THE STRUCTURE OF THE HELIOSPHERIC CURRENT SHEET: 1978-1982

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ABSTRACT

The structure of the heliospheric magnetic field changes substantially during the 11 year sunspot cycle. We have calculated its configuration for the period 1976 through 1982 using a potential field model, continuing our earlier study near solar minimum in 1976 - 1977 (Hoeksema et al. 1982). In this paper we concentrate on the structure during the rising phase, maximum, and early decline of sunspot cycle 21, from 1978 to 1982.

Early in this interval there are four warps in the current sheet (the boundary between interplanetary magnetic field (IMF) toward and away from the Sun) giving rise to a four-sector structure in the IMF observed at Earth. The location of the current sheet changes slowly and extends to a heliographic latitude of approximately 50°. Near maximum the structure is much more complex with the current sheet extending nearly to the poles. Often there are multiple current sheets. As solar activity decreases the structure simplifies until, in most of 1982, there is a single, simply shaped current sheet corresponding to a two-sector IMF structure in the ecliptic plane.

The Sun's polar fields, not fully measured by magnetographs such as that at the Stanford Solar Observatory, substantially influence the calculated position of the current sheet near sunspot minimum. We have determined the strength of the polar field correction throughout this period and include it in our model calculations. The lower latitude magnetic fields become much stronger as the polar fields weaken and reverse polarity near maximum, decreasing the influence of the polar field correction. The major model parameter is the radius of the source surface, the spherical surface at which the field lines become radial. Correlations of IMF polarity observed by spacecraft with that predicted by the model calculated at various source surface radii indicate that the optimum source surface radius is not significantly different from 2.5 R_s during this part of the solar cycle.

I. Introduction

Great changes occur in the structure of the heliospheric magnetic field during the course of the sunspot cycle. Near minimum the current sheet, the boundary between magnetic field toward and away from the Sun, is nearly equatorial, with four small excursions away from the solar equatorial plane in each rotation. Since the ecliptic plane is tilted only 7° to the solar equator even these small 10 - 15 degree excursions are large enough to affect the Earth and produce the four-sector structure commonly observed in the interplanetary magnetic field (IMF) near minimum (Svalgaard & Wilcox, 1975).

In an earlier paper Hoeksema et al. (1982) discussed the heliospheric magnetic structure during the early rising phase of sunspot cycle 21 as determined by applying a potential field model (first introduced by Schatten et al., 1969 and Altschuler & Newkirk, 1969) to the photospheric magnetic field observations made at the Stanford Solar Observatory in 1976 and 1977. We refer to that paper for detailed descriptions of the model, the observations, the simple current sheet structure near minimum, and of comparisons with the observed IMF polarity at Earth. In this paper we continue that analysis through the rising phase, maximum, and the beginning of the declining phase of the current sunspot cycle, from 1978 through 1982. We conclude with a discussion of the source surface radius selection and polar field correction.

The large scale structure evolves slowly throughout this entire interval. The latitudinal extent of the structure increases from approximately 30° early in 1978 to nearly 90° in 1979. Near maximum, 1979 - 1980, the structure becomes quite complex. Often for several consecutive rotations there are isolated current sheets, some of which are observed in the IMF polarity at Earth. The structure simplifies in 1981 as activity begins to decline and is reminiscent of the pattern in 1978: four equatorial sectors with large excursions in solar latitude but having the polarity of the solar poles reversed. In late 1981 and 1982 the structure simplifies even further to a situation indicating two sectors in the IMF. Late in 1982 four sectors reemerge.

We have compared the IMF polarity observed at Earth with that predicted from the calculations of the heliospheric magnetic structure throughout the entire interval. There is little change in the quality of the prediction from 1976 to 1980 during which the correlation coefficient is about 0.58. The simpler structure in 1981 and 1982 is predicted somewhat more accurately (correlation coefficient of about 0.68). Most errors are in the timing of sector boundaries rather than isolated errors, indicating that the general structure is predicted quite accurately while the details are subject to the effects of variable solar wind velocities, solar wind plasma accelerated by flares, and other causes.

While such comparison is one of the few possible tests of the model, it is important to note that this provides only a weak constraint. Earth and most spacecraft sample only the narrow region within 7° of the solar equator. Much of the interesting activity takes place at higher latitudes. When spacecraft can provide reliable measurements of solar wind parameters out of the ecliptic there will be a conclusive way to test the results of the potential field model at higher latitudes. We look forward to the International Solar Polar Spacecraft. The considerations described here could be used to predict what such a spacecraft would observe.

Comparison can also be made with direct coronal observations. Comparing computed current sheet locations near sunspot minimum with those derived from maximum polarization brightness measurements obtained with the Mauna Loa coronometer suggests that there is generally good agreement between the two methods (Wilcox & Hundhausen, 1983).

The Sun's polar field strength is very important for the potential field model results (Pneuman et al., 1978, Burlaga et al. 1981, Hoeksema et al. 1982, and Levine et al., 1982). This is especially true near sunspot minimum when the polar fields are strong and the lower latitude fields are relatively weak. The Stanford Solar Observatory magnetograph is a low resolution instrument and does not measure the flux in the polar regions completely. Only when the polar fields are corrected does the potential field model accurately predict the extent in latitude of the current sheet. We have determined the strength of the solar polar field correction for the entire interval by extending the method of Svalgaard et al. (1978) and have included it in the calculations. Near maximum the polar fields weaken and ultimately reverse polarity. Meanwhile the lower latitude fields become much stronger. This suggests that the relative importance of the polar fields in determining the magnetic configuration in the equatorial region is much less near maximum than near minimum.

The only free parameter in the model is the location of the source surface. We use a spherical surface at which we assume the field lines are radial and open to the solar wind. From the source surface it is assumed that the solar wind carries the magnetic field radially outward. Comparing the correlation of observed IMF polarity with that predicted by the model computed at several different source surface radii, we find that there is no significant change with time in the distance at which the source surface should be located. In light of the insensitivity of the determination of the optimum source surface radius, we will use a radius of 2.5 R_s in our discussions which reflects the uncertainty of about 0.25 R_s. At no time does the correlation with the observed IMF polarity using a radius of 1.6 R_s approach the accuracy of that at 2.5 R_s.

II. The Rising Phase of the Sunspot Cycle

The radial field strength at the source surface for Carrington Rotation 1665 is represented by a contour plot in Figure 1. This magnetic configuration is characteristic of the heliospheric structure throughout 1978. Dashed lines represent regions where the field is directed toward the sun and the solid lines field away from the sun. The heavy

