Solar Rotating Magnetic Dipole?

by

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Submitted to Solar Physics.

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Now at: Istituto di Fisica - Universita di Torino - Italy.

SOLAR ROTATING MAGNETIC DIPOLE?

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Abstract

A magnetic dipole rotating around an axis perpendicular to the rotation axis of the sun can account for the characteristics of the surface large-scale solar magnetic fields through the solar cycle. The polarity patterns of the interplanetary magnetic field, predictable from this model, agree with the observed interplanetary magnetic sector structure.

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SOLAR LARGE-SCALE MAGNETIC FIELDS

Weak large-scale magnetic fields appear on the sun organized in fairly regular patterns, which evolve slowly on a time-scale of the order of years. Besides direct observations of the photospheric magnetic field, the detection of the interplanetary magnetic field polarity represents a collateral source of information on solar large-scale magnetic fields (although how to relate the interplanetary field to its solar source is still object of discussion). While the weak photospheric magnetic field and the polar fields are detected from 1959 and 1953 on, respectively, the interplanetary field polarity data are available for a period as long as five solar cycles, from 1926 on.

Several investigators have been able to identify persistent structures, in their analyses, of both the photospheric and the interplanetary magnetic field. Altschuler et al. (1971) analyzed photospheric magnetic data, from the Mt. Wilson magnetograms, for the period 1959-1966. They described the evolution of the photospheric field in terms of surface harmonics which are dominant for periods approximately 2-years long. During the period 1959 - 1962, just after the maximum of solar cycle 19, the dominant harmonic corresponds to a dipole lying in the equatorial plane of the sun: the photospheric field is organized in two meridional sectors. In the declining phase of the solar cycle (1962 - 1964), four meridional sectors are the dominant structure. Around the time of sun spot minimum and immediately after (1965 - 1966), the harmonic of a north-south oriented dipole is significant.

Mt. Wilson data have been analyzed by Stenflo (1972) over a larger period, which includes also the beginning of cycle 20 until 1970. In Figure 1, the sector structure of the photospheric field, obtained averaging the field strength over all latitudes is shown. During cycle 19 the evolution from two to four meridional sectors is clear and agrees with the results of Altschuler et al. The appearance of a north-south aligned dipole around the minimum of activity is also confirmed. The situation of the photospheric magnetic sector structure during the rising part of cycle 20 is instead of quite difficult interpretation.

Stenflo studied also the zonal structure of the photospheric field (Figure 2), which is important in relation to one of the main features of the weak fields: the polar fields and their reversal of polarity near the activity maximum. Although the magnetic field observations used are not completely reliable at latitudes higher than $\pm 45^{\circ}$, the field averages over all longitudes reveal a regular persistence of positive polarity at the south pole from 1959 to 1969 and negative polarity at the north pole for the whole period considered (Figure 2). This is consistent with the polar magnetic configuration expected to persist until the activity maximum of cycle 20, after the first reversal of polar fields observed by Babcock (1959) at sunspot maximum during cycle 19. In early 1957 Babcock observed a reversal from negative to positive polarity at south and in November 1958 a reversal from positive to negative polarity at north. In cycle 20 the cyclic alternation of the polar fields, proposed by Babcock (1961) is confirmed; but the reversals take place with delay, essentially at the north pole, with respect to the time of maximum activity. Stenflo notes a polarity reversal at the south pole (from positive to negative polarity) in 1969. Howard (1974) confirms the occurrence of such reversal at south in June 1969 and reports definitive evidences for a polarity reversal at the north pole in July 1971.

Besides the polar fields, in the diagram of the zonal structure, shown in Figure 2, other large-scale magnetic features are clearly recognizable at low latitudes. Such features show the same equatorward migration of sunspots and photospheric faculae and their polarity coincides with the preceding polarity in sunspot groups, except in the southern hemisphere during cycle 19. Therefore these magnetic regions seem to follow the strong small-scale magnetic field cycle and can be considered related to solar activity.

Another source of information on solar magnetism became available in 1962, with the detection of the interplanetary magnetic field by spacecraft. The main characteristic of the interplanetary field, as observed in the ecliptic plane, is a clear polarity sector structure, corotating with the sun and slowly evolving from a 4-sector pattern, during the declining phase of cycle 19, to a 2-sector pattern during cycle 20 (Wilcox and Ness, 1965; Wilcox and Colburn, 1972).

