JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. A9, PAGES 7480–7486, SEPTEMBER 1, 1981

Energetics of Coronal Hole Expansion

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Based on the assumption of the undamped propagation of Alfven waves between 2 and 5 R_S, the possible range of Alfven wave energy flux density at the base of a polar coronal hole has been deduced. It is concluded that extended heating above 2 R_S is needed to maintain the temperature maximum above 2 R_S and to supply energy for the formation of high-speed wind streams. The energy contribution of extended heating to high-speed wind streams might be greater than that of Alfven waves by direct momentum addition.

1. INTRODUCTION

Since it was first suggested that high-speed wind streams arise from large regions of unipolar, diverging coronal magnetic fields (see the review in *Hundhausen* [1972]), it is now believed that large coronal holes, which are associated with divergent magnetic fields and lower coronal densities and are formed during the descending phase of the solar cycle, are the source regions of the recurrent high-speed wind streams [*Krieger et al.*, 1973; *Neupert and Pizzo*, 1974; *Hundhausen*, 1977; *Sheeley et al.*, 1976]. The potential-field, conductive solar wind models [*Pneuman*, 1976, 1978] are seen to be rather successful in predicting the spatial location and longitudinal extent of the observed high-speed wind streams. The speed predicted by the models for the 'monster' stream (Carrington Rotation 1599), however, is only about 250 km/s, whereas the actual observed speed is about 750 km/s. Recently it has been demonstrated in a comprehensive parameter study [*Holzer and Leer*, 1980] that even in the presence of a rapidly diverging flow geometry and/or strong (collisionless) inhibition of thermal conduction, it does not seem possible for a conductive solar wind model (without energy addition, including momentum addition and/or heat addition above the coronal base) to produce the high solar wind speeds frequently observed while also matching the observed coronal base pressure and solar wind mass flux density. It has also been found [*Leer and Holzer*, 1980] that energy addition in the region of subsonic flow increases the solar wind mass flux but either has little effect on (for heat addition) or significantly reduces (for momentum addition) the solar wind flow speed at 1 AU. In contrast, energy addition in the region of supersonic flow has no effect on the solar wind mass flux but significantly increases the flow speed at 1 AU.

It has been suggested that the high-speed streams are likely accelerated by waves [*Parker*, 1965; *Holzer and Leer*, 1979]. In situ observations have demonstrated the presence of Alfven waves in the solar wind propagating away from the sun. If the Alfven waves observed at 1 AU originate in the solar atmosphere, the direct momentum addition by Alfven waves may then be suggested [*Belcher*, 1971; *Hollweg*, 1973, 1978; *Wentzel*, 1977], although the value of the Alfvenic energy flux in coronal holes is not known. On the other hand the analysis of direct coronal hole observations [*Munro and Jackson*, 1977] showed that the effective temperature increases with height to at least 2.5 R_S. This implies that the material is being heated and/or that momentum is being transferred to the plasma in this height range.

Therefore, the existence of both the high-speed wind streams and the effective temperature profile in coronal holes requires energy addition to the expanding coronal plasma in holes. This paper attempts to deduce the possible Alfven wave energy flux density existing in a coronal hole and discusses the energy balance from the observed hole electron density and geometry based on the assumption of undamped propagation of Alfven waves below 5 R_S.

2. THEORETICAL ANALYSIS

According to Munro and Jackson's coronal hole observation, the central axis of the north polar hole during the period of June 31–July 13, 1973 is directed radially in the range of 2–5 R_S, and the hole is essentially axisymmetrical about the north pole. The cross-sectional area of the flow tube or magnetic flux tube normal to the central axis increases more rapidly than the square of the heliocentric distance. We assume that the cross-sectional area of the infinitesimal, radial, field-aligned flow tube varies in a manner similar to that of the entire hole. If there are outward-propagating Alfven waves and some other heat sources and/or sinks, then the steady magnetohydrodynamic expansion equations of the coronal plasma along the infinitesimal radial flux tube are

$$(d/dr)(\rho u A) = 0 \tag{1}$$

$$\rho u \frac{du}{dr} = -\frac{d}{dr}\left[\rho RT + \frac{\langle \delta B^2 \rangle}{8\pi}\right] - \frac{\rho G M_S}{r^2} \tag{2}$$

$$\frac{3}{2}\rho R u \frac{dT}{dr} + \frac{\rho RT}{A}\frac{d(Au)}{dr} = -\frac{1}{A}\frac{d}{dr}(A q_r) + Q_A + Q \tag{3}$$

$$(d/dr)(AB) = 0 \tag{4}$$

where A is the cross-sectional area of the infinitesimal, field-aligned flux tube; ρ, u, T, and B are the mass density, radial flow velocity, plasma temperature, and magnetic field, respectively; $\langle \delta B^2 \rangle$ is the average square amplitude of Alfven waves over the time interval much longer than wave periods; and R, G, and M_S are the physical gas constant, the gravitation constant, and the solar mass, respectively. The Alfven heating term is

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†The National Center for Atmospheric Research is sponsored by the National Science Foundation

