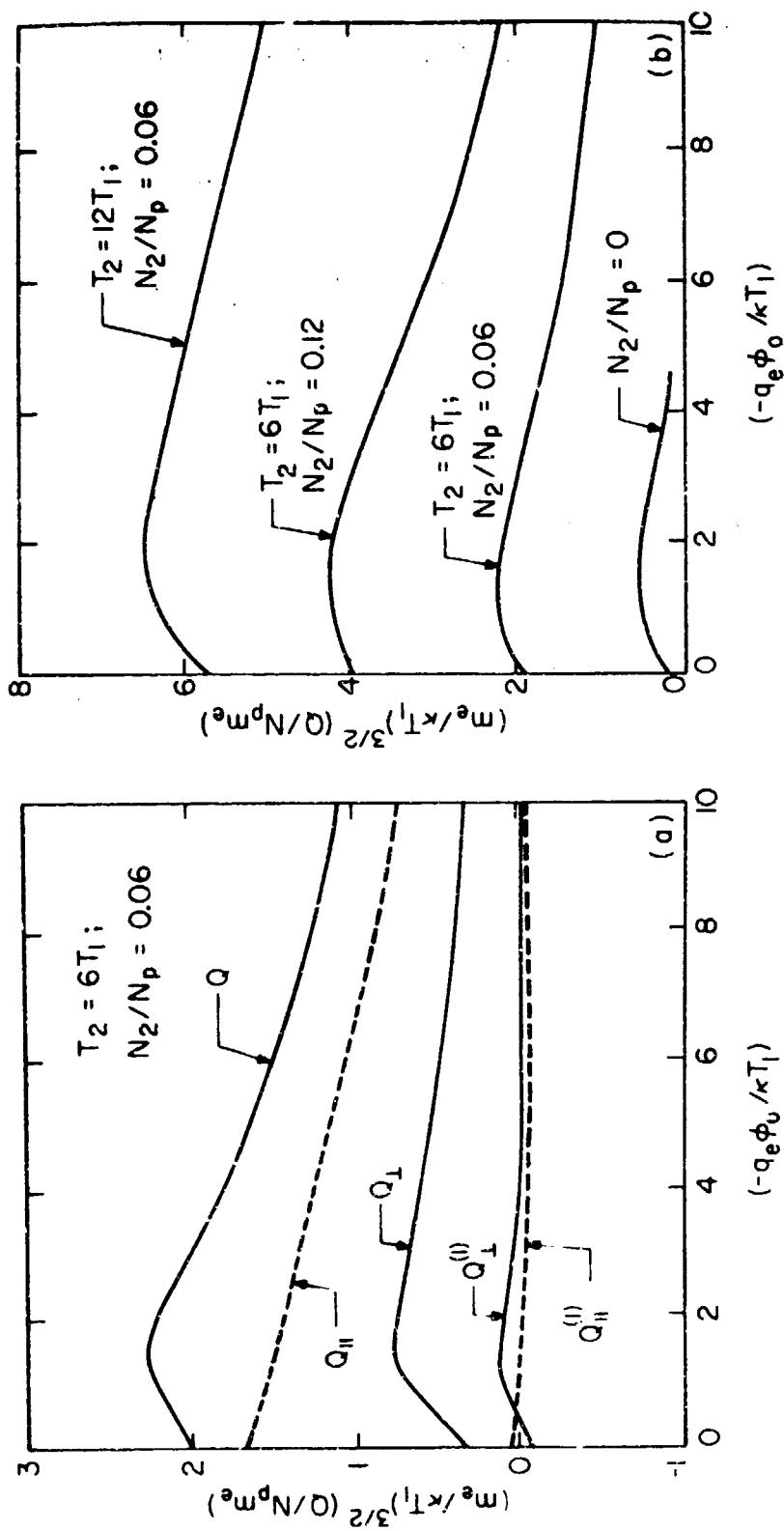
Figure 2. Dependence of heat flux (Q) along the magnetic field on electrostatic potential (φ_0) for selected values of N_2/N_p and T_2/T_1 at the base of an ideal solar exosphere. In the left panel (a), various contributions to Q are indicated separately.

to say that $Q = 4.04 \times 10^{-2}$ erg/cm^2 sec for $N_p = 8$ cm^{-3}, the proton density recommended by Hundhausen (1970). This heat flux should be compared with the corrected value $(Q \sim 1\text{-}3 \times 10^{-2}$ erg/cm^2 sec) obtained observationally by Montgomery et al. (1968). However, using the $N_2/N_p = 0$ contour in Figure 1, one would have obtained $(-q_e \varphi_0 / \kappa T_1) = 1.094$ or $\varphi_0 \approx 11.3$ 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^2 sec for $N_p = 8$ cm^{-3} 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 $\beta_j = 8\pi N_j \varkappa T_j / B^2$ 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

$$f_1(v_\parallel, v_\perp; r) \approx (m_e/2\pi\varkappa T_1)^{3/2} N_1 \exp(-m_e v_\perp^2 / 2\varkappa T_1)$$

$$\times \exp\left[-(m_e/2\varkappa T_1)(v_\parallel - u \sec \chi + \eta c_A)^2\right], \quad (7)$$

