CORONAL HOLE FLUX TUBES AND THE PROBLEM OF RELATING INTERPLANETARY AND SOLAR FEATURES

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Abstract. Coronal flux tubes have in general very large divergence, and the properties of their flow vary greatly inside the flux tube. We present here a general description of the evolution and the characteristics of coronal holes and discuss how these characteristics may lead to erroneous associations between interplanetary and solar structures.

Key words: Coronal holes – Solar wind sources

1. A Physical Definition of Coronal Holes

Solar coronal holes were first associated with dark regions in soft X-ray images of the corona or in white-light coronagraph photographs, which allow us to locate and estimate the form and size of the holes. It is also possible to map coronal holes by means of the HeI 10 830 Å chromospheric absorption line and this kind of maps have been extensively used in correlations with interplanetary features. However, all these observational definitions are somehow rough and, in order to include coronal holes in the structural and dynamic descriptions of the solar atmosphere, it is necessary to have a physical definition which emphasizes the very distinctive property of coronal holes. Such a definition would be that a coronal hole is a region in the corona where the magnetic field (and flux) lines are open to the interplanetary space.

2. The Evolution of Coronal Holes Along the Solar Activity Cycle

Coronal holes, like any other solar feature, change with the progress of the activity cycle. During the years of low activity, when a dipole nearly aligned to the solar rotation axis is the dominant magnetic structure, two large coronal holes are present at the heliographic poles of the Sun having tongues extending to lower latitudes and even crossing the equator. In total, polar coronal holes at these times can cover as much as 25% of the solar surface and their life-time is about seven years around the minimum. During the high-activity periods, when the dipolar component of the solar magnetic field is highly inclined with respect to the solar rotation axis and higher order

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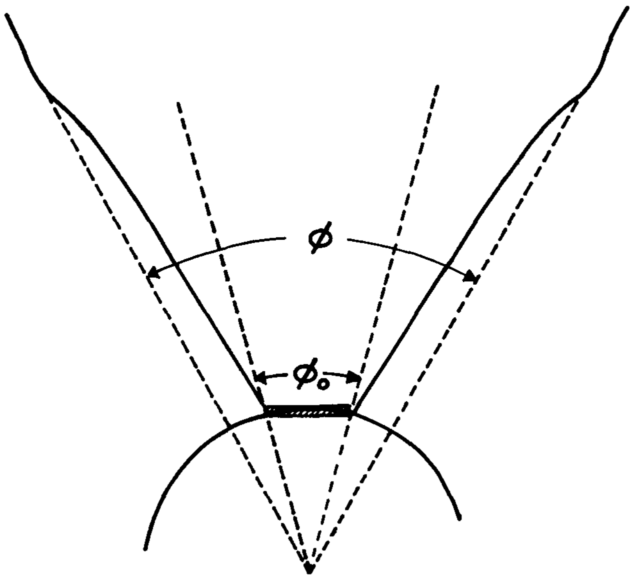

Fig. 1. Greater than radial divergence of a coronal hole.

is highly inclined with respect to the solar rotation axis and higher order multipoles are very important, several small coronal holes appear at low latitudes and the polar holes grow smaller and may even disappear. These low-latitude coronal holes during the maximum of solar activity cover from 1% to 10% of the Sun's surface and last of the order of one solar rotation or a few months, although some of them have been observed to last for a little more than one year.

3. Greater than Radial Expansion of Coronal Hole Flux Tubes

A very important characteristic of coronal holes is that the divergence of their flux tubes is always greater than radial. This means that the angular extension of the flux tube increases with height up to a maximum value where the radial solar wind is established, as shown in Figure 1.

We can compute the total divergence (or expansion) factor of a coronal hole's flux tube by comparing its cross-section area at the height where the expansion becomes radial with the cross-section area it had had if its

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expansion had been radial all the way from the solar surface. Polar coronal holes show a typical total divergence factor of about 4 (Bravo and Mendoza, 1989) and low-latitude holes have total expansion factors between 10 and 100 (Levine et al. 1977a). This should be really obvious because the tube fluxes from the holes, which cover only a fraction of the solar surface at the base of the corona, have to finally cover a whole sphere of solar wind in interplanetary space.

This can be seen clearly on coronameter white light intensity maps as those of the Mauna Loa High Altitude Observatory. Figure 2 shows the MK III K-Coronameter maps for Carrington rotation 1799 at two different heights, 1.3 Rs and 1.7 Rs. We can see how the darkest regions at the poles, associated with coronal holes, grow dramatically in latitude and longitude from 1.3 Rs to 1.7 Rs. Finally, at the source surface, where the supersonic radial expansion of the solar wind is established (between 2 and 3 Rs), the whole Sun will appear as a hole.