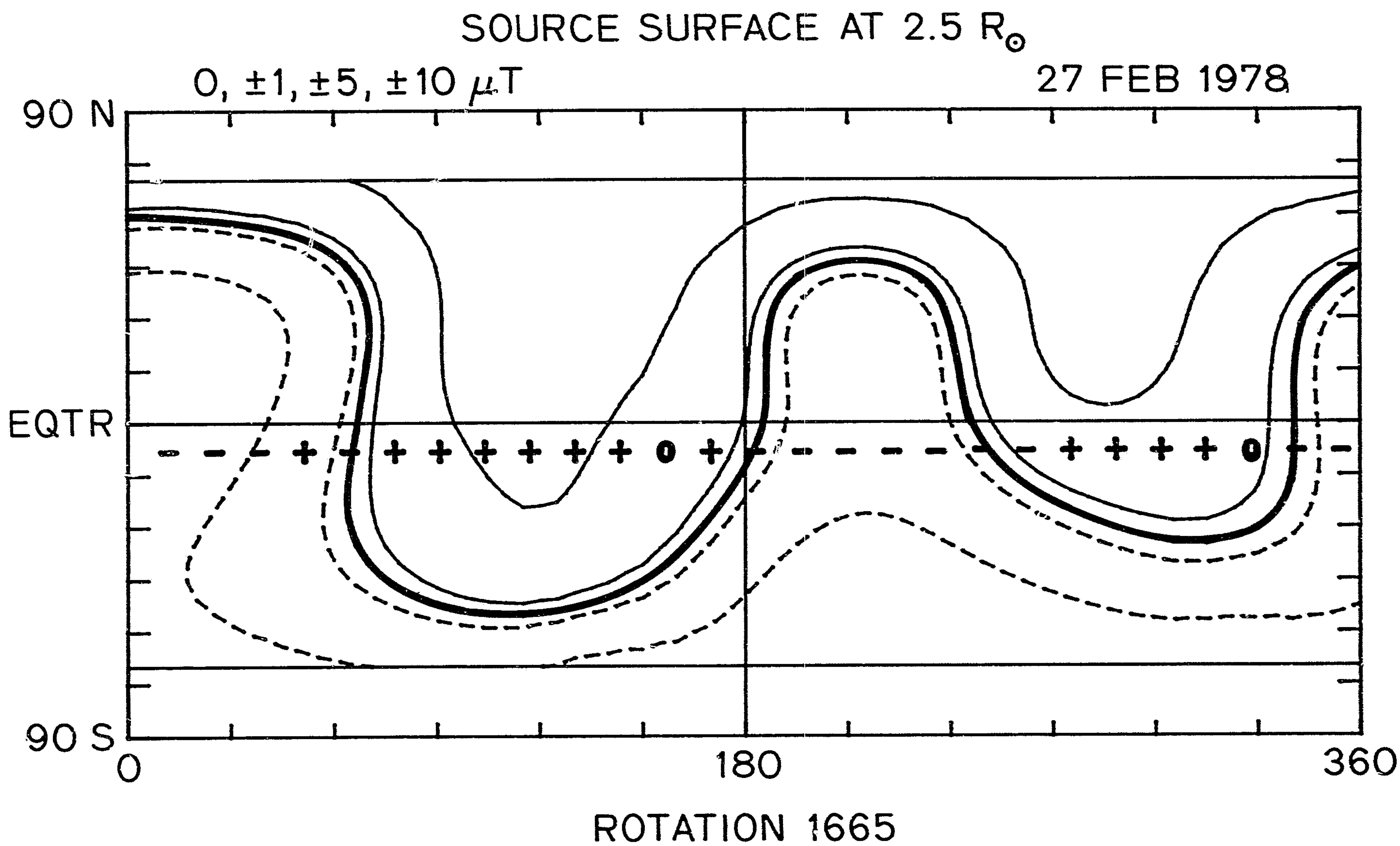

Figure 1. The radial field computed at the source surface for Carrington Rotation 1665 is typical of the interval 1978–1979. The contour levels are at 0, ± 1, 5, and 10 microtesla. Negative contours (toward the Sun) are dashed. The 0 contour, corresponding to the current sheet, has been broadened. Daily averages of the IMF polarity observed at Earth and corotated back to the source surface assuming a transit time of 5 days are plotted as a series of +'s, −'s and o's at the heliographic latitude of the Earth. The sector structure at Earth is much the same as it was near minimum though the current sheet extends to almost 60° latitude.

solid line is the contour of zero radial field. Extension of this contour line radially outward by the solar wind defines the current sheet in the heliosphere. We will henceforth refer to this line as the current sheet. Also plotted in this figure at the heliographic latitude of Earth are plusses and minuses representing daily averages of IMF polarity measurements made near Earth. These measurements are typically from spacecraft such as the International Sun-Earth Explorer-3 (ISEE-3) or from the Interplanetary Medium Data Book (King, 1979), but are occasionally inferred from geomagnetic activity (Svalgaard, 1976) when spacecraft measurements are not available. These values have been corotated back to the source surface assuming a propagation time from Sun to Earth of five days.

There are two extensions of the current sheet north of the equator and two extensions south of the equator, predicting a four-sector structure at Earth. The magnetic field polarity on the source surface agrees well with that observed at Earth five days later. The current sheet extends to a latitude of about 60° in each hemisphere so we would expect that a spacecraft anywhere within 60° of the equator would observe a four-sector structure similar to that at Earth. This is in contrast to the period near solar minimum in 1976 when the current sheet extended to only about 15° and Pioneer 11, at a latitude of 16° north, observed only a single polarity (Smith et al., 1978).

We now consider the evolution of the field structure. Figure 2 shows the current sheet at the source surface for Carrington Rotations 1641 through 1669, May 1976 through June 1978. Observations began at Stanford during Carrington Rotation 1641. The format for each rotation is the same as in Figure 1 except that only the zero contour is plotted (i.e. the locus of the current sheet). Regions of negative polarity (toward the Sun) are shaded. We have included an additional half rotation from the previous and following synoptic maps at the ends of each Carrington Rotation so that structures near rotation boundaries can be seen more easily. Evolution in the large scale structure occurs slowly with a time scale of several months. The basic pattern of two northward and two southward extensions of the current sheet persists throughout this interval. The locations of maximum latitudinal extent shift only a little in longitude. For example, the northward bulge of the current sheet near 30° longitude, already apparent in rotation 1641, is present through at least rotation 1670. This corresponds to a persistent toward polarity structure in the observed