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Paper number 1A0826.
0148-0227/81/001A-0826$01.00

$$Q_A = -\frac{1}{A}\frac{d}{dr}\left[A\frac{\langle\delta B^2\rangle}{4\pi}\left(\frac{3}{2}u + V_A\right)\right] + u\frac{d}{dr}\frac{\langle\delta B^2\rangle}{8\pi} \tag{5}$$

where V_A denotes the Alfven velocity. In (3), q_r denotes the radial heat flux density, for which we use the following assumptions. When the mean free path of electrons moving in the radial direction is less than the radial 'trapping distance,' which is approximately half the radial distance [*Perkins*, 1973], then

$$q_r = -K_0 \cos^2\vartheta\, T^{5/2}(dT/dr) \tag{6}$$

where $K_0 = 7.8 \times 10^{-7}$ erg cm^{-1} s^{-1} deg$^{-7/2}$, and ϑ is the local angle between the radial direction and the magnetic field. When the electron mean free path is not less than half the radial distance,

$$q_r = \frac{3}{2}\alpha nukT \tag{7}$$

where α is dependent on the radial wind velocity and electron temperature [*Hollweg*, 1974*a*, 1976]. Q in (3) includes the heat input in erg cm^{-3} s^{-1} (other than the possible Alfven wave heating) and the radiative loss.

Undamped Propagation Characteristics of Alfven Waves in Rapidly Diverging Flow Tubes

If we assume that the propagation of Alfven waves in coronal holes below 5 R_S is undamped [*Barnes*, 1966; *Hollweg*, 1973], then (5) becomes

$$\frac{d}{dr}\frac{\langle\delta B^2\rangle}{8\pi} = \frac{1}{Au}\frac{d}{dr}\left[A\frac{\langle\delta B^2\rangle}{4\pi}\left(\frac{3}{2}u + V_A\right)\right] \tag{8}$$

Using (1), we have

$$\langle\delta B^2\rangle = \langle\delta B_0{}^2\rangle\left(\frac{\rho}{\rho_0}\right)^{1/2}\frac{\left(1+\dfrac{u_0}{V_{A_0}}\right)^2}{\left(1+\dfrac{u_0}{V_A}\right)^2} \tag{9}$$

where the subscript 0 denotes the reference heliocentric distance r_0, i.e., the base of the corona. Formula (9) is just the same as the case for the transverse Alfven waves in the solar wind [*Hollweg*, 1974*b*].

Acceleration by Alfven Waves

Substituting (9) for $\langle\delta B^2\rangle$ in (8) and using (4), we have

$$\frac{d}{dr}\frac{\langle\delta B^2\rangle}{8\pi} = \frac{1}{Au}\frac{d}{dr}\left[A_0\frac{\langle\delta B_0{}^2\rangle}{4\pi}V_{A_0}\left(1+\frac{u_0}{V_{A_0}}\right)^2\frac{\left(\dfrac{3}{2}\dfrac{u}{V_A}+1\right)}{\left(\dfrac{u}{V_A}+1\right)^2}\right] \tag{10}$$

As pointed out by *Barnes* [1974], (10) shows that if the intensity of the Alfven waves $\langle\delta B^2\rangle$ at the coronal base is not sufficiently large in the place where $u/V_A \ll 1$, the differentiation of the quantity in the square bracket in the right hand side of (10) must be very small so that the acceleration by Alfven wave pressure for coronal plasma is negligible with respect to the kinetic pressure, and it is possible for Alfven pressure gradient force to become an important factor accelerating coronal plasma only when its amplitude is large enough (for the value comparison, see the next section).

On the other hand, combining (1) and (2) we have

$$\left(\frac{u^2}{RT}-1\right)\frac{du}{u} = \left[\left(\frac{1}{A}\frac{dA}{dr}-\frac{1}{T}\frac{dT}{dr}\right) - \frac{1}{RT}\left(\frac{1}{\rho}\frac{d}{dr}\frac{\langle\delta B^2\rangle}{8\pi}+\frac{GM_S}{r^2}\right)\right]dr \tag{11}$$

Formula (11) shows that inside the critical point the following relation must be satisfied for the coronal plasma to be able to be accelerated outward:

$$\left(\frac{1}{A}\frac{dA}{dr}-\frac{1}{T}\frac{dT}{dr}\right) - \frac{1}{RT}\left(\frac{1}{\rho}\frac{d}{dr}\frac{\langle\delta B^2\rangle}{8\pi}+\frac{GM_S}{r^2}\right) < 0$$

or

$$-\frac{d}{dr}\frac{\langle\delta B^2\rangle}{8\pi} < \frac{\rho GM_S}{r^2} - \rho RT\left(\frac{1}{A}\frac{dA}{dr}-\frac{1}{T}\frac{dT}{dr}\right) \tag{12}$$

It follows that inside the sonic critical point the Alfvenic pressure gradient force must be limited.

In view of these analyses made above and in order to effectively accelerate coronal plasma outward, the Alfvenic intensity (or energy flux density) in coronal holes must be sufficiently large but limited (their possible values are described below).

3. NUMERICAL ANALYSIS

Now we use (9) and the Munro-Jackson model of coronal hole density to integrate (1) and (2). We assume that the observed high-speed wind streams originate in such a hole and that the plasma consists of protons and electrons and satisfies the quasi-neutral condition.

