THE LARGE-SCALE STRUCTURE OF THE CORONA

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The solar corona serves as a prototype of the outer atmospheres of all cool stars. Because of its nearness we can study this prototype in more detail than any other example. Considerable progress has been made recently in understanding how the large scale structure of the solar corona controls the genesis of the solar wind and the distribution of slow and fast wind streams throughout the three-dimensional space surrounding the sun. In this review we will discuss some of the progress made in this field during the last few years. We will emphasize the observational data and the inferences that can be made more or less directly from them. T. Holzer will discuss the theoretical aspects of stellar wind acceleration in another paper in this symposium.

The large scale structures of the solar corona consist essentially of three kinds: streamers, active regions and coronal holes. Figure 1 is a familiar photograph of the solar corona, obtained in white light at the total eclipse of 30 June 1973 by the High Altitude Observatory. The streamers are the petal-like structures extending out from the black lunar limb. They taper to narrow radial spikes that have been traced out as far as 10-12 solar radii (Keller, 1979). Daily measurements of the white light corona at the Mauna Loa Observatory (Hundhausen *et al.*, 1979) and the Pic-du-Midi

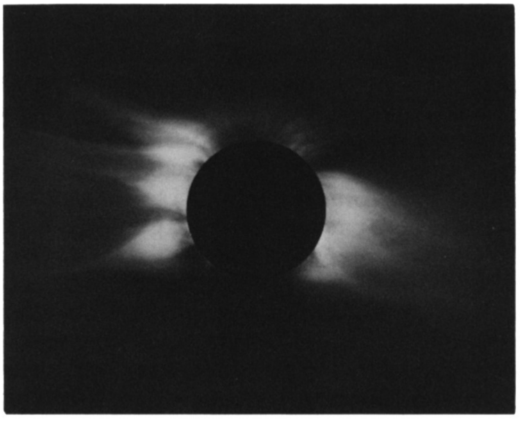

Fig. 1. The visible corona at the total eclipse of June 30, 1973. Reprinted with permission from HAO.

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Observatory (Dollfus *et al.*, 1977) since 1965 show that the streamers are fan-shaped structures that may extend 120° in solar longitude. We see them in various perspectives at the solar limb.

Streamers are of two types. A developing active region in the low solar corona will be enveloped in a streamer with approximately cylindrical or elliptical cross-section (Bohlin, 1970). In contrast, solar filaments (which are cool, ribbon-like structures in the low corona) are enveloped by a fan-shaped *helmet* streamer, such as the one in the northeast quadrant of Figure 1. Streamers are essentially related to active regions and their long-lived remnants (the prominences) and follow the same latitudinal distribution. Thus, at solar minimum the streamers are confined to the solar equatorial regions, while at solar maximum the helmet streamers fill in the high latitudes to give the solar corona at eclipse an approximately circularly-symmetrical appearance. These variations with the sunspot cycle have been known for many decades.

The white light of the streamer is photospheric light scattered from free coronal electrons. Photometry and polarimetry of eclipse photographs, such as Figure 1, yield electron density distributions in the streamers and their surroundings. The streamers turn out to have electron densities only two or three times larger than their surroundings (Newkirk, 1967).

At the north pole of the sun (see Figure 1), the corona is essentially missing. Such regions are called coronal holes and we will describe their physical properties in greater detail, further on in the article.

Figure 2 is an X-ray photograph of the corona obtained by the American Science and Engineering Company. The wavelength region is approximately 40-60 Å. Active regions appear as bright, intense knots in which tight loops can be resolved. The quiet corona consists mainly of coronal arches or in some places, unresolved fuzzy structures. The black polar cap and north-south lane is a huge coronal hole.

Fig. 2. Coronal structure in X-rays (40-60 Å). Reprinted with permission from the American Science and Engineering Company.

The structures we see in the corona are thought to outline coronal magnetic fields. Direct measurements of coronal magnetic fields, by means of the Zeeman effect or gyrosynchroton radiation, have given so far only crude estimates of field strength and little information on the field topology. Therefore, solar astronomers have developed a more indirect method for calculating coronal fields. Figure 3 compares white light structures at the total eclipse of 1966 with extrapolations of the photospheric magnetic field computed by Altschuler (1974). To calculate the coronal magnetic field Altschuler assumed that the coronal shell between the photosphere and some fictitious "source surface" (placed arbitrarily at about 2 solar radii), contains no electrical currents. The magnetic field therefore is a potential field which can be calculated from global measurements of the line-of-sight component of the photospheric magnetic field. The comparison between field and structures in Figure 2 is fairly good although there are clearly some discrepancies. This method of coronal field calculation has been extended by several investigators but without significant improvement in the match between observations and calculations.

