1977SoPh...51..159H

AN EXPLANATION OF THE OBSERVED DIFFERENCES BETWEEN CORONAL HOLES AND QUIET CORONAL REGIONS

A. G. HEARN

Sterrekundig Instituut, Utrecht, The Netherlands

(Received 20 January; in revised form 26 April, 1976)

Abstract. The main differences between a coronal hole and quiet coronal regions are explained by a reduction of the thermal conduction coefficient by transverse components of the magnetic field in the transition region of quiet coronal regions.

Calculations of minimum flux coronae show that if the flux of energy heating the corona is maintained constant while the thermal conductivity in the transition region is reduced, the coronal temperature, the pressure in the transition region and the corona, and the temperature gradient in the transition region all increase. At the same time the intensities of lines emitted from the transition region are almost unchanged. Thus all the main spectroscopically observed differences between coronal holes and quiet coronal regions are explained.

The flux of energy heating the corona in both coronal holes and quiet coronal regions is 3.0×10^5 erg cm^{-2} s^{-1}.

The energy lost from coronal holes by the high speed streams in the solar wind is not sufficient to explain the difference in the coronal temperature in coronal holes and quiet coronal regions. The most likely explanation of the high velocity streams in the solar wind associated with coronal holes is that of Durney and Hundhausen.

1. Introduction

Coronal holes are regions where the emission of coronal lines is much lower than from quiet coronal regions. This difference is most striking in the X-ray region, but it is also strong in extreme ultraviolet lines like Mg X and Si XII. On the other hand, the intensities of lines formed in the transition region below 800000 K differ little between quiet coronal regions and coronal holes.

Munroe and Withbroe (1972) have analysed the observations of a large coronal hole taken in the spectral range of 300 to 1400 Å with OSO-4. From these observations they have derived the temperature and pressure distribution with height in both coronal holes and quiet coronal regions. They specify these distributions in terms of three parameters: (1) the pressure in the transition region, with the pressure distribution with height determined from the assumption of hydrostatic equilibrium, (2) the temperature gradient in the transition region specified by a constant conductive flux where the coefficient K of thermal conduction is assumed to vary as $K_0 T^{5/2}$ where T is the temperature and K_0 is 1.1×10^{-6} erg cm^{-1} s^{-1} $\text{deg}^{-7/2}$; and (3) the temperature of the corona which is assumed to be isothermal.

In this way they concluded that the pressure at the transition region in a coronal hole is 3 times less than in a quiet coronal region, that the temperature gradient in the transition region is 9 times lower and that the coronal temperature is some 600000 K lower.

These and other results have been discussed by Withbroe and Gurman (1973).

Copyright © 1977 by D. Reidel Publishing Company, Dordrecht-Holland

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

Most recently observations from Skylab have confirmed the lower temperature gradient in coronal holes (Huber *et al.*, 1975).

Munroe and Withbroe (1972) assume that the thermal conduction coefficient K_0 in the transition region is the same in quiet coronal regions and coronal holes. Consequently they deduce from the different temperature gradients that the conductive flux in the transition region is 9 times lower in coronal holes than in quiet coronal regions. This would imply that much less energy is deposited at the bottom of the transition region of coronal holes, but the observed differences of the chromosphere in coronal holes and quiet coronal regions are not very great and this seems inconsistent with such a large difference in the conductive flux.

The present paper suggests that the flux heating the corona in coronal holes and in quiet coronal regions is about the same, but that the higher coronal temperature in a quiet coronal region results from a reduction of the thermal conduction coefficient in the transition region because the magnetic field lies at an angle to the radial direction. Such an explanation is consistent with investigations of the magnetic field which show that in coronal holes the magnetic field is approximately radial and weak, and that over other large areas of the solar surface the magnetic field has a closed loop configuration (Altschuler *et al.*, 1972; Krieger *et al.*, 1973; Timothy *et al.*, 1975).

Calculations of minimum flux coronae from an earlier paper (Hearn, 1975) have been modified to allow the effect of a reduction in the thermal conduction coefficient in the transition region of a hydrostatic corona to be studied. These calculations in the present paper show if the total flux of energy heating the corona remains the same, a reduction in the thermal conduction coefficient in the transition region not only increases the temperature of the corona, but also increases the pressure and the temperature gradient in the transition region. At the same time the intensities of lines emitted by the transition region are almost unchanged.