Parameter Selection

Based on the Munro-Jackson model, the cross-sectional area satisfies

$$A(r) = A(r_0)\left(\frac{r}{r_0}\right)^2 f(r)$$

$$f(r) = \frac{f_{max}e^{(r-r_1)/\sigma}+f_1}{e^{(r-r_1)/\sigma}+1} \tag{13}$$

$$f_1 = 1-(f_{max}-1)e^{(r_0-r_1)/\sigma}$$

where we will take $r_1 = 1.31\ R_S$, $\sigma = 0.51\ R_S$, $f_{max} = 7.26$, $r_0 = 1\ R_S$ with $A(r_0) = 0.52\ R_S{}^2$. Further, the electron number density is

$$n(r) = 5\times10^9\left(\frac{r}{R_S}\right)^{-14} + 2.41\times10^6\left(\frac{r}{R_S}\right)^{-3.28} \tag{14}$$

which is chosen to represent average conditions near the center of the hole. Because there are few if any observational data about Alfven waves and the outer coronal temperature between 2 and 5 R_S, we have to individually choose a set of values for them and combine them in different ways. For the Alfven energy flux density

$$\bar{F}_A = \frac{\langle\delta B^2\rangle}{4\pi}\left(\frac{3}{2}\bar{u}+\bar{V}_A\right)$$

at $r = R_S$, we will consider the values

$$F_{A1}(\text{erg cm}^{-2}\text{ s}^{-1}) = 0,\ 1 \times 10^5,\ 5 \times 10^5,\ 1 \times 10^6,\ 1.5 \times 10^6,\ 2 \times 10^6$$

The temperature at $r = 5\ R_S$ will be given the trial values

$$T_5(k) = 1 \times 10^5,\ 5 \times 10^5,\ 7.5 \times 10^5,\ 1 \times 10^6,\ 1.5 \times 10^6,\ 2 \times 10^6,\ 2.5 \times 10^6,\ 3 \times 10^6$$

It is not yet possible now to directly measure the proton flux density for solar wind flowing from a polar hole. Because the characteristics of polar and equatorial coronal holes are similar near the solar surface and because the inferred solar velocities and the proton flux densities at large heliomagnetic latitude are equivalent to that measured for equatorial high-speed streams [*Zhao and Hundhausen*, 1981], we assume that the solar wind emanating from the polar hole studied in this paper is similar to the high-speed streams that flow from equatorial coronal holes. The average proton number flux in the high-speed wind stream observed near 1 AU is taken from *Feldman et al.* [1977]: $nu = 3.0 \times 10^8$ cm^{-2} s^{-1}. Finally, the background radial component of IMF at 1 AU is taken to be $B_r = 3 \times 10^{-5}$ G.

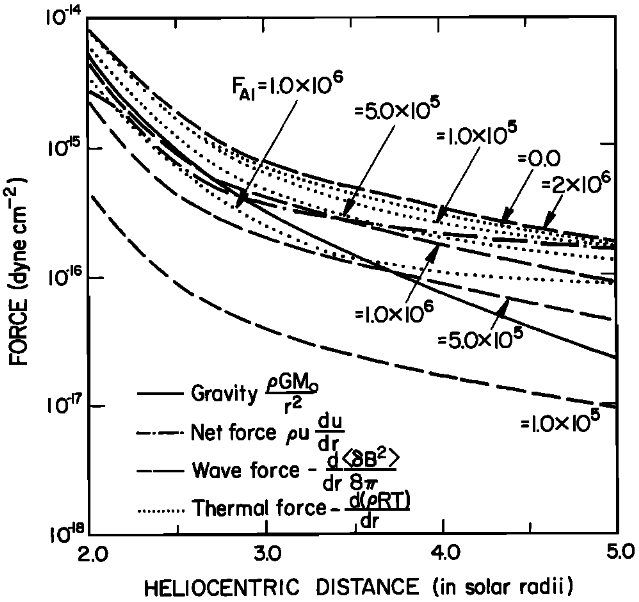

Fig. 1. The profiles of the solar gravity, Alfven wave pressure gradient force; the thermal pressure gradient force; and the net force exerted on the coronal plasma (all are taken to be absolute value) from 2 to 5 R_S in a coronal hole. F_{A1} labeled on the individual curves refers to the Alfven wave energy flux density in erg cm^{-2} s^{-1} near the solar surface.

Results and Discussion

Alfven wave energy flux density effective for accelerating outward in a coronal hole. In a procedure similar to the method used by *Brandt et al.* [1965] for a spherically symmetric geometry and by *Munro and Jackson* [1977] for a rapidly expansive geometry, we can, by using the conservation of electron mass flux (1), simply infer the radial distribution of the flow velocity u, the steady acceleration $u(du/dr)$, and the implied force $\rho u(du/dr)$ from the given flow tube and electron density between 2 and 5 R_S and the observed electron mass flux at 1 AU. Based on the conservation of radial magnetic flux (4) and the undamped propagation characteristic of Alfven waves in rapidly expansive flux tube (9), we can also deduce the Alfven wave pressure gradient force $-(d/dr) \cdot \langle \delta B^2 \rangle / 8\pi$ from the observed magnetic field intensity near the orbit of the earth and the assumed Alfven wave energy flux at coronal hole base F_{A1}. Figure 1 displays the radial profiles of gravity, total force, Alfven wave pressure gradient force, and thermal pressure gradient force. In Figure 1 the Alfven wave pressure gradient force and the thermal pressure gradient force vary as the assumed Alfven wave energy flux is changed. It follows from Figure 1 that between 2 and 5 R_S

$$\left| \frac{d}{dr} \frac{\langle \delta B^2 \rangle}{8\pi} \right| \Big/ \left| \frac{d}{dr}(\rho RT) \right| < \frac{1}{10}$$

when $F_{A1} \leq 1 \times 10^5$ erg cm^{-2} s^{-1}. That is, the contribution of Alfven wave to the acceleration of coronal plasma is small in relation to the thermal pressure between 2 and 5 R_S. This contribution gets larger as the assumed Alfven wave energy flux increases from 1×10^5 erg cm^{-2} s^{-1}.

