# THE INTERPLANETARY AND SOLAR MAGNETIC FIELD SECTOR STRUCTURES, 1962–1968

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ABSTRACT  The interplanetary magnetic field sector structure has been observed from late 1962 through 1968. During this time it has been possible to study the manner in which the sector pattern and its relation to the photospheric magnetic field configuration changes from solar minimum to solar maximum. Observations have also been made relating sector boundaries to specific regions on the solar disk. These and other observations related to the solar origin of the interplanetary field are briefly reviewed.

The interplanetary sector structure has been studied throughout a major portion of the period from August 1962 through December 1968, which corresponds to Bartel's solar rotation numbers 1967 through 1852. There are, however, two major data gaps in the interplanetary data. The first occurs during the interval between Mariner 2 and IMP 1 and amounts to 14 solar rotations. The second is for 9 solar rotations during the interval between IMPs 1 and 2. No large data gaps exist during the remainder of this period.

In constructing the sector pattern, the assignment of polarity was first made on a 3-hr basis, and then on a daily basis or longer. The polarity assigned was that which occurred most frequently during the particular data interval. If no single polarity dominated, the data interval was designated as "mixed." However, it is not clear what percentage was required before a data block was assigned either a positive or negative polarity. During the relatively stable period just prior to solar minimum there was little difficulty in assigning the polarity as there occurred data blocks of several days in which the ratio of occurrence of one polarity to the opposite was as high as 100 to 1 [*Fairfield and Ness*, 1967]. However, beginning with the new solar cycle, long intervals consisting of one dominant polarity occurred less frequently and hence the assignment of polarity was done with less certainty. For example, one

interval designated by one group as mixed was assigned a definite polarity by another [*Coleman et al.*, 1967; *Ness and Wilcox*, 1967].

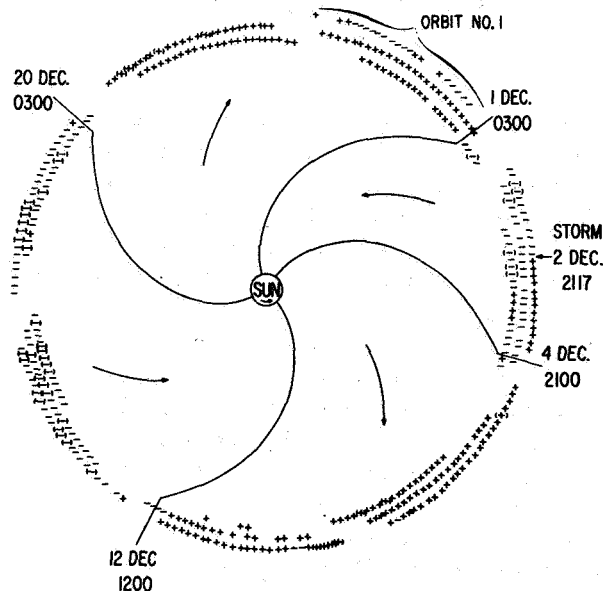Figure 1 illustrates the interplanetary sector structure



**Figure 1.**  *The interplanetary sector structure observed by IMP-1. The + signs (away from the sun) and − signs (toward the sun) at the circumference of the figure indicate the direction of the measured interplanetary magnetic field during successive 3-hr intervals [after Wilcox and Ness, 1965].*

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and shows the well-known 2/7, 2/7, 2/7, 1/7 alternating polarity pattern obtained from IMP 1 data that was reported by *Wilcox and Ness* [1965]. Each polarity symbol (+ or −) represents the dominant polarity observed in each 3-hr interval of the data. The sectors are clearly delineated by the spiral lines separating regions of differing polarity.

Figure 2, which is a sector polarity overlay on the daily C9 character figure for the years 1962 through 1968, portrays the manner in which the sector structure was seen to vary during this period. Each row shows the polarity pattern for one Bartel's solar rotation [*Wilcox and Colburn*, 1970]. The sector configuration is indicated by the shading—the dark intervals referring to

away sectors and the lighter gray intervals to toward sectors. Intervals that are white refer to times of mixed polarity or missing data. Diagonal bars indicate interpolated sector structure.

Referring to figure 2, note that the polarity pattern observed during the declining portion of the solar cycle prior to 1965 is characterized by the slow evolution of the sectors. During the interval between November and December of 1962 the data from Mariner 2 exhibited a 2-sector pattern [*Coleman et al.*, 1966]. The data from IMP 1, obtained between November 1963 and February 1964, showed a 4-sector pattern. A similar 4-sector pattern persisted from September through December 1964, as evidenced by the combined data from IMP 2
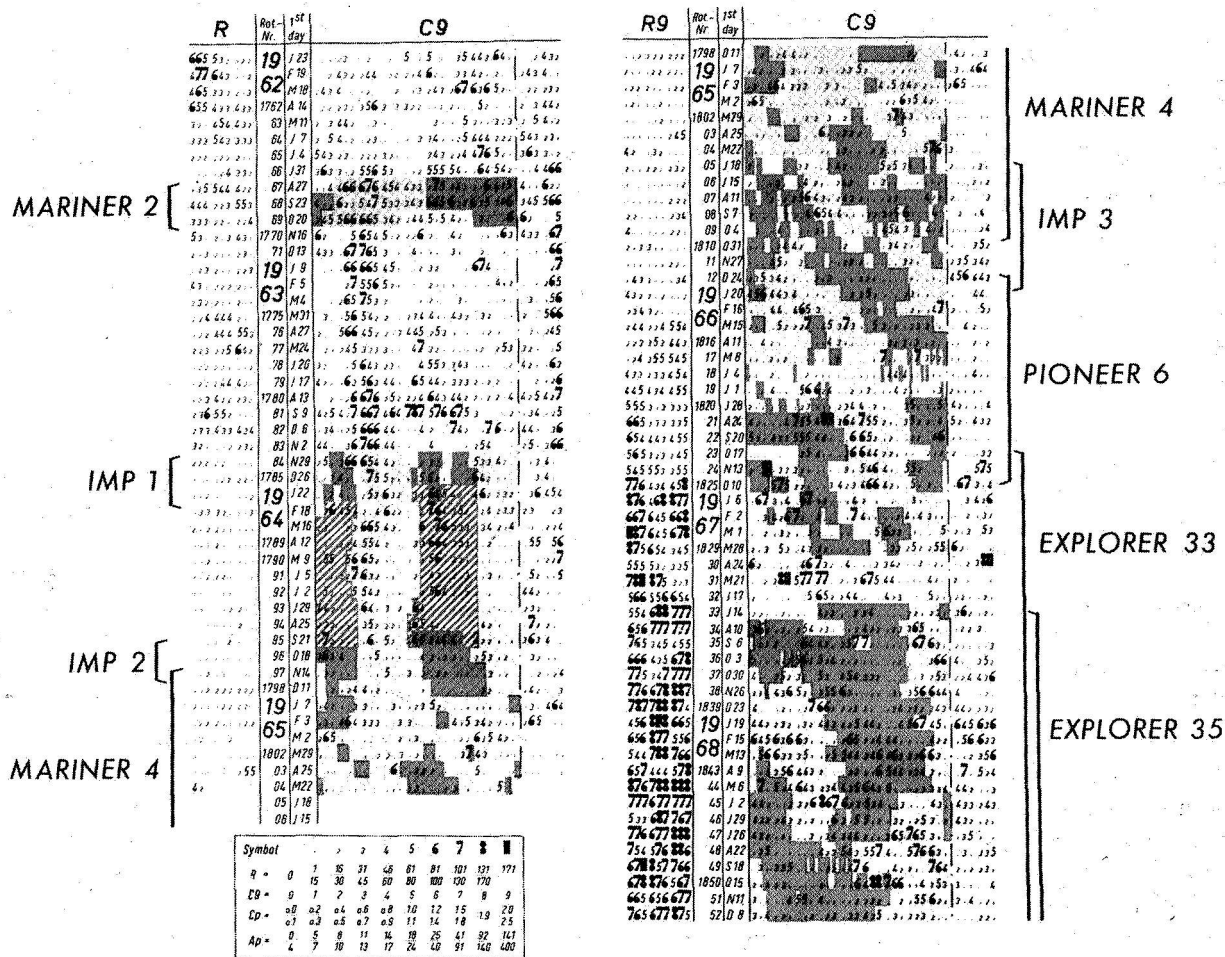