Thus the mechanism of changes in the thermal conduction coefficient in the transition region explains all the main differences between coronal holes and quiet coronal regions deduced from observations of X-ray and ultraviolet line intensities.

Noci (1973) and Pneuman (1973) have suggested that the coronal temperature in a coronal hole is lower because of the energy drained from the corona by the increased solar wind, and coronal holes have been shown to be the source of high velocity streams in the solar wind. However the calculations of minimum flux coronae show that the energy lost in this way is not sufficient to explain the observed reduction of the coronal temperature in coronal holes.

2. The Theory of Minimum Flux Coronae

In an earlier paper (Hearn, 1975), the energy losses from a corona by thermal conduction down the transition region, by radiation and by mass loss have been estimated for a corona specified by its base pressure p_0 and its average temperature T_0 for a star of given mass and radius. These calculations show that for a corona with a given base pressure there is an average temperature of the corona for which the energy losses are

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

a minimum. These minimum flux coronae give a monotonic relation between the properties of the corona and the flux of energy needed to heat it. Only if the corona lies on this locus of minimum flux coronae at such a pressure that the energy losses balance the energy input is the corona stable against perturbations in the average temperature.

These earlier calculations of minimum flux coronae show that for the Sun the energy loss through mass loss is not important in the overall energy balance of the solar corona and that the energy loss is dominated by thermal conduction towards the photosphere and by radiation. For such a hydrostatic corona, the expression for the minimum flux coronae is particularly simple.

The energy lost from the corona through thermal conduction towards the photosphere is calculated assuming that all the energy conducted away from the corona is radiated away by the material in the transition region. The derivation assumes also that no mechanical energy is dissipated in the transition region and that conduction of heat from the corona is the only source of energy in the transition region.

In the earlier paper it was assumed that the radiated energy coefficient J_0 was constant in the transition region. A better estimate for J_0 is $6 \times 10^{-17}/T$ erg cm^3 s^{-1} which was also used for estimating the energy loss directly from the corona by radiation.

With this new value for J_0, and with the thermal conduction coefficient K_0 retained explicitly in the expression, the temperature gradient in the transition region is

$$\frac{dT}{dr} = \frac{5.61 \times 10^7 \, p_0}{K_0^{1/2} T^{9/4}} \text{ deg cm}^{-1}, \tag{1}$$

where T is the temperature in the transition region at a distance r, p_0 is the pressure in the transition region and K, the thermal conduction coefficient, is equal to $K_0 T^{5/2}$.

The flux of energy conducted away from the corona is then

$$F_c = 5.61 \times 10^7 K_0^{1/2} p_0 T_0^{1/4} \text{ erg cm}^{-2} \text{ s}^{-1}, \tag{2}$$

where T_0 is the average temperature of the corona. F_c is expressed as a flux of energy measured at the base of the corona.

The energy lost directly from the corona by radiation is also conveniently expressed as a flux F_R of energy measured at the base of the corona. For an isothermal corona in hydrostatic equilibrium, where the pressure scale height is small compared with the radius of the Sun (Hearn, 1975),

$$F_R = \frac{6.50 \times 10^{22}}{g} \frac{p_0^2}{T_0^2} \text{ erg cm}^{-2} \text{ s}^{-1}, \tag{3}$$

where the radiated energy coefficient J_0 is again assumed to be $6 \times 10^{-17}/T$ erg cm^3 s^{-1} and g is the acceleration due to gravity.

The minimum flux coronae are defined by the equation

$$\frac{\partial F}{\partial T_0} = \frac{\partial F_c}{\partial T_0} + \frac{\partial F_R}{\partial T_0} = 0. \tag{4}$$

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

With Equations (2) and (3), Equation (4) gives the relationship between the coronal temperature T_0 and the base pressure p_0,

$$T_0 = \frac{1.25 \times 10^7 \, p_0^{4/9}}{K_0^{2/9} g^{4/9}} \text{deg.} \tag{5}$$

The total flux F of energy heating the corona, equal to $F_c + F_R$, may then be expressed in terms of the base pressure of the corona or of the coronal temperature:

$$F = 3.75 \times 10^9 \, \frac{K_0^{4/9} p_0^{10/9}}{g^{1/9}} \text{ erg cm}^{-2} \text{ s}^{-1}$$

or

$$F = 6.81 \times 10^{-9} \, K_0 g T_0^{5/2} \text{ erg cm}^{-2} \text{ s}^{-1}. \tag{6}$$

For the minimum flux coronae derived in this section and defined by Equations (6), it turns out that the conductive flux F_c is always a fixed fraction 0.89 of the total flux F heating the corona.