As the greater than radial expansion of coronal holes implies that the angular extension of a coronal hole flux tube in interplanetary space is much larger than its extension near the solar surface, the comparison of a latitude-longitude map of interplanetary features with the same kind of map at the solar surface, with the purpose of identifying the solar sources of the wind, is totally misleading. This kind of tracking is only appropriate back to the source surface, where the radial expansion of the plasma is already established. But any radial extrapolation of interplanetary features below the source surface is very dangerous, because in this region the movement of the plasma mostly follows the magnetic field lines which are, in general, strongly curved. So in order to properly relate interplanetary and solar features we need to know the magnetic structure below the source surface. This can be done roughly by means of a potential field model and, actually, this kind of tracking has already been done by Hakamada (1987) to associate solar wind properties obtained from interplanetary scintillation (IPS) (see also a more recent paper, Hakamada and Kojima, 1994).

4. Potential Field Models of the Coronal Magnetic Field

Figure 3 shows several examples of the configuration of the coronal magnetic field below the source surface according to the potential field model approximation. In this approximation, the coronal magnetic field is deduced from measurements of the photospheric field by solving Maxwell's equations assuming that there are no electric currents in the corona and that at the source surface the magnetic field lines are radial. More details on this approach can be found in the early papers by Altshuler and Newkirk (1969) and Shatten et al. (1969), and more recently in Hoeksema and Scherrer