**Figure 2.** *Observed sector structure of the interplanetary magnetic field, overlying the daily geomagnetic character index C9, as prepared by the Geophysikalisches Institut in Göttingen. Light shading indicates sectors with field predominantly away from the sun, and dark shading indicates sectors with field predominantly toward the sun. Diagonal bars indicate an interpolated quasi-stationary structure during 1964 [after Wilcox and Colburn, 1970].*

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and Mariner 4. However, in January 1965, one of the positive sectors disappeared.

The most stable sector configuration to date appears to be that which may have occurred between IMPs 1 and 2. Since this has been inferred by interpolation, we consider this point in some detail. The method of interpolating used was based on the manner in which the geomagnetic index sum $K_p$ varied within the sectors observed by IMPs 1 and 2, and the variation of sum $K_p$ during the interval in question [Wilcox and Ness, 1965; Ness and Wilcox, 1967]. Figure 3 displays the manner in which sum $K_p$ was observed as a function of position in the 2/7 sectors seen by IMP [Wilcox and Ness, 1965].
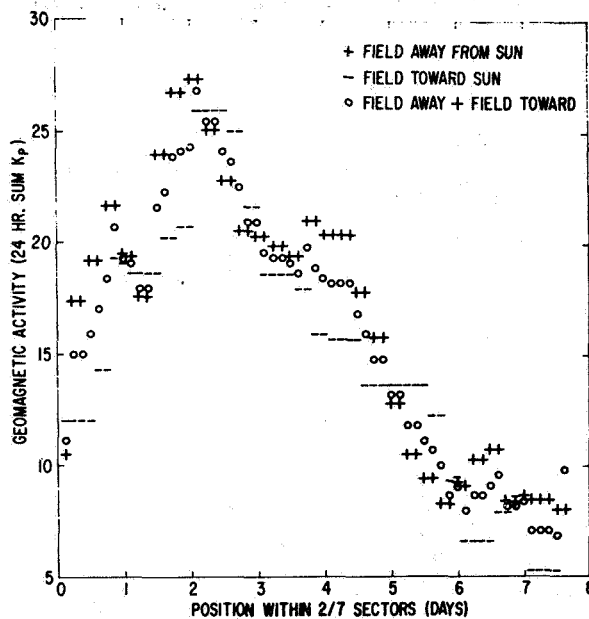


Figure 3. Superposed epoch analysis of the geomagnetic activity index 24-hr sum $K_p$ as a function of position within the 2/7 sectors [after Wilcox and Ness, 1965].

The observed variation in the Deep River neutron monitor counting rate with position in the 2/7 sectors observed by IMP 1 [Wilcox and Ness, 1965] has also been used in support of this interpolated pattern [Wilcox and Howard, 1968]. Also, Asbridge et al. [1967] reported that the galactic cosmic ray intensity measured by the Vela satellites at times exhibited an approximate 7-day periodicity for a number of solar rotations and suggested that this variation may be related to the sector structure observed by IMP 1.

However, neither the variation in geomagnetic activity nor cosmic ray intensity has been shown to be uniquely related to the sector pattern. For example, excellent

correlation between $K_p$ and fluctuations in the transverse component of the interplanetary field have been reported by Ballif et al. [1967, 1969]. Also, the Mariner 2 magnetic field and plasma data showed that whereas it is likely that high velocity streams in the solar wind originate in regions of the solar atmosphere throughout which the magnetic field has a single polarity, adjacent streams having the same polarity produce distinct geomagnetic events and no sector boundary is seen [Snyder et al., 1963; Coleman et al., 1966]. Coleman et al. [1966] have specifically investigated the possible persistence of a sector structure over the interval between Mariners 2 and 4 using observed correlations between geomagnetic effects and the solar wind velocity, and between polarity transitions of the field and minima in the solar wind velocity. They concluded that interpolation of the pattern between one observation and the next may be unreliable.

Figure 2 clearly portrays the rapid evolution of the sector pattern that began in 1965. In many cases the sectors are difficult to identify and the number and widths of intervals of constant polarity show considerable variability. Clearly the original concept of a magnetic sector, so evident in the earlier data, breaks down. Beginning with the latter half of 1966, there is a trend toward fewer sectors, and by 1968 it appears that the number of sectors has again reduced to 2. The evolution of the pattern near solar maximum is quite interesting as 2-sector patterns, differing in phase by about 180°, are separated by a period of about 4 solar rotations in which a 4-sector pattern persisted. During this time, however, it is difficult to see a direct relationship between dominant polarity intervals and the manner in which the $K_p$ index varies (fig. 4). Recalling the Mariner 2 polarity pattern, it is tempting to infer that the gross magnetic polarity pattern of the field may exhibit only 2 sectors during the remainder of the present solar cycle [Wilcox and Colburn, 1970].