On the other hand, although we cannot directly use inequality (12) to estimate the upper limit of Alfvenic energy flux for accelerating the plasma outward inside the transonic point because the deduced temperature is dependent on the assumed Alfven wave energy flux at the coronal base in our analysis, it appears possible to make an overestimate of the Alfvenic energy flux density on the basis of the relative contribution of wave force and gravity. The reason we can do so is that the term $[(1/A)(dA/dr) - (1/T)(dT/dr)]$ on the right hand side of (12) can be inferred to be always positive near the transonic point. That is, the Alfven wave pressure gradient force $-(d/dr)(\langle \delta B^2 \rangle / 8\pi)$ must be less than a value smaller than the gravity $(\rho GM_S/r^2)$. In fact if we examine the temperature profiles (Figure 2), which are deduced from the different assumed Alfvenic energy flux density at the coronal base and the different trial temperatures at 5 R_S, it can be seen that one of the effects of the Alfven waves in coronal hole is 'desteepening' the rising part of the temperature profile beginning at 2 R_S. Therefore, we need to compare only $(1/A)(dA/dr)$ (which is positive for the geometry of coronal holes) with $(1/T)(dT/dr)$, corresponding to no Alfven wave. As to the case of $r < 2\ R_S$, we use the temperature profile of R. H. Munro (personal communication, 1980). The table below lists $(1/T)(dT/dr)$ and $(1/A)(dA/dr)$ at different heliocentric distances.

distance	$(d\ln T/dr)$	$(d\ln A/dr)$
3.0 R_S	4.799×10^{-12}	1.146×10^{-11}
2.5 R_S	6.780×10^{-12}	1.146×10^{-11}
2.0 R_S	7.152×10^{-12}	2.220×10^{-11}
1.5 R_S	1.196×10^{-11}	3.986×10^{-11}
1.1 R_S	2.594×10^{-11}	6.013×10^{-11}

Then, inside the transonic point, the inequality

$$-\frac{d}{dr}\frac{\langle \delta B^2 \rangle}{8\pi} < \frac{\rho GM_S}{r^2}$$

can be used as a criterion to make an overestimate of the upper limit of Alfvenic energy flux density. Figure 3 displays the ratio of wave force to solar gravity vs. the heliocentric distance. The ratio decreases with decreasing heliocentric distance for each assumed Alfvenic energy flux density, and the heliocentric distance of the point where the wave force equals the gravity, which will be called the 'transgravity point,' decreases with increasing F_{A1}. Comparing Figures 2 and 3, we can see that the heliocentric distance of the 'transgravity

