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The Energy Budget in and out of Coronal Holes [and Discussion]

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The energy budget in and out of coronal holes

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Energy is transmitted into, out of and across the solar atmosphere by such physical processes as radiation, thermal conduction, waves and so forth. Estimates can be made of the magnitudes of some of these and hence an energy budget drawn up for different regions of the atmosphere. In particular it appears that the energy requirements of coronal hole regions of the solar surface are substantially greater than those of other regions. The main factor determining this conclusion is an estimate of the energy required to accelerate the solar wind in regions above coronal holes. Of two possible mechanisms for the acceleration of the solar wind, namely thermal plasma pressure and Alfvén waves, it may be shown that the former places even more severe demands on the energy budget of these regions, whereas the latter is more easily accommodated.

1. Introduction

This paper is about the energy budget of the solar atmosphere in the region above the chromosphere out to about 5 solar radii. A distinction is made between coronal hole regions where the magnetic field lines are open and where the solar wind originates, and the remaining regions where the field lines are generally closed. The latter will be referred to as coronal cloud regions (or simply as cloud regions) after their appearance in X-ray photographs of the Sun. Although the photographs show structure in these regions, there is need for a descriptive term such as that suggested to distinguish these regions from coronal holes.

It is necessary to be more specific about the boundaries of the hole and cloud regions. These are illustrated in figure 1. The surface corresponding to the isotherm at 10^4 K is taken to be a convenient lower boundary for both regions. The lateral boundaries between the hole and cloud regions are the magnetic field lines as illustrated in figure 1. For the purposes of this paper the upper boundary of the hole region of interest will be taken to be at 5 solar radii. Estimates will be presented for the total energy flux gained and lost across these boundaries. Values of energy flux will be presented in ergs per square centimetre per second,† where all fluxes have been projected back along the field lines to the visible solar surface at $r = R_\odot$.

In subsequent sections of this paper, account is taken of the following energy loss or gain mechanisms: thermal conduction, radiation loss, waves, gravitational and kinetic energy and enthalpy flux. The last three are related only to those cases where there is a flow of matter so that although they may be important internally they do not constitute an overall energy gain or loss for cloud regions. It is assumed, as usual, that the energy comes from the convective zone below the solar surface and that it is transmitted as waves into the upper atmosphere where it is deposited as heat or as the energy to accelerate the solar wind by their direct action. Radiation loss is the only energy loss mechanism which can be measured directly. It is important from the transition zones of both hole and cloud regions. Thermal conduction follows the field lines and is shown to be negligible across the lower boundaries of both regions. Each of

† 1 erg s^{-1} = 10^{-7} W.

these components contributes to the energy budget of hole and cloud regions but it will be seen that there are significant differences between them. These differences must be accommodated within theoretical models for the outer atmosphere of the Sun. The individual energy loss and gain mechanisms are now dealt with in turn.

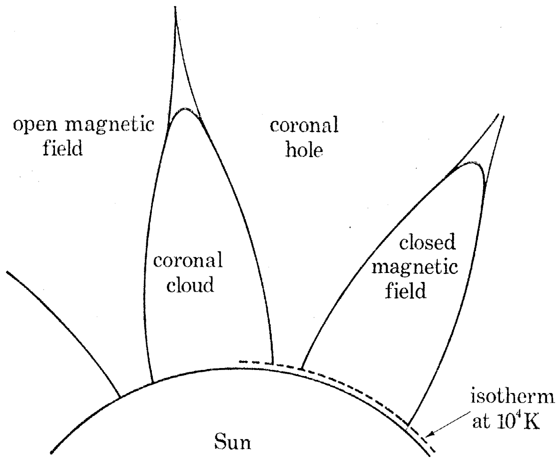

FIGURE 1. Diagram showing the boundaries between coronal holes and coronal cloud regions as discussed in the text.