A well-defined 27-day periodicity of the interplanetary field was seen in the Mariner 2 data and interpreted as evidence for a connection between the field at 1 AU and large persistent magnetic field patterns on the sun [Davis et al., 1964, 1965; Davis, 1965a, b]. The manner in which the sector pattern tends to move down and to the right suggests that the rotation period of the field may have increased between 1964 and 1966, and then returned to approximately 27 days in 1968. To obtain a quantitative estimate of the manner in which the rotation period of the field may have varied, autocorrelations of the interplanetary field were performed approximately each year from 1963 through 1968 [Ness and Wilcox, 1967; Wilcox and Ness, 1967; Wilcox and
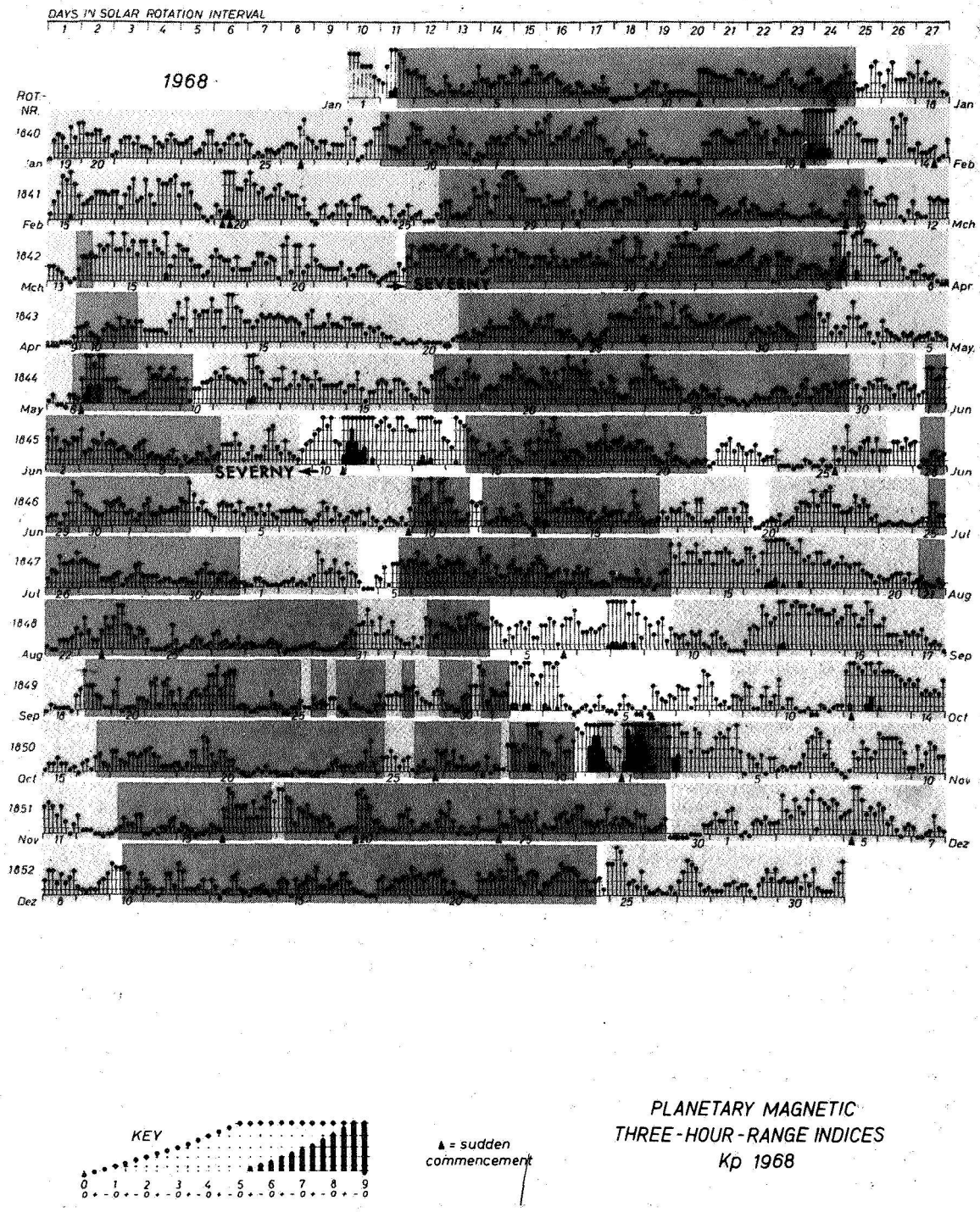
**Figure 4.** *Interplanetary sector structure observed with Explorers 33 and 35 overlying a chart of planetary magnetic 3-hr range indices $K_p$ [after Bartels]. Dark shading is field polarity toward the sun, and light shading is field polarity away from the sun [after Wilcox et al., 1969].*

*Howard*, 1968; *Wilcox and Colburn*, 1969; and *Wilcox and Colburn*, 1970]. Figure 5 summarizes these results and also shows the mean and present variation in sunspot number. The marked increase in the rotation
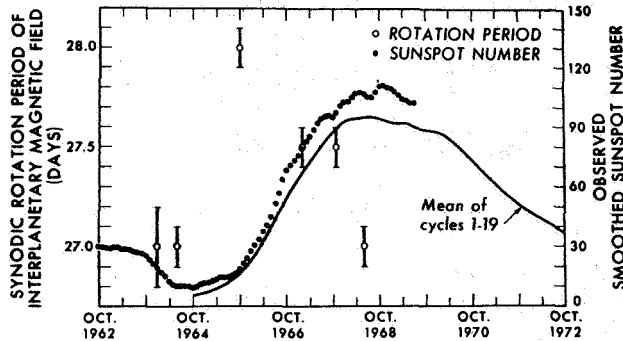


**Figure 5.** *The synodic rotation period of the interplanetary magnetic field and the observed sunspot numbers during the last several years [after Wilcox and Colburn, 1970].*

period that occurred near the beginning of the new cycle is quite evident and suggests that the interplanetary field source could have shifted to higher latitudes at this time much like the sunspots [*Wilcox and Colburn*, 1969], although other possibilities may exist. *Wilcox and Colburn* [1970] suggest that the period will likely remain at 27 days until solar minimum occurs again in 1975.

