THE ORIGIN OF INTERPLANETARY SECTORS

Kenneth H. Schatten
Goddard Space Flight Center
NASA
Greenbelt, MD 20771

1. EARLY CORONAL MAGNETIC MODELS

The coronal magnetic models of Altschuler and Newkirk (1969), Schatten, Wilcox and Ness (1969), and Schatten (1971) that allowed calculations of the coronal magnetic field from the observed photospheric magnetic field shed light on the origin of sectors. Figure 1 from Schatten's (1971) "Current Sheet Model" is a schematic representation of these similar models. There are three distinct regions in these models where different physical phenomena occur. The photosphere, where the magnetic fields are governed by the detailed motions and currents in the plasma is considered a boundary condition for the model. Above the photosphere, the plasma density diminishes very rapidly with only moderate decreases in the magnetic energy density. This results in the middle region where the magnetic energy density is greater than plasma energy density and hence controls the configuration. One may then utilize the force-free condition, $\underline{j} \times \underline{B} = 0$, and in fact make the more restrictive assumption that this region is current free. The magnetic field in this region can be derived from a solution to the Laplace equation.

Substantially farther out in the corona the total magnetic energy density diminishes to a value less than the plasma energy density, and the magnetic field can no longer structure the solar wind flow. The magnetic field has, however, become oriented very much in the radial direction, as suggested by Davis (1965). Thus, before the total magnetic energy density falls below the plasma energy density, a region is reached where the transverse magnetic energy density does so. It is this component of the magnetic field that interacts with the outward flowing plasma. On the "source surface", another boundary condition applies - transverse magnetic fields are transported away from the sun by the radially flowing plasma. Thus the magnetic field passing through the surface boundary is oriented in the radial direction (the 1969 models), serving as a source for the interplanetary magnetic field. In the current sheet model the fields calculated were in a Maxwell-stress equilibrium rather than requiring coronal forces to

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artificially bend the field into a purely radial configuration. The fields were constrained only to be "open" rather than radial. This conformed better to the theoretical MHD treatments of Pneuman and Kopp (1970).

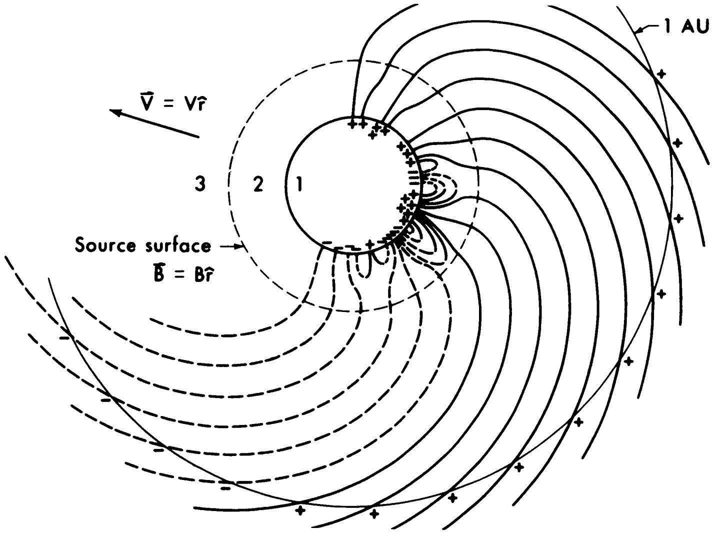

Figure 1. Concepts related to the current sheet model of sector boundaries.

2. CORONAL HOLES

Early Mariner 2 and IMP observations revealed that geomagnetic activity was related to streams of abnormally fast solar wind. The solar source of such streams (particle streams before 1960 or high-speed solar wind streams since) remained an intriguing mystery until recently. An important step in this development was the discovery around 1970 of coronal holes-sharply defined regions of very low emission, in X-ray and ultra-violet images of the sun. The appearance of holes in both X-rays and white light suggests that they are regions of open magnetic field lines that diverge rapidly with increasing altitude; this suggestion is strengthened by comparisons of the observed locations of holes with the coronal magnetic field models described.

3. THE ORIGIN OF SECTORS

It is the purpose of this section to clear up some misconceptions about interplanetary magnetic field sectors. Ness and Wilcox (1964) first related interplanetary sectors to solar features during the time of a quiet inactive sun. At this time a more or less one-to-one mapping

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existed between solar features and the interplanetary sector structure. Subsequently, however, the situation grew more complicated and the previously described coronal models became necessary to solve the configuration of the magnetic field patterns involved.

These models tell us that the quiet IMF sector structure is effectively, a low-bandpass filtered version of the photospheric field. This gives rise, often to a 2 or 4 sector structure pattern in the ecliptic plane and a unidirected high solar latitude field. Superposed on this are transients-filaments kinks, bottles, holes, etc. in the IMF.