(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

$$(2\pi m_e u^2/\varkappa T_2)^{1/2} \sec \chi + (2\pi m_e \eta^2 c_A^2/\varkappa T_2)^{1/2}(N_1/N_2)$$

$$= 2[1 - (q_e \varphi_0/\varkappa T_2)]\exp(q_e \varphi_0/\varkappa T_2)$$

$$\times [1 + \mathrm{erf}((- q_e \varphi_0/\varkappa T_2)^{1/2})$$

$$- 2(- q_e \varphi_0/\pi \varkappa T_2)^{1/2}\exp(q_e \varphi_0/\varkappa T_2)]^{-1} \qquad (8)$$

instead of (4). Comparison of (4) and (8) reveals that $(- q_e \varphi_0/\varkappa T_2)$ is the same function of $(2\pi m_e u^2/\varkappa T_2)^{1/2}\sec\chi + (2\pi m_e \eta^2 c_A^2/\varkappa T_2)^{1/2}(N_1/N_2)$ in (8) as $(- q_e \varphi_0/\varkappa T_1)$ is of $(2\pi m_e u^2/\varkappa T_1)^{1/2}\sec\chi$ for $N_2/N_p = 0$ in (4). Thus, the potential φ_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 ($N_2 = 0.06N_p$, $T_2 = 6T_1 = 7.2 \times 10^5$ °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 $(- q_e \varphi_0/\varkappa T_2)$

on the ordinate is 1.169, which is to say that $\varphi_0 \approx 72.6$ V. The electrostatic potential φ_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 $(-q_e\varphi_0/\varkappa T_2)$ and $(m_e u^2/\varkappa T_2)^{1/2} \sec \chi$ 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

$$(m_e/\varkappa T_1)^{3/2}(Q_\parallel^{(1)}/N_1 m_e)$$

$$= -(1/2)[3 + (m_e \eta^2 c_A^2/\varkappa T_1)](m_e \eta^2 c_A^2/\varkappa T_1)^{1/2} \qquad (9a)$$