2. Thermal conduction

Spitzer (1962) has shown that the heat flux that flows along a temperature gradient $\mathrm{d}T/\mathrm{d}r$ in a fully ionized hydrogen plasma at a temperature T is given by the expression

$$\phi_{\mathrm{th}} = \kappa T^{\frac{5}{2}}\, \mathrm{d}T/\mathrm{d}r \ \mathrm{erg\ cm^{-2}\ s^{-1}}.$$

This formula is adopted in the present paper, where sufficient accuracy will result if κ is put equal to 10^{-6} in units appropriate to T being in kelvins and r in centimetres (see Spitzer 1962). Spitzer also shows that in the presence of a magnetic field this expression adequately describes heat conduction along the field lines where the electrons are most effective. The heat conducted across the field is by the positive ions and is quite negligible by comparison.

In order that a significant heat flux be conducted across the lower boundary of the regions of atmosphere that are being considered, it would be necessary for there to be an unrealistically large temperature gradient at $r \approx R_{\odot}$. The application of Spitzer's formula gives for example a gradient of 10 K $\mathrm{cm^{-1}}$ for a heat flux of 10^5 erg $\mathrm{cm^{-2}\ s^{-1}}$, which flux will be seen to be somewhat smaller than estimates of other energy fluxes. Realistic estimates of the temperature gradient give heat conduction fluxes between one-tenth and one-hundredth of this amount. To the accuracy of the present considerations this may be neglected.

The remaining boundary region, namely the upper boundary of hole regions presents some difficulty when attempting to give an estimate of the energy conducted across it. This arises for the following reasons:

(*a*) the high temperature of the corona allows large heat fluxes to flow for relatively small gradients;

(*b*) relatively little is known about the structure of this part of the atmosphere;

(*c*) the electron and ion temperatures are probably different.

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In summary it may be concluded that the conducted heat flux across all the boundaries of cloud regions is negligible and the only possibly significant thermal conduction across the hole boundaries is at the upper boundary where it cannot be estimated.

However, within these regions the large temperature difference between the corona and chromosphere means that thermal conduction is an important mechanism for the internal transfer of energy. By taking model atmospheres based on emission measure analysis of spectral lines such as that due to Jordan (1965) or Dupree & Goldberg (1967) an estimate may be made of the conducted heat flux at each level. Values are found to lie in the range 10^5–10^6 erg cm^{-2} s^{-1}. Models based on theoretical considerations of the energy balance also lead to the conclusion that fluxes within this range are necessary to sustain the temperature gradient that must exist between the chromosphere and corona. There will be further consideration of the influence of thermal conduction in later sections of this paper.

3. Radiation

Of all the energy gain or loss mechanisms considered in this paper, radiation loss is the one that can be measured directly. The most comprehensive full disk measurements are those due to Heroux *et al.* (1974) for the range $\lambda\lambda$50–1220 Å,† Higgins (1976) for the range $\lambda\lambda$230–1220 Å and Heroux & Swirbalus (1976) for the range $\lambda\lambda$1230–1940 Å. The difficulty in deriving a value for the radiated power loss above the 10^4 K isotherm is in deciding which of the lines of wavelength longer than about 1000 Å to include. Lines arising from neutral atoms are assumed to originate in the chromosphere, with the possible exception of hydrogen and helium. Since hydrogen Lyman α is the strongest line in the spectrum, its inclusion makes a large difference. When included, the total estimated radiated power loss is 7×10^5 erg cm^{-2} s^{-1}, and when excluded is 3×10^5 erg cm^{-2} s^{-1}. Since at least some Lyman α radiation is generally taken to arise from the chromosphere (see, for example, Vernazza *et al.* 1976) ($T < 10^4$ K), the value appropriate to the regions of atmosphere considered here must lie somewhere in the range covered by the values given above. It will be noted later that the emission from hole and cloud regions is the same within about ± 20%.

