THE SUN'S MAGNETIC SECTOR STRUCTURE

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Abstract. The synoptic appearance of solar magnetic sectors is studied using 454 sector boundaries observed at Earth during 1959–1973. The sectors are clearly visible in the photospheric magnetic field. Sector boundaries can be clearly identified as north-south running demarcation lines between regions of persistent magnetic polarity imbalances. These regions extend up to about 35° of latitude on both sides of the equator. They generally do not extend into the polar caps. The polar cap boundary can be identified as an east-west demarcation line marking the poleward limit of the sectors. The typical flux imbalance for a magnetic sector is about 4×10^{21} Mx.

The interplanetary magnetic field originates in the Sun and has been found (Wilcox and Ness, 1965) to be organized into longlived and large-scale sectors of predominantly unipolar fields. The magnetic field structure corotates with the Sun and evolves only slowly with time (e.g. Svalgaard and Wilcox, 1975). A similar ordering of the solar magnetic fields has been demonstrated (Wilcox and Howard, 1968; Severny *et al.*, 1970; Scherrer, 1973). These studies reveal a large-scale pattern in the photospheric magnetic field extending over a wide range of heliographic latitude on both sides of the equator. The boundary between oppositely directed fields was found to be nearly north-south crossing the equator. Such boundaries have been identified in computed coronal magnetic field (Wilcox and Svalgaard, 1974) and associated with density enhancements of the whitelight corona near the Sun by Hansen *et al.* (1974) and further observed as distinct coronal streamers between 3 and 10 $R_\odot$ from the center of the Sun by Howard and Koomen (1974). All these observations have been organized by Svalgaard *et al.* (1974) into a simple model of large-scale solar magnetic fields. We note that the sector structure of these fields exerts a controlling influence in shaping magnetic fields from the bottom of the photosphere through the corona and into interplanetary space to Jupiter and beyond.

The large-scale nature of these fields is clearly illustrated by the fact that the sector structure becomes increasingly more difficult to observe as spatial resolution increases. It is in fact maybe best observed with no spatial resolution at all – observing the Sun as a star. With increasing resolution we always find a more complicated magnetic structure; even the polar regions and the classical unipolar magnetic regions (UMRs) are seen to include magnetic elements of both polarities and even to be populated by tiny bipolar features (Bumba and Howard, 1965; Severny, 1967; Harvey *et al.*, 1975). There is now a growing acceptance of a further complication, namely that most, if not all, observed magnetic flux outside sunspots is concentrated into very small ($<1''$)

