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I. THE QUIET SUN

Large-scale solar magnetic fields, coronal holes and high-speed solar wind streams

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The connection between geomagnetic disturbances recurring with the 27 day synodic solar rotation period and streams of plasma emitted from particular regions on the Sun (so-called M-regions) has been one of the long-standing problems of solar-terrestrial physics. The 'plasma streams' have been identified with long-lived streams of fast solar wind, imbedded in unipolar magnetic 'sectors', for more than a decade. The solar sources of these streams have been identified unequivocally only within the past few years as large-scale coronal regions of open, diverging magnetic fields and abnormally low particle densities, observed as 'coronal holes'. The temporal evolution of holes and streams seems to reflect the evolution of the large-scale solar magnetic fields; the observed spatial pattern of holes suggests a grand three-dimensional structure of solar wind flow and interplanetary magnetic fields organized by a near-equatorial neutral sheet. The conclusion that much of the solar wind comes from coronal holes implies several important modifications of our ideas regarding the physical origins of the solar wind and any theoretical models of solar wind formation.

1. Introduction

The tendency for geomagnetic activity to recur with the 27 day rotation period of the Sun (as viewed from the Earth) was recognized as early as the 1850s. This effect, illustrated by the display of modern data in figure 1, was later found to be strongest during the declining phase of each individual 11 year sunspot cycle. Such recurrent geomagnetic activity has long been attributed (e.g. by Chapman & Bartels 1940) to long-lived 'particle streams' emitted from some localized solar source and swept past the Earth every 27 days by solar rotation. The search for the solar sources, named M-regions by Bartels in the 1930s, of these streams has remained a topic of continued interest for the past 50 years.

The recognition in the late 1950s that the Sun was a continuous, rather than a sporadic, emitter of particles (or to be more precise, a highly ionized plasma) led to only minor revisions of these notions. Early observations of the continuously expanding solar corona, or solar wind, revealed the existence of streams of abnormally fast solar wind that recurred with the solar rotation period. These streams were correlated with recurrent geomagnetic activity in the early 1960s. The 'high-speed streams' in the solar wind were also found to be embedded in regions of nearly unipolar magnetic fields (i.e. where the field pointed predominantly toward or away from the Sun), the now well known interplanetary 'magnetic sectors'. Although this latter relation led to suggestions that the high-speed solar wind originated from open magnetic structures in the corona, centred above unipolar regions observed in the photospheric magnetic field (see, for example, Billings & Roberts 1964), no association of M-regions with readily

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observable solar features was attained until the early 1970s. The study of solar images obtained in the radiation characteristic of the corona itself, soft X-rays and emission lines in the ultra-violet, led to the identification of coronal holes, features now known with considerable certainty to be the sources of high-speed streams. The phenomenological foundations of this association and its implications for our physical understanding of the coronal expansion have been reviewed by us elsewhere (Hundhausen 1977; Holzer 1979). In the limited space available here some of the highlights of these discussions will be presented.

FIGURE 1. The daily magnetic character index, C9, for the years 1973–5. The time coordinate is broken into 27 day rows so that any event recurring with the 27 day rotation period of the Sun will fall along a vertical line. The values of C9 are printed in characters whose size and boldness increases with value. Thus 27 day recurrent geomagnetic activity will appear as a dark, vertical strip on this display.

2. The phenomenological identification of coronal holes as M-regions

Coronal holes are perhaps most conspicuous and best known as sharply defined regions of extremely low X-ray or coronal u.v. emission. They are also observable by other techniques and appear to have been first recognized (and named) as regions of low white-light (photo-spheric radiation scattered by free electrons in the corona) intensity observed at total solar eclipses (Waldmeier 1957). Their physical characteristics are summarized in figure 2. The low scattered light from coronal holes clearly indicates a low density; low emission is consistent with low density or low temperature (or some combination of these). The appearance of