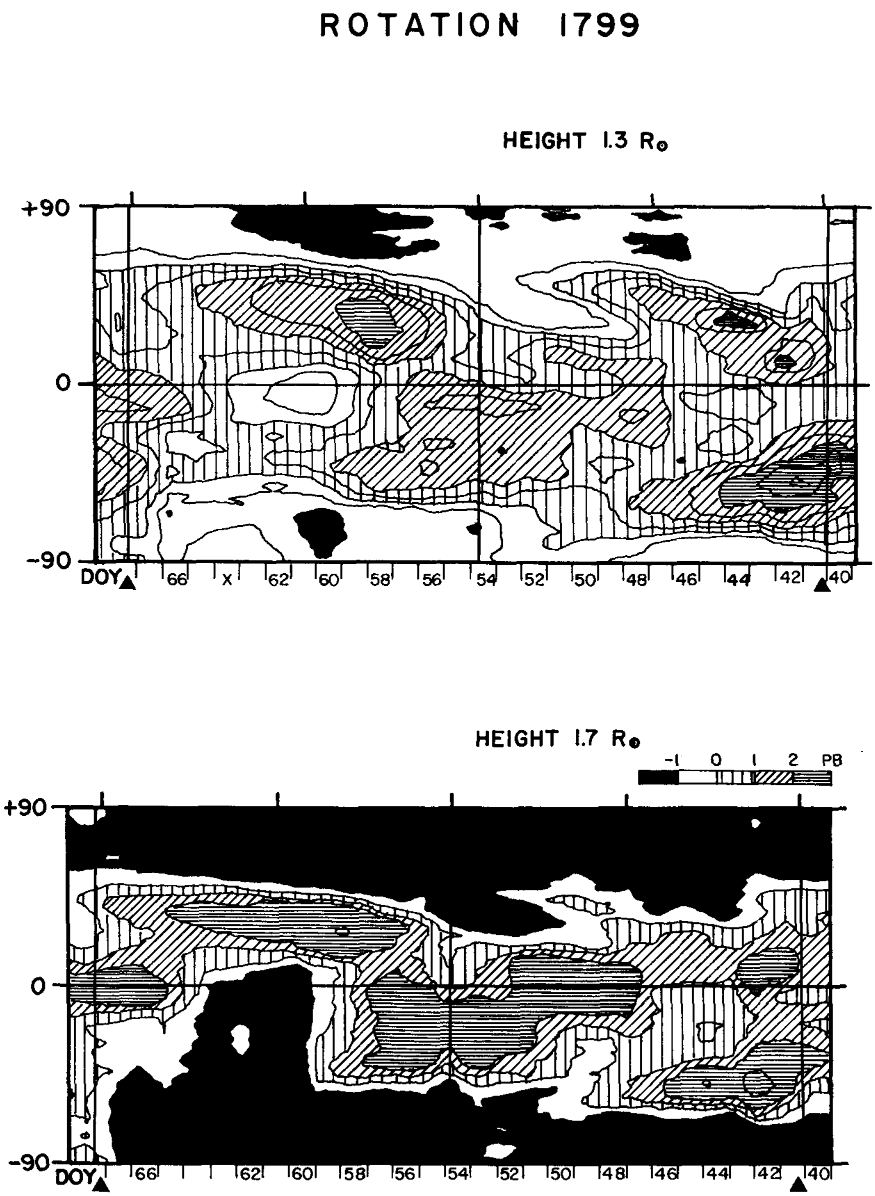

Fig. 2. K-coronameter maps at 1.3 and 1.7 solar radii.

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(1986). An improved version of this method has been developed by Wang and Sheeley (1992).

The potential field model descriptions of the coronal field have been tested against coronal images at the times of total solar eclipses and the general agreement found is very satisfactory. It is interesting to notice the particular case of the coronal field during the 11 July 1991 total solar eclipse (Figure 3c), obtained by Sykora et al. (1994) which corresponds to a time near solar activity maximum. Two small, low-latitude coronal holes can be observed (evidencing the high inclination of the heliomagnetic equator at this time) whose divergences are enormous. In the Figures we have also shown several examples of how different solar sources for the wind are obtained if a radial back-tracking is used below the source surface, instead of following the field lines.

In the case of interplanetary transients, these "hairy-ball" pictures cannot tell the whole story because they represent magnetostatic situations. But the mapping of the field structure before the event and a comparison with the structure after the event might give us some indications of the coronal processes associated with the transient.

5. The Velocity of the Solar Wind from Coronal Holes

The ignorance of the great divergence of the flux from holes has lead to the erroneous idea that coronal holes are the sources of only the high-speed solar wind and that low-speed wind is not coming from holes, but from magnetically closed coronal regions! In fact, it is not physically possible to obtain a coronal hole in stationary conditions which emits exclusively high-speed wind, and this has been clear since the very early (and most ideal) models of the solar wind in a magnetic ambient. As an example of this, we are showing in Figure 4(a) the magnetic field configuration of the corona in Pneuman and Kopp (1971) model which assumes an isothermal corona in a dipolar magnetic field. The topology obtained is roughly the typical structure of the magnetic field around the minimum of activity when the dipole axis almost coincide with the rotational axis of the Sun and two large coronal holes are established at the Sun's poles. This is a meridional view and the three dimensional structure can be obtained by rotating the Figure about its vertical axis; this will show the belt of coronal helmets around the equator and a disk-shaped, equatorial current sheet which extends through interplanetary space. We can see that the open field lines from the coronal hole have, in general, a greater than radial expansion and that any point in interplanetary space is connected with a point at the solar surface inside a hole.