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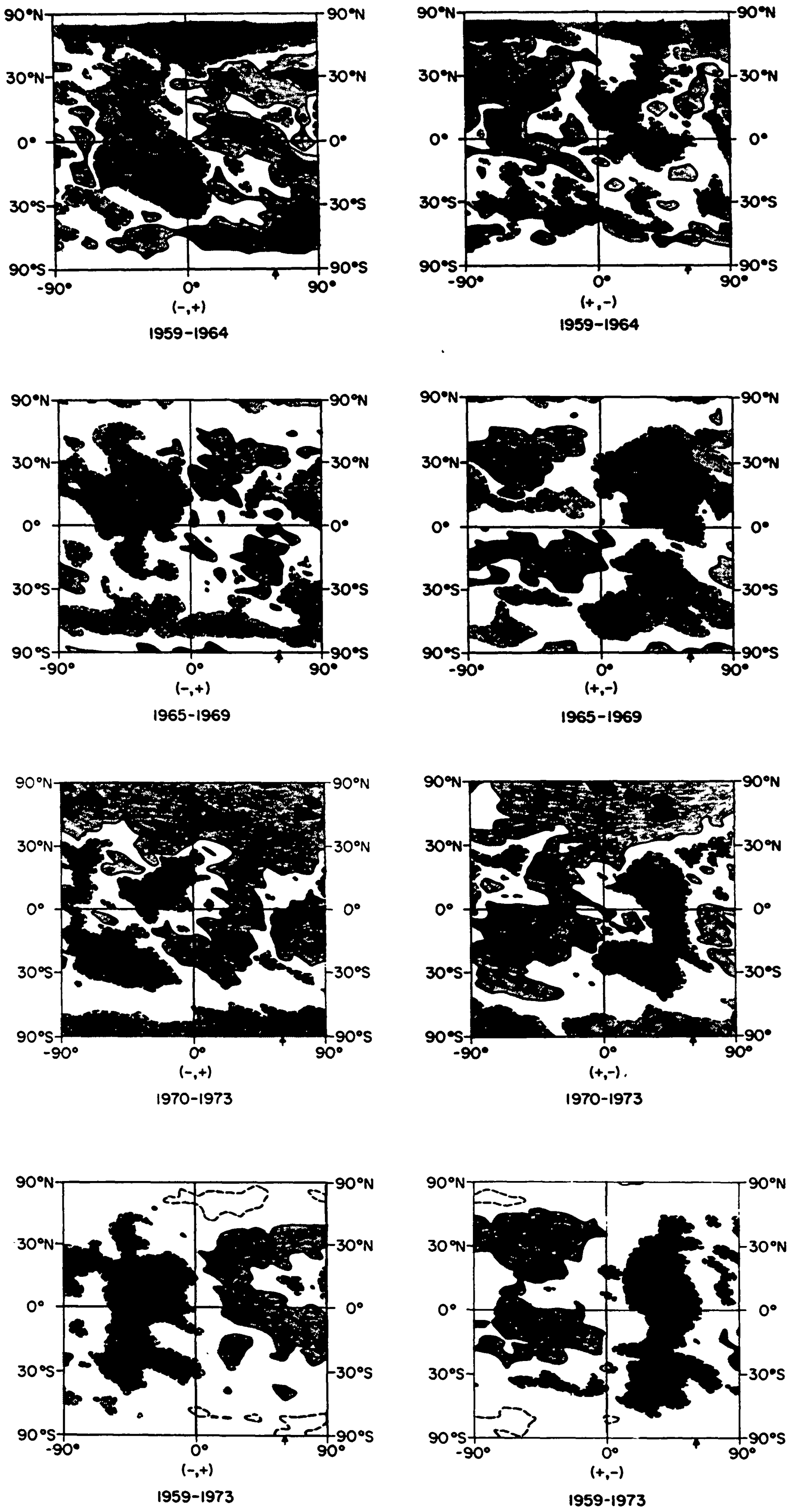

(−,+)
1959–1964

(+,−)
1959–1964

(−,+)
1965–1969

(+,−)
1965–1969

(−,+)
1970–1973

(+,−)
1970–1973

(−,+)
1959–1973

(+,−)
1959–1973

knots, normally not resolved by solar magnetographs. The field strength in these knots is very high, of the order of 2000 G (Stenflo, 1973; Frazier, 1974). Although solar magnetographs, such as the one at Mt. Wilson, record extended regions of weak 'background' fields of only about 1–5 G field strength, such regions should not be considered to be unipolar *weak* field areas. The magnetograph is basically a flux measuring device and will record the magnetic flux integrated over the aperture of the instrument. If the number of positive polarity (field directed away from the Sun) elements or knots exceeds the number of negative elements, the magnetograph will generally measure a positive excess flux for the integrating area. It is this imbalance – as seen by solar magnetographs – that has been found to be ordered in large-scale sectors. It is also this imbalance that controls the structure of the magnetic field in the solar wind.