At the present it is possible to extend the study of the interplanetary polarity structure over a long period of time, because of the availability of polarity data inferred from high-latitude polar geomagnetic observations (Svalgaard, 1968; Mansurov, 1969). Svalgaard (1972), analyzing inferred polarity data from 1926 on, notes that, at the beginning of a new cycle, the polarity sector structure is not well-defined. Instead after sunspot maximum the sector pattern develops clearly with higher probability of the occurrence of a 4-sector structure. Just at sunspot minimum negative sectors almost disappear and for a few solar rotations the polarity of the interplanetary magnetic field is constant.

Phenomenological Model of the Solar Weak Magnetism

A simple phenomenological model of the weak large-scale magnetic fields can account for the dominant photospheric magnetic configurations, observed on the sun, through the solar cycle. The surface harmonics, found by Altschuler et al. (1971), assumed to be characteristic of the corresponding solar cycle phases, might be interpreted as manifestations of a continuous slow evolution of the solar large-scale magnetism. In fact if the magnetic dipole, lying in the equatorial plane of the sun at the middle of a sunspot cycle, slowly rotates around an axis perpendicular to the rotation axis of the sun, the magnetic configuration of a north-south oriented dipole, chacteristic of sunspot minimum, could be the result of a continuous evolution. Let us assume the rotation of a magnetic dipole with period of 22 years, around an axis perpendicular to the solar rotational axis. The consequent time evolution of the large-scale magnetic fields for a complete rotation period, corresponding to solar cycles 19 and 20 is presented in Figure 3. The phase is determined assuming that the dipole is aligned to the rotation axis of the sun, at the beginning of a solar cycle (in agreement with both the result of Altschuler et al. and the traditional interpretation of the shape of the solar corona at minimum).

Figure 3a represents the situation at the beginning of cycle 19, at that time the polar magnetic field is positive at north and negative at south. As the rotation progresses from position a, through b, to position c, the general magnetic field assumes the configuration of a dipole lying in the equatorial plane, at half solar cycle, as observed during the years 1959-1962. Moreover immediately after the dipole assumes position c in Figure 3, the polar fields should undergo a polarity reversal. At the next sunspot minimum the dipole is again aligned with the solar rotation axis, but the dipole polarities are reversed with respect to the preceding solar minimum, as shown in Figure 3e. Another solar cycle can start with the correct initial polarities.

Except the photospheric 4-sector structure present in 1962-64, this description can account for the main photospheric characteristics of the weak magnetic field: namely the alternation of sign of the polar fields every 11 years and the magnetic configurations at sunspot maximum and minimum. Furthermore the rotation of the dipole implies large-scale polarity migrations on the solar disk, which are at least qualitatively in agreement with observational evidences such as the poleward migration of prominences in the rising portion of the solar cycle and the expansion and poleward migration of the magnetic regions of following polarities of sunspot groups.

Prominences are supposed to be associated with neutral lines lying between large-scale regions of opposite magnetic polarity. Stenflo (1972) points out that the maximum of prominence activity can trace the evolution, in function of latitude and time, of polarity patterns on the sun. The data relative to the period 1960-1969 are shown in Figure 4.

Clearly the maximum of prominences migrates toward high latitudes starting from sunspot minimum and reaches approximately 90^{o} at the beginning of 1970, namely at half solar cycle. If the association of prominences with neutral lines between magnetic regions of opposite polarities is correct, the trend of prominences maximum agrees with the rotation of the boundary between the opposite polarity regions of the dipole on the sun from an equatorial position (Figure 3e) to a meridional position (Figure 3g) in the first half of cycle 20 from 1965 to 1970. This poleward migration of polarity patterns leads to the polar field polarity reversal observed in 1969 - 1971. The trend of prominence activity maximum is particularly clear from 40^{o} up to 90^{o} latitude; the pattern inside the zone $\pm 40^{o}$ is probably affected by the effects of solar activity.

The expansion and poleward migration of the magnetic fields of following polarity, in bipolar sunspot groups, is also qualitatively in agreement with the rotation of a magnetic dipole. This phenomenon has been usually considered as leading to the understanding of the mechanism which builds up the solar dipolar field and induces the reversal of polar field polarities (Babcock, 1961; Leighton, 1969). The overall effect can be described as a poleward migration of large-scale weak magnetic fields of opposite polarity with respect to the polar field polarity, although a single migration of the following regions of sunspot groups proceeds on a time-scale short compared to the solar cycle period. In the first part of a solar cycle as shown in Figure 3b and 3f, a large-scale magnetic region, with polarity opposite to the polar one, is indeed migrating toward high latitudes, leading to the reversal of the polar field polarity.

