SECTOR STRUCTURE OF THE SOLAR MAGNETIC FIELD

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Abstract. The solar sector structure consists of a boundary in the north-south direction such that on one side of the boundary the large-scale weak photospheric magnetic field is predominantly directed out of the Sun, and on the other side of the boundary this field is directed into the Sun. The region westward of a solar sector boundary tends to be unusually quiet and the region eastward of a solar sector boundary tends to be unusually active. This tendency is discussed in terms of flares, coronal enhancements, plage structure and geomagnetic response.

A solar magnetic sector pattern has been inferred from comparisons of the observed photospheric magnetic field with the observed interplanetary magnetic sector pattern. A schematic of an average boundary during 1965 of the solar sector pattern is shown in Figure 1. The boundary is approximately in the north-south direction. Over a large region on both sides of the equator to the west of the boundary the large-scale weak photospheric magnetic field is predominantly into the Sun, and similarly to the east of the boundary this field is predominantly out of the Sun. The solar sector boundary rotates in an approximately rigidly rotating system since the shearing effects to be expected from differential rotation have little or no effect on the boundary. Thus the solar sector pattern differs from the classical model of solar magnetism given by Babcock (1961) in two fundamental respects: (1) The sector magnetic structure rotates in a rigid system while the Babcock model depends on differential rotation for field amplification, and (2) the solar sector pattern extends across the equator without

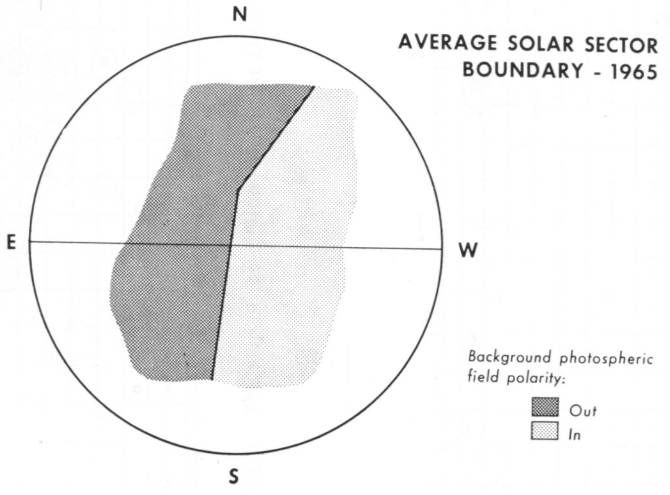

Fig. 1. A schematic of the average position of a solar sector boundary during 1965. On each side of the boundary the weak background photospheric magnetic field is predominantly of a single polarity in equatorial latitudes on both sides of the equator (after Wilcox *et al.*, 1969).

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change of polarity while the Babcock model has opposite polarities for bipolar regions on the two sides of the equator. In the Babcock model (and in observations of sunspots) the solar equator is a well defined position such that if sunspots are only a degree or two away from the equator they will almost always obey the polarity law of the Babcock model. By contrast the analysis that leads to the sector structure crosses the equator without any perceptible change.