In the present study we shall utilize solar magnetograms obtained over the 15-yr interval 1959–1973 at Mt. Wilson Observatory to confirm and extend previous conclusions about the sector-structured solar magnetic fields. The analysis covers 1½ sunspot cycles and uses data – solar as well as interplanetary – that are obtained with different techniques and with improving quality over the years. These factors do not, however, seem to have any significant influence on the results, which appear to be largely independent of the observing techniques and of sunspot cycle phase. The solar magnetograms are used to construct synoptic maps of the magnetic field distribution in heliographic latitude and longitude for each Carrington rotation in the 15-yr interval analyzed. The heliographic longitudes of the solar sector boundaries were determined by adding 60° to the longitude of central meridian at the time of passage by the Earth of an interplanetary sector boundary. The 4½ day transit time from the Sun to the Earth of the solar wind plasma corresponds to about 60° of solar rotation. Average synoptic maps were then computed for regions centered on the solar sector boundaries and extending 90° of longitude away from the boundary to both sides. We shall primarily discuss properties of these average maps which give a synoptic representation of the average latitudinal and longitudinal extent of the solar sectors.

A description of the Mt. Wilson magnetograph system is given in Howard (1974a). Here we note that changes in the system occurred in June, 1963 and in the summer of 1966. The sector boundary passages are taken from a compilation by Svalgaard (1975). Before 1965 very little spacecraft data is available so the boundary passages during 1959–1964 are mainly deduced from polar geomagnetic data. The accuracy of this process has been discussed by Svalgaard (1975) and found adequate for defining the large-scale features (i.e. the sector *structure*) of the interplanetary magnetic field.

Figure 1 shows the average synoptic appearance of solar magnetic sectors. The data

Fig. 1. Photospheric magnetic sector structure. Mt. Wilson magnetic synoptic maps have been superposed around solar sector boundaries (see text). Inward polarity (−) is red; outward polarity (+) is blue. The contour levels are ±0.25, ±0.75, ±1.25,... G. The upper panels show data for the indicated years, while in the lowest panel the data for all years is superposed around respective boundaries. In this panel the polar fields are not shown in color because of the averaging of cancelling fields from different sunspot cycle phases. A small upward pointing arrow points to the central meridian at the time of sector boundary passage at the Earth.

have been divided into three intervals corresponding to different phases of sunspot cycles 19 and 20. The lower panel shows the result of superposing all the data for the entire interval 1959–1973 about sector boundaries where the polarity changes from inwards to outwards (−, +) and for sector boundaries with the opposite change of polarity (+, −). In both cases 227 boundaries were available and have been used in the analysis. Inward polarity (−) is shown in red color while outwards polarity (+) is shown in blue. The lowest contour levels are ±0.25 G and regions with average field strength below that are not colored. The contour interval is 0.5 G and regions with field strengths above ±0.75 G are shown in heavy color. We will later discuss further details of the data analysis; for the moment let us concentrate on the physical content of the result. The sector boundaries can be identified as essentially north-south running demarcation lines between extended regions of persistent magnetic polarity imbalances. These regions extend up to about 35° of latitude on both sides of the equator and for about 90° longitude away from the boundary. They generally do not extend into the polar caps which seem to be largely unaffected by the boundary. The polar field reversal near the maximum of cycle 20 is clearly seen. We can identify the polar cap boundary as a generally east-west demarcation line marking the poleward limit of the sectors. These observed properties of the large-scale photospheric field are very much as suggested on general grounds by Svalgaard *et al.* (1974) in their discussion of large-scale solar fields.

The amount of information in Figure 1 is not exhausted by the above comments, and we shall be concerned with further investigation of details of these elusive and extended magnetic structures. Some of these details are related to differences between the appearance of the sectors at the various epochs. The overall impression is, however, one of consistency and invariance. At all times, the sectors can be identified; they stretch across the equator with no change of polarity, and the transit time from the Sun to the Earth seems to be near $4\frac{1}{2}$ days (or 60° of rotation) throughout the interval 1959–1973. The sector boundaries in the upper photosphere (where the spectral line used at Mt. Wilson – $\lambda 5250$ – is formed) run north-south with no shearing or distortion by differential rotation. The field strengths in the sectors seem to be comparable to the polar fields, and during the descending phase of the sunspot cycle the net flux from the sectors and from the polar regions are also comparable (because the areas are about equal) suggesting the possibility of a significant interplay between the sector and the polar fields.