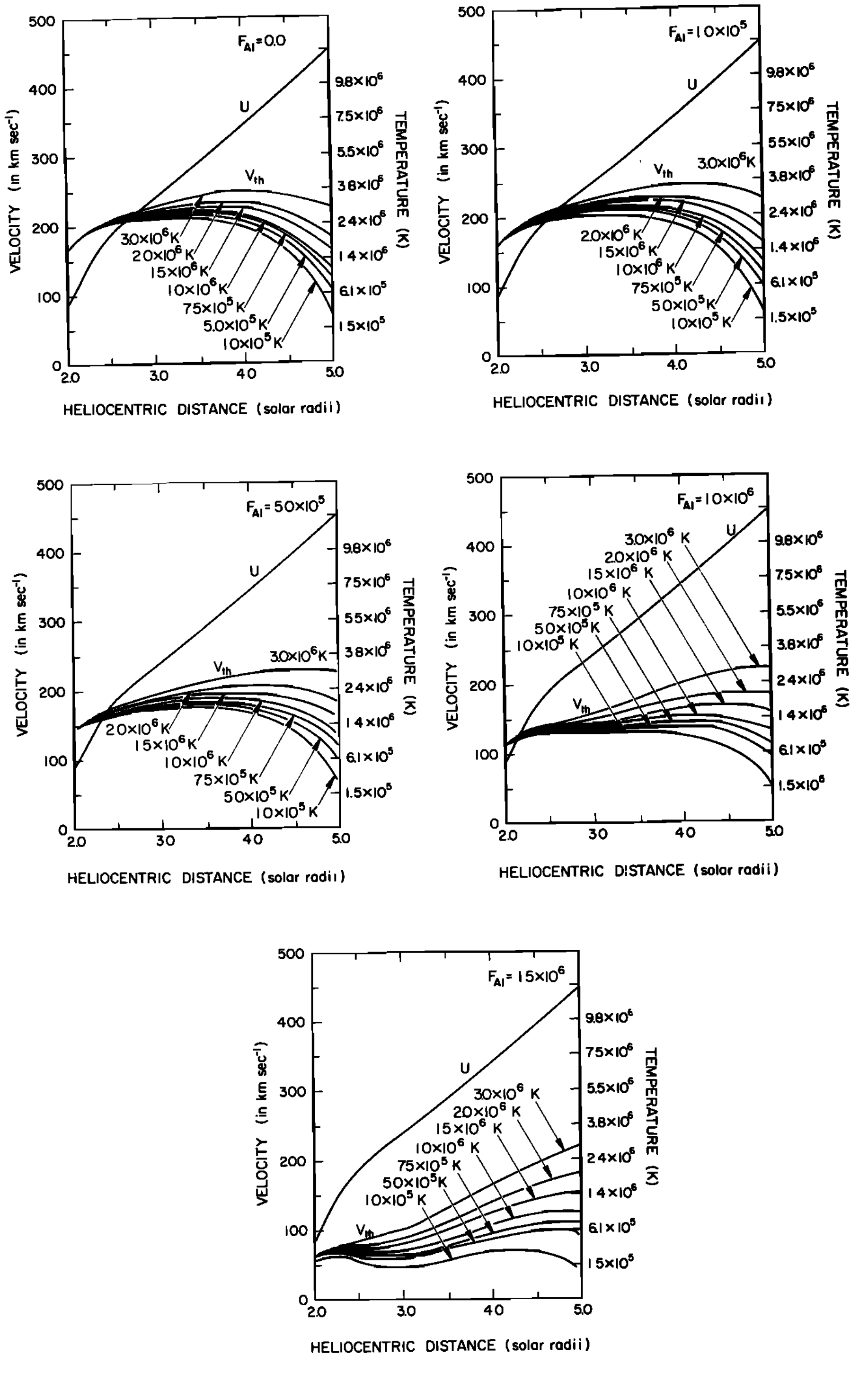

Fig. 2. The temperature (right-hand scale) and thermal velocity (left-hand scale) profiles for various assumed Alfven wave energy flux density at 1 R_S and temperature at 5 R_S in a coronal hole. Included is flow velocity to examine the critical points. F_{A1}, U, and V_{th} represent the Alfven wave energy flux density near the solar surface, the inferred flow speed, and the thermal speed, respectively. The numbers labeled on the individual curves refer to the plasma temperature at 5 R_S.

point' decreases more rapidly than that of the transonic point as F_{A1} increases. Both of these points are near the heliocentric distance of about 2.2 R_S if we take $F_{A1} = 1 \times 10^6$ erg cm^{-2} s^{-1}. In other words, when $F_{A1} < 1 \times 10^6$ erg cm^{-2} s^{-1}, the transonic point is lower than the 'transgravity point,' and (12) is satisfied inside the transonic point, whereas when F_{A1} is taken to be greater than the value, (12) would be broken down. From the viewpoint of effective acceleration of coronal plasma by Alfven wave force, therefore, the Alfven wave energy flux density at the coronal hole base should be

$$1 \times 10^5 \text{ erg cm}^{-2} \text{ s}^{-1} < F_{A1} < 1 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$$

Possible Alfven wave energy flux density in the coronal hole. It is evident from Figure 2 that when $F_A \geq 1 \times 10^6$ erg cm^2 s^{-1}, the calculated temperature at 2 R_S is lower than 1×10^6 K, a value that appears to be too low compared to empirical coronal hole models lower than 2 R_S [*Withbroe and Noyes,* 1977; R. H. Munro, personal communication, 1980]. In fact, if $F_{A1} = 2 \times 10^6$ erg cm^{-2} s^{-1} were taken, the calculated temperature would have become negative, which is obviously unreasonable. For the purpose of getting reasonable coronal temperature, therefore, the possible Alfven wave energy flux density at the coronal hole base should be

$$F_{A1} < 1 \times 10^6 \text{ erg cm}^{-2}\text{ s}^{-1}$$

or at 2 R_S

$$F_A < 4.6 \times 10^4 \text{ erg cm}^{-2}\text{ s}^{-1}$$

Extended heating. It is seen from Figure 2 that there are maxima in the calculated temperature profiles between 2 and 5 R_S. Figure 4 displays the positions of the highest temperature corresponding to the different assumed Alfven wave energy flux at the coronal base vs. the assumed temperature at 5 R_S. Figure 4 indicates that an increase in Alfvenic energy flux density produces an increase in the position of the highest temperature. Then there is no way to eliminate maxima above 2 R_S by adding undamped propagating Alfven waves. This suggests that there must be extended heating above 2 R_S if the undamped propagation of the existing Alfven wave is a valid assumption. This extended heating in the region of supersonic flow will significantly increase the flow speed at 1 AU [*Holzer and Leer,* 1979].

Energy balance in the coronal hole. It is well known that in coronal holes the high-speed solar wind streams are a major source of energy loss and the radiative loss can be neglected [*Withbroe and Noyes,* 1977]. The total energy loss by solar wind is of the order of 7.0×10^5 erg cm^{-2} s^{-1} at 1 R_S. This estimate is based on the wind observation near Earth orbit [*Feldman et al.,* 1977] and the configuration of the coronal hole expansion cited above. Using the conservation equations (1)–(3), we have

$$\begin{aligned}(\rho u)|_{2R_S} \Bigg[\Bigg(\frac{1}{2}u^2 + \frac{5kT}{m_p} - \frac{GM_S}{r} + \frac{1}{\rho u} q_r \\ + \frac{\langle \delta B^2 \rangle}{8\pi}\frac{3u + 2V_A}{\rho u}\Bigg)\Bigg|_{1\text{AU}} - \left(\frac{1}{2}u^2 - \frac{GM_S}{r}\right)\Bigg|_{2R_S}\Bigg] \\ = \left[\frac{\langle \delta B^2 \rangle}{8\pi}(3u + 2V_A) + q_r + \frac{5kT}{m_p}\rho u\right]\Bigg|_{2R_S} \\ + \int_{2R_S}^{1\text{AU}} \frac{A(r)}{A(2R_S)} Q dr \end{aligned} \qquad (15)$$