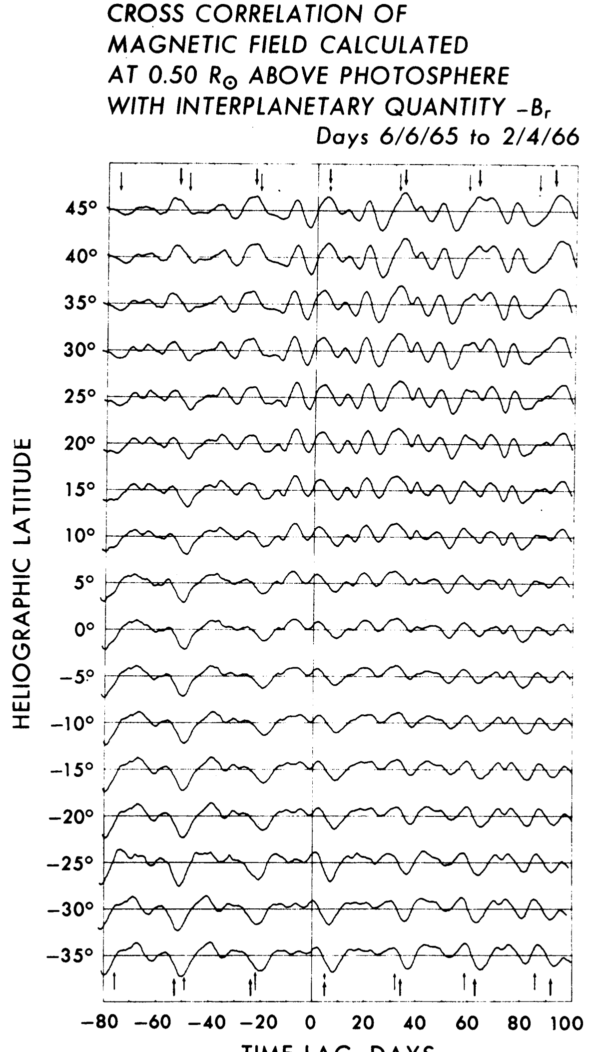

Fig. 2. Cross correlation of the magnetic field near the Sun with the radial component of the interplanetary magnetic field as a function of time lag. Nine solar rotations of data are utilized with correlations extending from 45° N to 35° S in intervals of 5°. The horizontal line labeled 45° represents zero correlation for this latitude. The line just above represents 1.0 and the line just below represents − 1.0. Correlations for all other latitudes are displaced in the same format (after Schatten *et al.*, 1969).

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The solar sector pattern is obtained from cross correlations of the interplanetary sector pattern observed with spacecraft near the ecliptic and the photospheric magnetic field observed with the solar magnetograph at Mount Wilson Observatory. The result of such a cross correlation is shown in Figure 2. Consider first a cross correlation in Figure 2 for a solar latitude near the equator. This correlation has a peak at a lag near $4\frac{1}{2}$ days, which represents the transit time of solar wind plasma from Sun to Earth. This peak may be regarded as the result of a physical transport by the solar wind plasma of field lines from the Sun to the spacecraft near the Earth. If we now examine the other cross correlations in Figure 2 we find that at each solar latitude there is a peak near a lag of 4 or 5 days. All of these peaks are interpreted not in terms of a direct connection from the solar latitude involved to the position of the spacecraft but rather as indicating that all of the solar latitudes have a common pattern in the large-scale field.

The observation of this large-scale solar pattern is a signal-to-noise problem. Two kinds of 'noise' obscure the observation of this pattern: first, the magnitude of the photospheric fields involved is comparable to the minimum fields that can be detected with the solar magnetograph, and second, small-scale features such as active regions and bipolar sunspots appear as 'noise' in the attempts to observe a large-scale region with a single predominant polarity. The solar sector boundaries schematic in Figure 1 can be inferred from the cross correlations of Figure 2 in a manner described by Severny *et al.* (1970).

During the last solar minimum the interplanetary sector pattern consisted of four sectors per rotation that existed in a quasi-stationary manner for approximately one year. Each of these sectors was a coherent entity in the sense that several observed interplanetary quantities changed in a smooth and unitary manner within each sector. In the years near solar maximum attention has been concentrated on the solar sector boundaries. In this paper we present several lines of evidence indicating that the region westward of a solar sector boundary tends to be unusually quiet and that the region eastward of a solar sector boundary tends to be unusually active.