coronal holes in X-rays suggests that they are open magnetic structures in which the magnetic field lines diverge rapidly to 'fill in' the space over neighbouring closed magnetic regions before becoming lost (or at least invisible) in interplanetary space. This impression is strengthened by approximate models of the extension of observed photospheric magnetic fields into the corona (see, for example, Levine 1977; Pneuman *et al.* 1979). These basic properties are readily understandable if holes are regarded as magnetically open 'channels' from which coronal material expands to form the solar wind. Such a region would be expected to be less dense and cooler (Pneuman 1973) than surrounding, magnetically closed coronal regions in which the plasma is constrained to be nearly static. These channels should occur, again as observed, over the centres of regions in the solar photosphere where a net magnetic flux imbalance is present over a large area. The magnetic field reaching into interplanetary space from one such channel should have a predominant magnetic polarity and hence give rise to an interplanetary sector.
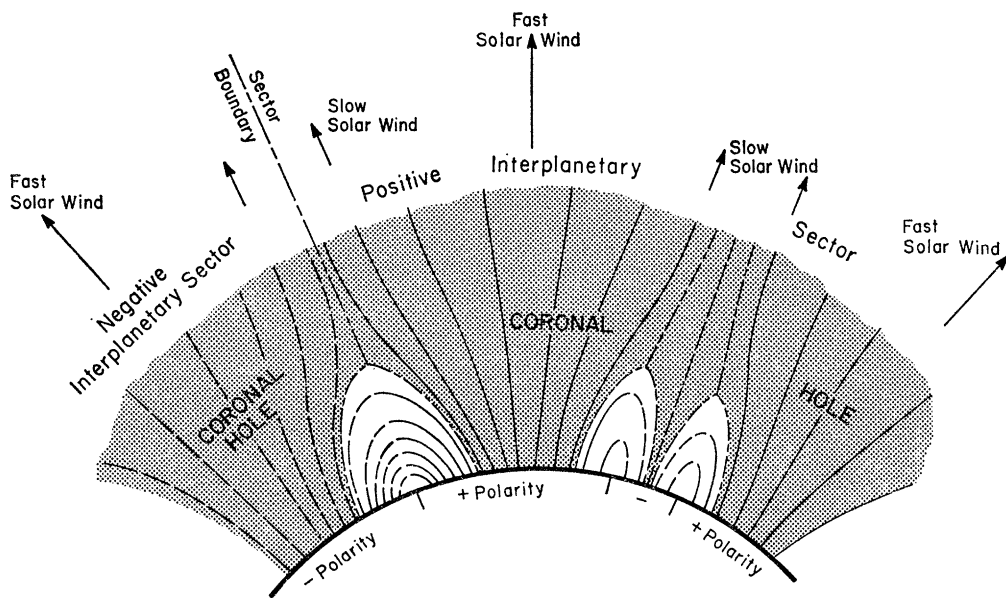

FIGURE 2. A sketch of the magnetic field and density structure of a coronal hole. Coronal holes occur in regions that are magnetically open to interplanetary space. Their low densities make them appear dark in any radiation emitted (X-rays, ultraviolet, or forbidden lines in the visible) or scattered (white light) from the corona.

The evidence that observed coronal holes are indeed the sources of high-speed solar wind streams stems from comparisons of coronal and solar wind data such as those shown in figure 3. The right-hand frame on this figure is a map of the polarization brightness product of the white-light corona (observed at the Mauna Loa Observatory) at half a solar radius above the limb of the Sun, as a function of solar latitude and longitude (the latter conventionally defined by using a single solar rotation rate applicable to near-equatorial regions of the Sun). As the polarization brightness is directly related to electron density, coronal holes can be identified in these data as regions of very low brightness. On figure 3 such regions have been shaded with + or − symbols indicating the dominant magnetic polarity of the underlying photosphere (+ indicates magnetic fields pointing outward from the Sun, − indicates fields pointing toward the Sun). The left-hand frame of the figure shows the speed of the solar wind observed