The left hand side of (15) denotes the required energy supply at 2 R_S for the observed high-speed wind streams; this is estimated to be 3.2×10^4 erg cm^{-2} s^{-1}. The first three terms on the right hand side of (15) denote, Alfven wave energy flux, thermal conduction, and enthalpy at 2 R_S, respectively. The last term denotes the energy supplied by heating, which should be positive because the radiative loss included in Q can be neglected in coronal holes, especially above 2 R_S. Calculation (Table 1) shows, first, that if the assumed Alfven wave energy flux density F_{A1} at the coronal base were raised to 9.0×10^5 erg cm^{-2} s^{-1}, the energy supplied by heating would have become negative, which is obviously unreasonable (thereby providing an upper limit for F_{A1}); second, that when $F_{A1} < 9.0 \times 10^5$ erg cm^{-2} s^{-1}, extended heating is needed to compensate for the thermal conduction flux toward the sun and to maintain the temperature peak; third, that generally speaking, the energy contribution to high-speed wind streams from Alfven waves is the same order of magnitude as that from extended heating. If $F_{A1} < 6.0 \times 10^5$ erg cm^{-2} s^{-1}, the contribution of the former is smaller than the latter. If $F_{A1} \geq 6.0 \times 10^5$ erg cm^{-2} s^{-1}, the contribution of the former is somewhat greater than the latter. With respect to energy balance, therefore, Al-

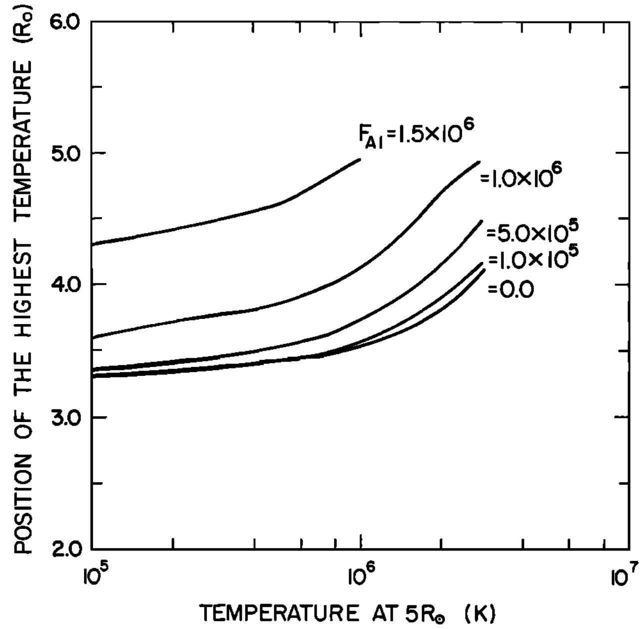

Fig. 4. The positions of the highest temperature for various assumed Afiven wave energy flux density at 1 AU vs. assumed temperatures at 5 R_S. F_{A1} labeled on the individual curves refers to the Alfven wave energy flux density in erg cm^{-2} s^{-1} near the solar surface.

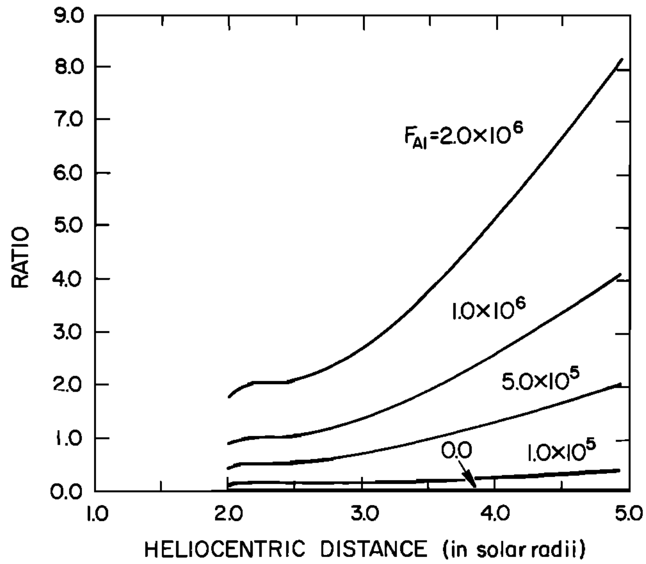

Fig. 3. The ratio of the wave force to the solar gravity vs. the heliocentric distance for the assumed Alfven wave intensities at coronal base. F_{A1} labeled on the individual curves refers to the Alfven wave energy flux density in erg cm^{-2} s^{-1} near the solar surface.

TABLE 1. The Prediction of Different Energy Flux Densities Corresponding to the Assumed Wave Intensity at $2R_S$ and Temperature at 5 R_S