The Mt. Wilson magnetograph records the net magnetic flux over regions of the order of $20 \times 20''$ as seen from the Earth, equivalent to about 1 × 1 deg of heliographic coordinates near the center of the disk. If the flux is very large, a saturation of the instrument occurs; this happens regularly within active regions. For the purpose of investigating large-scale fields a further averaging of the fluxes over a large area (4 × 10 deg at center of disk) was performed. This larger area is larger than most active regions, tending to lead to a cancellation of most of the flux from the bipolar regions. This can be directly verified by the fact that the net flux from the larger area – containing an average active region – is about one order of magnitude smaller than the flux from each pole of the bipolar active region. Occasionally the cancellation is less complete and large, spurious fluxes result. Such cases of small-scale imbalance should be avoided in a study of large-scale fields. This statement is not true *a priori*, but must be verified observationally. In computing the average synoptic maps of Figure 1, areas where the average flux density exceeded 8 G were omitted. This corresponds to about 15% of the data in the sunspot zones. If these few cases of high fluxes were *not* omitted the sector structure was much less distinct, if discernable at all. Including the strong field regions thus increases the noise level to the point where the sector structure is almost lost. There is, of course, nothing significant about the magnitude, 8 G, of the threshold defining a strong field region to be omitted. With a larger number of sector boundaries this threshold could be lowered. Various other thresholds have been tried and it was found that 8 G gave the clearest sector structure signal for the number of boundaries (≈ 100) available for each of the six average synoptic maps of Figure 1.

A consequence of the fact that it is necessary to omit active regions in order to extract a solar sector structure from the synoptic maps seems to be that the sector structure is not caused by or controlled by the strong magnetic fields of active regions. More directly this follows also from the existence and stability of sectors at sunspot minimum. Large-scale and longlived solar magnetic fields are *conventionally* thought to be the dispersing remnants of the strong fields in active regions and sunspots. The follower part of an active region drifts poleward as it expands and weakens forming a unipolar magnetic region (UMR). Each UMR has its smaller, weaker counterpart – the ghost UMR – that has leader polarity and moves toward the equator. Both regions are sheared by differential rotation and the result of the whole process would seem to be a *zonal* structure, where leading polarity would accumulate in a belt or zone near the equator, and the following polarity would form a zone polewards of the equatorial leading polarity zone. Such an arrangement is precisely what is observed (e.g. Howard, 1974a) and appears also superposed on the sectorial structures of Figure 1. In particular, a zone of negative (leading) polarity can be seen extending through the positive sector of the $(+, -)$ sector-pair during 1965–1969.

Harvey *et al.* (1975) extended their earlier (Harvey and Martin, 1973) study of Ephemeral Regions (ER). These are very small bipolar regions found all over the solar surface; hundreds of ERs are present on the Sun at any time even in the polar regions and in coronal holes (extended areas of low temperature and density). The magnetic flux appearing in the form of ERs is as large as appears in regular active regions, but the orientation of the line connecting the two poles of the ERs is almost random – not nearly east-west as for the larger active regions. It is not clear how the ERs are dispersing or disappearing – their lifetime is only of the order of $\frac{1}{2}$ day. Due to the random orientation of the ERs very little order would be expected in the dispersing flux from decaying Ephemeral Regions. The importance of the ERs for the present study arises from the demonstration that not all magnetic structures and phenomena necessarily derive from the dynamics of existing active regions. It is becoming increasingly apparent that alternative interpretations are viable. Maybe the various magnetic structures are all symptoms or byproducts of a number of different precesses operating on a broad spectrum of temporal and spatial scales. Some of these processes may be coupled in ways we at the present are completely unaware of. It is certainly true that the Sun is more complex on all scales that we thought just a few years ago. The concept of solar sector magnetism (Wilcox, 1971) and its possible interplay with other large-scale fields (Svalgaard *et al.*, 1974) isolate but one aspect of this complexity. The large scale – both spatial and temporal – of this aspect suggests that a sector structure is among the fundamental properties of the Sun and possibly also of other magnetic stars.