Equations (6) show how the base pressure of the corona and the coronal temperature depend on the total flux F heating the corona and the thermal conduction coefficient K_0. The corona is thus completely specified by any two of these four parameters. The temperature gradient at a temperature T in the transition region is then determined from Equation (1) for a corona specified by the base pressure p_0 and the thermal conduction coefficient K_0. In particular Equations (1) and (6) show how the properties of the corona depend on the thermal conduction coefficient K_0 in the transition region.

Finally the effect of changing the thermal conduction coefficient on the intensity of lines emitted from the transition region is required.

The intensity I of a line emitted by the transition region is proportional to the square of the electron density and the volume emitting that line. Since a line is emitted over the same temperature range, the volume emitting the line is inversely proportional to the temperature gradient. With Equation (1) for the temperature gradient, the line intensity

$$I \sim p_0^2 \frac{\mathrm{d}r}{\mathrm{d}T} \sim p_0 K_0^{1/2} \tag{7}$$

since T for a given line is constant.

With the first Equation (6) this may be written as

$$I \sim F^{0.9} K_0^{0.1}. \tag{8}$$

It is this small dependence of the transition region line intensities on the thermal conduction coefficient K_0 that enables the pressure and temperature of the corona to be increased by reducing K_0 without making at the same time significant changes to the intensities of lines emitted by the transition region. Equation (8) also shows that the intensities of the lines emitted by the transition region depend mainly on the total

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

flux of energy heating the corona. This is a consequence of the assumption that the energy conducted down from the corona is radiated away by the transition region.

Equations (6) show that if the total flux F of energy heating the corona is maintained constant, both the pressure p_0 and the temperature T_0 are proportional to $K_0^{-2/5}$. This means that as the thermal conduction coefficient K_0 is reduced by the effect of an inclined magnetic field, the pressure at the base of the corona and the coronal temperature increase linearly with each other. This result may be seen directly from the definition of the coefficient of thermal conduction and Equation (3) for the energy lost from the corona by radiation. If the conductive flux is maintained constant in the transition region and the coefficient of thermal conduction is reduced, the temperature gradient will be increased and this will reduce the volume in the transition region emitting radiation. Since the transition region cannot now radiate all the conductive flux, the pressure in the transition region rises until it does so. The increase in the pressure in the transition region and in the corona increases the energy radiated by the corona. Equation (3) shows that to restore the energy radiated by the corona to its original level the coronal temperature must then increase proportionally with the pressure.

3. Comparison with the Observations

Figure 1 shows the results discussed by Withbroe and Gurman (1973). The coronal temperature and transition region pressure obtained from the three parameter