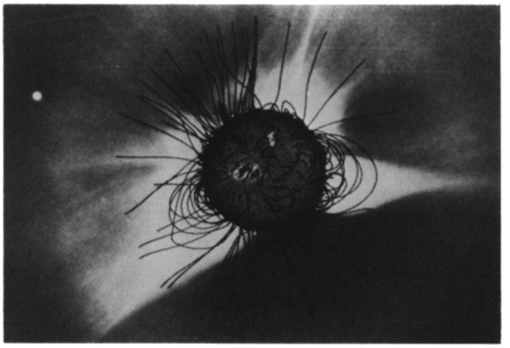

Fig. 3. Comparison of white light structures and calculated magnetic field. Reprinted with permission from Altschuler, 1974.

As shown in Figures 1 and 2, coronal holes are essentially regions of low brightness in both white light and X-rays, a fact which immediately implies that they are low density regions of the corona. This conclusion was first reached by the Harvard investigators (Munro and Withbroe, 1972) who analyzed EUV observations of the corona made on Orbiting Solar Observatory 4. Munro and Withbroe found that the electron pressure in a coronal hole was approximately three times smaller than in its surroundings. Moreover, the electron temperature was approximately 1 million degrees instead of the "normal" 2 million degrees. The physical origin of holes began to emerge with the observation by Krieger *et al.* (1973) that the recurrence of a coronal hole coincided with the reappearance of a stable high-speed wind stream observed near earth. The existence of such streams in the wind, with speeds up to 700 km/s, had been known since the flight of Mariner II in 1962 but the location on the solar surface where these streams originate, was unknown until the work of Krieger *et al.* A succession of large, stable coronal holes was observed during the Skylab mission and it was possible to establish a strong correlation between the recurrence of these holes and associated high speed wind streams (Bohlin, 1977). The association is better than 80%, which means that nearly all the high-speed wind we observe near earth arises in the holes. Figure 4 displays this association (Sheeley *et al.*, 1978). The left panel shows the recurrence of large coronal holes within 40° of the solar equator from 1973 through 1977. The middle panel shows the associated variations of solar wind

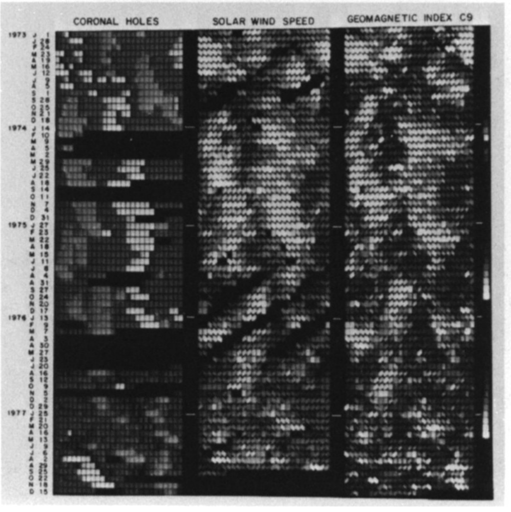

Fig. 4. Correlation of wind speed at 1 AU, coronal hole appearance, and geomagnetic activity. Reprinted with permission from Sheeley and Harvey, 1978.

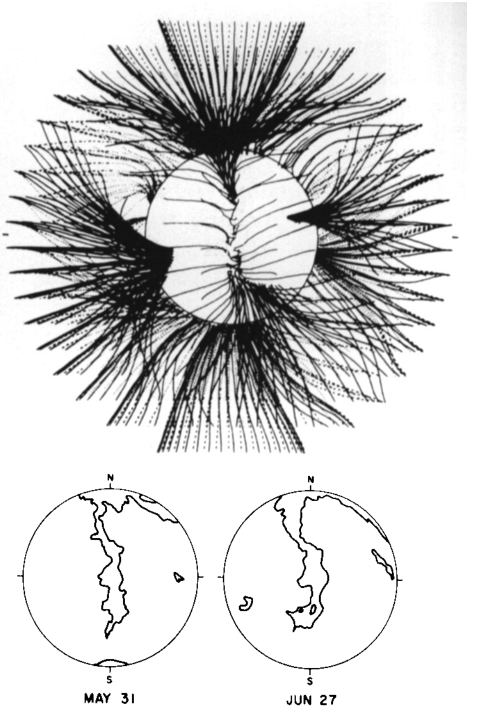

Fig. 5. Open magnetic fields rooted in coronal holes. Reprinted with permission from Levine *et al.*, 1977.