The implication of the sector concept as stated above is that the sectors are *not* just particular arrangements of remnants of dispersing active regions as discussed for instance by Hansen *et al.* (1974), but are fundamental entities created and maintained independently of specific active regions. Physical processes that may lead to sector-like organisation of the solar fields in and below the photosphere have been discussed by a number of workers (e.g. Stix, 1974; Suess, 1975; Wolff, 1975); we have no assurance that the possibilities are exhausted by the mechanisms proposed so far.

We now proceed to a quantitative analysis of the sector signal that is so vividly displayed in Figure 1. The solar magnetograph data was averaged over areas covering 10° of longitude and $\frac{1}{30}$ of the diameter of the disk in latitude. This means that the ordinate of Figure 1 actually is expressed in units of $\sin b$, where b is the heliographic latitude. The contour lines were drawn from a 30×19 matrix of numbers each expressing the average flux density for that particular area, characterized by its distance from a sector boundary and from the equator. Because the sectors extended up to or slightly beyond 30° of latitude, we computed the average flux density for each average 10° longitude section but including only areas within 32.2° of the equator, corresponding to 16 strips of each $\frac{1}{30}$ of a diameter. In short, we are computing the field strength within a solar magnetic sector as function of distance from the sector boundary. Again, data values greater than ± 8 G were omitted. The result is shown in Figure 2, separately for $(+, -)$ and for $(-, +)$ sector boundaries.

The flux density seems to attain its maximum value, about 0.5 G, some tens of degrees from the sector boundary. The gradual change across the boundary may be related to variations in transit time or to local deviations from a perfect north-south sector boundary. We shall not comment further on this problem, but instead note that the field is not zero at the boundary. In both cases a field strength of -0.08 G is found. This discrepancy might be interpreted as a systematic error in the determination of the zero-level for the solar magnetograph. This interpretation is supported by the finding by Scherrer (1973) that the correlation between the photospheric magnetic field and the interplanetary field was best assuming a zero-level of -0.10 ± 0.05 for the solar field. The average field strength for the whole disk during the interval 1967–1973 was found to be -0.071 G by Howard (1974a) and might be interpreted as a zero-level error. Because only the line-of-sight component of the magnetic field is observed, such zero-level errors could arise from systematic differences between the field inclinations to the radial in the photosphere and are thus not necessarily purely instrumental, although they might very well be so.

It seems reasonable to conclude that the typical field strength within a solar mag-