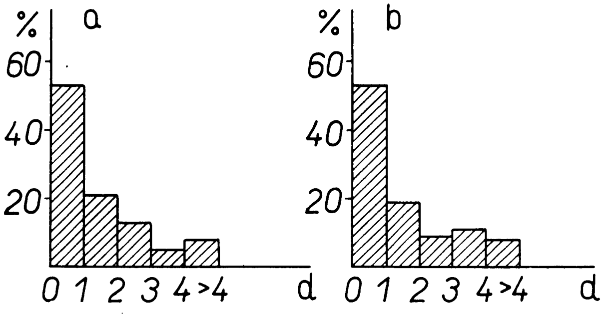

Fig. 3. Histograms of frequency distribution of the time difference between the central meridian passage of spot groups and the position of solar sector boundaries for the groups: (a) with flares of importance 1+ or greater; (b) with a number of flares equal or greater than 10 (after Bumba and Obridko, 1969).

Flares are most likely to occur near sector boundaries, and the larger the flare the more likely it will be near a boundary (Bumba and Obridko, 1969). Figure 3 shows their results for a histogram of frequency distribution of the time differences between the central meridian passage of spot groups and the position of the solar sector boundary for the groups: (a) with flares of importance 1+or greater; (b) with a number of flares equal or greater than ten. Eleven of the fourteen proton-flare regions examined by Bumba and Obridko occurred at a distance smaller or equal to one day from the boundary of the sector structure. It is interesting to note from the work of these authors that the solar sector structure is consistent with but more quantitative and precise than the concept of active longitudes. When Bumba and Obridko constructed histograms similar to Figure 3 but referring to the center of gravity of an active longitude they found peaks in the distribution that were smaller and broader than the peaks shown in Figure 3. Vladimirsky (private communication) using a more recent and larger data sample has confirmed the results of Bumba and Obridko. Vladimirsky has found that flares tend to be concentrated in the region just eastward of the sector boundary.

Coronal enhancements have been detected just eastward of solar sector boundaries by Couturier and Leblanc (1970) using the Nançay radio interferometer at 169 MHz (1.77 m). Most of the emission detected originates at altitudes between 0.2 and 0.5 $R_\odot$

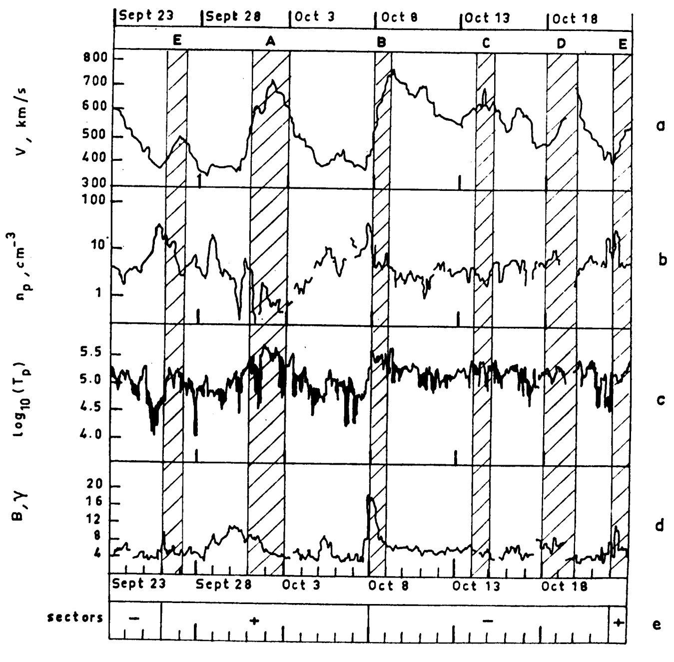

Fig. 4. Solar wind activity during solar rotation 1768. The vertical hatched regions represent CMP of coronal enhancements. a, solar wind velocity; b, proton density; c, temperature (upper and lower limits); d, interplanetary magnetic field magnitude; and e, sector polarity pattern (after Couturier and Leblanc, 1970).

above the photosphere. The electron density and temperature of these enhancements are higher than those of the 'quiet' Sun. Their results are shown in Figure 4. At the bottom of this figure there is shown the sector polarity pattern. The vertical cross hatched regions above indicate the position of the coronal enhancements. It can be seen that just after (eastward) each sector boundary there is a coronal enhancement. The opposite however is not necessarily correct. We see that within a sector there may be one or two additional coronal enhancements. These may be related to what we may term 'subsectors', i.e. a single magnetic sector may consist in some cases of two or three adjacent subsector regions on the Sun.