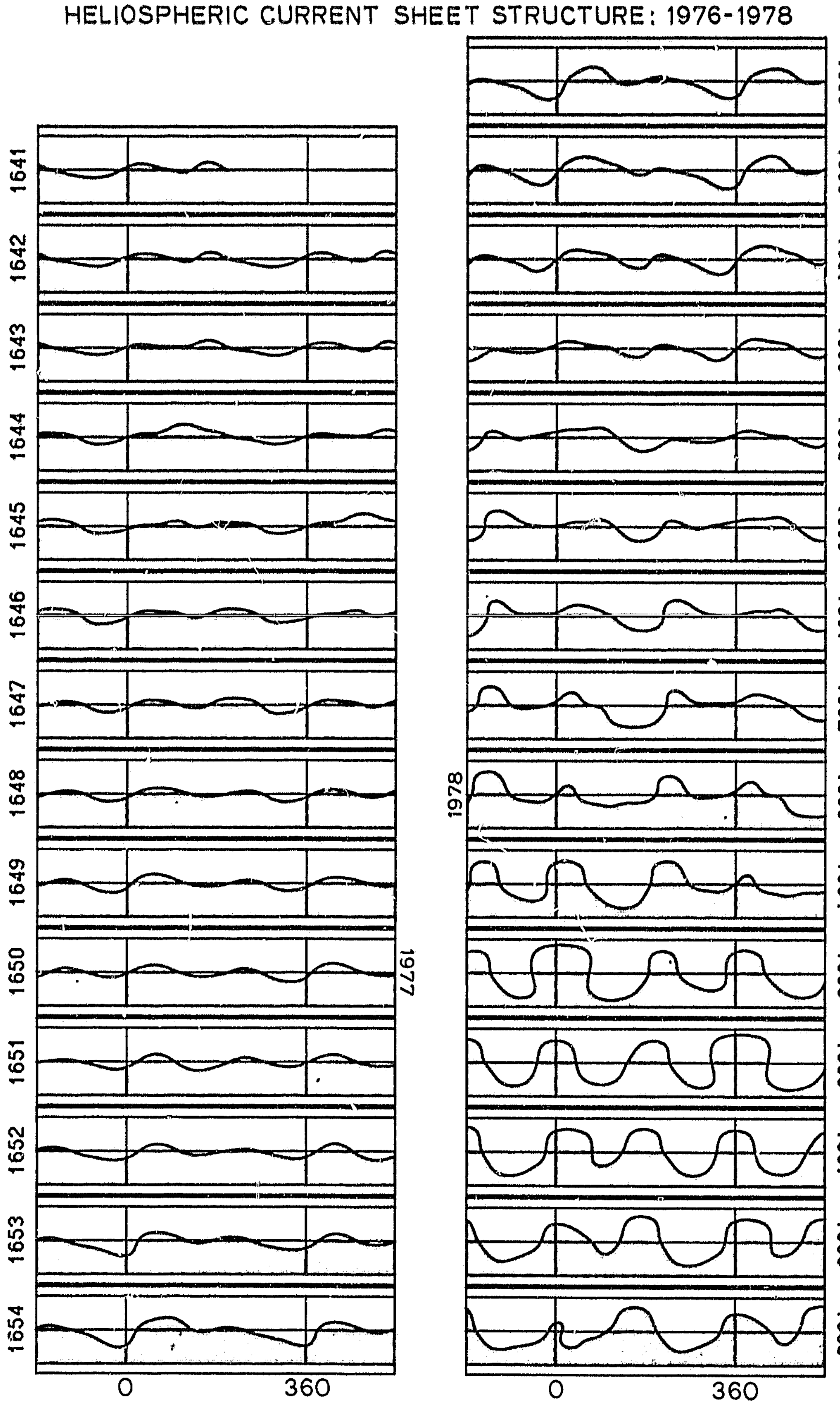

Figure 2. The heliospheric current sheets for Carrington Rotations 1641-1669 are shown. Regions of negative polarity are shaded. Each box shows the labelled rotation plus half a rotation added to each side; each box is two rotations wide so that structures near the ends of a rotation can be traced more easily. Vertical lines show rotation boundaries. Horizontal lines denote $\pm$ 70° and the equator. Rotations which include January 1 are labelled in the center with the year. The latitudinal extent of the current sheet increases greatly from 1976 to 1978, though the underlying 4-sector pattern in the ecliptic plane persists. Most features can be traced for at least 10 rotations and show little distortion by differential rotation.

Figure 2

IMF polarity. Other features show much the same longevity with only small, slow drifts in longitude. A permanent marked increase in latitudinal extent and size of the warps in the current sheet occurs in early 1978 (rotations 1663 - 1665) and the pattern begins to drift slowly westward (left).

Each Carrington Rotations is 27.28 days long. Features on the sun which rotate with a synodic period of 27 days will arrive a little earlier on each successive rotation. This will be observed as a drift to the right of about 3.5 degrees per rotation or about 55° in 15 rotations. For comparison, some structures in the IMF recur with a period near 28.5 days (Svalgaard & Wilcox, 1975) which would be observed as a rather rapid drift to the left of about 20° per rotation.

Generally this interval can be characterized by slow changes in the heliospheric magnetic field. The major change is in the latitudinal extent of the current sheet. The large scale structure does not in general participate in differential rotation. This has been noticed earlier for large scale photospheric magnetic structures (Wilcox et al., 1970), for the green line corona (Antonucci & Svalgaard, 1974) and for coronal holes (Timothy et al., 1975).

III. Sunspot Maximum

Near maximum, 1979 - 1980, the field structure was more complex. The dominance of the polar fields gradually disappeared and the current sheet commonly extended to the poles. The format for Figure 3 is the same as for Figure 1. The structure shown for Rotation 1679 is fairly typical of the structure near maximum. There were two large unipolar regions on the source surface with a smaller region of the opposite polarity in each. At Earth only two sectors were observed. The positive region near 45° longitude was connected to the positive polar region, but did not extend far enough south to intersect the latitude of the Earth. The main current sheet extended almost from pole to pole in an approximately north-south direction at 150° and 330° longitude; spacecraft at any latitude would have seen a change in IMF polarity. The small negative polarity region at 270° was completely disconnected from the large negative region thus forming a second closed current sheet. The second current sheet lay in the Sun's northern hemisphere and would therefore have been detected only by an observer there. The Earth at that time was several degrees south of the solar equator and so did not see the effect of this region.

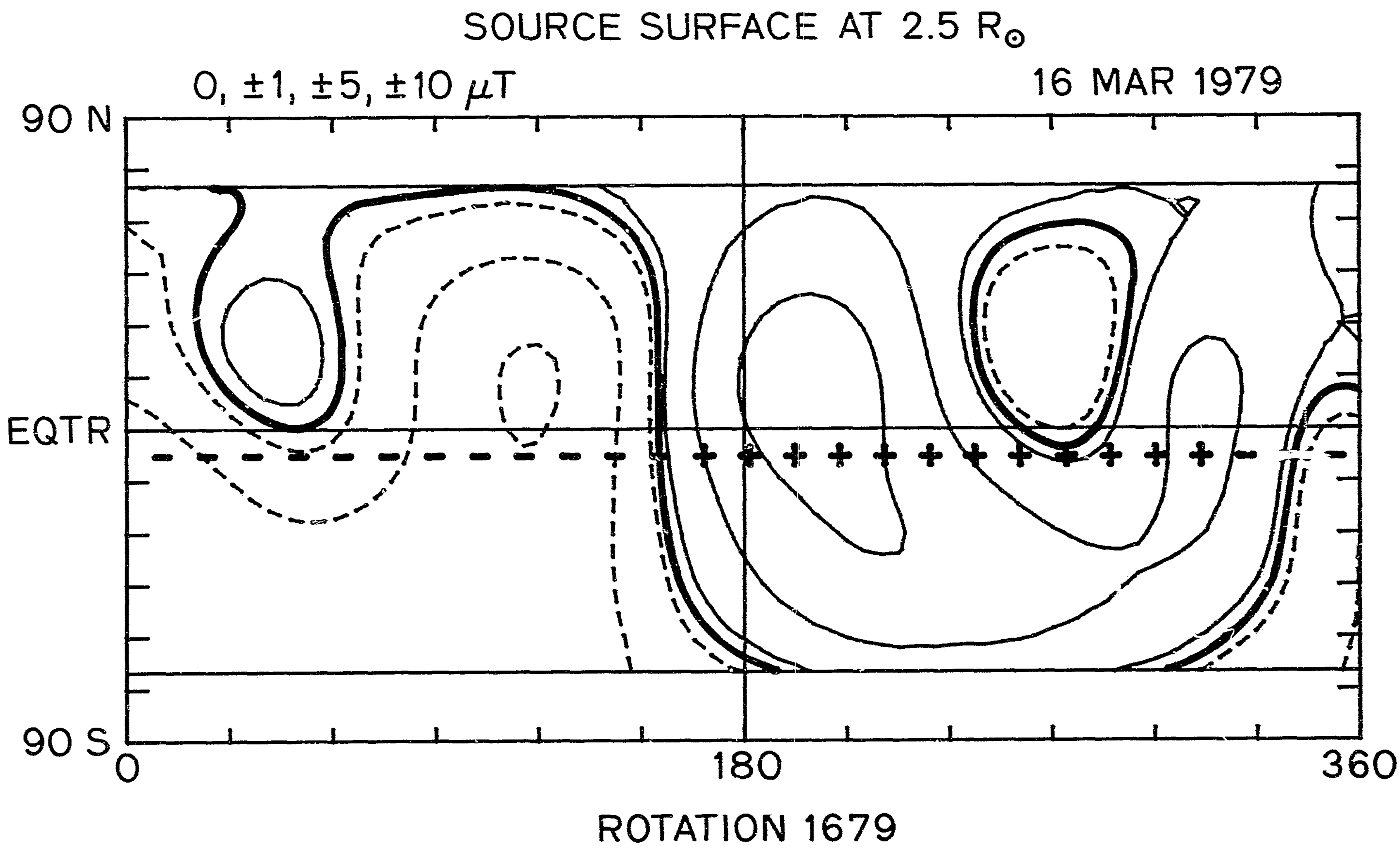

Figure 3. Carrington Rotation 1679 is shown in the same format as Figure 1. There is a disconnected current sheet near 270° longitude in the northern hemisphere which does not intersect the latitude of the Earth. A two-sector pattern is observed at Earth. Such complex configurations of the current sheet are common during the period near sunspot maximum.

Carrington Rotation 1698, shown in Figure 4, is another typical example. Near longitude 90 a positive region connected to the south pole intersected the latitude of the Earth and there was a single day of away polarity. A second current sheet enclosing positive polarity, somewhat larger than in Rotation 1679, intersected the latitude of Earth. There was an away sector corresponding to it in the IMF.