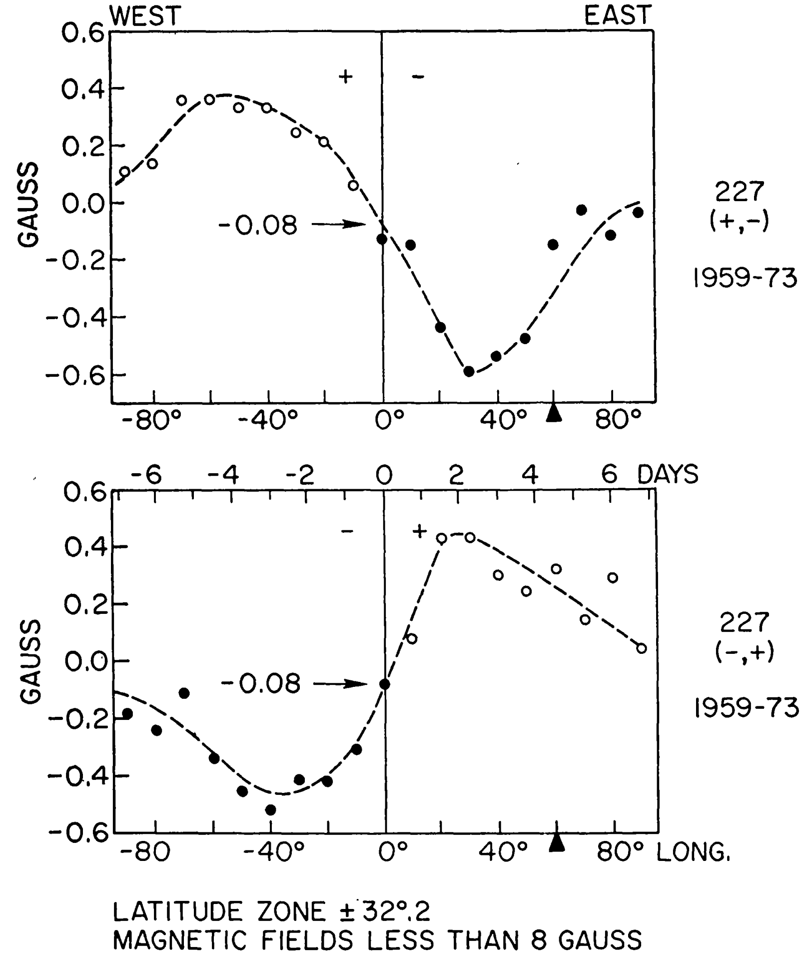

Fig. 2. Variation of magnetic field strength within solar sectors as function of distance from sector boundaries. The average field of 10° wide longitude strips extending from 32°S to 32°N is shown. The upper panel shows the result for 227 (+, —) boundaries and the lower panel shows the result for 227 (—, +) boundaries. Time runs from left to right in this Figure (as in Figure 1). The probable error of the averages is of the order of ±0.1 G.

netic sector, as observed by the Mt. Wilson magnetograph, is about 0.5 G. This is very similar to the typical magnitude of the mean field of the Sun, i.e. the field observed using just integrated sunlight with no spatial resolution at all (e.g. Scherrer, 1973). We again remind the reader that what is really observed in both cases is a flux *imbalance* of the order of 2×10^{21} Mx. Due to various systematic errors (e.g. Scherrer, 1973) this flux is probably too low by a factor of about 2, raising the typical average field strength to about 1 G and the flux to 4×10^{21} Mx. It is interesting to note that about 1.8 G is required to give the observed radial component of 4×10^{-5} G of the interplanetary magnetic field near the Earth assuming a simple inverse-square scaling. We conclude that both the solar magnetograph data and the interplanetary field data indicate a flux density of the order of 1–2 G of the open field lines that extend into the solar wind. This is about one order of magnitude smaller than the probable flux density in the sunspot zones within ±40° of the equator (Howard, 1974b; Livingston and Harvey, 1975) indicating that most field lines are closed very near the Sun and that only about 10% of the flux is making up the interplanetary magnetic field.

It was suggested by Svalgaard *et al.* (1974) that although sector boundaries are north-south in the photosphere they may be tilted away from the north-south direction at some distance from the Sun. The various observations of sector boundary indicators that were discussed in the beginning of the present paper may be utilized to investigate possible tilts of the boundaries as a function of distance from the Sun. We will discuss the tilt in terms of the inclination of the boundary to the solar equator as measured at the plane of the solar equator.