speed near the earth and the right panel, the variation of the geomagnetic index, C9. Beginning in late 1973 and extending through 1974 to mid-1975, two large coronal holes dominated the coronal structure and two associated high-speed wind streams dominated the solar wind. These associations show that *coronal structure is the dominant factor in controlling the speed and distribution in space of the high speed wind.*

The low density of the holes is a consequence of the expansion of coronal material into space. Because of the high electrical conductivity of the coronal gas, such expansion can occur only along magnetic field lines that stretch far out into interplanetary space. Figure 5 shows the coronal magnetic fields, as calculated with the potential field assumption, at the time that the X-ray photograph in Figure 2 was taken (Levine *et al.*, 1977). All magnetic field lines that loop back to the sun within a solar radius have been suppressed in this diagram, leaving only the "open" field lines. These originate primarily in coronal holes.

Notice that the field lines diverge rapidly with height at the north pole of the sun. The magnetic field forms a "nozzle" through which coronal gas expands. As shown by Kopp and Holzer (1976), this field line geometry is an essential aspect of the expansion of the corona and the birth of the solar wind. The divergence of the field lines requires that more energy be deposited in the corona to accelerate the wind to a given speed. If this energy is available, however, the acceleration takes place and a remarkable reduction in height of the sonic point of the wind occurs.

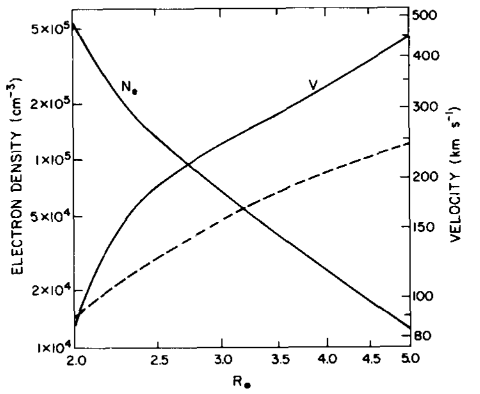

Fig. 6. Velocity and density distributions in a coronal hole. Reprinted with permission from Munro and Jackson, 1977.

The High Altitude Observatory operated a coronagraph on Skylab that produce time-sequences of photographs much like Figure 1. From these white-light photographs, Munro and Jackson (1977) were able to derive an empirical model for the variation of cross-section and electron density as functions of distance along the axis of the coronal hole at the north pole of the sun. Then, assuming a mass flux from the hole that was typical of other large holes nearer to the ecliptic, they were able to determine the profile of wind speed from the equation of continuity. Figure 6 shows their results. The wind accelerates from 80 to 450 km/s within 5 solar radii. Although the maximum temperature in this range is unknown, "reasonable" values are less than 2.5 million degrees, so that the wind speed reaches the sound velocity between 2 and 3 solar radii. Thus, *primary acceleration of the solar wind in coronal holes occurs very close to the sun and is strongly modified by the shape of the magnetic field in that region.*

Spectroscopic studies of the corona (Athay, 1966; Withbroe, 1970) show that most of the energy deposited in closed field regions returns to the chromosphere a~ a flux of conducted heat and is radiated into space through out the temperature transition zone and upper chromosphere. In comparison, more than 80% of the energy deposited in a coronal hole is carried off as kinetic and gravitational energy in the solar wind (Mariska, 1976; Withbroe and Noyes, 1977). Table 1 compares the energy losses of a hole and a typical closed magnetic field region of the quiet corona. The downward flux of conducted heat is an order of magnitude less in the hole than in the quiet region, although the total amounts of energy are comparable. Thus, nonthermal energy transforms efficiently into the energy of the solar wind. Theorists are challenged to understand how this occurs.