Assumed Wave Intensity at $2R_S$, $\times 10^4$	Assumed Temperature at $5R_S$, $\times 10^5$	Thermal Conduction at $2R_S$, $\times 10^4$	Enthalpy at $2R_S$, $\times 10^4$	Integration of Heating Term $2R_S - 1$AU, $\times 10^4$
	30.0	−11.0	0.54	13.0
	20.0	−11.0	0.54	14.0
	15.0	−11.0	0.55	14.0
0.0	10.0	−11.0	0.55	14.0
(0.0)	7.5	−12.0	0.55	14.0
	5.0	−12.0	0.55	15.0
	1.0	−13.0	0.56	15.0
	30.0	−3.2	0.38	3.5
	20.0	−3.3	0.38	3.6
	15.0	−3.4	0.39	3.7
2.3	10.0	−3.5	0.39	3.8
(50.0)	7.5	−3.7	0.39	4.0
	5.0	−3.8	0.40	4.1
	1.0	−4.2	0.40	4.5
	30.0	−2.4	0.35	2.2
	20.0	−2.5	0.35	2.3
	15.0	−2.5	0.35	2.4
2.8	10.0	−2.6	0.36	2.5
(60.0)	7.5	−2.7	0.36	2.6
	5.0	−2.9	0.36	2.7
	1.0	−3.2	0.37	3.0
	30.0	−1.7	0.32	1.1
	20.0	−1.8	0.32	1.2
	15.0	−1.8	0.32	1.3
3.2	10.0	−1.9	0.32	1.3
(70.0)	7.5	−2.0	0.33	1.4
	5.0	−2.1	0.33	1.5
	1.0	−2.3	0.34	1.8
	30.0	−1.2	0.29	0.20
	20.0	−1.2	0.29	0.26
	15.0	−1.3	0.29	0.29
3.7	10.0	−1.3	0.29	0.33
(80.0)	7.5	−1.4	0.30	0.41
	5.0	−1.5	0.30	0.50
	1.0	−1.7	0.31	0.68
	30.0	−0.79	0.25	−0.63
	20.0	−0.83	0.26	−0.58
	15.0	−0.86	0.26	−0.56
4.1	10.0	−0.89	0.26	−0.53
(90.0)	7.5	−0.96	0.26	−0.47
	5.0	−1.0	0.27	−0.40
	1.0	−1.2	0.27	−0.27

* The parenthetical values in the first column are the assumed Alfven wave energy flux densities at the coronal base; the unit used in the second column is °K; the unit used in other columns is erg cm^{-2} s^{-1}.

fven wave energy flux density at the coronal base must be smaller than 9.0×10^5 erg cm^{-2} s^{-1}, and the extended heating is needed and important.

In summary, based on the assumption of the undamped propagation of Alfven waves between 2 and 5 R_S in coronal holes, we have deduced that the Alfven wave energy flux density at the coronal base must be $F_{A1} < 9.0 \times 10^5$ erg cm^{-2} s^{-1}, both from examination of the temperature profile and the energy balance and from discussion of the efficiency of the Alfvenic acceleration for the plasma in coronal holes. The extended heating above 2 R_S is needed from the standpoint of both maintenance of the temperature maximum above 2 R_S and formation of the high-speed wind streams. The energy contribution of extended heating to high-speed wind streams is comparable to that of Alfven waves by direct momentum addition if F_{A1} equals about 6.0×10^5 erg cm^{-2} s^{-1}.

So far there have been few if any direct measurements of Alfven waves in coronal holes. The observations near 1 AU are usually mapped back to the coronal base under assumed wave propagation characteristics in the sun-earth space to determine or to test the possible existing Alfven waves in the corona, but it is uncertain for the moment whether Alfven wave propagation is damped or not. Some observational results suggested that the radial evolution of the amplitude of the Alfvenic fluctuations associated with the recurrent high-speed wind streams might be considered to be consistent both with undamped fluctuations of solar origin and with waves that saturate at some value of the ratio between the wave energy density and the background magnetic field energy density [*Belcher and Burchsted,* 1974; *Mariani et al.,* 1978, 1979]. If the undamped propagation is the case, a value of 2.4×10^3 erg cm^{-2} s^{-1} for F_A at 2 R_S or 5.0×10^4 erg cm^{-2} s^{-1} at 1 R_S, can be estimated from an observed F_A value of 9.6×10^{-3} erg cm^{-2} s^{-1} at 1 AU [*Feldman et al.,* 1977]. It is less than the lower limit of 1.0×10^5 erg cm^{-2} s^{-1} deduced above for the Alfven wave acceleration to be effective, namely, it could have no great effect on the coronal hole expansion. The recently experimental results suggest that the radial evolution of the wave amplitude might be considered to be more consistent with saturated waves propagating between 0.41 and 0.65 AU

[*Villante,* 1980]. If it is true, such a conclusion would lead to the prediction, as shown by some theoretical works [*Hollweg,* 1978; *Whang,* 1980], that the contribution of the Alfvenic fluctuations to the energetics of the solar wind expansion might be more effective than was previously estimated for the case of undamped propagation. However, considering the small observed value of the Alfven wave energy flux density at 1 AU cited above, and the results of the wind speed observation that the solar wind speed is almost constant in the outer part of the sun-earth space [*Intriligator and Neugebauer,* 1975; *Coles and Rickett,* 1976], it is possible that the energy contribution of extended heating to high-speed wind streams might be more important than that of the Alfven waves by direct momentum addition.

Acknowledgments. I am thankful to T. E. Holzer and A. J. Hundhausen for valuable discussions and helpful comments about this paper and to R. H. Munro for permitting me to use his unpublished results. I also thank to J. V. Hollweg and L. F. Burlaga for interesting discussions and Karen Lynch for typing the manuscript. I also express my thanks for the hospitality of R. M. MacQueen and the staff of the High Altitude Observatory while I was a visitor here.

The Editor thanks A. Barnes for his assistance in evaluating this paper.

REFERENCE

Barnes, A., Collisionless damping of hydromagnetic waves, *Phys. Fluids, 9,* 1483, 1966.