Some information regarding the variation in general latitude of the solar source of the interplanetary field can be inferred from the observed rotation period of the latter. Figure 6, derived by performing an autocorrelation on latitude strips of the photospheric field data [*Wilcox et al.*, 1970], displays the manner in which the rotation period of the photospheric field varies with heliographic latitude. We see that the variation in period noted previously can be interpreted in terms of a variation in the heliographic latitude of the source. It appears that the average latitude of the source of the observed interplanetary field may have changed from about 15° N during solar minimum to a latitude higher than 25° N near the start of the new sunspot cycle, and then gradually declined as the cycle progressed [*Ness and Wilcox*, 1967; *Wilcox and Colburn*, 1969].

Cross and autocorrelations of the photospheric and interplanetary fields have also been computed by *Ness and Wilcox* [1964], *Winters et al.* [1969] and *Schatten et al.* [1969] to determine the solar origin of the interplanetary sector structure and the manner in which
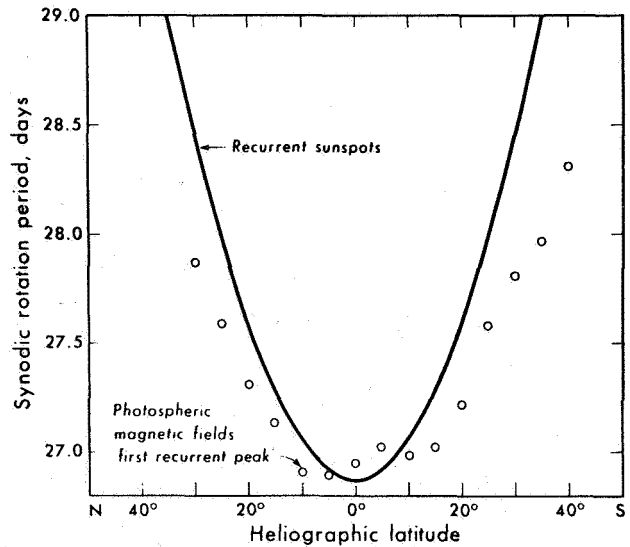


**Figure 6.** *Solar differential rotation. The solid curve represents the results for long-lived sunspots. The circles are at the period associated with the first recurrence peak at each latitude in autocorrelations of photospheric magnetic field direction [after Wilcox et al., 1970].*

any relationship might change as the solar cycle progresses. Using synoptic charts of the photospheric field supplied by R. Howard, *Ness and Wilcox* [1967] obtained cross-correlation coefficients of about 0.8 at a lag consistent with the plasma data when the IMP 1 data were compared to 5° wide latitude strips of the photospheric field data between 15° S and 15° N (fig. 7). It was also found that autocorrelations of the photospheric data between 10° and 20° N displayed the same sector-like character seen in the interplanetary field, in spite of the fact that IMP 1 was 3.5° south. These results suggested a "mapping" relation between the interplanetary and photospheric fields. On the other hand, *Winters et al.* [1969] were unable to duplicate these results using Mariner 4 data. Although poor correlations might be expected as a result of the evolving character of the sector structure noted earlier, one would have expected better correlations if the mapping hypothesis were indeed the case. *Schatten et al.* [1969] found that the IMP 3 data also correlated poorly with the photospheric field data, but they were able to obtain cross-correlation coefficients as high as 0.3 at the proper lag when the interplanetary field was compared instead with a "source surface" field derived from the photospheric field data and corresponding to about $0.5\, R_{\Theta}$ above the photosphere (fig. 8). Thus, it would appear that the relationship seen earlier that led to the mapping hypothesis
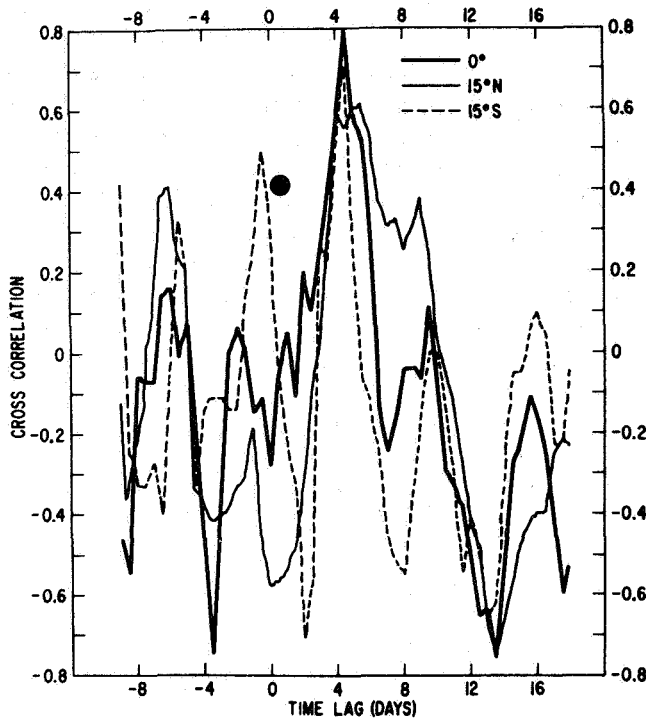
**Figure 7.** *Cross correlation between IMP magnetic field direction (toward or away from the sun) and the photospheric field direction (into or out of the sun) for three latitudes on the sun [after Ness and Wilcox, 1964].*



**Figure 8.** *Cross correlation of the magnetic field calculated on a source surface 0.5 $R_\odot$ above the photosphere 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 35°S to 45°N in intervals of 5°. Arrows at the bottom of the graph indicate time lags of 5 days plus an integral number of solar rotations [after Schatten et al., 1969].*

relating the interplanetary and solar fields may have been unique to that particular data interval.