We referred earlier to the changes in large-scale coronal structure throughout the sunspot cycle. Near solar minimum, the solar corona simplifies to a belt of streamers in the equatorial region. At the same time, the polar coronal holes expand to fill large areas with opposite

Table 1. Chromospheric and coronal energy losses

Parameter	Quiet Sun	Coronal hole	Active region
Transition layer pressure (dyn cm^{-2})	$2x10^{-1}$	$7x10^{-2}$	2
Coronal temperature (K, at $r \approx 1.1\ R_{\odot}$)	1.1 to $1.6x10^{6}$	10^{6}	$2.5x10^{6}$
Coronal energy losses (erg cm^{-2} sec^{-1})			
Conduction flux F_c	$2x10^{5}$	$6x10^{4}$	10^{5} to 10^{7}
Radiative flux F_r	10^{5}	10^{4}	$5x10^{6}$
Solar wind flux F_w	$\lesssim 5x10^{4}$	$7x10^{5}$	$(<10^{5})$
Total corona loss $F_c + F_r + F_w$	$3x10^{5}$	$8x10^{5}$	10^{7}
Chromospheric radiative losses (erg $cm^{-2} sec^{-1}$)[a]			
Low chromosphere	$2x10^{6}$	$2x10^{6}$	$\gtrsim 10^{7}$
Middle chromosphere	$2x10^{6}$	$2x10^{6}$	10^{7}
Upper chromosphere	$3x10^{5}$	$3x10^{5}$	$2x10^{6}$
Total chromospheric loss	$4x10^{6}$	$4x10^{6}$	$2x10^{7}$
Solar wind mass loss (g cm^{-2} sec^{-1})	$\lesssim 2x10^{-11}$	$2x10^{-10}$	$(<4x10^{-11})$

[a]Based on Athay's (1976) estimates for the quiet sun. Table reprinted with permission from Withbroe and Noyes, 1977.

magnetic polarity in the northern and southern solar hemispheres. Thus, near solar minimum, the solar corona takes on the appearance of a magnetic dipole whose axis may be tipped with respect to the axis of rotation. A current sheet, extending outward from the belt of coronal streamers, separates opposite magnetic polarities in interplanetary space. According to this picture, due to Hundhausen (1977), the high speed wind we sample in the ecliptic arises as a polar flow at high heliographic latitudes and bends down into the ecliptic plane. As the sun's tipped dipole rotates, the earth sees first the positive and then the negative polarities associated with the opposite magnetic hemispheres of the sun. This picture is intended to represent a state of affairs near solar minimum. Coronal holes begin to appear at mid-latitudes on the rise toward sunspot maximum, however, and as Broussard *et al.* (1978) found, recurrent wind streams correspond to such holes, at latitudes less than 40°. Thus, the polar influences on the wind seems to maximize near solar minimum. The Skylab results show beyond any reasonable doubt that the large scale structure of the corona must control the structure of the solar wind at all phases of the sunspot cycle.

Pneuman (1979) has carried Hundhausen's picture a step further toward a quantitative description. He constructed a coronal magnetic field, consistent with the photospheric field observed over a particular rotation during Skylab. Assuming reasonable values for the temperature and electron density at the base of the corona, he then calculated the three-dimensional distribution of wind speed. Figure 7a shows the wind speed at 1 AU in all directions. Near the ecliptic a belt of low wind speed coincides with the extrapolation of the belt of coronal streamers. The belt is warped somewhat however, and as the sun rotates, the earth is exposed to the higher wind speeds, poleward of the belt. The lower panel of the figure (7b) compares speed and magnetic polarity measurements in the two predominant wind streams with Pneuman's calculations. The positions and widths of the streams agree moderately well with the measurements. However, like all recent solar wind models, Pneuman's predicts velocities too small by at least a factor of two. Theorists are now exploring the reasons for this disparity, using the more recent information on physical conditions within coronal holes. However, Pneuman's basic result is that coronal structure controls the structure of the wind, at least near solar minimum.