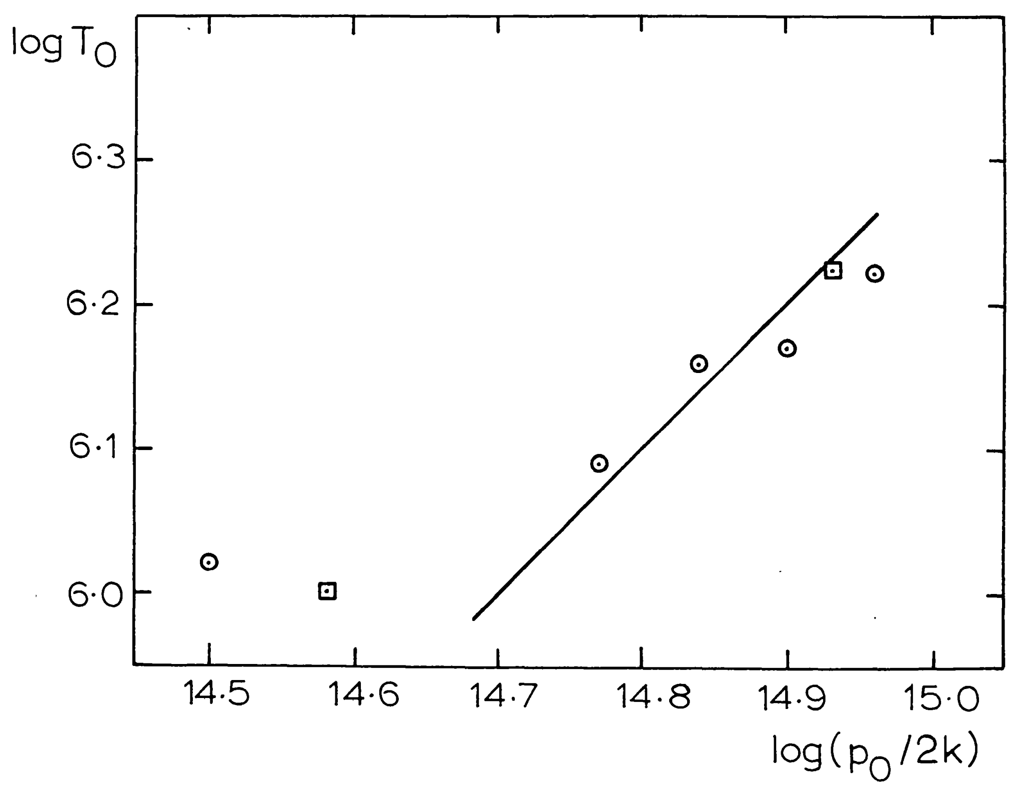

Fig. 1. The coronal temperature is plotted logarithmically against the pressure. The circles are the results of Munro and Withbroe (1972) and the squares are the results of Withbroe and Wang (1972). The continuous line has a slope of unity which is predicted in Section 2 for coronae heated by the same flux of energy but with different thermal conduction coefficients.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

fit to the observations are plotted logarithmically against each other. The circles are the results of Munro and Withbroe (1972) obtained from observations across a coronal hole. The right hand circle is from a typical quiet region outside the coronal hole and the left hand circle is from the centre of the coronal hole. The other circles are from either side of the coronal hole, near the boundary between the hole and the surrounding area. The squares are the results of Withbroe and Wang (1972) for a coronal hole observed near the solar pole and the surrounding area.

The continuous line has a slope of unity which is the relationship predicted in the previous section for coronae heated by the same flux of energy having different thermal conduction coefficients.

Clearly the two points at the lowest pressure which represent the centre of a coronal hole do not fit the line. The most likely explanation is that the pressure has been underestimated in the interpretation of the two observations. If the energy conducted down from the corona is radiated away by the transition region then the intensities of the lines from the transition region give no direct information about the pressure. The pressure must be determined from the intensities of coronal lines after the coronal temperature has been determined from the ratios of coronal line intensities. The intensities of the lines from the transition region then give the conductive flux. Since the coronal lines are so weak in coronal holes the determination of the pressure is difficult. It seems therefore that the discrepancy of the two points in Figure 1 can be explained by a small positive error in the coronal temperature determination leading to a much larger negative error in the pressure.

The Skylab observations (Huber *et al.*, 1975) show that the intensity of the lines from the transition region are 25 to 30% lower in the coronal holes than in the quiet regions. Since these line intensities are proportional to the conductive flux, there must be a small reduction in the total flux heating coronal holes. This is not sufficient though to explain the discrepancy of the two points in Figure 1.

The conductive flux calculated by Munro and Withbroe (1972) and Withbroe and Wang (1972) is really a measure of the temperature gradient in the transition region since they assume a conduction coefficient K equal to $1.1\times10^{-6}\ T^{5/2}$ erg cm^{-1} s^{-1} deg^{-1}. Their conductive flux is therefore $1.1\times10^{-6}T^{5/2}(\mathrm{d}T/\mathrm{d}r)$. This quantity may be calculated from Equation (1) and Equation (6) for the minimum flux coronae obtained by varying the thermal conduction coefficient K_0 when the total flux of energy heating the corona is maintained constant, and it is proportional to $p_0^{9/4}$.

Figure 2 shows $1.1\times10^{-6}T^{5/2}(\mathrm{d}T/\mathrm{d}r)$ derived from the observations plotted logarithmically against the pressure. The continuous line has a slope of $\frac{9}{4}$ predicted from the minimum flux coronae derived in Section 2. The agreement between the theory and the observations is excellent, but this just represents the result that the intensities of the lines from the transition region are determined by the conductive flux, which is all radiated away by the gas in the transition region.