The theoretical calculation of the radiated power loss involves the adding together of the energy radiated by many individual spectral lines and continuum. A number of authors have made such a calculation, including Summers & McWhirter (1979), whose results will be used for the present estimate. The power radiated by unit volume (in cubic centimetres) of a fully ionized solar plasma in steady-state ionization balance and of density n (= electron density = proton density) is $n^2 P_{rad}$ erg cm^{-3} s^{-1}, where the quantity P_{rad} is a function only of the electron temperature of the plasma. Summers & McWhirter give P_{rad} to an estimated accuracy of a factor of 2. However, it may be noted that to a factor of 2.5 it may be taken as constant and equal to 2×10^{-22} erg cm^{-3} s^{-1} over the temperature range 10^4 to 2×10^6 K. This result will be adequate for present purposes. It means that the radiation loss has only a small dependence directly on the temperature. But notice that it is proportional to the square of the density and that therefore, in conditions of uniform thermal pressure, it is the regions of low temperature that radiate most efficiently. This has a number of important consequences, among which is the prediction that it is the lower part of the transition zone that radiates most energy per unit volume; another is that a radiating plasma has a tendency to be unstable. Thus if the energy

† 1 Å = 10^{-10} m = 10^{-1} nm.

supply maintaining a body of radiating plasma at a high temperature decreases slightly for some reason so that its temperature and hence thermal pressure falls, a catastrophic collapse is likely to follow unless the heating mechanism preferentially selects high density (i.e. low temperature) regions. Thermal conduction cannot maintain the temperature since the conductivity falls strongly with falling temperature. Conversely, an increase in the amount of energy deposited increases the temperature, reduces the density and reduces the radiation loss so that a runaway temperature rise can result. This situation is quite contrary to that of everyday experience where Stefan's law ensures that radiation provides an effective stabilizing thermostat.

However, it is more usual to assume a model having a stable atmosphere in hydrostatic equilibrium where, as already remarked, it is the cooler, lower part of the transition zone that is most effective in radiating energy. It is also generally assumed that some, if not all, of this energy reaches the lower transition zone by thermal conduction, although Pneuman & Kopp (1978) have recently shown that enthalpy flux associated with down-flow could be an effective mechanism in circumstances where the down-flow is sufficiently small that it hardly disturbs hydrostatic equilibrium. This is discussed later.

By writing the equation of energy balance between the thermally conducted flux and the radiation loss, McWhirter *et al.* (1975) derived a model for an atmosphere in hydrostatic equilibrium. They showed that the solution that they obtained could be adequately represented by the equation

$$T^3 - T_0^3 = 9.5 \times 10^{-7} \langle n_e T \rangle h,$$

where T_0 is the base temperature, $\langle n_e T \rangle$ is the average pressure in units of kelvins per cubic centimetre in the transition zone and h is the height in centimetres above the surface (where $T = T_0$).

Since hardly any heat flux can be conducted out of the bottom of the transition zone and since a static atmosphere is postulated, it is necessary that all of the energy conducted from the top of this model atmosphere be radiated out. Since the density determines the ability of the atmosphere to radiate, the average density and hence average pressure must be adequate to ensure a proper balance.

McWhirter *et al.* (1975) show that the heat flux ϕ_{th} at a great height, h, that can just be radiated by a transition zone having a pressure $\langle n_e T \rangle$ is adequately represented by the equation

$$\phi_{th} = 3.2 \times 10^{-14} \langle n_e T \rangle^{\frac{7}{6}} h^{\frac{1}{6}} \text{ erg cm}^{-2}\text{ s}^{-1}.$$

It will be shown later that a similar relation may be derived where enthalpy flux is the dominant mechanism instead of thermal conduction. In each case it is important that there be a sufficient amount of material in the transition zone to radiate all of the heat energy entering it. It is possible in the real atmosphere that energy is deposited directly as heat in the transition zone from waves. This would be an additional source of heat for the atmosphere to lose to maintain a balance and requires therefore that there be additional material present. The additional material may add to the thickness of the transition zone or its density or both.