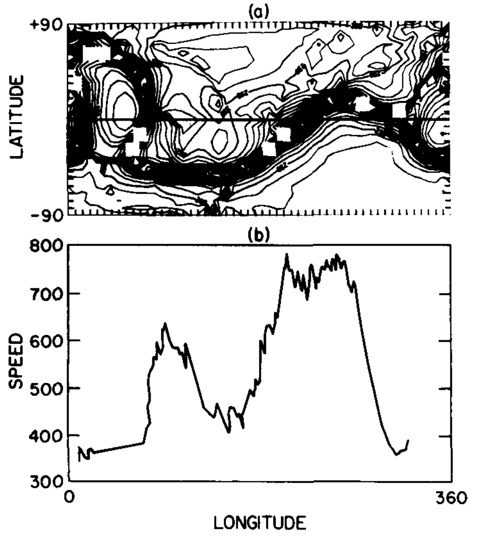

Fig. 7. (a) Predicted wind speed contours at 1 AU. (b) Observed wind streams in ecliptic at 1 AU. Reprinted with permission from Pneuman, 1979.

The Skylab results have emphasized the high speed wind that coincides with a coronal hole. We are still not sure, however, where the *slow* wind originates in the corona. There are several possibilities that need to be explored. As is evident in Figure 7, the edges of coronal holes, where the magnetic field lines diverge more rapidly, produce slow wind. However, not all the open field lines in the corona originate in holes. Some originate within active regions and possibly also other locations within the quiet corona that have not developed into holes. These are possibly sites of slow wind generation. It does not appear likely that the coronal streamers are the sources of slow winds; however, Pneuman and Kopp (1970) calculated the velocity profile along the axis and outside of a model coronal streamer. The slow wind arises between streamers, not at their cores. Inter-streamer regions may or may not be associated with coronal holes.

While we still have a great deal to learn about the physical basis of the origin of the wind, both slow and fast, we have made considerable progress in the last five years. The essential relationship, that coronal structure controls wind structure, is now on a firm observational basis.

References

Altschuler, M. D.: 1974, in G. Newkirk (ed.), *Coronal Disturbances* IAU Symposium #57, Reidel Publishing Co., Dordrecht, p. 3.
Athay, R. G.: 1966, *Astrophys. J.* 145, 784.
Athay, R. G.: 1976, *The Solar Chromosphere and Corona: Quiet Sun,* Reidel Publishing Co., Dordrecht, p. 504.
Bohlin, J. D.: 1970, *Solar Phys.* 13, 153.
Bohlin, J. D.: 1977, in J. B. Zirker (ed.), *Coronal Holes and High Speed Wind Streams,* Colorado Associated University Press, Boulder, p. 27.
Broussard, R. M., Sheeley, N. R., Tousey, R. and Underwood, J. H.: 1978, *Solar Phys.* 56, 161.
Dollfus, A. and Martres, J.-J.: 1977, *Solar Phys.* 53, 449.
Hundhausen, A. J.: 1977, in J. B. Zirker (ed.), *Coronal Holes and High Speed Wind Streams,* Colorado Associated University Press, Boulder, p. 225.
Hundhausen, A. F., Hansen, R. T., Hansen, S. F.: 1979, "Coronal Evolution during Sunspot Cycle 20: K Coronameter Data," (in preparation).
Keller, C. F.: 1979 (private communication).
Kopp, R. A. and Holzer, T. E.: 1976, *Solar Phys.* 49, 43.
Krieger, A. S., Timothy, A. F. and Roelof, E. C.: 1973, *Solar Phys.* 29, 505.
Levine, R. H., Altschuler, M. D., Harvey, J. W. and Jackson, B. V.: 1977, *Astrophys. J.* 215, 636.
Mariska, J. T.: 1976, *Bul. Am. Astron. Soc.* 8, 338.
Munro, R. H. and Jackson, B. V.: 1977, *Astrophys. J.* 213, 874.
Munro, R. H. and Withbroe, G. L.: 1972, *Astrophys. J.* 176, 511.
Newkirk, G.: 1967, *Ann. Rev. Astron. Astrophys.* 5, 213.
Pneuman, G. W.: 1979, *Astrophys. J.* (in press).
Pneuman, G. W. and Kopp, R. A.: 1970, *Solar Phys.* 13, 176.
Sheeley, N. R. and Harvey, J. W.: 1978, *Solar Phys.* 59, 159.
Withbroe, G. L.: 1970, *Solar Phys.* 11, 42.
Withbroe, G. L. and Noyes, R. W.: 1977, *Ann. Rev. Astron. Astrophys.* 15, 363.