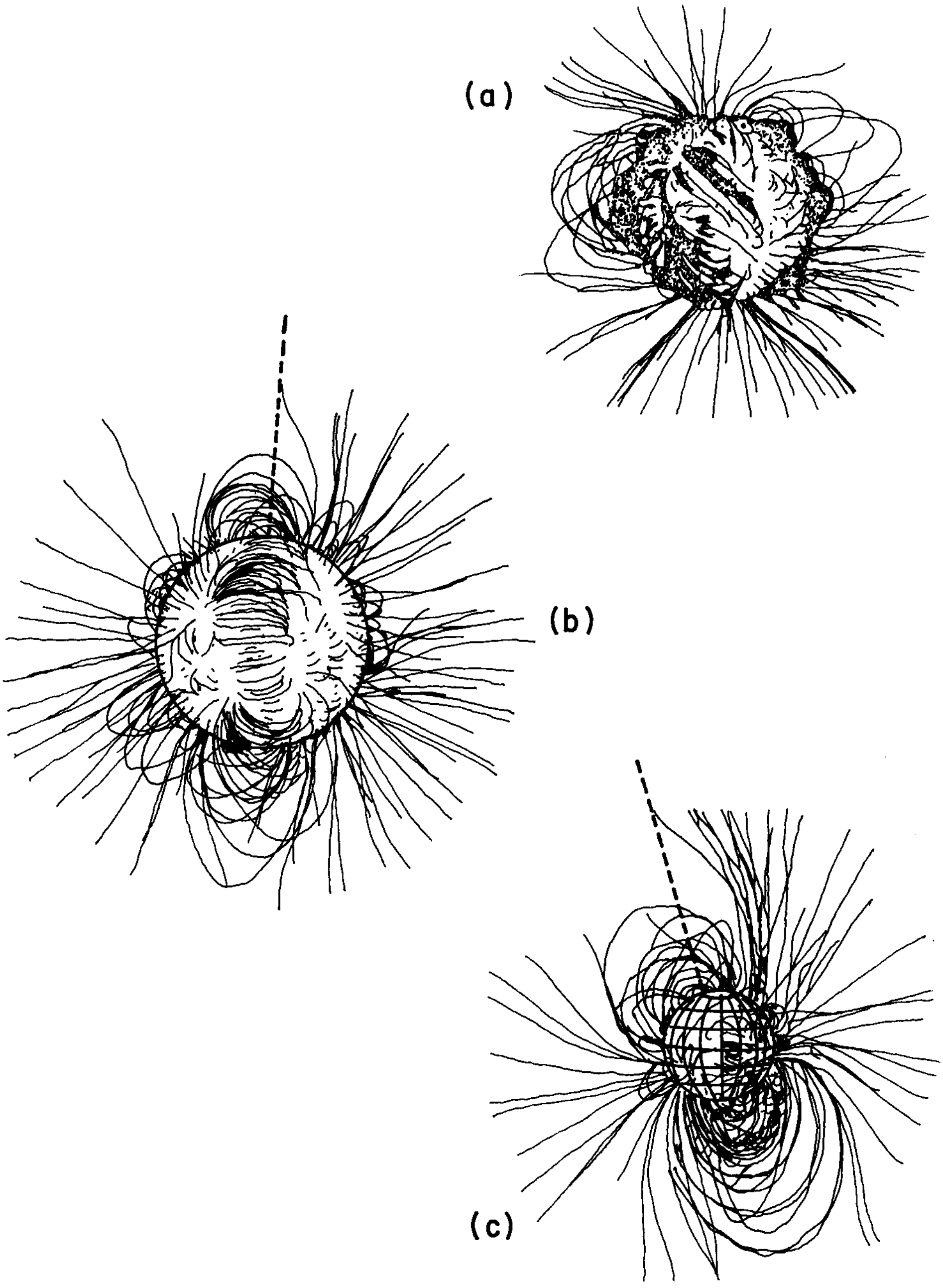

Fig. 3. Examples of coronal magnetic field lines obtained with potential field models at different times: a) Minimum of solar activty (1965); b) Maximum of solar activity (1969); c) 11 July 1991 total solar eclipse.

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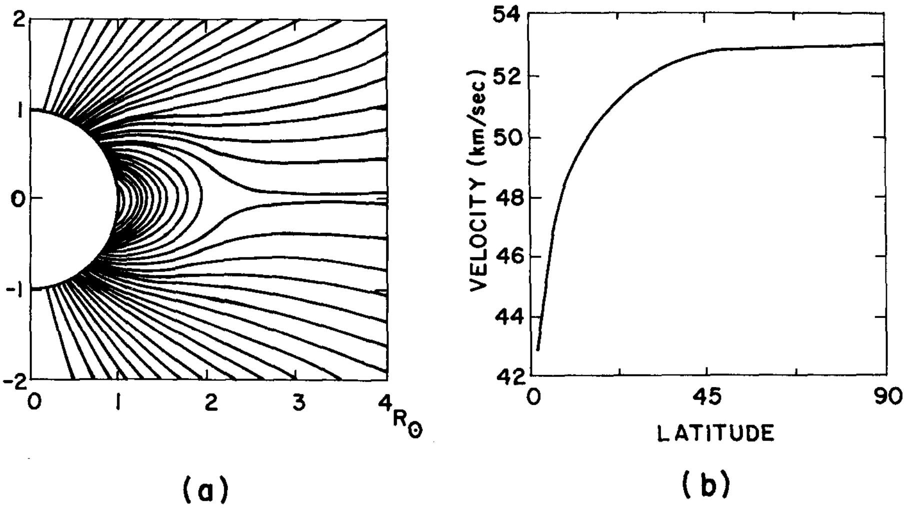

Fig. 4. 4a. Coronal magnetic field lines in the Pneuman and Kopp (1971) model. 4b. Latitudinal velocity profile of the solar wind in the magnetic configuration of 4a.