During the interval near maximum, changes in magnetic configuration occurred somewhat more rapidly, yet individual features last for a long time. Figure 5 shows the current sheets for Carrington Rotations 1670 - 1699, July 1978 through September 1980, in the same format as Figure 2. The polarity of the solar polar fields reversed near the beginning of 1980 -- about Carrington Rotation 1690. Many rotations exhibit multiple current sheets and often there are two sheets at the same longitude. From one rotation to the next the changes are usually small: a region of magnetic flux may grow a little, shrink a little, drift a little in longitude or latitude, or connect in a different way with the surrounding regions of flux. The transition of the polar fields from one polarity to the other occurs smoothly. Catastrophic changes in field alignments or structure occur neither near the poles nor at the latitude of the Earth.

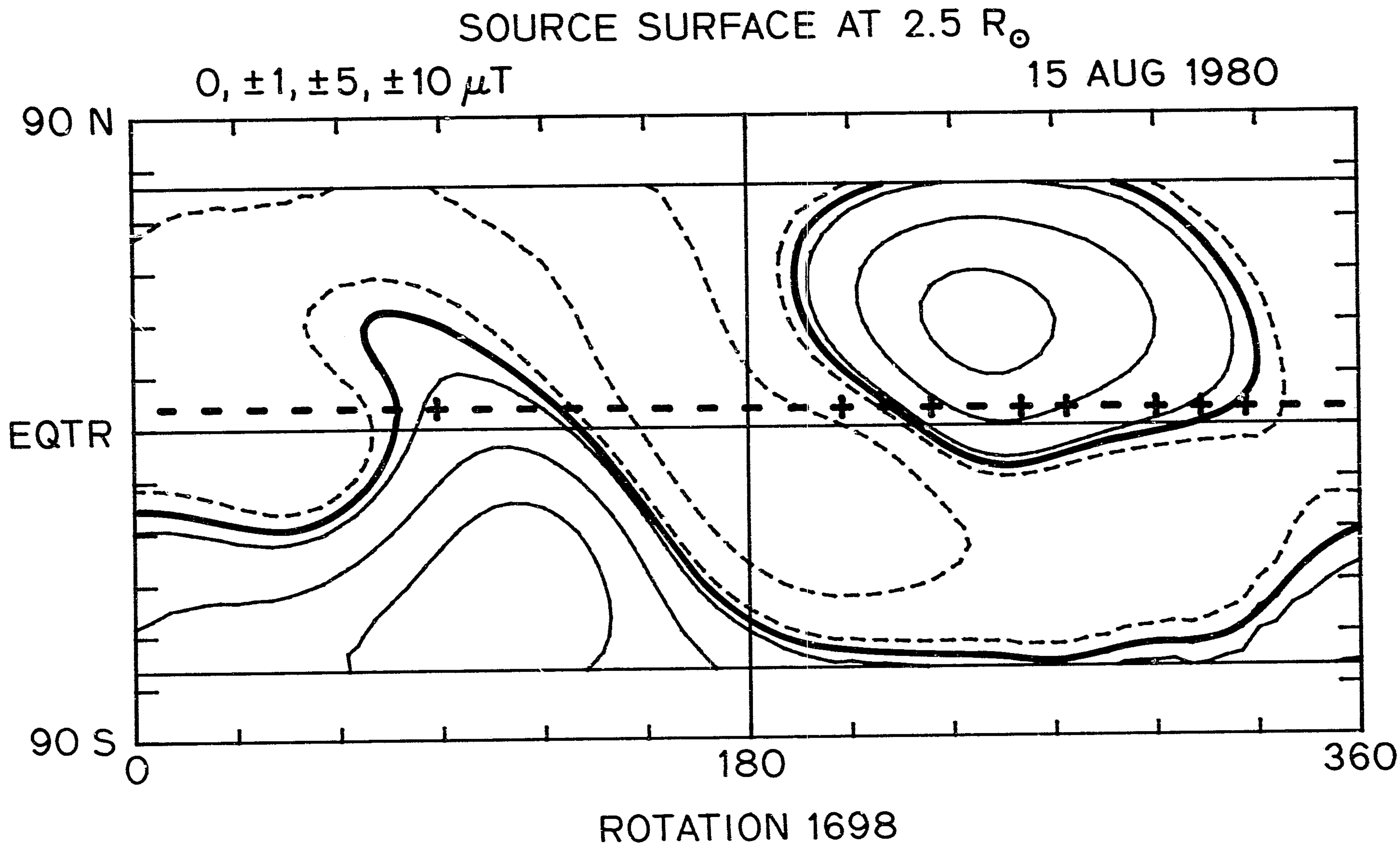

Figure 4. After solar polar field reversal the northern hemisphere is predominantly negative polarity. Carrington Rotation 1698 shows a large disconnected positive field region in the northern hemisphere around 270° longitude. The south polar region has become positive. The southern current sheet reaches the equator near 90° longitude and we observe a single day of away polarity at Earth. The sector structure is essentially two-sector with a predominance of toward polarity.

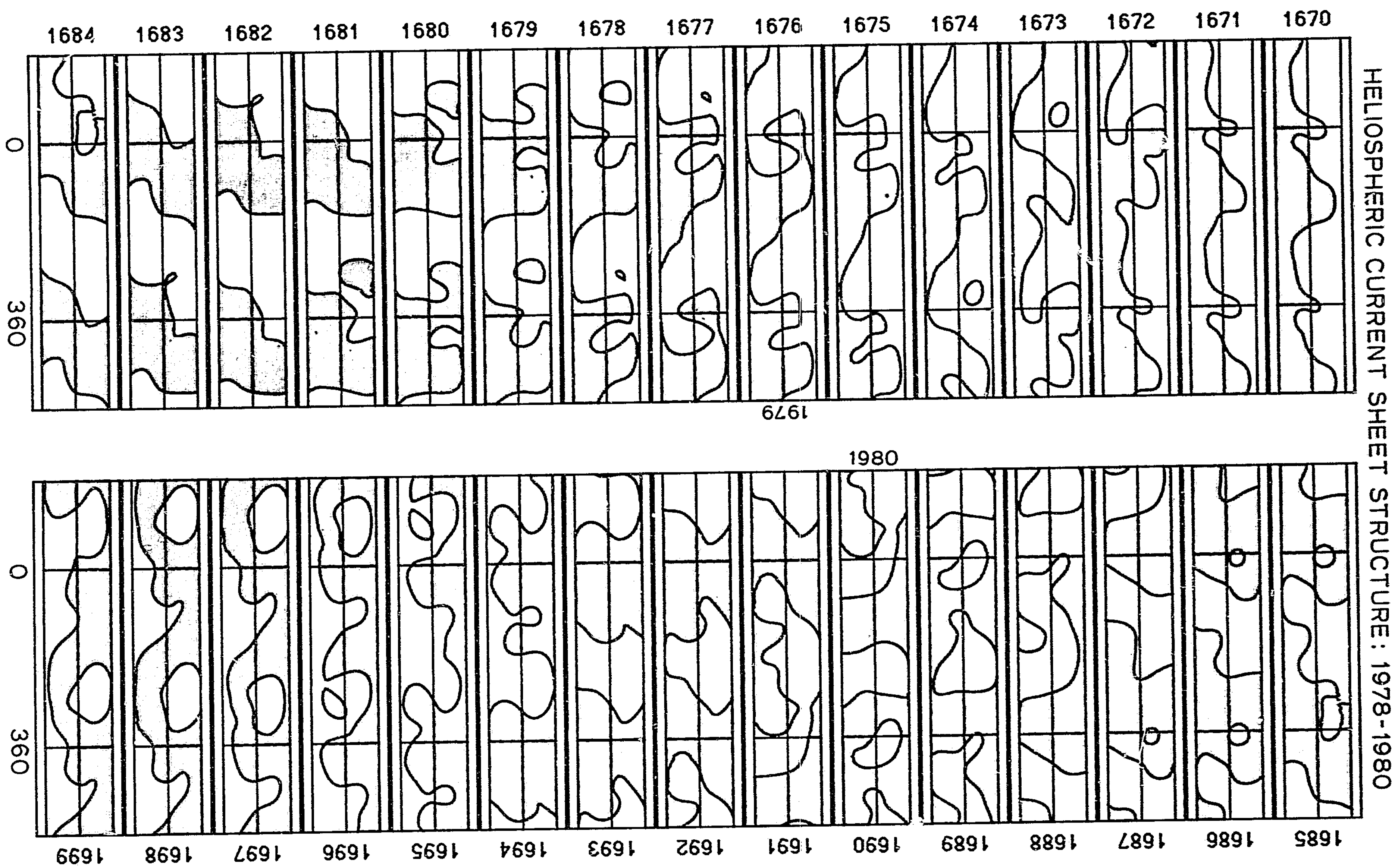

Figure 5. The evolution of the current sheet near sunspot maximum is shown for rotations 1670–1699 in the same format as Figure 2. The polar fields reverse near Carrington Rotation 1690. The structure is complex throughout this interval, extending to the poles through most of the period and often having multiple current sheets. Many features can be traced for long periods of time. Most structures show less distortion than would be expected from differential rotation. In spite of the complexity, Earth experiences slowly varying two and four sector structures.