Evidence for the existence of subsectors has already been available from observations of the solar wind velocity. It is found that just after almost every sector boundary the solar wind velocity rises (as is shown in the top panel of Figure 4) but that again the converse is not necessarily true. Within a given magnetic sector there may be two or three large-scale increases in solar wind velocity. Near the last solar minimum each sector was a discrete entity, i.e. it did not contain any subsectors. With the increase of

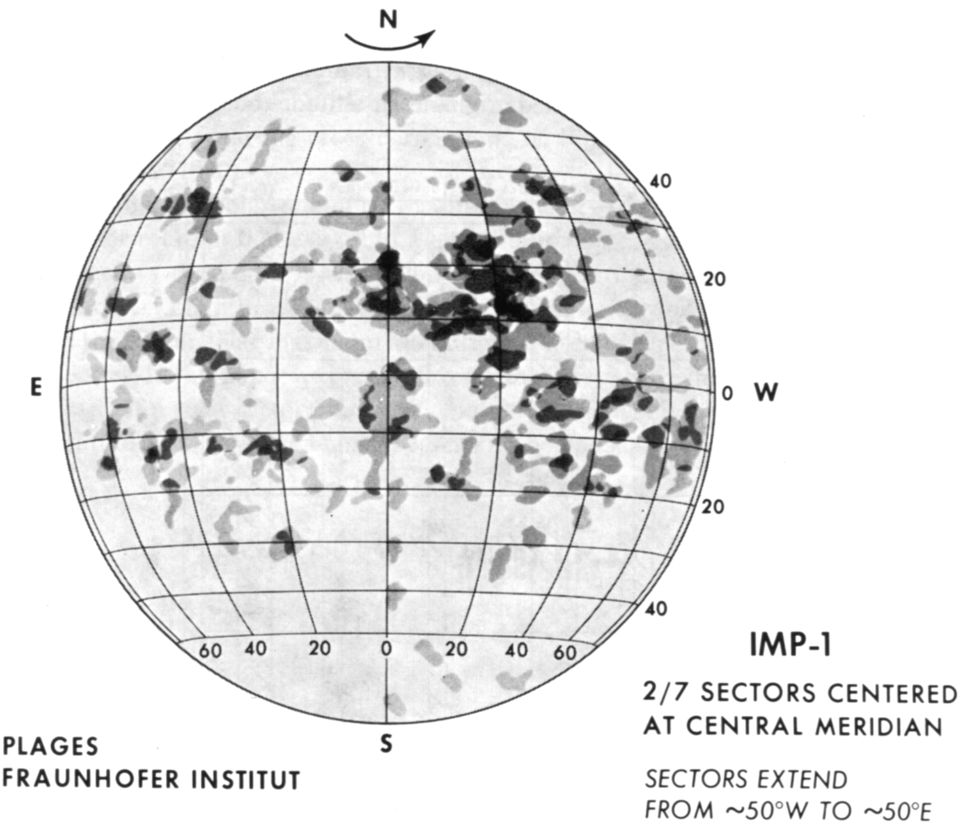

Fig. 5. Superposed-epoch analysis of calcium plage structure obtained from the daily Fraunhofer Institute maps of the Sun. The sectors are approximately centered at central meridian, so that the leading edge of the sector is at about 50° W and the trailing edge of the sector about 50° E longitude (after Wilcox and Ness, 1967).

solar activity in the rising portion of the sunspot cycle the concept of the subsector appears. Therefore much attention during the period of solar activity has been concentrated on the sector boundaries rather than on the entire sectors, which may be complicated by the presence of one or two subsectors. It remains a challenging problem in solar physics to understand the origin of both the sectors and the subsectors.