Equation (7) shows that the temperature gradient deduced from a given observed line intensity from the transition region by Munro and Withbroe (1972) and Withbroe and Wang (1972) is proportional to the square of the pressure p_0 deduced for the

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

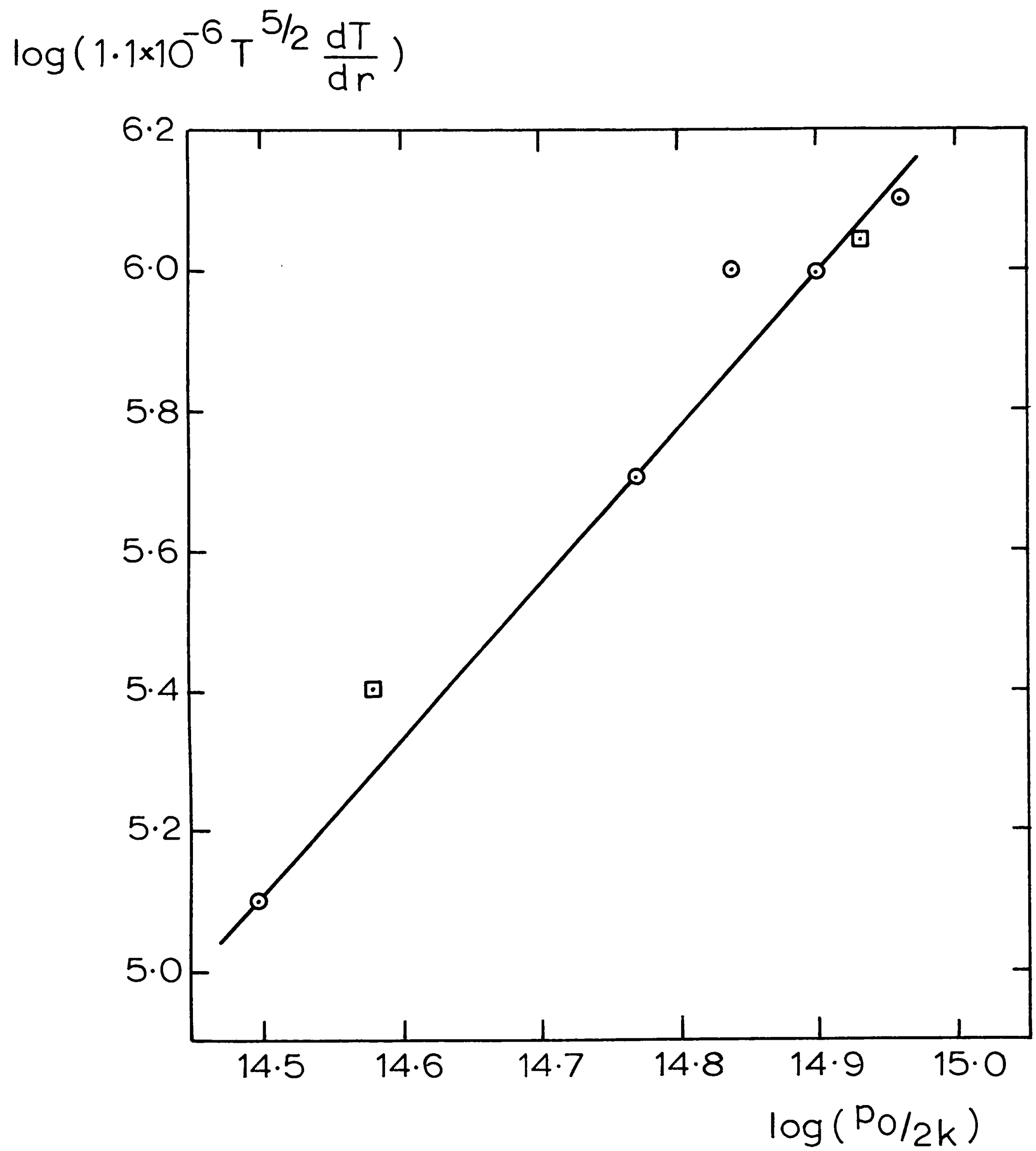

Fig. 2. The quantity $1.1 \times 10^{-6} T^{5/2}(\mathrm{d}T/\mathrm{d}r)$ is plotted logarithmically against the base pressure of the corona. The circles are the results of Munro and Withbroe (1972) and the squares are the results of Withbroe and Wang (1972). These authors denote this quantity as the conductive flux. The continuous line has a slope of $\frac{9}{4}$ which is predicted in Section 3 for coronae heated by the same flux of energy but with different thermal conduction coefficients.