By performing a cross correlation between latitudinal strips of the solar field and interplanetary sector configuration (40% observed, 60% interpolated) spanning the interval from December 1963 through December 1964, *Wilcox and Howard* [1968] found that a similar photospheric sector configuration may have existed over a range of latitudes of at least 40° N to 35° S (fig. 9). During this period, the pattern was found to change at all latitudes investigated within an interval of a few solar rotations. Because the shapes of the IMP 3 source surface correlations were different in the northern and southern solar hemispheres (fig. 8), *Wilcox* [1970a] has suggested that during the interval from June 1965 to February 1966 the persistent solar magnetic pattern may have been significantly different in the north and south. However, one should note that the correlation peaks obtained in this latter study were only 0.3 to 0.4.
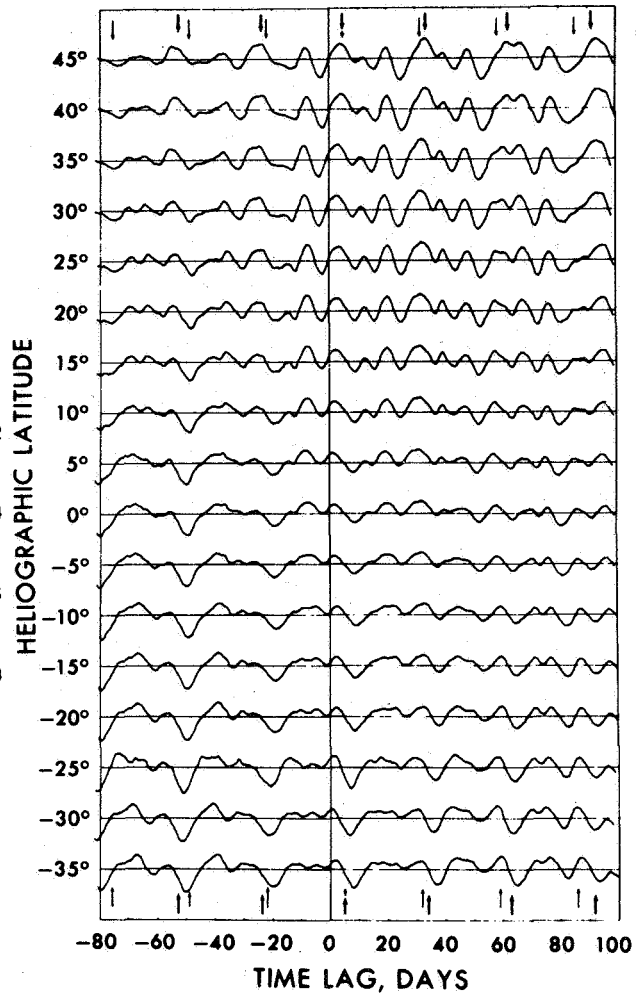
The weighted mean solar field and the interplanetary field near earth for a period of several solar rotations in 1968 have been compared by *Wilcox et al.* [1969] and *Severny et al.* [1970] (fig. 10). They found a peak in the cross-correlation coefficient of nearly 0.7 at a lag of about 4-1/2 days. This significant result has been considered by *Schatten* [1970] who has shown that a high correlation is to be expected because of the similar dependence on subsolar angle of the mean solar field
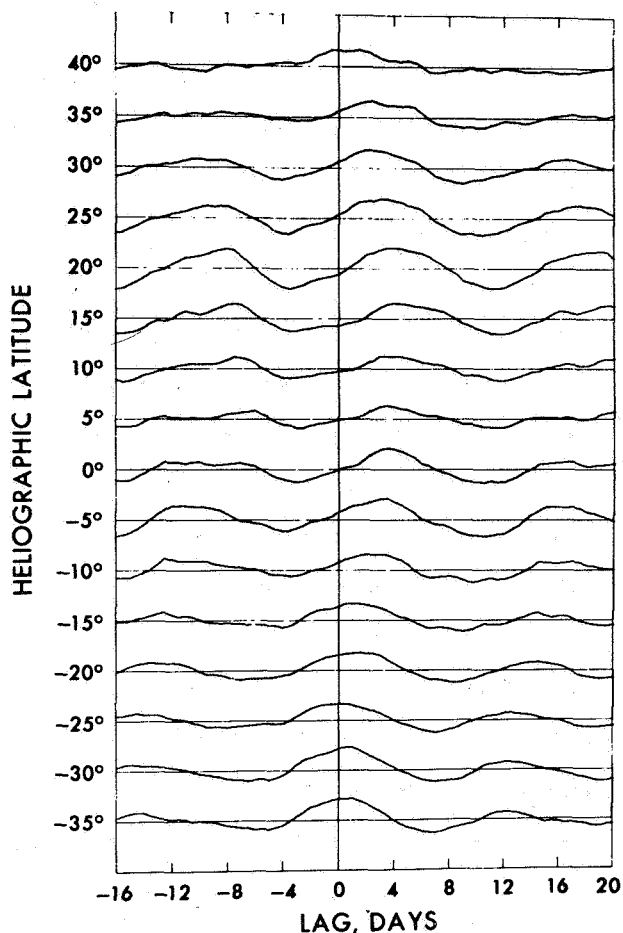
Figure 9. *Cross correlation of the direction of the photospheric magnetic field and an interpolated pattern of the direction of the interplanetary magnetic field during a 1-year interval, from December 1963 to December 1964 [after Wilcox and Howard, 1968].*

weighting factor and the weighting factor present in his source surface model. Assuming a symmetric brightness distribution, the weighting factors for the mean solar field integral and source surface integral for a $2.0\,R_\odot$ surface peak at subsolar angles between $30°$ and $35°$. This apparent outward shift of the source surface to $\sim 2.0\,R_\odot$ appears consistent with the trend suggested by a comparison of the cross-correlation studies in 1963 and 1965 if one interprets the 1963 results in terms of a source surface at the photospheric level. One might conclude, therefore, that near solar minimum, the source surface lies essentially at the photospheric level, and as solar activity increases it moves outward, reaching a peak height above the photosphere of roughly $2\,R_\odot$ near solar maximum.

The mean field results offer an alternate interpretation, however. If one considers the presence of active centers and the attendant biasing effect on the brightness distribution across the solar disk, it would appear that perhaps all we are seeing is an excellent correlation between the magnetic polarity of an interplanetary plasma stream and the smoothed field of the solar active center that is its source. This could be checked by constructing ring averages of the photospheric field that incorporate brightness weighting factors derived from H-alpha and similar photographs of the sun, and comparing these with the mean field data.