at the orbit of Earth (courtesy of S. J. Bame and colleagues, Los Alamos Scientific Laboratory) by Imp spacecraft, plotted as a function of the source longitude estimated by assuming radial propagation from the Sun at the speed (constant for each fluid element) observed at 1 AU. Superposed on the speed–longitude curve is the interplanetary magnetic polarity (or sector pattern), again indicated by $+$ or $-$ symbols. These observed solar wind properties apply along the path in solar latitude and longitude traced by the Earth at the time of observation, as indicated on the figure.
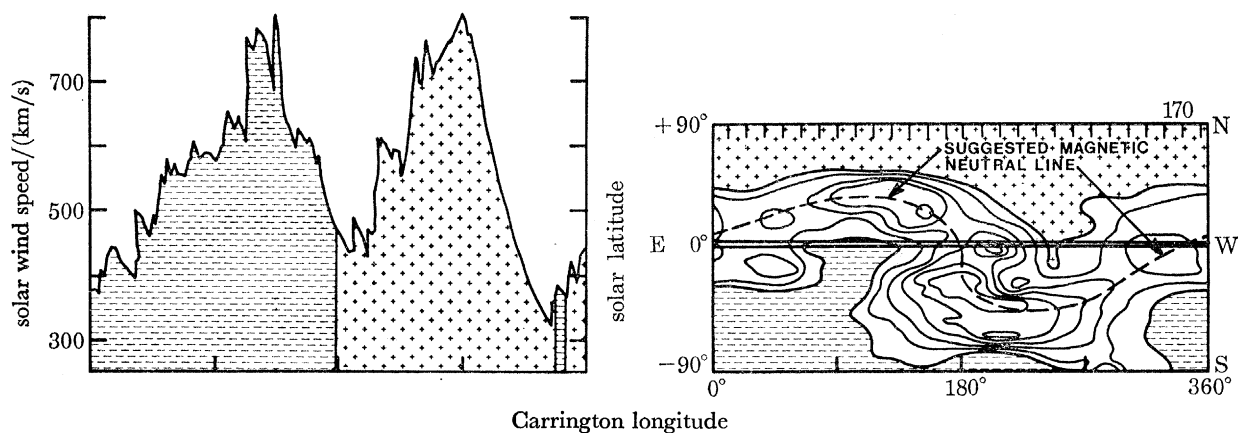

FIGURE 3. A comparison of coronal and solar wind structures observed during Carrington Solar Rotation 1616, in mid-1974. The right-hand frame is a synoptic map of the coronal polarization brightness product observed at the Mauna Loa Observatory (courtesy R. T. Hansen and S. F. Hansen). Low brightness regions identified as coronal holes are shaded with a pattern of $+$ or $-$ signs indicating the dominant magnetic polarity of the underlying photosphere. The left-hand frame shows the solar wind speed observed on Imp spacecraft (courtesy S. J. Bame and colleagues) at the orbit of Earth, plotted as a function of the source longitude estimated by constant speed, radial flow extrapolation back to the Sun. The interplanetary magnetic polarity (inferred by Svalgaard 1976) is superposed on this plot by using the same $+$ or $-$ symbols. A suggested location of the interplanetary magnetic neutral sheet, separating hemispheres of opposite magnetic polarity, has been drawn above the brightest parts of the corona on the right-hand frame.

Coronal holes are most often seen on such maps in the polar regions of the Sun and occasionally near the solar equator. The latter type of hole is most often an extension of the polar cap holes, as seen near 90° longitude (extending from the south polar hole) and near 270° longitude (extending from the north polar hole) on figure 3. The observation of a near-equatorial hole is almost always accompanied by the observation of a stream of high-speed solar wind at the corresponding source longitude. Further, the solar wind stream shows the same predominant magnetic polarity as the coronal hole. This coincidence between holes and streams extends to their slow temporal evolution; the growth, maturity and decay of a near-equatorial hole is regularly accompanied by the appearance, recurrence and disappearance of a high-speed wind stream of the proper magnetic polarity in the ecliptic plane.