The solar wind speed for this magnetic topology was obtained by Pneuman (1976) and the latitudinal velocity profile at 5 Rs is shown in Figure 4(b). The conditions for these calculations were very simplistic (see Pneuman, 1973, 1976 for details) and the values obtained are not realistic, but a qualitative exploration of these Figures can give us a general idea of how coronal hole fluxes are. We can see from Figure 4(b) that the velocity in the central region of the flux tube (around 90° latitude) is high and almost latitude independent, but it drops very fast towards the border of the hole (0°). Then high-speed wind, as well as low-speed wind are both emitted from the coronal hole, but from different regions inside the hole. In the case of a polar coronal hole, this variation is observed in interplanetary space as a variation of the solar wind speed with heliospheric latitude. In the case of low-latitude coronal holes, this variation will appear on the ecliptic as a central high-speed stream bordered by narrow slow-wind regions. It is easy to see from Figure 4(a) that a radial tracking of the slow wind back to the Sun's surface will lead to the helmet region, but a correct tracking below the source surface will connect the slow wind with the coronal-hole's outer regions. We want to stress here the fact that in this model the change between high-speed regions and low-speed regions is very sharp, and that the slow wind flows only within a small angular region near the current sheet. This is in agreement with interplanetary observations.

As Pneuman (1976) mentioned, and has been proved by many other modelling efforts, the higher divergence of the magnetic lines at the border of the hole results in correspondingly lower speeds. In fact, it is easy to see from Figure 4(a) that the divergence of the lines is not uniform inside the coronal hole: the divergence is smaller at the centre (where the field lines are more straight) and greater near and at the borders (where the field lines are more curved). This inverse relation between the solar wind speed and the divergence of the lines along which it is coming out from the coronal hole has actually been demonstrated by combining interplanetary observations and potential field model calculations of the coronal field (see for instance Durney and Pneuman, 1975; Levine et al., 1977b; and more recently Wang and Sheeley, 1991).

Although observations have proved that slow wind and high-speed wind are both coming from coronal holes, and coronal hole models show the same, we do not have at present any model which can explain all the differences observed between low- and high-speed winds. We know that the slow wind shows magnetic and plasma characteristics clearly distinct from those of the fast wind, and it is obvious that any simplistic, one-fluid MHD model cannot account for all of them, as they cannot account for the high velocities of the wind, either. Additional ingredients, as, for example, the presence of Alfvén waves, which will make the solar wind from straight lines even faster, will increase the sharpness of the transition between slow and fast wind and may add other characteristics to the slow wind from the highly curved bordering lines. Boundary-layer effects between the "static" plasma of the helmet and the flowing plasma near the borders of the hole might contribute also to the characteristics of the slow wind. It is clear that more effort must be done in the development of more realistic models of coronal hole fluxes in order to be able to explain all the differences observed between the central region wind of high velocity and the low velocity wind at the borders of the hole.

6. A Heliomagnetic Coordinate System

As mentioned in Section 2., the size, shape, location, and life time of the solar wind sources vary along the solar cycle as a consequence of the evolution of the solar magnetic field. This is clearly evidenced in the magnetic field maps at the source surface produced by Hoeksema and Scherrer (1986) where the variation in time of the inclination of the heliospheric neutral line can be observed, as well as the appearance of higher order multipoles at times of high solar activity. This heliospheric neutral line can be interpreted as the intersection of the source surface with a "heliomagnetic equator" that extends in interplanetary space as a heliospheric neutral sheet. If the solar magnetic field were purely a constant dipole changing only its orientation with respect to the solar rotational axis as the activity cycle progresses, the magnetic field and solar wind distributions in interplanetary space as seen from a heliographic reference frame will change dramatically, because, as we discussed before, the solar wind from a coronal hole is not homogeneous. Then spatial differences in the differently inclined heliomagnetic reference frame will appear as temporal changes throughout the activity cycle. The situation is more complicated by the fact that when the heliomagnetic equator is inclined, a fixed point in the heliosphere will sweep different heliomagnetic latitudes and longitudes as the Sun rotates with its 27-day period. So, even in the most simple heliomagnetic structure, the heliographic organization of solar wind data will appear very complex. In the real case, the heliographic picture of the solar wind and the interplanetary magnetic field will be even more complicated because the solar magnetic field is more complex than just a rotating, inclined dipole, and temporal changes of the magnetic field and solar wind also occur in the reference frame of the heliomagnetic equator. Near the maximum of activity we cannot even properly define a heliomagnetic reference frame. But at times of low activity, when an inclined heliomagnetic equator can be more or less well defined, it would be interesting to see how the solar wind data order with respect to the heliospheric neutral sheet. This will be especially interesting in the case of Ulysses's data.

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