Another important result seen in the cross-correlation studies of *Schatten et al.* [1969] and later by *Severny et al.* [1970] is that the magnitude of the correlation peak at a lag of 4-1/2 + 27 days was greater than that corresponding to a lag of 4-1/2 days. *Schatten et al.* [1969] have interpreted this as suggesting that there may be a delay of approximately one solar rotation between the appearance of a new magnetic feature in the photosphere and a change in the interplanetary sector pattern that may result. It will be of great interest to follow changes in the lag over a major portion of a solar cycle. One might ask, for example, whether or not the additional lag always occurs or whether it is necessary that the field configuration in the vicinity of an active region change after it is at least $\sim 45°$ west of CMP.

On an even larger scale, *Rosenberg and Coleman* [1969] have found evidence suggesting that the dominant polarity of the interplanetary magnetic field follows the direction of the sun's dipolar field except perhaps just before solar minimum, near solar maximum, and at other times of high geomagnetic activity [*Rosenberg*, 1970]. They found, for example, that between 1965 and 1967 the dominant polarity of the interplanetary field was inward at heliographic latitudes above the solar equatorial plane and outward at latitudes below this plane. They also suggest that different polarity sectors can originate from different solar latitudes. However, *Wilcox* [1970b] extended this type of analysis to include the 1968 and 1969 data from Explorers 33 and 35 and found a disagreement between the observed polarity and the predicted curve. Wilcox has proposed that the 1965 result reported by *Rosenberg and Coleman* [1969] could be easily explained in terms of the dominant polarity exhibited by the synoptic charts of the photospheric magnetic fields at this time. On the other hand, *Rosenberg* [1970] attributes the negative results obtained with the 1968 and 1969 data to a southward shift of the dipolar field
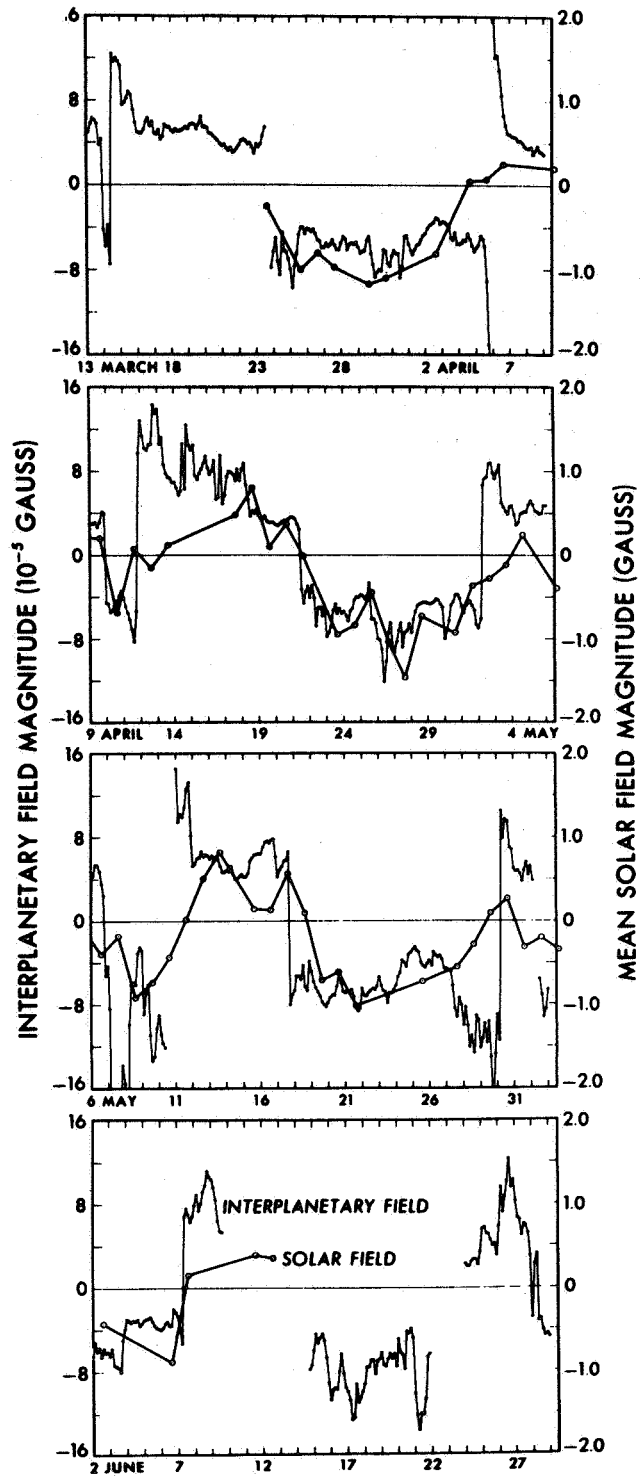
**Figure 10.** *Comparison of the magnitude of the mean solar field and of the interplanetary field. The open circles are the daily observations of the mean solar field, and the dots are 3-hr average values of the interplanetary field magnitude observed near the earth. The solar observations are displaced by 4-½ days to allow for the average sun-earth transit time. The abscissa is the time of the interplanetary observations [after Severny et al., 1970].*

boundary in space that was caused by dominating activity in the northern hemisphere at this time. Data obtained during the new solar cycle should offer critical tests for the models that have been proposed.

There has also been much attention given to the solar source of the sector boundary and its effect on geomagnetic activity. Results of several radio interferometric studies of the sun have recently been reported which offer crucial information regarding the possible solar origin of sector boundaries. *Couturier and Leblanc* [1970], operating at 169 mHz, have recently found that coronal enhancements occur just eastward of solar sector boundaries although figure 11 shows that the converse is not necessarily true. *Wilcox* [1970a] has postulated the existence of subsectors.
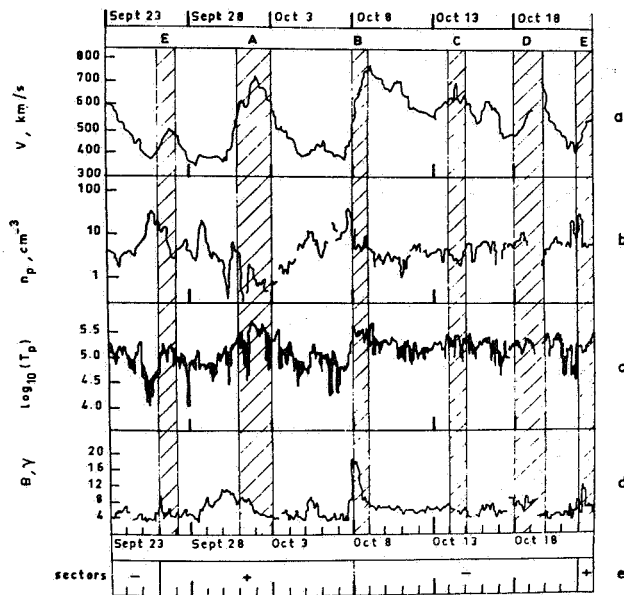