Such observations from the Skylab mission (1973–4) and the following years in the declining phase of the past solar cycle have been extensively studied (Krieger *et al.* 1973; Neupert & Pizzo 1974; Bell & Noci 1976; Hansen *et al.* 1976; Hundhausen *et al.* 1976; Nolte *et al.* 1976; Sheeley *et al.* 1976; Wagner 1976; Hundhausen 1977) and leave little room for doubt that coronal holes and the interplanetary stream–sector structure are physically related. This same epoch also saw the development of several sequences of recurrent geomagnetic disturbances (shown in figure 1), with a pair of remarkably stable sequences persisting through 1974–5.

The three-dimensional relation between coronal holes observed in emission from the low corona, scattered light from the outer corona, the solar wind speed and magnetic structure observed in the ecliptic plane near the orbit of Earth, and geomagnetic activity detected at the surface of the Earth is illustrated for one solar rotation from this epoch, Carrington Rotation 1610, in figure 4. Thus the classical phenomenon of recurrent geomagnetic activity was present at this time and it seems clear that the solar origins of this activity, coronal holes, are the long-sought M-regions.

In addition to solving this old puzzle, recent studies of coronal holes have led to a consider-able advance in our understanding of the three-dimensional structure of the solar wind. Coronal holes appear to occur in a coherent global pattern on the Sun; in particular we have already

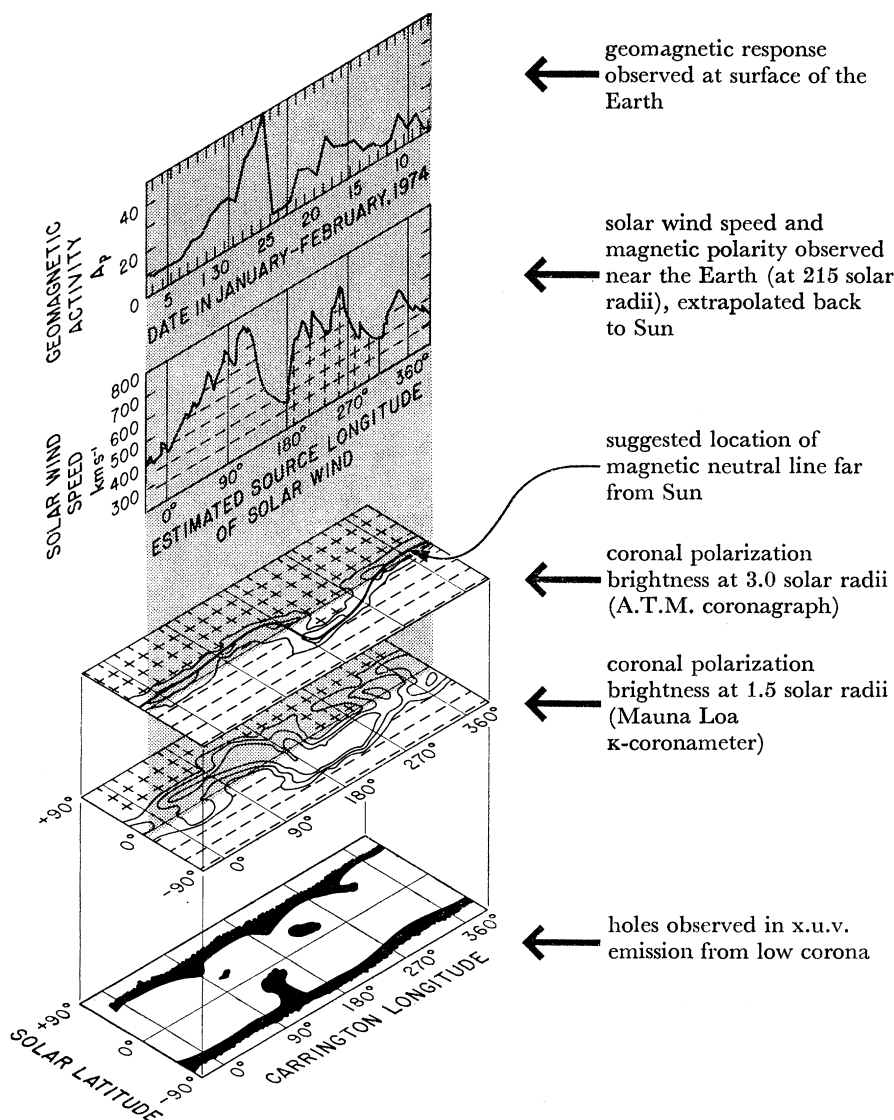FIGURE 4. The three-dimensional relations among coronal hole observations at different heights in the solar atmosphere, the solar wind structure observed in the ecliptic plane, and the resulting geomagnetic activity for Carrington solar rotation 1610, in early 1974. In this figure the magnetic polarity is indicated by + signs for magnetic fields pointing out of the Sun and − signs for fields pointing into the Sun.