Most features can be observed for many rotations and their evolution can be traced. For example the large positive region clearly visible in Rotation 1689 centered near 200° longitude can be traced through Rotation 1717. The small positive feature that appears near 120° on Rotation 1694 does not disappear until at least Rotation 1712. The extension of negative polarity into the northern hemisphere that first expands in Rotation 1660 at longitude 230 drifts slowly westward until it connects to the northern polar region in Rotation 1682 or 1683. The eastern boundary of this region can be traced to Rotation 1687. The small negative feature clearly visible in the northern hemisphere of Rotation 1678 near 300° longitude can be followed from rotation to rotation in all but Rotation 1684 until it merges with a larger negative region in rotation 1685. The small region of positive polarity lying across the equator on Rotation 1674 near 60° longitude drifts slowly westward from rotation to rotation. During Rotations 1681 through 1683 it is evident only as a warp in the current sheet, but reappears in 1685 through 1687 at 360° longitude. During the course of 15 rotations it shifts a total of about 60° westward in longitude, corresponding to a rotation rate very close to 27.5 days.

The greatest changes occur during Rotations 1688 through 1692, just at the time of solar polar field reversal determined from the magnetograph polar region measurements. The solar field added to our computation at this time is very small and so has little effect on the overall configuration of the fields. During these few rotations the positive flux region becomes disconnected from the poles and seems gradually to move southward, enveloping the southern polar region completely by Rotation 1695. This is independent of the inclusion of additional polar flux; graphs of the solutions with no polar field correction show essentially the same result. Throughout this interval the changes near the equatorial plane are small. There are few sudden changes in the IMF sector structure observed at Earth. After maximum the pattern returns to the four-sector structure commonly observed before maximum.

IV. Declining Phase of the Sunspot Cycle

As the new polar fields strengthen during the beginning of the declining phase from late 1980 through 1982, the large scale heliospheric magnetic structure simplifies and becomes more ordered. Figure 6 shows the computed current sheets for Rotations 1700 - 1729, October 1980 through

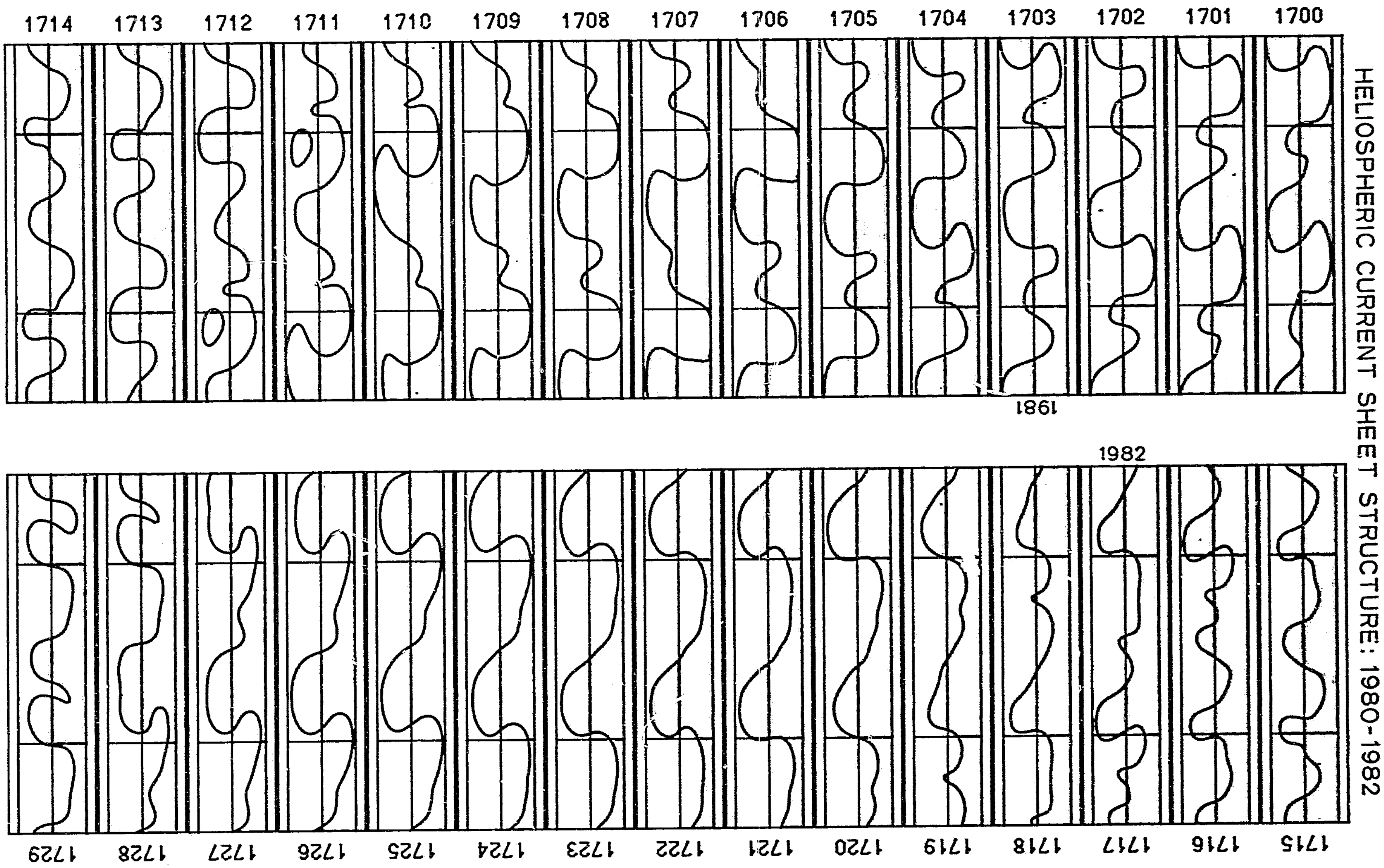

Figure 6

Figure 6. The evolution of the current sheet after sunspot maximum during Carrington Rotations 1700–1729. The current sheet becomes much simpler and the extent in latitude decreases a little. Earth experiences both two and four sector structures during this period. Changes in structure occur slowly and many features again persist for more than a year. Some features undergo differential rotation, while others do not. The structure is simple and almost stationary through most of 1982.

December 1982. Through most of 1981 the structure resembles the structure observed in 1978 except that the polar region polarity is reversed. Again there are two extensions of the current sheet into each hemisphere, but now the south pole is positive polarity and the north pole negative.

The large positive polarity region near 270° longitude in Rotation 1698 connects to the positive south polar region in Rotation 1700 and moves southward in succeeding rotations, disappearing by rotation 1719. The large negative flux region extending from the north pole at at 180° remains strong through Rotation 1710. This region is apparently undergoing differential rotation and splits in Rotation 1711. The flux region which remains connected to the north pole begins to die away and by Rotation 1718 has disappeared. The differentially rotating negative polarity region in the southern hemisphere merges with another small extension of negative flux in Rotation 1712 near 0°. This new region grows and continues to move westward at a slower rate, broadening considerably until by Rotation 1718 there is only one sector of each polarity. The structure remains essentially unchanged through most of 1982 (Rotation 1725), exhibiting almost no signs of differential rotation. A four-sector structure seems to be emerging again in the last few rotations. Throughout this interval the latitudinal extent of the current sheet is very great, extending almost to the poles. This is very different from the structure near minimum.