Figure 11. *Solar wind activity during solar rotation 1968. The vertical hatched regions represent CMP of coronal enhancements. a, solar wind velocity, b, proton density, c, temperature (upper and lower limits) d, interplanetary magnetic field magnitude, and e, sector polarity pattern [after Couturier and Leblanc, 1970].*

Using interferometer data obtained at 169, 408, and 9300 mHz, *Martres et al.* [1970] found further that coronal condensations associated with eruptive active centers are never found coincident with sector boundaries, but are related to the size of the sectors. They also found that when sector boundaries do follow coronal condensations, the meridian passage of a sector boundary always occurs within one day of the observed

crossing of the coronal condensation. In addition, the effect of active centers is to systematically displace the boundary toward the east.

The manner in which the 3-hr geomagnetic index $K_p$ varies with time relative to the passage of a sector boundary may also have important implications in this regard. Using IMP 1 data, *Wilcox and Ness* [1965] found that when a superposed epoch analysis of $K_p$ as a function of position within the 2/7 sectors was performed, the geomagnetic index exhibited a rapid increase after the passage of a sector boundary, reached a peak about 2 days later, and then slowly declined. This type of relationship was also noted then a comparison was made using the IMP 2 data [*Ness and Wilcox*, 1967]. A similar type of study has been performed using data related to the rising and maximum portions of the solar cycle by *Wilcox and Colburn* [1969, 1970]. The results for these three periods are shown in figure 12.
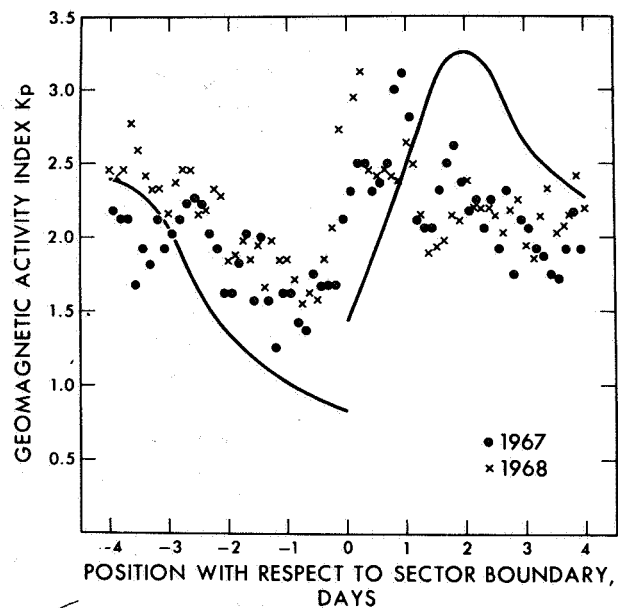


Figure 12. *Superposed epoch analysis of the magnitude of the planetary magnetic 3-hr range indices $K_p$ as a function of position with respect to a sector boundary. The abscissa represents position with respect to a sector boundary, measured in days, as the sector pattern sweeps past the earth. The solid line represents similar results obtained near solar minimum by Wilcox and Ness [1965], and the dots and crosses represent results obtained during the rising portion and near solar maximum, respectively [after Wilcox and Colburn, 1970].*

The same general relationship noted in the earlier data appears to be present although some differences are seen, perhaps resulting from the different level of activity. During the later periods, $K_p$ appears to increase more rapidly, and the peak appears to have moved closer to the time of the boundary crossing. One also notes that for 1967 and 1968 the minimum in $K_p$ occurs as much as 18 hr before the sector boundary crossing. If real, this effect could be interpreted as an eastward shift in the position of the sector boundary with respect to the plasma stream causing geomagnetic activity that results from the increased level of activity at the sun in a manner consistent with the radio data. Evidence has also been given by *Ballif and Jones* [1969a,b] and *Ballif et al.* [1971] suggesting a direct relationship between localized flare producing regions on the sun and the geomagnetic and cosmic ray variability measured at earth. Certainly, regions of localized activity on the sun must play an important role in solar-terrestrial relations.

## ACKNOWLEDGEMENTS

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DISCUSSION    *J. M. Wilcox*    I rise to the defense of the sector interpolation in 1964. The physical evidence cited by Doug Jones has always seemed fairly convincing to me, but there is very recent evidence that, from observing the geomagnetic field in the polar regions, a close correlation with the sector polarity is obtained in the sense that in an away sector the field lines leaving the polar region near the north pole have a larger drag on them than would be the case in a toward sector. Using this one again finds the same four-sector polarity through the interval in which the interpolation was made.

COMMENTS

*E. J. Smith*    This short contribution deals with the propagation of sector boundaries over widely separated points in space. E. J. Rhodes and I have just finished a study of sector boundaries using Mariner 5 magnetic field data. Mariner 5 was on its way toward Venus at the time. Those measurements were compared with measurements of the interplanetary field near earth by Explorers 33 and 35. It seemed appropriate to show these data at this session because, as you heard this morning, there are several studies under way that attempt to relate the sector boundaries in interplanetary space to solar magnetic fields. In addition, what happens to the sector boundaries as they propagate from the sun to the earth is one way of studying the large scale interactions that are occurring in the solar wind.

Figure 1 shows the essential geometry of the problem. The Mariner trajectory is shown as projected into the plane of the ecliptic. The horizontal direction is the sun-earth direction. Solar rotation numbers are marked along the trajectory. As you can see, the difference between the two spacecraft grew to be as large as about 0.3 AU, and, similarly, the angular separations grew to be substantial. We have used the sector boundaries identified by Wilcox and Colburn to find the corresponding sector boundaries in our data. We then used the corresponding sector boundaries to determine the propagation time between the two points of observation.