By inserting appropriate values into the equation (it is insensitive to the value chosen for h) it may be seen that a conducted flux of 3×10^5 erg cm^{-2} s^{-1} requires a pressure, $\langle n_e T \rangle$, of about 5×10^{14} cm^{-3} K.

Once the temperature and density structure of the atmosphere have been defined, it is possible to calculate the intensity emitted by selected spectral lines on the basis of available atomic data. In this way, Bruner & McWhirter (1979) have calculated the intensity of the C IV 2s–2p line by using the same model atmosphere. They show that the observed intensity of C IV (about 5×10^{13} photons $cm^{-2} s^{-1} sr^{-1}$) corresponds to a total radiated power loss of about 3×10^5 erg $cm^{-2} s^{-1}$. In all these calculations of radiated power loss the uncertainty is about a factor of 2, so that the better agreements between the various values that have been presented should be regarded as somewhat fortuitous. However, to the quoted accuracy, a consistent picture emerges between the observations and theoretical predictions.

Spatially resolved observations show that hole and cloud regions cannot be distinguished in the radiation emitted by their transition zones (to $\pm 20\%$) (Withbroe 1977). Thus if the transition zone of a hole region is thicker than of a cloud region (Withbroe 1977), then (*a*) it must be of lower mean pressure to give the same spectral output; (*b*) it must receive a smaller conducted flux from the corona (since the thermal gradient is less); (*c*) it must receive energy by some other means in order to balance its radiation loss. Possible energy sources for (*c*) are the direct dissipation of wave energy in the transition zone and the enthalpy flux associated with down-flow. The latter is discussed later in this paper.

4. Energy fluxes associated with plasma flow

Three forms of energy flux associated with the flow of plasma are considered, namely (*a*) gravitational, (*b*) kinetic, (*c*) enthalpy. Since the hole regions are those associated with the out-flow of the solar wind, it is to these regions that the analysis will be applied in the first instance. The model of the atmosphere taken for this analysis is that based on observations of the white light corona by Munro & Jackson (1977), together with the observation of the high speed solar wind flux at 1 AU reported by Hundhausen (1977). Munro & Jackson's observations gave fairly directly the electron density distribution and the geometrical form of a polar coronal hole in the range between 2 and 5 solar radii. When taken with the measured particle flux in the solar wind, and assuming conservation of particle flux, these data yielded an estimate of the solar wind velocity between 2 and 5 solar radii. With this information, the energy flux in the three components may be calculated. In the lower part of the atmosphere, one of the models for the transition zone already discussed may be taken to be valid. Here, the most important component is the enthalpy flux required to provide for the heating of the out-flowing atmosphere. This is about one-tenth of the conducted and radiation fluxes. At 2 solar radii, the energy flux required to overcome gravity becomes greatest and then as 5 solar radii is approached the kinetic energy flux becomes the largest. The total energy requirement to provide for the needs of the solar wind is about 7×10^5 erg $cm^{-2} s^{-1}$. It should be noted, however, that the kinetic energy component, which is the largest, depends on the cube of the measured particle flux at 1 AU, so that quite a small error in this measurement makes a large difference to the energy needs. Another point to come out of this analysis is that the majority of the source energy is required to be available to provide the wind with mechanical energy (gravitational and kinetic) above 2 solar radii. Thus whatever the mechanism of accelerating the solar wind it requires to be effective over a height range above 2 solar radii and to suffer relatively little dissipation at lower heights (on the assumption that it originates in the convective zone below the solar surface).

Since most of the solar wind arises from hole regions and since cloud regions occupy a greater fraction of the solar surface, the energy flux requirements of the solar wind from cloud regions are negligible in comparison. Thus it is possible to draw up an energy flux budget comparing the relative needs of the two regions. This is presented in table 1, and takes account only of the energy fluxes crossing the boundaries of the regions. It is clear from this table that the energy requirements of these two regions are quite different, with the hole regions requiring about twice as much energy as cloud regions. Such a difference must have important implications for the energy source and its modes of transfer and interaction with the atmosphere.