and

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

rather than by (6). The various contributions to $(m_e/\varkappa T_1)^{3/2}$ $(Q/N_p m_e)$ have been plotted (using $\eta \approx 1$) in Figure 3a for comparison with Figure 2a. Inserting $\varphi_0 = 72.6$ V and $N_p = 8$ cm^{-3}, one obtains $(m_e/\varkappa T_1)^{3/2}(Q/N_p m_e) = 1.519$ or $Q \approx 2.72 \times 10^{-2}$ erg/cm^2 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.
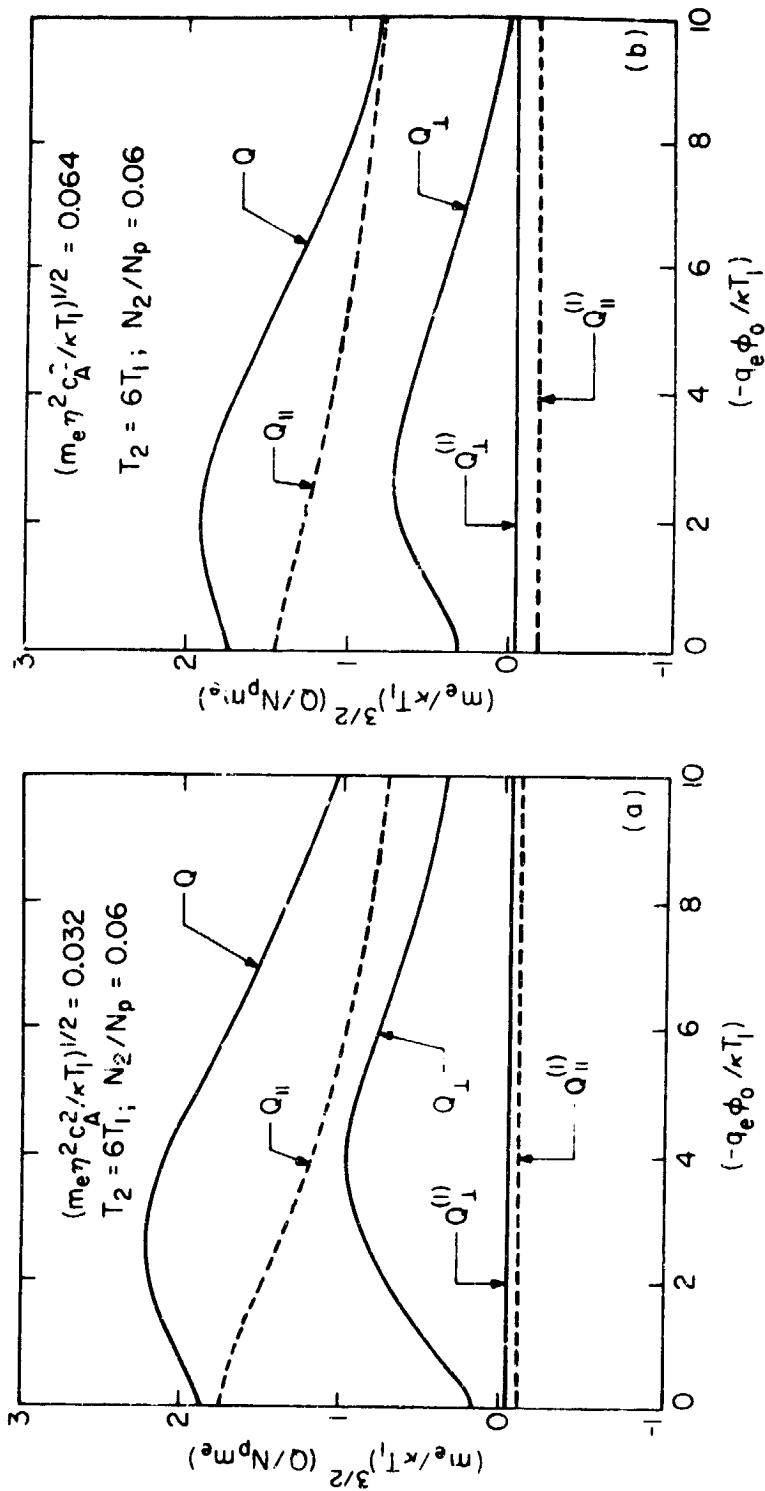
Figure 3. Dependence of field-aligned heat flux (Q) and its constituent parts on electrostatic potential (φ_0) for selected values of N_2/N_p, T_2/T_1, and $(m_e \eta^2 c_A^2/\kappa T_1)^{1/2}$ at the base of an ideal hot-electron exosphere. Cooler electrons (j = 1) here belong to isotropic Maxwellian with bulk velocity $u \sec \chi - \eta c_A$ 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 <u>magnetosonic</u> instability at $r \sim 1$ AU. For the solar-wind parameters used above, this choice of η 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 $Q \approx 3.16 \times 10^{-2}$ erg/cm^{2}sec. This lies between the value for $\eta \approx 1$ ($Q \approx 2.72 \times 10^{-2}$ erg/cm^{2}sec, as shown above) and the exospheric value ($Q \approx 4.04 \times 10^{-2}$ erg/cm^{2}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).

⁻. 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 φ_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 $\dot{f}_2(v_\parallel, v_\perp; r)$ as observed, without drastically modifying the electrostatic potential φ_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 φ_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 $\varphi_0 \sim 40$-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 $r \sim 10\text{-}20\ r_\odot$ (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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The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military concepts and systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space and missile systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

Aerophysics Laboratory: Launch and reentry aerodynamics, heat transfer, reentry physics, chemical kinetics, structural mechanics, flight dynamics, atmospheric pollution, and high-power gas lasers.

Chemistry and Physics Laboratory: Atmospheric reactions and atmospheric optics. chemical reactions in polluted atmospheres, chemical reactions of excited species in rocket plumes, chemical thermodynamics, plasma and laser-induced reactions, laser chemistry, propulsion chemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, photosensitive materials and sensors, high precision laser ranging, and the application of physics and chemistry to problems of law enforcement and biomedicine.

Electronics Research Laboratory: Electromagnetic theory, devices, and propagation phenomena, including plasma electromagnetics; quantum electronics, lasers, and electro-optics; communication sciences, applied electronics, semiconducting, superconducting, and crystal device physics, optical and acoustical imaging; atmospheric pollution; millimeter wave and far-infrared technology.

Materials Sciences Laboratory: Development of new materials; metal matrix composites and new forms of carbon; test and evaluation of graphite and ceramics in reentry; spacecraft materials and electronic components in nuclear weapons environment; application of fracture mechanics to stress corrosion and fatigue-induced fractures in structural metals.

Space Physics Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, studies of solar magnetic fields; space astronomy, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

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