The results are shown in figure 2, which is simply a plot of the observed time delay versus the day number of the year. The time delays are represented by points and vertical lines. The lines indicate either a data gap or an uncertainty in identification. The curves
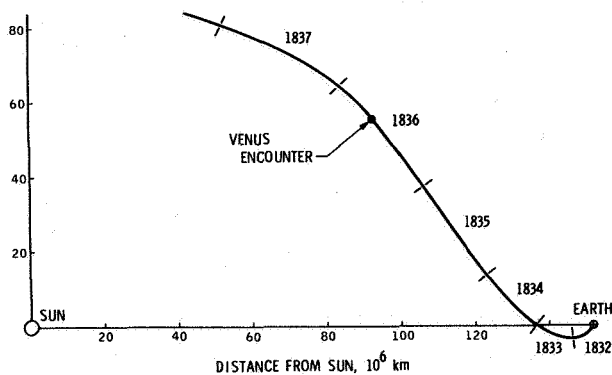
**Figure 1** *Mariner 5 trajectory projected into the plane of the ecliptic.*
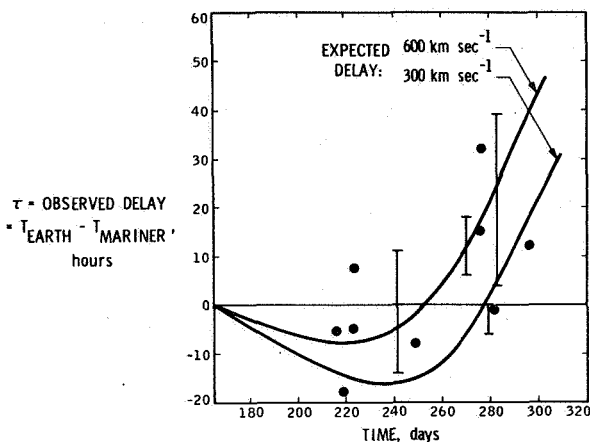


**Figure 2.** *Observed and expected delay times for sector boundaries at Mariner 5 and at the earth.*

drawn through the data show the expected time delays corresponding to two solar wind speeds, one at 600 km/sec and the other at 300 km/sec. These values bracketed the minimum and maximum velocities measured at Mariner during this time interval.

There is a general correspondence between the observations and the expectations based on a simple model of the solar wind, namely, assuming constant solar wind speed. But there are very large deviations, some of which are as large as one day. Figure 3 was prepared in an attempt to reduce the scatter somewhat and to investigate the causes of these deviations. We calculated the time delay not on the basis of some average solar wind speed but using the actual speed as measured by the Mariner plasma probe. Knowing when the solar wind carried the sector boundary past Mariner 5, and assuming that the wind speed would be constant for the remaining distance to earth, it was possible to compute the delay time. Plotted here are the residuals, which are the differences between the observed and computed delays, assuming a constant solar wind speed between Mariner 5 and earth. Again, the residuals or deviations are quite large. Several deviations seen here are as large as a day. There appears to be a tendency for more of the sector boundaries to arrive late at earth than early.

We interpret these results from two points of view. First, we believe the reason for the large discrepancies is the interaction between adjacent solar wind streams. There are any number of interaction effects that might be invoked. We are investigating several now. I'm
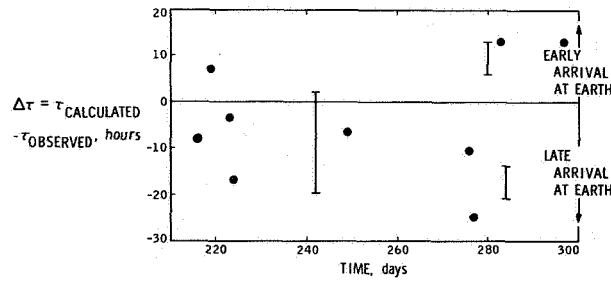
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$$\Delta\tau = \tau_{CALCULATED} - \tau_{OBSERVED}, \text{ hours}$$

EARLY ARRIVAL AT EARTH

LATE ARRIVAL AT EARTH

TIME, days

**Figure 3.** *Difference between calculated and observed delay times for sector boundaries observed at Mariner 5 and at the earth. The solar wind velocities observed by Mariner 5 were used in the calculation.*

a little partial, myself, to an explanation based on the deflection of the solar wind as a result of these interactions. One need not have a very large deflection, say only 5° or so, to account for the differences in the delays as large as those that are actually being seen.

The other viewpoint concerns the desire to make the sector boundary measurements near earth and extrapolate backwards toward the sun. One has to be careful in doing that because deviations as large as a day would correspond to something like 10° to 15° in longitude on the sun. Of course, how important such errors are, and how significant these deviations are, will depend on what it is you're trying to study.

DISCUSSION

*A. J. Dessler* Would you say the fact most of them arrive late means that interactions are all decelerating interactions or wouldn't you? Those interactions between adjacent streams, wouldn't you have as many arriving early as late?

*E. J. Smith* Well, you might think so; I think there probably are several factors involved. But based just on a preliminary investigation I think that the sector boundaries much more commonly than not tend to occur in the velocity minima ahead of the solar wind streams. And I think that then there is a preferential deflection in the solar wind flow. That's the sort of hypothesis I'm investigating now.

*R. L. Carovillano* I wonder if your study might not be able to reflect a little bit on whether the neutral sheet has one shape or another. For example, whether we have something that is fluted, going around azimuthally, or something like an orange peel, or something like that. Various interpretations might be implied by fitting your delay time to various geometries.

*K. H. Schatten* I think these observations point out non-Archimedean spiral nature of the field at times, and that it is only a spiral on the average, and deviations occur. I think we might try to improve the correlations of observed delay times by calculating not just an average Archimedean spiral field but rather, say, using the observed field to get what the shape of the field is as it's going by between the two points, or utilizing the observations of velocity and calculating the field deflection from the gradient in the velocity. And you might try that on these delay times.

*E. J. Smith* That would give you a longitude density, right.

*J. M. Wilcox* You pointed out if one observes the sector boundary at earth and takes it back to the sun, the result is uncertain by plus or minus a day or so. In other words, plus or minus 15°.

*E. J. Smith* That's correct, that's right.

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*J. M. Wilcox* It may be worth noting that the observations of the mean solar field that are now in progress will probably help this, because one is then observing directly at the sun. It seems quite likely that we can get the time at which the field goes through zero or, in other words, the time when the sector boundary should be centered near central meridian, up to within a couple of hours; which would greatly facilitate comparisons with other solar features.