Table 1. The energy requirements of coronal hole and coronal cloud regions

energy component	energy, hole regions / $erg\ cm^{-2}\ s^{-1}$	energy, cloud regions / $erg\ cm^{-2}\ s^{-1}$
thermal conduction at lower boundary	$< 10^3$	$< 10^3$
thermal conduction at upper boundary	unknown	negligible
radiation loss	3×10^5 to 7×10^5	3×10^5 to 7×10^5
enthalpy flux	$< 10^5$	negligible
gravitational and kinetic	7×10^5	negligible

5. Acceleration of the solar wind

Two physical mechanisms have been suggested for the acceleration of the solar wind. These are (*a*) the action of a thermal pressure gradient and (*b*) the deposition of momentum flux carried by Alfvén waves. In reality, both probably contribute but one will dominate. In this section the implications of each being the dominant mechanism will be investigated in turn by adopting a somewhat simple-minded approach. It is hoped in this way to identify some of the essential physics without the confusion of secondary considerations. However, there are dangers in this approach and its value can only be judged by making comparison with the results of more detailed calculations. For these, reference may be made to the work of Hollweg (1978), Holzer (1977) and Jaques (1977).

If thermal pressure is the accelerating mechanism, then the pressure balance equation may be written

$$GM_{\odot} m_{\mathrm{H}} n/r^2 + m_{\mathrm{H}} nv\, \mathrm{d}v/\mathrm{d}r + \mathrm{d}(2nkT)/\mathrm{d}r = 0,$$

where the terms relate respectively to the gravitational force, the inertial reaction to acceleration and the divergence of the thermal pressure; T is the average of the electron and positive ion temperatures; m_{H} is the mass of a hydrogen atom and it is assumed that the electron and proton densities are equal to n; v is the solar wind flow velocity. Both n and v are taken from the model of the solar wind due to Munro & Jackson (1977) already discussed. Solutions, which depend on the initial value chosen for T, are shown in figure 2. If too small values are chosen for T at $r = 2R_{\odot}$ then negative values of T arise. By taking the minimum solution that does not lead to negative values in the range covered, it is possible to calculate the conducted thermal flux due to the temperature gradient at $r = 2R_{\odot}$. This turns out to be 2×10^6 erg $cm^{-2}\ s^{-1}$ and is an additional energy requirement of a model that depends on a thermal pressure gradient to accelerate the solar wind. This acceleration mechanism also appears to imply a need for temperatures in the outer corona in excess of 3 MK.

The other possibility is that the solar wind is accelerated directly by the action of Alfvén waves which, because of the decreasing density and magnetic field above $2R_{\odot}$, suffer a gradual change in propagation velocity and hence deposit momentum in the atmosphere. In their interaction with the medium through which they propagate it is assumed that the waves remain as pure Alfvén waves with equal average energy in their velocity and magnetic components and that they are not accompanied by any plasma compression effects. A solution of the three conservation equations of energy, momentum and mass in an isothermal atmosphere and with the simplification described has been obtained by McWhirter & Kopp (1979). The energy balance equation contains the divergences of the fluxes of gravitational energy, kinetic energy and the work done by Alfvén waves. Radiation and enthalpy flux are shown to be negligible and thermal conduction is zero since the temperature gradient is taken to be zero.

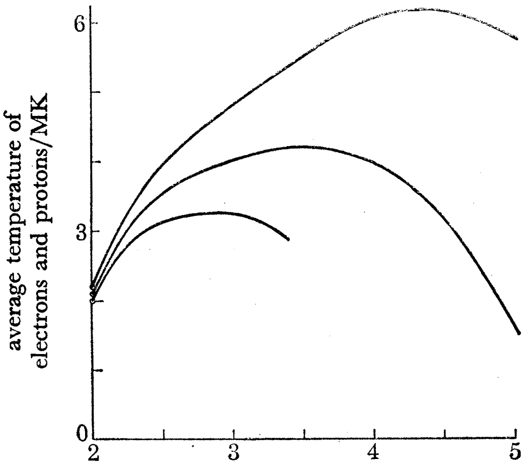

FIGURE 2. Coronal temperature profiles required to accelerate the solar wind, corresponding to about 10^{14} protons $cm^{-2}\ s^{-1}$ at the solar surface ($r/R_\odot = 1$) at the base of a coronal hole.