A better understanding of the large-scale effects induced by the processes of expansion and migration of the following regions of sunspot groups could confirm the validity of the hypothesis of the slow evolution of the solar weak magnetic field proposed in the paper.

Consequences on the Interplanetary Magnetic Field Polarity Patterns

A solar rotating magnetic dipole implies well-defined polarity patterns of the interplanetary magnetic field. Recently an interesting line of interpretation of the interplanetary polarity structure has been proposed by Schulz (1973). He assumes that the heliomagnetic field is frozen into the expanding solar wind, from the Alfvén radius outwards, where only dipole and quadrupole terms of the magnetic scalar potential, deduced from the photospheric field, are likely to contribute. A dipolar magnetic field, with axis aligned to the rotation axis of the sun, because of the solar wind flow, forms an equatorial neutral sheet, separating the two regions of opposite polarity above and below the equatorial plane of the sun. In the interplanetary field, at the orbit of the earth, no sector structure corotating with the sun should be detected. But, if the magnetic axis of the dipole is inclined with respect to the rotation axis, a 2-sector pattern is observed in the interplanetary field. In fact, during a solar rotation an observer at the earth crosses the neutral plane twice, detecting a polarity reversal (sector boundary) and spends half rotation above and below the neutral plane, in regions of uniform opposite polarity (polarity sectors). The 4-sector structure is achieved introducing, beyond the dipole term, a quadrupole term, namely an azimuthal asymmetry. The consequence is a neutral sheet warped with respect to the equatorial magnetic plane. Therefore the neutral sheet intersects the equatorial and ecliptic plane four times, this corresponds to four sector boundaries, separating four opposite polarity regions.

In the hypothesis of the rotating magnetic dipole the annular neutral sheet lies in the equatorial plane of the sun at solar minimum, because magnetic and rotational axis are aligned. As a consequence the sector structure of the interplanetary field disappears. This might explain the lack of sector structure, lasting for a few solar rotations, noticed by Svalgaard (1972) around solar minima. As the rotation goes on, the magnetic axis becomes inclined with respect to the rotation axis. Therefore, in the assumption of a simple dipolar field, a 2-sector polarity structure develops in the interplanetary magnetic field, between two consecutive solar minima. Moreover the sector pattern preceding solar minimum is reversed with respect to the sector pattern after solar minimum. In fact, because of the rotation of the magnetic dipole, the same equatorial region corotating with the sun, which at the end of a cycle is of positive polarity (Figure 3d), at the beginning of the following cycle is of negative polarity (Figure 3f). Provided the fact that during the years around minimum of activity the rotation period of the interplanetary magnetic features is constant, near 27 days (Svalgaard, 1972), a reversal of the 2-sector pattern should be observed. Namely the periodic time series of the polarity data should display a phase shift corresponding to half a period.

To compare the observed polarity with the features predictable in case of a rotating magnetic field simply dipolar, 2-sector patterns should be isolated from the 4-sector structure. This can be done correlating the polarity data with a sinusoidal test-function, with period equal to the corotation period of the polarity patterns. A period of 27 days, characteristic of the declining phase and the minimum of the solar cycle, is chosen. A test-function simulating an ideal 4-sector pattern should have a period of half a corotation period of the interplanetary field. Svalgaard's inferred polarity data have been used for the period 1926 - 1973. They can be represented by a time series of daily values of the kind ±1 respectively for positive and negative polarity. Consecutive samples of polarity data, 27 Bartels rotations long, are cross-correlated with the same test-function of equivalent length, with a time lag varying from 0 to 26 days. Each row of the plot of Figure 5 represents a set of 27 cross-correlation coefficients reported in function of time lag (a row is actually formed by 54 values, because each set of cross-correlation coefficients is repeated twice on the same row). The sets of coefficients are plotted in sequence in the consecutive rows. On the left of the plot the numbers of the first Bartels rotation of the data sample, reported in the corresponding row, are represented. Dashed areas indicate positive cross-correlation coefficients >0.1. Therefore the plot in Figure 5 provides an information about the time lag for which polarity data and test-function are positive correlated in the subsequent periods. The phase shifts of the polarity data with respect to the test-function as a reference, describe how the phase of the 2-sector pattern changes in time. The phase information is not completely reliable for periods around the maximum of solar activity, because, at that time, the corotation period of the polarity pattern approaches a value of 28.5 days (Svalgaard, 1972), deviating from the test-function period.