Barnes, A., Theoretical studies of the large-scale behavior of the solar wind, *Advan. Electron. Electron Phys., 36,* 1, 1974.

Belcher, J., A wave-driven model of the solar wind, *Astrophys. J., 168,* 509, 1971.

Belcher, J., and R. Burchsted, Energy densities of the Alfven waves between 0.7 and 1.6 AU, *J. Geophys. Res., 79,* 4765, 1974.

Brandt, J. C., R. W. Michie, and J. P. Cassinelli, Interplanetary gas x, coronal temperature, energy deposition, and the solar wind, *Icarus, 4,* 19, 1965.

Coles, W. A., and B. J. Rickett, IPS observations of the solar wind speed out of the ecliptic, *J. Geophys. Res., 81,* 4797, 1976.

Feldman, W. C., J. R. Asbridge, S. J. Bame, and J. T. Gosling, Plasma and magnetic fields from the sun, in *The Solar Output and Its Variation,* edited by O. R. White, Colorado Associated University Press, Boulder, 1977.

Hollweg, J. V., Alfven waves in a two-fluid model of the solar wind, *Astrophys. J. 213,* 874, 1973.

Hollweg, J. V., On electron heat conduction in the solar wind, *Astrophys. J., 79,* 3845, 1974*a*.

Hollweg, J. V., Transverse Alfven waves in the solar wind: Arbitrary k, v_0, B_0, and $|\Delta B|$, *J. Geophys. Res., 79,* 1539, 1974*b*.

Hollweg, J. V., Collisionless electron heat conduction in the solar wind, *J. Geophys. Res., 81,* 1649, 1976.

Hollweg, J. V., Some physical processes in the solar wind, *Rev. Geophys. Space Phys., 16,* 689, 1978.

Holzer, T. E., and E. Leer, Theory of mass and energy flow in the solar wind, in *Proceeding of Solar Wind IV,* edited by H. Rosenbauer, Springer-Verlag, Berlin, 1979.

Holzer, T. E., and E. Leer, Conductive solar wind models in rapidly diverging flow geometries, *J. Geophys. Res., 85,* 4665, 1980.

Hundhausen, A. J., *Coronal Expansion and Solar Wind,* Springer-Verlag, New York, 1972.

Hundhausen, A. J., An interplanetary view of coronal holes, in *Coronal Hole and High-Speed Wind Streams,* edited by Z. B. Zirker, Colorado Associated University Press, Boulder, Colo., 1977.

Intriligator, D. S., and M. Neugebauer, A search for solar wind velocity changes between 0.7 and 1.0 AU, *J. Geophys. Res., 80,* 1332, 1975.

Krieger, A. S., A. F. Timothy, and E. C. Roelof, A coronal hole and its identification as the source of high velocity solar wind stream, *Solar Phys., 29,* 505, 1973.

Leer, E., and T. E. Holzer, Energy addition in the solar wind, *J. Geophys. Res., 85,* 4681, 1980.

Mariani, F., B. Bavassano, U. Villante, L. F. Burlaga, and N. F. Ness, The large-scale structure of the interplanetary magnetic field between 0.3 and 1 AU during the primary mission of Helios 1, *J. Geophys. Res., 83,* 5161, 1978.

Mariani, F., U. Villante, R. Bruno, B. Bavassano, and N. F. Ness, An extended investigation of Helios 1 and 2 observations: The interplanetary magnetic field between 0.3 and 1 AU, *Solar Phys, 63,* 411, 1979.

Munro, R. H., and B. V. Jackson, Physical properties of a polar coronal hole from 2 to 5 R_S, *Astrophys. J., 213,* 874, 1977.

Neupert, W. M., and V. Pizzo, Solar coronal holes as sources of recurrent geomagnetic disturbances, *J. Geophys. Res., 79,* 3701, 1974.

Parker, E. N., Dynamical theory of the solar wind, *Space Sci. Rev., 4,* 666, 1965.

Perkings, F., Heat conductivity, plasma instabilities, and radio star scintillations in the solar wind, *Astrophys. J., 179,* 647, 1973.

Pneuman, G. W., Latitude dependence of the solar wind speed: Influence of the coronal magnetic field geometry, *J. Geophys. Res., 81,* 5049, 1976.

Pneuman, G. W., The physical structure of coronal holes: Influence of magnetic fields and coronal heating, *Astron. Astrophys., 81,* 161, 1980.

Sheeley, N. R., Jr., J. W. Harvey, and W. C. Feldman, Coronal holes, solar wind streams, and recurrent geomagnetic disturbances: 1973–1976, *Solar Phys., 49,* 271, 1976.

Villante, U., On the role of Alfvenic fluctuations in the inner solar system, *J. Geophys. Res., 85,* 6869, 1980.

Wentzel, D. G., On the role of hydromagnetic waves in the corona and the base of the solar wind, *Solar Phys., 52,* 163, 1977.

Whang, Y. C., A magnetohydrodynamics of corotating interplanetary structures, *J. Geophys. Res., 85,* 2285, 1980.

Withbroe, G. L., and R. W. Noyes, Mass and energy flow in the solar chromosphere and corona, *Ann. Rev. Astron. Astrophys., 15,* 363, 1977.

Zhao, X.-P., and A. J. Hundhausen, Organization of solar wind plasma properties in a tilted, heliomagnetic coordinate system, *J. Geophys. Res.,* in press, 1981.

(Received March 20, 1981;
revised May 13, 1981;
accepted May 13, 1981.)