We shall first consider times away from sunspot maximum or more precisely away from the polar field reversal. At such times an interplanetary sector with the same polarity as the north (south) polar region is observed at the Earth to be wider when the Earth is to the north (south) of the equatorial plane of the Sun and to be narrower when the Earth is to the south (north) of the solar equator. The magnitude of this Rosenberg-Coleman effect (Rosenberg and Coleman, 1969; Hedgecock, 1975) is such as to indicate an inclination of about 15°. The streamers observed by Howard and

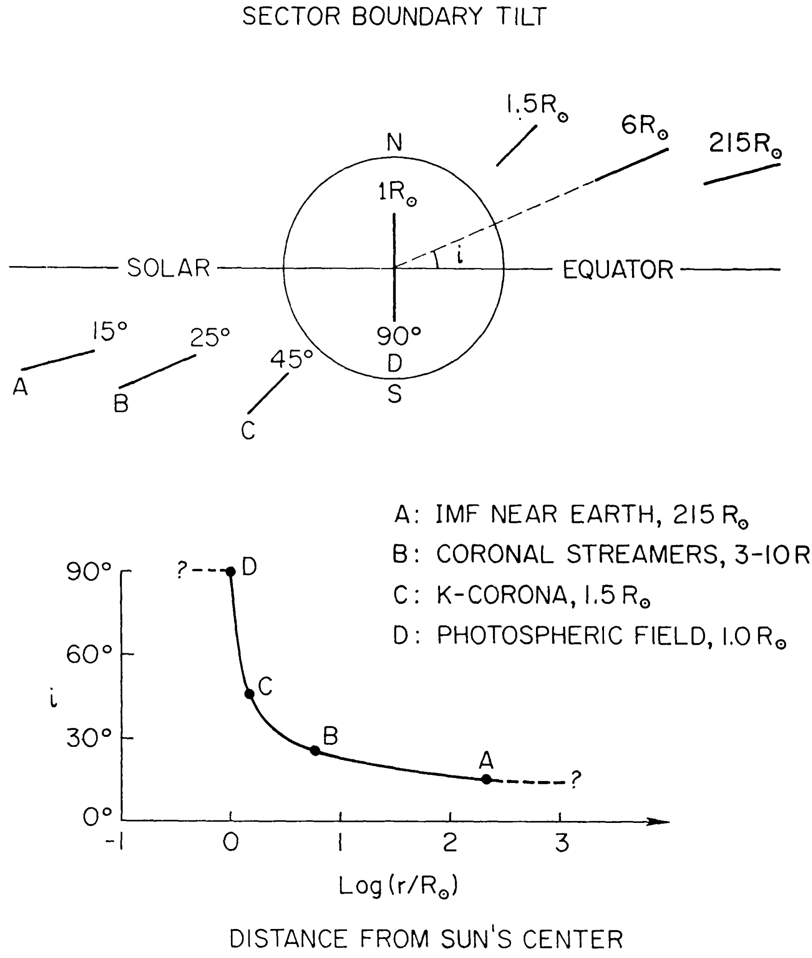

Fig. 3. Schematic summarizing various observations of the inclination of sector boundaries to the solar equator. See text for references. Short line segments indicate the inclination of the boundaries and are marked with the inclination angles to the left of the solar disk and with the heliocentric distances to the right. The lower panel shows the inclination, *i*, as function of heliocentric distance.

Koomen (1974) between 3 and 10 $R_\odot$ from the center of the Sun seem to have an inclination of about 25°, while the streamers observed by Hansen *et al.* (1974) at 1.5 $R_\odot$ are inclined about 45° to the solar equator. Finally in the photosphere – at 1.0 $R_\odot$ – the inclination is close to 90°.

Figure 3 summarizes all these observations and leads to the suggestion that the inclination of the sector boundaries changes systematically with distance from the Sun as shown in the lower panel of Figure 3. Since most of the change takes place near the Sun, we suggest that the sector structure of the interplanetary magnetic field is confined to a rather thin region near the solar equatorial plane. The implication is that in most of the heliosphere the polar fields determine the polarity of the interplanetary magnetic field. Near the time of polar field reversal the situation is much less clear and the geometry of the field at such times remains an open problem. Out-of-ecliptic spacecraft at different phases of the sunspot cycle should be instrumental in resolving these problems.

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