The clear pattern arising from the plot of the positive cross-correlation coefficients indicates that a 2-sector polarity pattern exists for most of the time and has a phase fairly constant for several years. The 2-sector pattern is not significant only during the 2-year periods starting with Bartels rotation number 1381 and 1408. At each sunspot minimum the phase of the 2-sector pattern changes abruptly, in fact in Figure 5 the dashed areas shift of about half a Bartels rotation in correspondence to the horizontal lines which separate one solar cycle from another. This means that the 2-sector polarity pattern before solar minimum is in opposition of phase with respect to the 2-sector polarity pattern after minimum. The direct observation of this effect in the polarity data can be easily masked by the presence of a 4-sector polarity structure at sunspot minimum. But the effect can be clearly revealed by using cross-correlations of polarity data and test-function, as just described.

An annual variation in the predominant polarity of the interplanetary field has been observed by Rosenberg and Coleman (1969). Wilcox and Scherrer (1972) confirmed this effect, analyzing the inferred interplanetary polarity data for the period 1926-1971. The polarity annual variation is related to the heliolatitude of the earth: at northern heliolatitudes the predominant polarity detected during a solar rotation agrees with the polarity of the northern polar magnetic field of the sun (at south it agrees with the southern polar field). Therefore the phase of the polarity yearly variation has to change at the reversal of the polar fields. This effect is indeed observed about 2.6 years after the sunspot maximum by Wilcox and Scherrer, for all the examined solar cycles.

The neutral line of the solar magnetic dipole separates only the equator in two equal regions of opposite polarities. At latitude different from zero, the solar parallels cut the solar surface in two unequal regions of opposite polarity. Therefore an observer, north of the helioequator will detect, in the interplanetary magnetic field, a predominance of the polarity of the northern polar fields of the sun, during one solar rotation. The degree of predominance of one polarity with respect to the other should be proportional to the heliolatitude of the observer and, for the same latitude, should change through the solar cycle with maximum at sunspot minimum and zero at the middle of a solar cycle. In fact, at the reversal of the polar fields, at each latitude, the opposite polarities are in balance, because the neutral line is meridional (Figure 3c). Therefore the proposed magnetic model can easily explain the Rosenberg-Coleman effect. Furthermore it is worth noting that the reversal of polar fields, inferred by the phase change of the polarity annual variation (Wilcox et al., 1972), takes place 2.6 years after sunspot maximum, and therefore around the middle of a solar cycle. In fact such reversal should occur at the time in which the dipole lies in the equatorial plane; this occurs at 1/4 of the rotation period of the dipole or half solar cycle.

Expected Photospheric Magnetic Sector Boundaries

Recently Svalgaard, Wilcox and Duvall (1974) proposed a model of the boundary separating large-scale photospheric fields, which reveals to be rather successful in the interpretation of several patterns observed in the solar corona. This model represents an attempt to link the photospheric magnetic sectors (associated with the interplanetary polarity patterns) and the polar magnetic fields. The solar sector boundaries, separating regions of opposite polarity, are assumed to be meridional. But, if the polarity of the large-scale unipolar regions at lower latitudes is reconnected to the polar region polarity, the sector boundaries should assume a distorted "S" shape. In Figure 6a, d, the sector boundaries, separating respectively (+,-) and (-,+) polarities, are represented for the first part of cycle 20. When the polar field polarity reverses, the reconnection between magnetic sectors and polar field changes as well as the orientation of both kinds of sector boundaries (Figure 6c, f). After this transition the geometry of the photospheric magnetic fields is supposed to persist until the next polar field reversal.

In the assumption of a rotating magnetic dipole, the (+,-) and (-,+) photospheric boundaries are present, for most of the solar cycle, just because of the rotation of the neutral line separating the two magnetic regions of the dipole. The inclination of the solar boundaries varies continuously, in particular at the middle of a solar cycle they assume the traditional meridional configuration (Figure 6c, g).