The momentum balance equation contains terms for gravity, thermal pressure, solar wind inertia and the Alfvén wave momentum flux. The parameters of the particular solution presented were chosen to give a good fit to Munro & Jackson's model for a hole region. The particular values chosen, which are not necessarily unique, are as follows:

proton flux at $r = R_\odot$	$0.78 \times 10^{14}\ cm^{-2}\ s^{-1}$;
temperature	0.94 MK;
magnetic field at $r = R_\odot$	9G;†
Alfvén wave energy flux at $r = R_\odot$	$10^6\ erg\ cm^{-2}\ s^{-1}$.

Thus for this acceleration mechanism the only energy requirement is that required to provide for the mechanical energy of the solar wind. It is also possible to achieve the required acceleration with a relatively modest coronal temperature. As far as the present considerations are concerned, it clearly presents fewer problems than the mechanism based on therma pressure.

6. Enthalpy

Pneuman & Kopp (1978) have pointed out that, when associated with a down-flow of material, enthalpy flux is an effective mechanism of transferring energy from the corona to the lower transition zone where it can be radiated. They derive a model atmosphere by balancing the divergence of the enthalpy flux and the radiation loss in an atmosphere in hydrostatic

† 1 G = 10^{-4} T.

equilibrium. This may also be done in a way analogous to the simpler approximation adopted by McWhirter *et al.* (1975), thus:

$$\mathrm{d}(nv5kT)/\mathrm{d}h = n^2 A_R T^{-\frac{1}{2}},$$

where the radiation power loss function has been approximated by $P_{rad} = A_R T^{-\frac{1}{2}}$ erg cm³ s⁻¹. Suppose constant pressure in the transition zone so that $nT = \langle nT \rangle$ cm⁻³ K and a particle down-flow $= \phi = nv$ cm⁻² s⁻¹ assumed constant over the full depth of the transition zone. Then on integrating:

$$T^{\frac{7}{2}} - T_0^{\frac{7}{2}} = \tfrac{7}{10} \langle nT \rangle^2 A_R h / k\phi.$$

This may be compared with the expression found by McWhirter *et al.* on balancing the divergence of the conducted flux and radiation loss and quoted earlier. With appropriate choice of values for the parameters, the equations become hardly distinguishable. This is the same result as found by Pneuman & Kopp, who also took account of the varying area factor of the supergranulation network. The similarity in these solutions means that in order that there should be a total energy balance between radiation loss and enthalpy flux, the average density of the transition zone must follow a law closely similar to that found for conduction–radiation balance, i.e. the mean pressure, $\langle nT \rangle$, must lie in the range 4×10^{14} to 10^{15} cm⁻³ K, so that the radiation should correspond with the range of uncertainty of the observed value. The particle flux that gives an enthalpy flux of 3×10^5 erg cm⁻² s⁻¹ is 4×10^{14} cm⁻² s⁻¹. This is similar to the value of 7×10^{14} cm⁻² s⁻¹ found by Pneuman & Kopp to give a model closely similar to that of Gabriel (1976), which is also based on a balance of thermal conduction and radiation loss.

A difficulty with Pneuman & Kopp's model is that they assume that thermal conduction is negligible. By extending the analysis given above, it may be shown that the condition for enthalpy flux to exceed thermal conduction is that

$$\phi^2 > \kappa \langle nT \rangle^2 A_R / (5k)^2 T,$$

where κ is the coefficient of thermal conduction already defined. Thus if this condition is to be met by a transition zone that (*a*) has sufficient density to radiate the observed flux and (*b*) extends down to 10^4 K, then the particle flux, ϕ, must exceed 1.6×10^{15} cm⁻² s⁻¹. However, such a particle flux carries too much enthalpy flux for the atmosphere to radiate. Thus it is possible to conclude that if enthalpy flux does contribute to the energy balance of the transition zone, it cannot exceed the conducted flux in that part lying lower than about 10^5 K. This requirement is relaxed if the particle flux, ϕ, is not constant over the full depth of the transition zone.