transition region. Thus if the pressure is wrong, the temperature gradient will be in error proportional to $p_0^{8/4}$. The error in the pressure therefore will move the point in Figure 2 almost parallel to the theoretical curve with a slope of $\frac{9}{4}$. This explains how a point can lie away from the theoretical curve in Figure 1 and yet be in good agreement with the theory in Figure 2.

If one assumes from Figure 1 that the conditions in a coronal hole are defined by $\log(p_0/2k)$ of 14.7 and that under these conditions the thermal conduction coefficient K_0 is not modified by the magnetic field and equals 1.1×10^{-6} erg cm^{-1} s^{-1} deg$^{-7/2}$, then Equation (6) shows that the total flux heating the coronae represented by the line drawn in Figure 1 is 3.0×10^5 erg cm^{-2} s^{-1}.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

This means also that the base coronal pressure in a coronal hole is barely a factor of 2 less than in a quiet coronal region. Since the temperature gradient in the transition region is proportional to $p_0^{9/4}$, the temperature gradient in a coronal hole is about 5 times less than in a quiet coronal region.

Measurements made with Skylab (Huber *et al.*, 1975) suggest a factor 6 between these gradients.

Equation (6) shows that the pressure in the corona depends on $K_0^{-2/5}$ if the flux F is constant. A factor 2 increase in the pressure requires then a reduction by a factor of 5.5 in the thermal conduction coefficient K_0. If the magnetic field lies at an angle ϕ to the radial direction and thermal conduction transverse to the magnetic field is negligible, then the thermal conductivity is modified by a factor $\cos^2 \phi$ (Hundhausen, 1972, p. 68). The difference between a coronal hole and a quiet coronal region can therefore be explained by a magnetic field that is radial in coronal holes and at an angle of 65° to the radial direction in quiet coronal regions. This seems quite consistent with interpretations of the magnetic field (Altschuler *et al.*, 1972; Krieger *et al.*, 1973; Timothy *et al.*, 1975).

4. Coronal Holes and the Solar Wind

Krieger *et al.* (1973) and Neupert and Pizzo (1974) have compared X-ray observations of the Sun and satellite measurements of the solar wind at the Earth's orbit and concluded that coronal holes are the source of the high velocity streams in the solar wind. Satellite observations of these high velocity streams have been reviewed by Hundhausen (1972, p. 122). For example, measurements of Vela 3 show the wind speed increasing from 335 km s^{-1} up to 500 km s^{-1}, while the density increased initially by a factor of 3, but then was followed by unusually low densities for the main period of the observed high speed stream.

Noci (1973) and Pneuman (1973) have suggested that the coronal temperature in coronal holes is lower because of the extra energy drained from the corona by the solar wind. The mass loss from the Sun by an average solar wind of $1.4 \times 10^{-14}\ M_\odot$ yr^{-1} corresponds to an energy flux at the photosphere of only 10% of the conductive flux deduced from the interpretation of coronal holes in the present paper. The observations of high velocity streams suggest that the energy loss from coronal holes may be from 2 to 5 times greater than from the average solar wind. The calculations of minimum flux coronae show that the coronal temperature increases only as $F^{2/5}$ (Equation (6)). So that even if the energy loss by the solar wind from coronal holes was 10 times greater than for the average corona and hence comparable with the conductive flux the coronal temperature would only be reduced by a factor of $2^{2/5}$ or by only 30%. Consequently it appears that the observed energy losses in the high speed streams of the solar wind are not sufficient to explain the low coronal temperature of coronal holes.

The calculations of minimum flux coronae in the earlier paper (Hearn, 1975) show that the base pressure of the corona and the coronal temperature are not

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

independent parameters. Each is completely specified by the flux of energy heating the corona. Similarly in the minimum flux coronae discussed in the present paper, each is completely specified by the flux of energy heating the corona and the thermal conduction coefficient K_0. For these coronae Equations (6) show that if the flux heating the corona is changed, the change in the base pressure is much more rapid than the change in the coronal temperature.