Even if the dynamics of the large-scale fields and the interpretation of the magnetic boundaries differ in the two models, the weak field geometry, proposed by Svalgaard et al., agrees fairly well with the magnetic configurations, expected in the rising part of the cycle, at half cycle and in the declining part, in case of a rotating dipole (Figure 6a, d; b, e; c, f compared with Figure 3f, g, h). Yet these configurations should not be considered stationary, but in the context of a continuous rotation. Obviously the interpretation of the magnetic pattern, proposed by Svalgaard et al., has been restricted to the case in which two sectors are present. Therefore the S-shaped sector boundaries (+, -) and (-, +) reconnect separating the polar surface into two main regions of opposite polarity. And Figure 6 roughly suggests the existence of dipoles with magnetic axes inclined with respect to the solar rotation axis. As far as the proposed photospheric boundaries are concerned, the orientation E-W or W-E on the solar disk, predicted by the two models through the solar cycle, is the same, except at sunspot minimum. However for a rotating dipole the inclination of the sector boundary with respect to the solar equator should slowly change in time.

The sector boundary orientation and configuration can be tested by means of coronal observations. Field lines, coming from large-scale photospheric magnetic regions of opposite polarity, are likely to assume a configuration of closed loops in the inner corona and of streamers in the outer corona, extended by the solar wind in the interplanetary space. Observations of coronal streamers (Hansen et al., 1972; Howard et al., 1974) and evidences for the existence of closed loops in the inner corona

(Antonucci et al., 1974) indicate that such features are organized in a remarkably regular geometry, which can be associated with the polarity structure of the interplanetary magnetic field.

Closed magnetic loops, developing over the photospheric sector boundaries, should be associated with high density coronal regions, which originate enhancements in the coronal line emission. The proposed configuration of photospheric boundary for a dipole (2-sector structure) predicts correlation between enhanced emission regions at high latitudes in the northern and southern hemisphere, with a time lag equal to half solar rotation, for most part of the solar cycle. In fact the neutral line of the dipole (Figure 3b) reaches the highest latitudes at north and south at 180° longitude apart, this corresponds to half solar rotation period in time. A study of the cross-correlation of coronal green line emission, in the range of 40°-60° in latitude in the northern and southern hemisphere, over an extended period of time 1947-70, confirms these predictions (Antonucci et al., 1974).

Furthermore at the limbs the position of a sector boundary should be recognizable through the associated coronal streamer. Svalgaard et al. discuss the relation of high-latitude streamers with the configuration of the magnetic sector boundary. In particular, during the last part of cycle 20, very stable high latitude streamers have been observed by Howard et al. (1974) in white light, from 3 to 9$R_{\odot}$, with the OSO-7 coronograph. A streamer is observed at the limb, at high latitude position, for a few days. Then the white light enhancement drifts slowly towards the equator and finally a streamer becomes visible in the opposite hemisphere. Such a pattern of alternate northern and southern streamers seems to be very persistent over several solar rotations. At the end of 1972, only one streamer appears in each rotation, in the northern hemisphere, separated by 180° in longitude from a corresponding southern streamer. This simple coronal pattern of two streamers, one at north and one at south, starts when in the interplanetary field a 2-sector structure appears. Moreover both streamers are visible at the limbs (they are 180° longitude apart) in correspondence to the central meridian passage of a sector boundary (Svalgaard et al., 1974). The ideal line which joins the two streamers intersects the central meridian at the equator, where the photospheric sector boundary is individuated, tracing back to the sun the interplanetary sector boundary. When, for example, a (-,+) boundary inferred from the interplanetary boundary is at central meridian, the line joining the streamers coincides with the neutral line of the dipole visible on the solar disk in correspondence of a (-,+) equatorial sector boundary (Figure 3h and Figure 6f, which refer to the last part of cycle 20).

Conclusion

The knowledge that we have of persistent large-scale solar phenomena associated with the weak photospheric magnetism, seems to suggest the possibility of a continuous evolution of the magnetic pattern. This evolution can be simulated by the presence of a rotating magnetic dipole, with a 22-year period, on the solar surface. The implications of this hypothesis seems to agree with the following observational evidence:

a) The zonal and sector structures of the photospheric field through cycle 19;

b) The alternation of the polar field polarities every 11-years;

c) The large-scale migration of features associated with polarity patterns, such as prominences and following magnetic regions of bipolar sunspot groups;

d) The polarity pattern expected in the interplanetary magnetic field and, in particular, the reversal of polarity of a sector at sunspot minimum;

e) The yearly variation of the interplanetary polarity associated with the heliolatitude of the earth;

f) The geometry of (+,-) and (-,+) photospheric sector boundaries through the solar cycle, inferred from contemporary interplanetary and coronal observations.