With a model of this kind, where enthalpy flux plays a significant role, the additional constraint of conservation of matter is important. A down-flow must be balanced by a corresponding up-flow which in hole regions must in addition provide for the needs of the solar wind. Pneuman & Kopp suggest that the up-flow is provided by the spicules. Since they are composed of cool material, there is no significant enthalpy flux associated with them.

7. Conclusion

From the considerations discussed in this paper, it is possible to draw the following conclusions.

(*a*) Since the spectral lines from the transition zones of hole and cloud regions have similar intensities and since they account for most of the radiation, the radiated power losses from the two regions are about equal. The simple conclusion to draw is that the transition zones have the same structure, but it should be noted that a combination of lower average density and greater depth (smaller dT/dr) gives the same power loss. However, a smaller thermal gradient means a smaller conducted flux and hence for the same power loss more energy deposited by some other mechanism such as direct deposition of wave energy.

(*b*) The analysis has shown that the energy required to accelerate the solar wind is comparable with or greater than the radiated energy. It is concluded from this that the nett primary wave-energy flux through the top of the chromosphere into hole regions is at least twice that into c.c. regions. The individual contributions making up the budget are given in table 1.

(*c*) It is shown that the energy required to maintain the thermal structure of a model atmosphere, that is necessary to accelerate the wind by thermal pressure, in the presence thermal conduction is a large additional component that is not present if the acceleration is by the divergence of the Alfvén wave momentum flux.

(*d*) Whatever mechanism of acceleration applies, it is necessary that the energy be transported to heights above 2 solar radii without significant dissipation in the intervening region.

(*e*) If a fraction of the heat flux from the corona is carried to the transition zone by enthalpy, then unless the particle flux varies with height the majority of the heat flux in the region below about 10^5 K must be carried by conduction for energy balance with radiation.

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Discussion

D. B. Beard (*Blackett Laboratory, Imperial College, London, U.K.*). The best information on the solar wind between 2 and 10 solar radii from the centre of the Sun comes from observations of the Thomson scattering of sunlight by electrons comprising the *K* component of the solar corona. Interpretations of the solar corona in the interval 2–10 solar radii distant from the Sun lead directly to a first-hand knowledge of the accelerating force on the solar wind. The dependence of the force on solar distance suggests that both thermal pressure and momentum transfer from Alfvén waves contribute to the acceleration, the relative importance of each being dependent on solar distance.

The F component due to sunlight scattered by interplanetary dust is independent of solar activity and constant in time. If due account is taken of the loss due to evaporation near the Sun, the contribution to the total coronal intensity of the F component is readily ascertained. What is left is the K component. The function $(K_1/\rho^3)\exp(K_2/\rho)$ fits the observations as a function of elongation, ρ, precisely when K_1 and K_2 are fitted to the observations and/or the measured electron density near the Earth. This amounts to a single parameter fit to a wide range of observational data. This particular elongation dependence will be caused by an electron density of $(N_0/r^2)\exp(W/r)$, where N_0 and W are linearly related to K_1 and K_2. This leads to a velocity dependence of $v_0\exp(-W/r)$ and an accelerating force per particle of mv^2W/r^2. A reasonable temperature profile may be derived which will yield such an accelerating force if, for example, only gravitational and pressure gradients are assumed to act. Nevertheless a bump in the temperature profile appears at the distance where momentum transfer from Alfvén waves might be expected.

The two points that seem to me worth emphasizing are that coronal holes are not the only contribution to the acceleration of the solar wind and that further study and interpretation of the K component of the solar corona will yield direct information about the accelerating forces on the solar wind.

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