An analysis near solar minimum showed that plages were most probable in the preceding portions of solar sectors. Fraunhofer Institute daily solar charts were selected for days on which a solar sector was approximately centered at solar meridian. A number of these charts were then overlayed to form a kind of superposed epoch analysis of plage location with respect to sector position. The results are shown in Figure 5. It can be seen that plage activity is more intense to the west of central meridian (the preceding part of the sector) than to the east of central meridian (the following portion of the sector). Thus the above result that flare activity and coronal enhancements are most pronounced eastward of the sector boundary extends also to plage activity.

In the discussion of Figure 3 we showed that the position of flare-producing regions is related to the solar sector boundaries. We now show that the magnetic polarity of sunspots tends to be related to the solar sector pattern. The mean magnetic field of the Sun observed as though it were a star has been compared with the observed interplanetary sector structure (Wilcox *et al.*, 1969). The top portion of Figure 6 shows the results, in which the dots represent the observed mean solar field and the bars represent the polarity of the observed interplanetary sector pattern. The transit time of $4\frac{1}{2}$ days of solar wind plasma from the Sun to the Earth has been allowed for in this comparison in Figure 6. The agreement between the two sets of observations is seen to be very good. The bottom portion of Figure 6 shows the contribution of sunspot magnetic

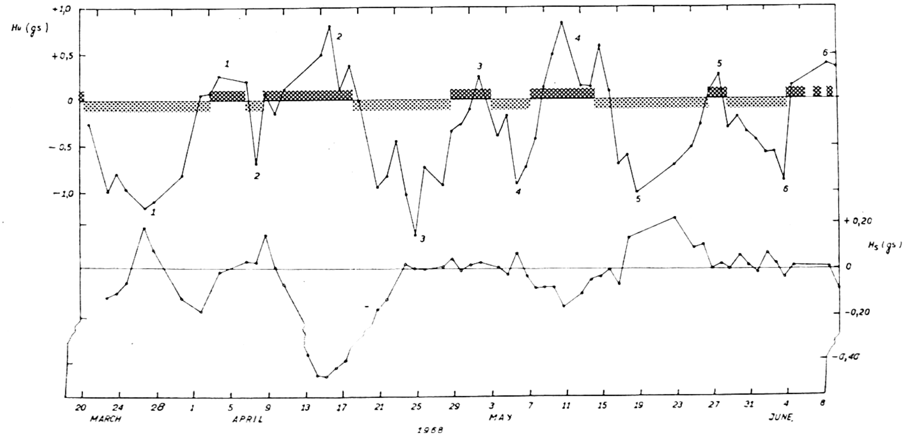

Fig. 6. Top: mean value of the solar magnetic field (dots) and polarity of the interplanetary magnetic field (bars). The interplanetary field is displaced to allow for the transit time of solar wind plasma from the Sun to the Earth. Bottom: contribution of sunspot magnetic fields to the mean solar field shown above (after Wilcox *et al.*, 1969).

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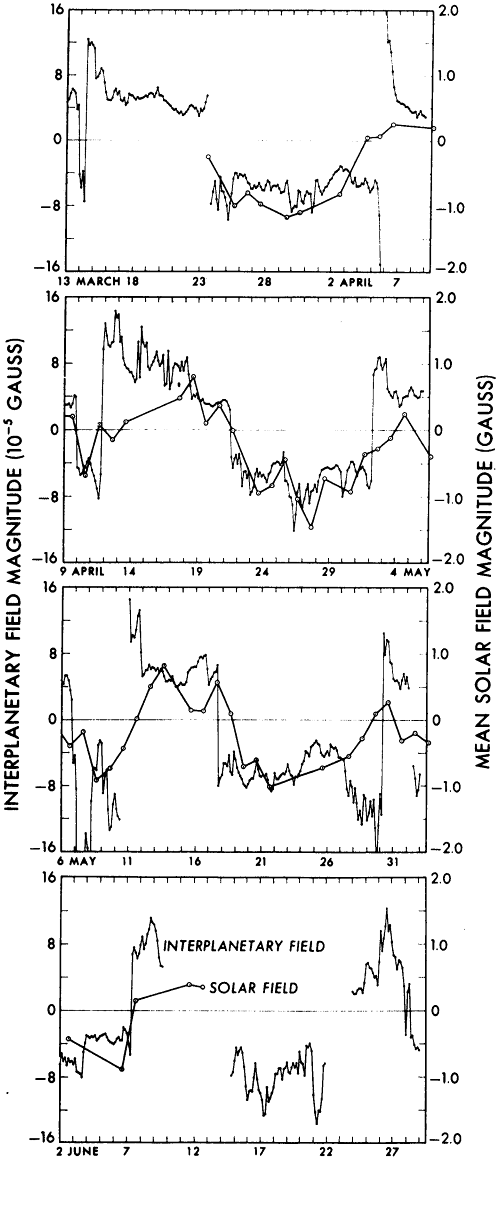