noted their tendency to become 'connected' to the polar hole of the same dominant magnetic polarity. The resulting coronal pattern, with a belt of bright, presumably closed magnetic fields encircling the Sun near its equator and separating holes (both polar caps and their equatorward extensions), has been interpreted as evidence for a near-equatorial neutral sheet extending outward from the Sun, separating hemispheres of opposite magnetic polarity in the outer corona and interplanetary space. This simple concept of a three-dimensional magnetic structure has emerged from several related pieces of evidence in the past 5 years: the strong heliographic latitude dependence of the magnetic sector pattern observed in the ecliptic plane (Rosenberg & Coleman 1969; Schultz 1973; Saito 1975); geometric arguments concerning the combination of 'polar and sector' magnetic fields (Svalgaard *et al.* 1974; Alfvén 1977); and *in situ* magnetometer observations as far as 16° out of the solar equatorial plane (Smith *et al.* 1978). One particular example illustrating the displacement of a neutral sheet from the equatorial location expected for a simple, rotation aligned dipole field of the Sun suggested by coronal observations can be illustrated by using figure 3. In this case single large extensions of each polar cap, separated by *ca.* 180° of longitude, suggest the simplest of possible displacements of an equatorial neutral sheet, an overall tilt. The resulting interplanetary magnetic polarity pattern would then rotate with the Sun to give the observed positive sector where the ecliptic observer is above the neutral sheet, the observed negative sector below the sheet, and sector boundaries where the ecliptic plane intersects the neutral sheet. The two-hole corona also leads to two prominent high-speed solar wind streams and to the pair of recurrent geomagnetic disturbances mentioned above.

It is tempting in the context of this picture to map interplanetary magnetic field lines back to the solar surface within the boundaries of the observed coronal holes. Then field lines that lie a short distance apart on opposite sides of the interplanetary neutral sheet can map to the Sun at locations widely separated by intervening, closed magnetic structures. In particular, interplanetary field lines lying near the solar equator may be rooted in the polar cap holes or their extensions *at fairly large solar latitudes*. Further, the occurrence of high-speed solar wind streams in the ecliptic whenever an extension of a polar cap hole reaches sufficiently close (*ca.* 30° near the base of the corona) to the solar equator suggests that the polar holes are long-lived sources of high-speed solar wind. This suggestion is supported by radio scintillation determinations of the solar wind speeds at high heliographic latitudes (see, for example, Sime & Rickett 1979). All of this evidence leads to the concept of a coronal expansion that is highly structured by the influence of the large-scale magnetic field of the Sun. At times when this magnetic structure is relatively simple, the resulting coronal and interplanetary structure seems to be largely organized by the near-equatorial neutral sheet. This view attributes an important role to the polar cap holes of the Sun as the sources of interplanetary plasma and magnetic fields, even as observed near the solar equator.