Figure 7 shows Carrington Rotation 1720 which is characteristic of the simple two-sector structure. A predominantly two-sector structure in the IMF has been observed after solar maximum in most of the five previous sunspot cycles according to Svalgaard and Wilcox (1975). Again there is good agreement with the IMF polarity measured at Earth.

V. Polar Field Strength & Source Surface Radius

The polar fields near sunspot minimum are much stronger than those measured by line-of-sight magnetograph measurements (Stenflo, 1971; Howard, 1977; Suess et al., 1977; Pneuman et al., 1978; and Svalgaard et al., 1978). This can be seen in the Stanford measurements by considering the field measurements obtained in the apertures nearest the poles. Svalgaard et al. (1978) determined the strength of the polar fields by considering the annual variation in measured field strength due to the 7^{o} inclination of the solar rotation axis to the ecliptic plane. That study

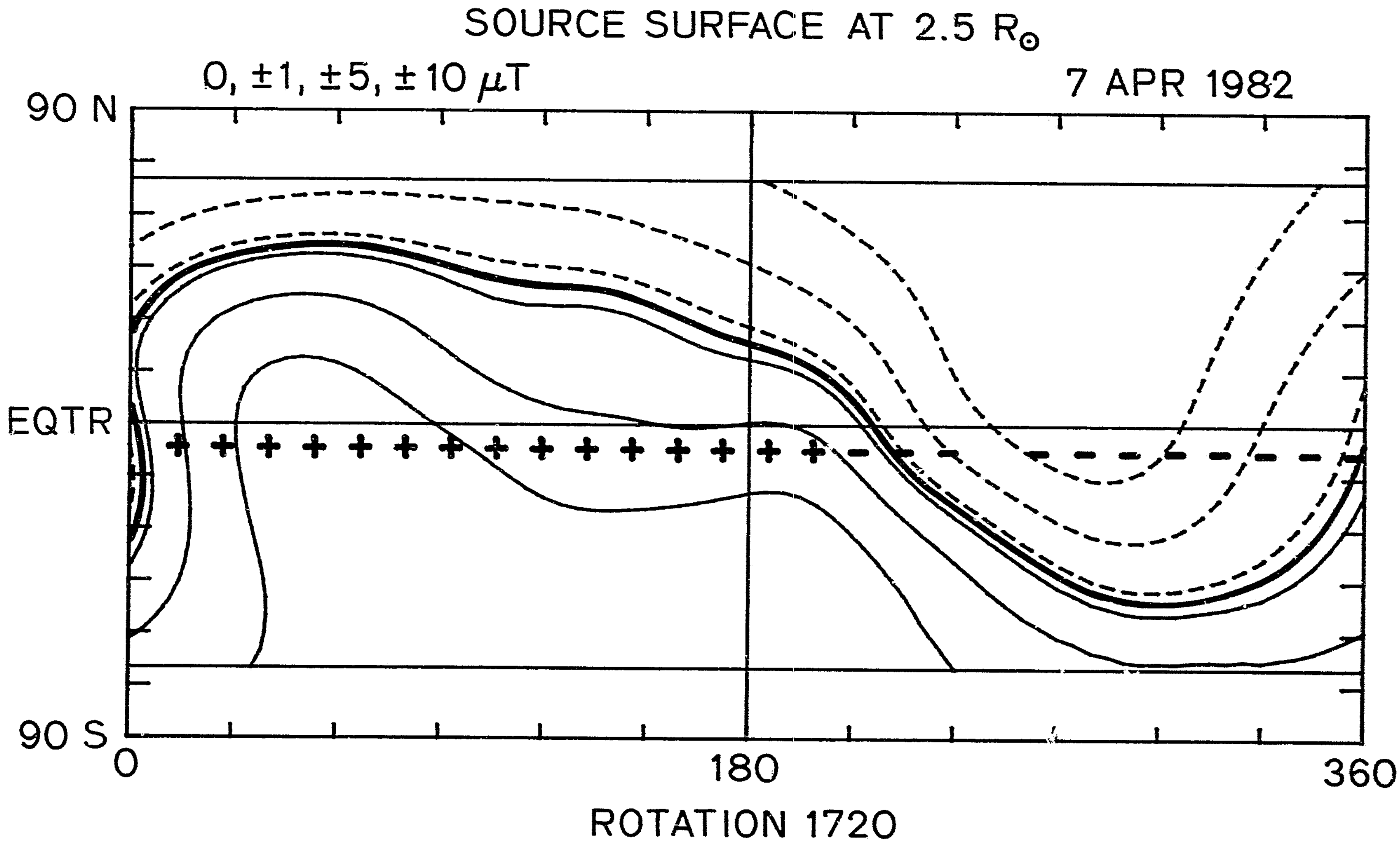

Figure 7. In the same format as Figure 1, Rotation 1720 is typical of most of 1982 exhibiting a two-sector structure at Earth and changing very slowly in time.

showed that a sharply peaked field of the form 11.5 $\cos^8(\theta)$ Gauss reproduced the observed variation.

Near minimum this strong field has a large effect on the potential field model results as pointed out by Burlaga et al. (1981) and discussed in Hoeksema et al. (1982). Figure 8 shows a diagram of the northernmost aperture of a Stanford magnetogram. The aperture is 3 arc minutes square. Ten-day averages of the field strength measured in this aperture are shown. The annual variation is clearly seen, as is the reversal of the field polarity which occurred near the end of 1979. The corresponding plot for the south pole is very similar.

We cannot use the same method to calculate the polar correction near maximum, since the polar field strength changes substantially in a year. The straight lines in Figure 8 show an estimate of the average polar field strength. We have used this value to scale the strength of the polar field correction. Thus a nominal field of 11.5 $\cos^8(\theta)$ Gauss is added in 1976, 0 Gauss at the end of 1979, and a field of about half the original magnitude with the opposite sign in 1981. As in our earlier work, we have considered several values of the polar field and investigated the effect on the correlation of IMF polarity predicted by the