Fig. 7. Comparison of the magnitude of the mean solar field and of the interplanetary field. The open circles are the daily observations of the mean solar field, and the dots are 3-hr average values of the interplanetary field magnitude observed near the Earth. The solar observations are displaced by 4½ days to allow for the average Sun-Earth transit time. The abscissa is at the time of the interplanetary observations (after Severny *et al.*, 1970).

fields to the observed mean solar field. The net sunspot field contribution is often sensibly zero, but when it has an appreciable magnitude the net spot polarity is usually opposite to the polarity of the mean solar field and the interplanetary sector pattern. This suggests that the magnetic polarity of sunspots may be related to the solar sector pattern. The details of this relationship are another challenging problem in solar physics.

A comparison of the magnitude of the observed mean solar field with the magnitude of the observed interplanetary magnetic field is consistent with the solar sector pattern. A comparison of these magnitudes is shown in Figure 7. The scale of the ordinate has been chosen so that in the middle portions of large sectors the two fields approximately coincide. This then yields an experimental scaling of an average interplanetary field of 6×10^{-5} G corresponding to an average mean solar field of 0.75 G. Let us see if this scaling is reasonable. The average magnitude for the interplanetary field of 6×10^{-5} G corresponds to a radial component of 4×10^{-5} G, since the Archimedes spiral angle near the Earth is about 45°. If we now scale this field by $1/r^2$ corresponding to the spherical expansion of the solar plasma (and field) we reach a magnitude of 1.8 G at the solar surface. The mean field observations refer to the line-of-sight component of the field and depending on specific assumptions about the average direction of the photospheric field the 1.8 G will correspond to an observation in the range of 1.3 to

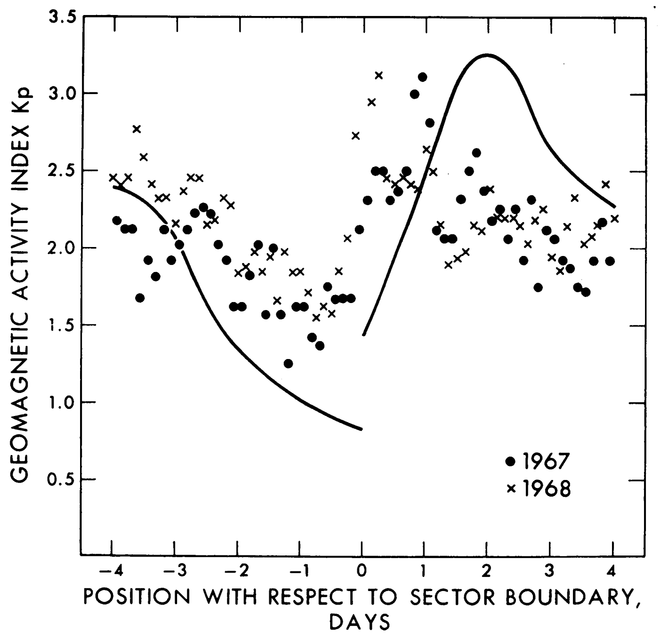

Fig. 8. Superposed epoch analysis of the magnitude of the planetary magnetic 3-hr-range indices *Kp* as a function of position with respect to a sector boundary. The abscissa represent position with respect to the sector boundary, measured in days, as the sector pattern sweeps past the Earth. The solid line represents similar results obtained near solar minimum, the dots represent results in 1967 and the × represent results during 1968 (after Wilcox and Colburn, 1970).