The related patterns of temporal evolution for coronal holes and the solar wind stream–sector pattern are of additional interest as indicators of the evolution of the large-scale solar magnetic field. While the streams during the Skylab epoch displayed the expected 27 day recurrence period (Gosling *et al.* 1976), the magnetic sectors observed at Earth recurred with a longer, *ca.* 28.5 day period (Svalgaard & Wilcox 1975). Individual coronal holes tended to remain nearly stationary in the Carrington longitude system, indicating a rotation period close to 27 days. In fact, holes with a considerable north–south extent appeared to resist the shearing expected from the well known differential rotation of the solar atmosphere (Timothy *et al.*

1975). The global distribution of holes during the Skylab study showed an interesting evolutionary pattern. While the individual holes remained fixed in Carrington longitude, the set of holes with a given magnetic polarity grew and decayed systematically to produce an eastward drift on the solar surface. This drift led to the longer recurrence period of the interplanetary sector structure. Within this pattern, the individual holes did not occur randomly, but tended to develop at regular longitude intervals, suggesting a 'modal' pattern in the solar magnetic field. By early 1974 this curious pattern of evolution ceased and the two-hole coronal-structure of figures 4 and 5, along with the associated two-stream, two-sector interplanetary structure, appeared and became stable. This change may be part of a solar cycle evolution of coronal holes related, of course, to the evolution of the large-scale solar magnetic field.
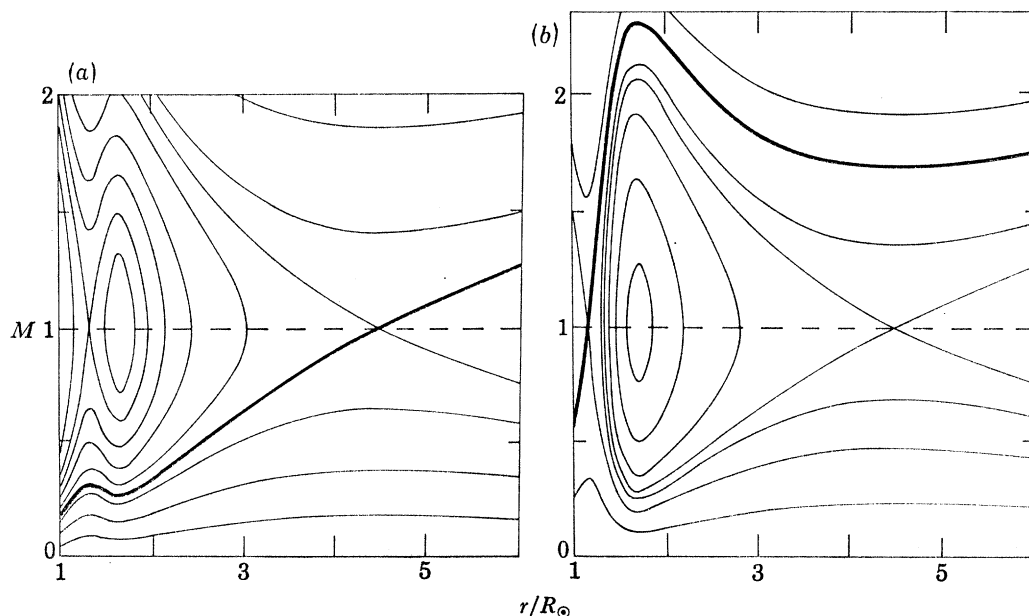

FIGURE 5. Families of solutions of the solar wind equation of motion for polytropic flow ($\alpha = 1.1$), with the Mach number, M (i.e. the ratio of the flow speed to the polytropic sound speed), plotted against the heliocentric radial distance in solar radii. In both cases the radially oriented flow tube diverges more rapidly (near the Sun) than for spherically symmetric flow, with the net enhancement of the flow tube area being a factor of 3 in (a) and a factor of 12 in (b). In each case, three critical points (rather than the usual one critical point) appear: two saddle points and one centre. In the mildly diverging flow tube (a), the solar wind solution passes through the usual (outermost) critical point, whereas in the rapidly diverging flow tube (b), the solar wind solution passes through the innermost critical point, leading to very high flow speeds near the Sun, which result from the large pressure-gradient force associated with the rapid flow tube divergence. It is extremely important to note that the solar wind speed at the orbit of Earth is the same in both (a) and (b). (From Kopp & Holzer (1976).)

3. SOME PHYSICAL IMPLICATIONS

The evidence summarized above for a physical relation between coronal holes and solar wind streams suggests (although it falls short of proving) that much or all of the plasma in such streams emanates from the major open magnetic regions of the corona that are identified as coronal holes. This statement has several implications for the physics of the coronal expansion that raise new problems or intensify old problems for our understanding of solar wind formation.