FIELD STRENGTH IN NORTHERNMOST APERTURE

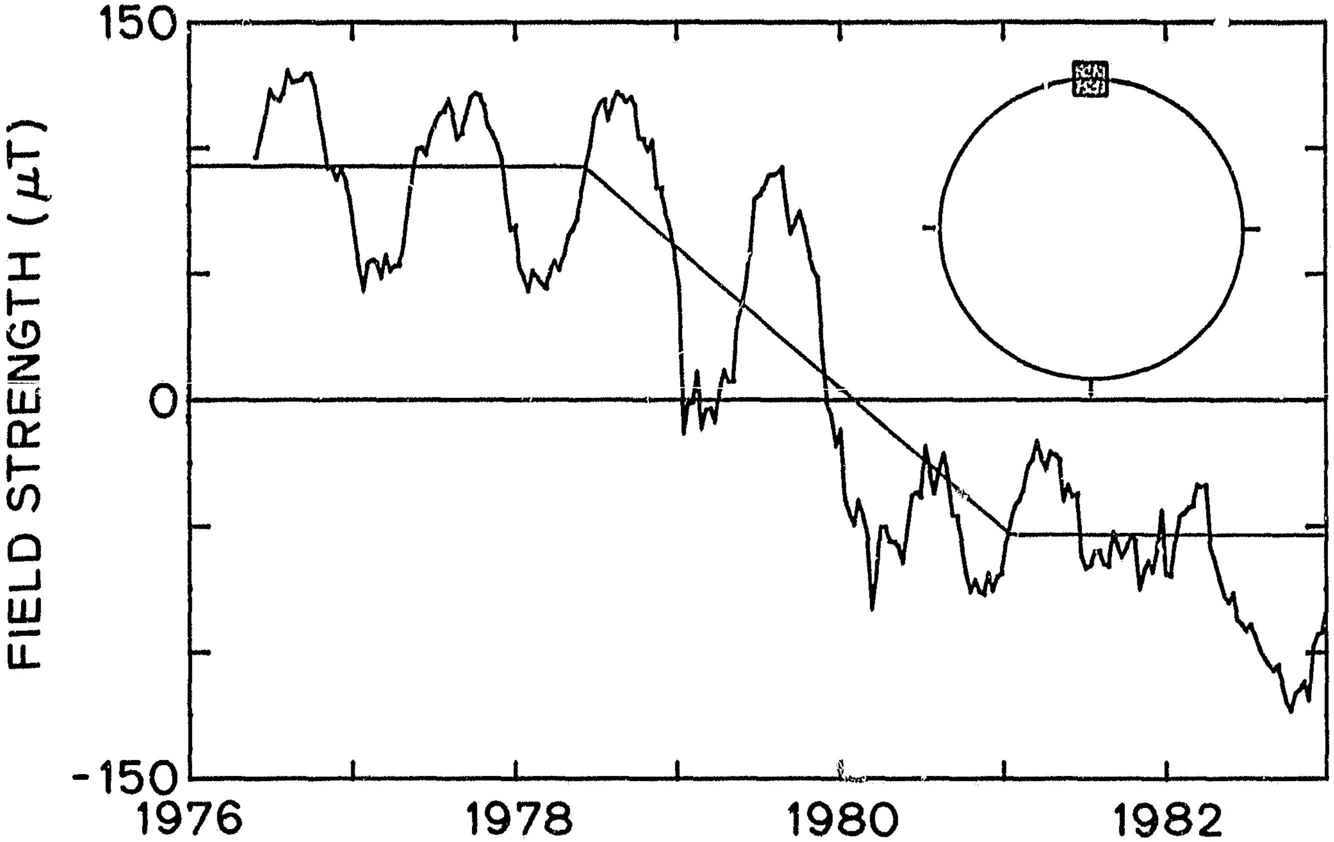

Figure 8. The diagram shows the approximate location and size of the northernmost aperture on the Sun during the observations for a magnetogram. The aperture is 3 arc minutes square. Ten-day averages of the field strength measured in this aperture from May 1976 through December 1982 are plotted. The annual variation due to the inclination of the solar pole to the ecliptic can be clearly seen. Before polar field reversal the average field strength was about 95 μtesla. After reversal it was about 45 μtesla. The straight lines show the scaling factor used to determine the polar field correction throughout this interval with 11.5 $\cos^8(\Theta)$ gauss being the canonical value in 1976-1977.

model and observed by ISEE-3 or other spacecraft. Figure 9, described in more detail below, indicates that near maximum the added polar field has very little effect on the correlation. This is to be expected since the polar fields are much weaker (zero right at maximum) and the lower latitude fields are much stronger. At higher heliographic latitudes the effect would be greater (Levine, 1982). Comparison with coronagraph measurements might allow a better determination.

As in our earlier paper, we have also investigated the effect of varying the source surface radius. Previous workers (Schatten et al., 1969, Levine 1977a and b) have used a source surface radius of 1.6 R_s near minimum. Near maximum and over regions of high activity others (Altschuler & Newkirk, 1969 and Jackson & Levine, 1981) have used a radius of 2.6 R_s. Hoeksema et al., (1982) found that a radius of 2.35 R_s gave the best correlation with IMF polarity near minimum. We have computed the field on source surfaces with radii ranging from 1.6 to 3.1 R_s for several values of polar field correction. From these we have constructed datasets of predicted IMF polarity. Figure 9 shows the correlation coefficient of measured IMF polarity with predicted IMF polarity (lagged 5 days to account for the transit time from Sun to Earth) vs. source surface radius.

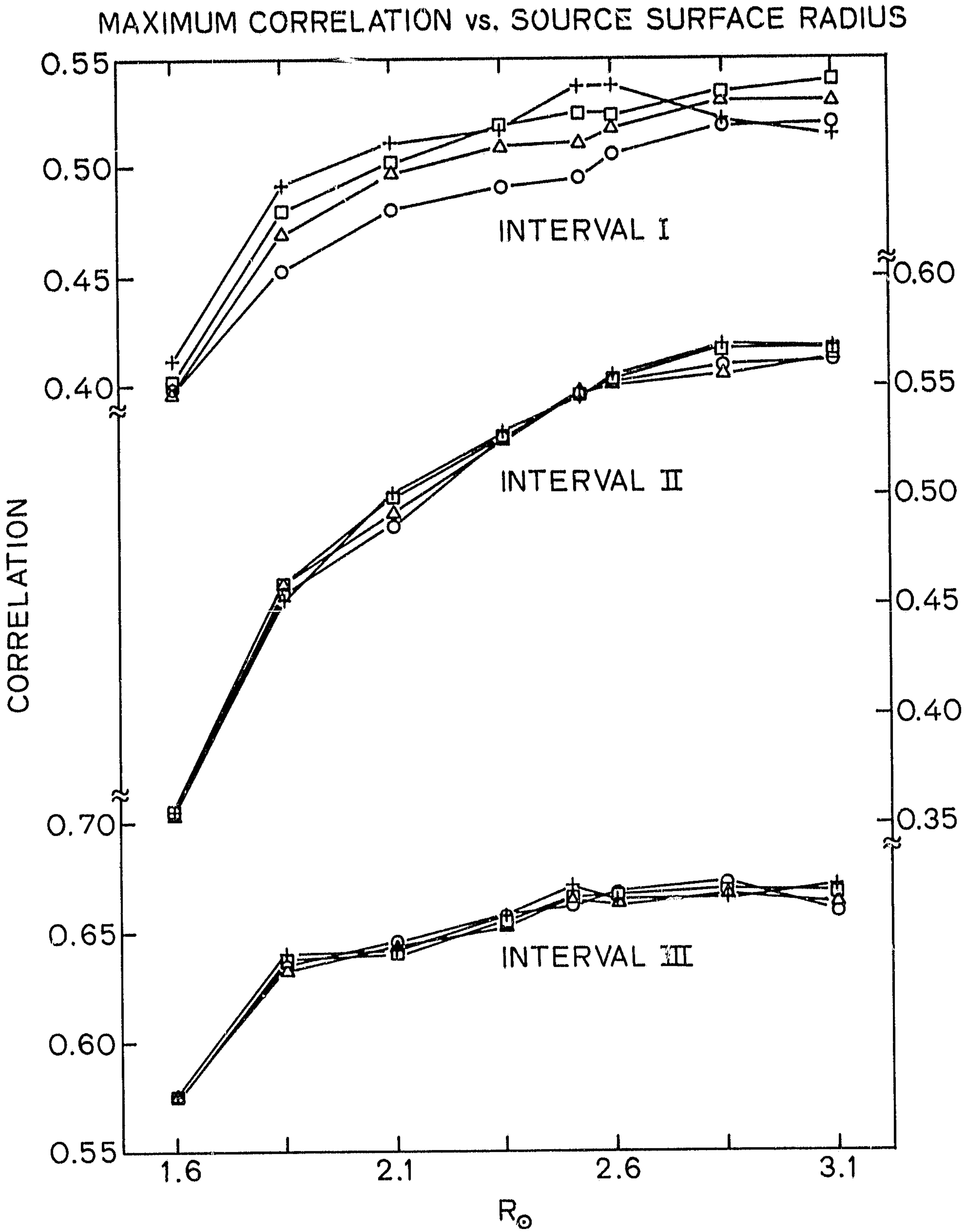

Figure 9. Correlation of the measured IMF polarity with that predicted by the model vs. source surface radius. The maximum correlation coefficient for the time period May 1976 to June 1978 (Interval I), indicates an optimum source surface radius near 2.5 R_S. Circles show the result computed with no polar field correction; triangles for half the standard field; squares for the standard polar field correction of 11.4 $\cos^8(\Theta)$ Gauss; and plusses for 1.5 times that strength. Interval II shows the results for the period around maximum, July 1978-August 1980, and Interval III for the period September 1980 to December 1982. The correlation is somewhat higher for this last period. 2.5 R_S still seems to be about the best source surface radius, and the magnitude of the polar field correction does not affect the predictions at the latitude of the Earth.