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0.9 G. Thus we find an agreement within less than a factor of two with the experimental scaling. This indicates that the solar sector pattern must occupy a large area on the Sun. If the solar sector pattern that is the source of the interplanetary sector pattern were confined to a small range of latitudes on the Sun the comparison of scaling discussed above would be changed by a large factor.

Finally, we may use the Earth as a detector for sector conditions. Figure 8 shows the average response of geomagnetic activity as a sector boundary rotates past the Earth. It can be seen that on the average geomagnetic activity has a monotonic decline in the following portion of a sector with an abrupt increase near the sector boundary to a peak early in the preceding portion of the sector. Again we find that the region just after (eastward) a sector boundary is the most active and that the region just before (westward) the sector boundary tends to be the most quiet.

Acknowledgements

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Discussion

Krause: It seemed that the rigid rotation of an active region observed by you indicates that the toroidal field of the Sun is mainly produced by a radial variation of the angular velocity at deeper layers, and not – as it is the general opinion up till now – by the variation of the angular velocity with the latitude as observed at the surface of the Sun. Just this fact is used in the dynamo model for the Sun developed by us.

Pick: You have noted that active centers with large flare activity are located near a sector boundary. What is in this case the size of the interplanetary sector? Sometimes, we may note the existence of 'a secondary' boundary inside a large sector – this kind of boundary is probably associated directly with an active center. I would like to note that the enhancement observed on metric wavelengths is not characteristic of the activity.

Wilcox: The analysis includes the average properties of all solar sector boundaries. It is true, however, that newly-formed sectors tend to have large associated geomagnetic activity. Newly-formed sectors are quite narrow, starting with a width of perhaps 30° in longitude, and growing as they become older.

Vaiana: (1) Could you clarify the relation between the sector structures and the large scale complex of activity (the so-called active longitudes) seen for instance in the synoptic magnetic charts?

(2) You mentioned that one of the problems of establishing sector boundaries on the basis of solar

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observations alone is the fact that one is dealing with a basically noisy set of maps. I would like to notice that X-ray maps may be a noise-free method of correlation with interplanetary sectors.

Wilcox: (1) The active longitudes and complexes of activity can fit within the solar sector structure. This can be seen in a quantitative way in the work of Bumba and Obridko already referred to. They made a histogram of flare occurrence as a function of active longitudes, but the resulting peak was shorter and broader as compared with the analysis using sector boundaries. It appears that solar sectors are more precisely defined than are active longitudes.

(2) I quite agree, and believe that the X-ray maps are a very promising technique.

Bumba: If we compare the 'supergiant regular structure' I showed before with Dr Wilcox's fine structure of interplanetary magnetic field sectors, we may see that individual smaller structures, in the photospheric magnetic field distribution (the internal structure of the supergiant features) nicely coincide with Dr Wilcox's 'subsectors' and other details.

Newkirk: One aspect of the sector structure appears to imply a contradiction. On the one hand we have the sector structure itself which, as you have mentioned, does not participate in the differential rotation. On the other hand there appears to be a statistically preferred position of active regions within the sector structures. The active regions, of course, display differential rotation and this one should expect that any preferred position would be quickly destroyed unless we are dealing with something like a standing wave pattern for the sector structure.

Wilcox: This is indeed an interesting problem. Part of the solution may be found in the property of the photospheric magnetic field to display both *differential* and *rigid* rotation. The field pattern near a solar sector boundary seems to display differential rotation on the time scale of a few Solar rotations and to display rigid rotation on a time scale of several rotations.