Thus calculations which treat the base pressure and coronal temperature as independent variables can give results that are completely artificial. A calculation which studies a change in the energy balance of the corona keeping the base pressure of the corona constant will thus seriously overestimate the effect of the change on the coronal temperature.

The most likely explanation of the high velocity streams seems to be that put forward by Durney and Hundhausen (1974). They point out that a reduction in the density at the bottom of a conductively maintained solar wind gives an increased expansion speed throughout interplanetary space, although their calculations have not removed the long standing discrepancy between the observed properties of the solar wind at the Earth's orbit and the theory.

5. Conclusions

Previously, the difference in the coronal temperature of coronal holes and quiet coronal regions has been explained by processes which reduce the temperature of the quiet coronal region to that observed in a coronal hole. In the present paper it is suggested that the coronal temperature of quiet coronal regions is higher than in coronal holes because the thermal conduction coefficient in the transition region of a quiet coronal region is reduced by transverse components of the magnetic field.

Calculations of the minimum flux coronae show that if the total energy heating the corona is kept constant and the thermal conductivity in the transition region is reduced, then the temperature of the corona, the pressure of the transition region and the corona and the temperature gradient in the transition region all increase. At the same time the intensities of the lines emitted by the transition region are barely altered. Thus all the main differences between coronal holes and quiet coronal regions deduced from X-ray and ultraviolet measurements can be explained by this mechanism of changes in the thermal conductivity in the transition region.

The calculations of minimum flux coronae show also that the energy lost from coronal holes through high speed streams in the solar wind is not sufficient to explain the observed differences between the coronal temperatures in coronal holes and quiet coronal regions. The most likely explanation of the high speed streams in the solar wind is the suggestion by Durney and Hundhausen (1974) that a reduction in the density at the bottom of a conductivity maintained solar wind will increase the velocity of expansion in interplanetary space.

Coronal holes and quiet coronal regions can both be explained by a flux of energy of 3.0×10^5 erg cm^{-2} s^{-1} heating the corona of which 2.7×10^5 erg cm^{-2} s^{-1} is

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1977SoPh...51..159H

removed by thermal conduction down the transition region towards the photosphere.

A reduction by a factor of 5.5 in the thermal conduction coefficient is required to turn a coronal hole into a quiet coronal region.

Acknowledgements

This work was stimulated by a discussion of the problems of coronal holes with Dr A. H. Gabriel and Dr Carole Jordan, Appleton Laboratory.

I am very grateful to Dr C. Zwaan for many suggestions for improving the presentation of this paper.

References

Altschuler, M. D., Trotter, D. E., and Orrall, F. Q.: 1972, *Solar Phys.* **26**, 354.
Durney, B. R. and Hundhausen, A. J.: 1974, *J. Geophys. Res.* **79**, 3711.
Hearn, A. G.: 1975, *Astron. Astrophys.* **40**, 355.
Huber, M. C. E., Foukal, P. V., Noyes, R. W., Reeves, E. M., Schmahl, E. J., Timothy, J. G., Vernazza, J. E., and Withbroe, G. L.: 1975, *Astrophys. J.* **194**, L115.
Hundhausen, A. J.: 1972, *Coronal Expansion and Solar Wind*, Springer Verlag, Berlin.
Krieger, A. S., Timothy, A. F., and Roelof, E. C.: 1973, *Solar Phys.* **29**, 505.
Munro, R. H. and Withbroe, G. L.: 1972, *Astrophys. J.* **176**, 511.
Neupert, W. M. and Pizzo, V.: 1974, *J. Geophys. Res.* **79**, 3701.
Noci, G.: 1973, *Solar Phys.* **28**, 403.
Pneuman, G. W.: 1973, *Solar Phys.* **28**, 247.
Timothy, A. F., Krieger, A. S., and Vaiana, G. S.: 1975, *Solar Phys.* **42**, 135.
Withbroe, G. L. and Gurman, J. B.: 1973, *Astrophys. J.* **183**, 279.
Withbroe, G. L. and Wang, Y.: 1972, *Solar Phys.* **27**, 394.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System