Interval I includes May 1976 through June 1978, the rising phase of the sunspot cycle as shown in figure 2. The four curves correspond to different values of the polar field correction. Circles show the result for no polar field addition; triangles for half the standard field; squares for the standard correction of 11.4 $\cos^8(\Theta)$ Gauss; and plusses for 1.5 times the standard strength. We show similar curves for the period around maximum, July 1978 to August 1980, labelled Interval II. There is almost no difference in the curves for this interval, which shows the unimportance of the polar field in determining the equatorial structure. Interval III, September 1980 through December 1982, shows the results for the beginning of the declining phase. The maximum correlation is substantially higher, due primarily to the structure's simplicity during most of 1982. Again the correlation is rather insensitive to polar field strength.

In no interval is there a sharp peak suggesting that one source surface radius or polar field strength is clearly the best. There is, therefore, substantial uncertainty in the selection of source surface radius and polar field. Good choices are a source surface radius of 2.5 R_s and the standard polar field correction. At no time is 1.6 R_s as good. We must emphasize that Earth is not a good probe of the heliosphere being limited to solar latitudes less than 7.5 degrees. When the latitudinal extent of the current sheet is much greater than this we cannot easily determine which source surface radius or polar field correction is best using this method.

One additional correction has been made in the results presented in this paper which was not made in Hoeksema et al. (1982). For a variety of reasons there is usually a small zero offset in the average magnetic field value for a given Carrington Rotation. This is partially due to measurement errors in the magnetograph: saturation effects, luminosity deficiency of strong magnetic field regions, measuring only line-of-sight fields, missing data, and the tilt of the polar regions (Pneuman et al., 1978). In addition the measurements making up one rotation are observed over a period of 27 days during which the fields are evolving. Furthermore rotation rates are slower away from the equator and so a complete rotation is not observed at higher latitudes in 27 days. The zero offset is usually small, being only a few per cent of typical field values at the photosphere. Its value has been computed for the 360° surrounding each Carrington longitude and removed.

VI. SUMMARY & DISCUSSION

The heliospheric current sheet reaches high latitudes for much of the solar cycle. From 1978 through at least 1982 the extent was greater than 50°. The large scale structure of the heliosphere changes slowly during most of this period. Even near maximum there is continuity for many rotations in the structure, in spite of the complexity of the photospheric fields. The IMF polarity predicted by the model agrees fairly well with that observed near Earth by spacecraft such as ISEE-3 in every interval. This suggests that the potential field model, which does not treat rapidly evolving fields accurately, is adequate to approximate the heliospheric magnetic structure for this period. We would expect improved comparisons if we used a more complex, non-spherical source surface (Levine et al., 1982).

The structure of the IMF observed at Earth remains fairly simple, consisting of either four or two polarity sectors. The three dimensional configuration of the helio-sphere is more complex near maximum. These calculations show that multiple current sheets probably exist in the two or three years near maximum. The current sheets shown in Figure 5 show that the time of polar field reversal is not one of cataclysmic change in the heliospheric magnetic structure, but rather marks the moment when an ongoing process reaches a certain stage.

That the current sheet extends to such high latitudes over such a large fraction of the solar cycle suggests that cosmic ray propagation models may need to take this into account. Jokipii and Thomas (1981) considered the effect of a simple two-sector current sheet on the solar modulation of galactic cosmic rays by varying the latitudinal extent of the current sheet from 10 to 30 degrees. This study shows that not only is the structure much more complex, but the extent in latitude is greater than 50° from 1978 through 1982. Comparison of IMF observations taken in the last few years with inferred measurements of five previous sunspot cycles (Svalgaard & Wilcox, 1975) suggests that the structures observed during this cycle are not very different from those observed in past epochs. We expect that similar configurations of heliospheric magnetic field occur in each cycle.

While a few of the large scale structures shown here exhibit differential rotation effects, many of them do not, even though they stretch over great ranges in latitude. This is similar to the rotation of coronal holes. This suggests that some sort of underlying magnetic structure far beneath the photosphere may be rotating rigidly. Discussion of the nature of such a structure is beyond the scope of this paper.

Acknowledgements

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Bibliography

Altschuler, M.D., R.H. Levine, M. Stix, and J.W. Harvey, "High resolution mapping of the magnetic field of the solar corona," Solar Phys, 51, 345-76, 1976.

Altschuler, J.D. and G. Newkirk, Jr., "Magnetic fields and the structure of the solar corona," Solar Phys., 9, 131-49, 1969.

Antonucci, E. and L. Svalgaard, "Rigid and differential rotation of the solar corona," Solar Phys., 34, 3-10, 1974.

Burlaga, L.F., A.J. Hundhausen, and X.-P. Zhao, "The coronal and interplanetary current sheet in early 1976," J. Geophys. Res., 86, 8893-98, 1981.

Hoeksema, J.T., J.M. Wilcox, and P.H. Scherrer, "Structure of the heliospheric current sheet in the early portion of sunspot cycle 21," J. Geophys. Res., 87, 10331-38,1982.

Jackson, B.V. and R.H. Levine, "A Comparison of type III metric radio bursts and global solar potential field models," Solar Phys., 73, 183-190, 1981.

Jokipii, J.R., and B. Thomas, "Effects of drift on the transport of cosmic rays IV: Modulation by a wavy interplanetary current sheet," Ap. J., 243, 1115-1122, 1981.

King, J.H., Interplanetary Medium Data Book (Supplement 1), Rep. NSSDC 7908, NASA Goddard Space Flight Center, Greenbelt, Md. 1979.

Levine, R.H., "Open magnetic structure on the Sun: the Skylab period", Ap.J., 218, 291-305, 1977a.

Levine, R.H., "Chap. 4," in J.B. Zirker, Coronal Holes and High Speed Solar Wind Streams, Colo. Assoc. Univ. Press, Boulder, 1977b.

Levine, R.H., "The relation of open magnetic structures to solar wind flow," J. Geophys. Res., 83, 4193-99, 1978.

Levine, R.H., "Open magnetic fields and the solar cycle, I," Solar Phys, 79, 203-230, 1982.

Levine, R.H., M. Schultz, and E.N. Frazier, "Simulation of the magnetic structure of the inner heliosphere by means of a non-spherical source surface," Solar Phys., 77, 363-92, 1982.

Pneuman, G.W., M. Schultz, and E.N. Frazier, "On the reality of potential magnetic fields in the solar corona," Solar Phys., 59, 313-330, 1978.

Suess, S.T., A.K. Richter, C.R. Winge, S.F. Nerney, "Solar polar coronal hole -- a mathematical simulation," Ap.J., 217, 296-305, 1977.

Smith, E.J., B.T. Tsurutani, and R.L. Rosenberg, "Observations of the interplanetary sector structure up to heliographic latitudes of 16°: Pioneer 11," J. Geophys. Res., 83, 717-24, 1978.

Schatten, K.H., J.M. Wilcox, and N.F. Ness, "A model of interplanetary and coronal magnetic fields," Solar Phys., 6, 442-55, 1969.

Svalgaard, L., "Interplanetary sector structure 1947-1975", Stanford University Institute for Plasma Research Rpt No. 648, Stanford, California, 1976.

Svalgaard, L., T.L. Duvall, Jr., and P.H. Scherrer, "The strength of the Sun's polar fields," Solar Phys., 58, 225-40, 1978.

Svalgaard, L. and J.M. Wilcox, "Long term evolution of solar sector structure," Solar Phys, 41, 461-75, 1975.

Timothy, A.F., A.S. Krieger, and G.S. Viana, "The structure and evolution of coronal holes." Solar Phys., 42, 135-56, 1975.

Wilcox, J.M., K.H. Schatten, and A.S. Tanenbaum, "Photospheric magnetic field rotation: rigid and differential," Solar Phys., 14, 255-62, 1970.

Wilcox, J.M. and A.J. Hundhausen, "Comparison of heliospheric current sheet structure obtained from potential magnetic field computations and from observed maximum coronal brightness," (submitted to J. Geophys. Res., 1983).

Wilcox, J.M., P.H. Scherrer and J.T. Hoeksema, "The Origin of the Warped Heliospheric Current Sheet," Science, 209, 603-605, 1980.