The first of these problems stems from estimates of the mass flux at the base of a coronal hole implied by this mapping of solar wind streams back to coronal holes. For the steady flow of an ionized hydrogen plasma along a given flow tube, the quantity nuA (where n is the proton or electron density, u the flow speed, and A the cross sectional area of the flow tube) is conserved. We can thus write

$$n_{r_{\rm cor}} u_{r_{\rm cor}} = n_{1\,{\rm AU}} u_{1\,{\rm AU}} A_{1\,{\rm AU}}/A_{r_{\rm cor}},$$

where r is some position in the corona. The observation of solar wind density and speed at 1 AU and an estimate of the ratio $A_{1\,{\rm AU}}/A_{r_{\rm cor}}$ can then be used to estimate the particle flux density in the corona; deduction of $n_{r_{\rm cor}}$ from white-light coronagraph observations allows the expansion speed $u_{r_{\rm cor}}$ to be estimated. For several different examples of correlated streams and coronal holes, with several means of estimating $A_{1\,{\rm AU}}/A_{r_{\rm cor}}$, one obtains

$$n_{r_{\rm cor}} u_{r_{\rm cor}} \approx 10^{14}\ {\rm cm}^{-2}\ {\rm s}^{-1}$$

near the base of the corona ($r \approx r_0$). The use of density values from Munro & Jackson (1976) then gives

$$u_{r_{\rm cor}} \approx 10\text{--}20\ {\rm km\ s}^{-1}.$$

Both of these values are appreciably higher than earlier estimates based on the assumption of a spherically symmetric expansion. The high flow speed in the low corona demands a more rapid acceleration of plasma in the low corona than given by most theoretical models of this process. Similar considerations have led to the realization that even the familiar topology of solutions to the Bernoulli equation changes if the cross sectional area, A_r, of a coronal flow tube increases more rapidly than the $A_r \propto r^2$ law for radial expansion. Kopp & Holzer (1976) have shown (see figure 5) that additional critical points appear and modify the detailed nature of the flow.

Similar arguments can be used to derive the energy flux density, w, at the base of the corona required to produce the observed solar wind streams. The resulting estimates for several actual examples give

$$\langle w \rangle \approx 5 \times 10^5\ {\rm erg\ cm}^{-2}\ {\rm s}^{-1}.\dagger$$

This value is considerably higher than earlier estimates, both because of the large energy fluxes found in solar wind streams during the Skylab and post-Skylab epochs and because of the mapping of these fluxes to a fraction of the area at the base of the corona. Such values imply that the solar wind is the major energy loss mechanism for magnetically open regions of the corona; they pose serious difficulties for theoretical models of the coronal expansion. For example, the long-standing unresolved problem of coronal heating is aggravated by the additional requirements imposed by the large solar wind energy flux from coronal holes. Of course, these requirements on the upward energy flux density from the lower solar atmosphere may be eased somewhat if the mechanical energy flux entering the corona can be focused (by transport across magnetic field lines) toward the centre of coronal holes (by coronal propagation). However, there remains the difficulty that the large mechanical energy flux density required to drive high-speed solar wind streams must be deposited relatively high in the corona (see, for example, Leer & Holzer 1979), and this places rather severe restrictions on the nature of the mechanical flux. If too large a fraction of the mechanical energy were deposited below the sonic point in the coronal expansion, the solar wind mass flux would be increased so much

$$\dagger\ 1\ {\rm erg\ s}^{-1} = 10^{-7}\ {\rm W}.$$

that the solar wind speed at the orbit of Earth (which is related to the ratio of the solar wind energy flux to mass flux) could not attain the speeds observed in high speed streams.

It is clear, then, that the association of coronal holes with high-speed solar wind streams has required us to modify significantly our view of the coronal expansion. It is hoped that the next several years will see the development of good understanding of the physical processes important to the acceleration of the solar wind in coronal holes.

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