Thus the sector structure arises in the corona and does not exist on the sun, either in the photosphere or below the surface. Suitably tailored analyses (see Wilcox and Gonzales, 1971, and Wilcox et al., 1970) give correlations for certain time periods suggesting sector structure exists within the sun. The description is partly correct, partly not. Firstly, suitable low-bandpass averaging shows the "average fields" are calculable, however, their influence is often misinterpreted. The average field value in a region, although calculable, is not physically present - thus has little meaning. Secondly, considering the size-scale of the features and the time it takes to transport magnetic flux on the sun, these "average fields" certainly persist for a while. Thirdly, there are no significant individual solar features found, despite numerous investigative correlations, which statistically correlate with these "average fields". Shapiro (1965), for example, finds "the principal source of power at harmonics of the 27-day fundamental in... solar indices is due to the periodic but non-sinusoidal nature of the variation ... not due to a tendency for equidistant spacing of active regions on the sun."

Thus, if one ascribes a physical reality to these "average fields" on the sun, one would make the same error ascribing reality of the main solar dipole field to the photospheric fields at low latitudes. That is, suitably tailored averaging (over the northern and southern hemisperes) could show a north-south average dipole over all latitudes, nevertheless the sun's polar fields appear to be limited to the higher latitudes and few would argue for their reality at all latitudes despite a tailored averaging process. Thus, interplanetary sector structure should be confined to studies of the outer corona, interplanetary space and objects therein, not the sun itself. Solar structure does exist but not in the form of "Solar Sector Boundaries". Coronal holes or open field line boundaries, which are very different from the projection of the IMF current sheet onto the solar surface, may play some role.

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DISCUSSION

Ahluwalia: In your historical introduction you stated that no one knew about the sector structure in the interplanetary magnetic field (IMF) before it was actually observed. I wish to set the historical record straight by drawing your attention to the fact that Ahluwalia and Dessler (1962) predicted the existence of the sector structure in IMF. In fact, John Wilcox acknowledged this in his paper announcing the discovery of the sector structure in IMF!

Schatten: Yes, you are quite right! At the 1st solar wind conference, where a fuller review was given, I also referred to your work. Only due to the brevity of this talk was your work omitted. As I recall, you predicted the sector structure on the basis of the IMF originating from sunspots. So, like all of us, you were partly right, partly wrong. Thank you for the correction.

McIntosh: I must continue to disagree with you on two points: (1) the Hα synoptic charts clearly show a major neutral line, on most solar rotations, that divides the sun into two hemispheres in longitude, revealing the fundamental magnetic dipole in the east-west direction; (2) the sunspot, flare and X-ray emissivity statistics show an unmistakable longitude dependence. Active longitudes are clearly discernable in Hα synoptic charts as well. Confusion as to their reality has arisen from taking data over too long a time interval so that the drifts of long-lived active zones with respect to heliographic longitude produced an appearance of random occurrence. Certainly the active longitudes are more clearly defined with the larger and less-frequent categories of activities.

Schatten: I understand that not everyone will agree with this view as other views have been forcefully supported with analyses which appear to yield an opposite picture.

With regard to your question (1): Yes, during certain time intervals there is an east-west dipole, but at others there is not. For example, the June 1954 solar eclipse showed an almost exact north-south symmetry-denying an east-west dipole! In any case, the corona responds to the large-scale photospheric field and if it is east-west, then there is a two-sector structure at 1AU.

With regard to (2): I believe for "active region longitudes" to have real physical importance, they must be long-lived, and continue to arise at a specific longitude in a particular rotating (Ω = constant) coordinate system. Otherwise, they can be attributed to just relatively short persistence effects. So that for a few months a particular longitude is active. As an example, Jysiter's Red Spot exists at a specific longitude (in one coordinate system) but over a long-time it wanders in longitude - more than 360°! Thus it has a similarity to "active longitudes" in so far as it exists at one longitude for only a limited period. Thus, I can agree with you, in part, as follows. Large-scale solar fields have a long persistence due to the divergence B condition and the problems of changing the net flux in a short amount of time. This large-scale structure would to a large extent relate to the IMF sector structure as shown by the fine work of Wilcox and colleagues. It may then, also relate, for moderately long time intervals, to active regions, but this hasn't to my knowledge been demonstrated. In the absence of this, I have yet to understand "active longitudes".

Bhonsle: Is the presence of coronal hole a necessary condition for the existence of interplanetary magnetic field (IMF) sector structure? If so, what happens to the sector structure in the absence of coronal holes?

Schatten: The solar wind depletes the corona of material, and cools it. Thus, there is generally a close relation between the IMF sector structure and coronal holes. This is, however, a quasi-stationary view. If conditions are changing, the above will not be universally true! For example, a new sector may take time to deplete the coronal material, and no hole would be immediately apparent; thus, a 1 to 1 relation need not always exist.

Further, sector structure would generally exist even if no coronal holes were visible. However, some interplanetary field structures may arise from dynamic events - blast waves, bottles, bubbles, etc. That is, interplanetary magnetic fields are sometimes more complex than the simple sector viewpoint.

Tandon: Would you comment on the correlation of the sector structure with coronal holes, extending from pole to equator, in the absence of high latitude solar wind observations?

Schatten: I believe these features (coronal holes) occur through depletion of coronal plasma on long-lived "open" field lines, as calculated in the coronal theories reviewed by Levine. Thus, the "high latitude" spacecraft observations should show a general high speed wind with a uni-directed sector structure above about 20° latitude (as suggested in Schatten, 1971, Reviews of Geophys. and Space Phys.) except when the polar fields are reversing; with perhaps occasional variability due to solar activity (blast waves, bottles, etc.).