In the attempt to give a simple general interpretation of the large-scale solar magnetism, in terms of a rotating dipole, I stressed the importance of the 2-sector photospheric and interplanetary magnetic patterns.

The occurrence of a 4-sector structure, more likely at the end of a sunspot cycle, has not been taken into account and may indicate the presence of a quadrupole contribution (which would affect the magnetic dipole in the way proposed by Schulz, 1973).

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Figure Captions

Figure 1. Sector diagram of the photospheric magnetic field averaged over all latitudes. Solid lines represent positive polarity, dotted lines negative polarity. The contour levels correspond to ±0.5, ±1, ±2, ±4, ±8 and ±16G (Stenflo, 1972).

Figure 2. Butterfly diagram of the magnetic field. Solid lines represent positive polarity, dotted lines negative polarity. The contour levels correspond to ±0.5, ±1, ±2, ±4, ±8 and ±16G (Stenflo, 1972).

Figure 3. Solar large-scale magnetic configurations through two consecutive solar cycles 19 and 20, predicted in the hypothesis of a solar magnetic dipole, rotating around an axis perpendicular to the rotation axis of the sun, with a period of 22 years. Configurations of the solar photospheric magnetic field after sunspot maximum and around sunspot minimum (Altschuler et al., 1971) agree with the observations.

Figure 4. Latitude distribution of prominences. The contour levels correspond to the prominence areas 50, 100, 150, 200, 250, 300, 350, 400 and 450 units.

Figure 5. The coefficients computed cross-correlating interplanetary polarity data and a sinusoidal test-function with a period of 27 days are plotted in function of the time lag varying from 0 to 26 days. In each row, the set of cross-correlation coefficients, relative to a period, 27 Bartels rotation long, are reported twice. Positive cross-correlation coefficients correspond to dashed areas. On the left, the number of the first

Bartels rotation of the period of date, used to compute the values of the respective row, is reported. The horizontal lines, separate consecutive solar cycles.

Figure 6. Photospheric magnetic sector boundaries proposed by Svalgaard, Wilcox and Duvall (1974) before, during and after the reversal of the polar magnetic fields of the sun, during solar cycle 20. For each phase of the solar cycle reported, the two kinds of boundaries (+,-) and (-,+) are reported, in the case of a simple two-sector structure. A dipole, with magnetic axis inclined with respect to the rotational axis of the sun, is suggested by the geometry of the sectors (a, d), which, connected, separate the solar surface into two opposite polarity regions. Stages (b, e) and (c, f) can be achieved by the rotation of the magnetic dipole (a, b).

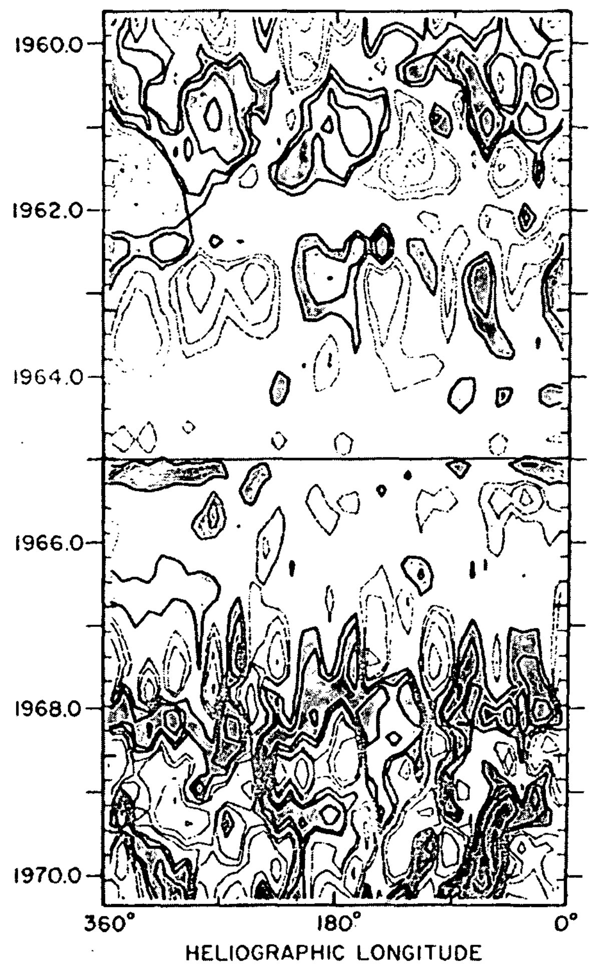
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Figure 1

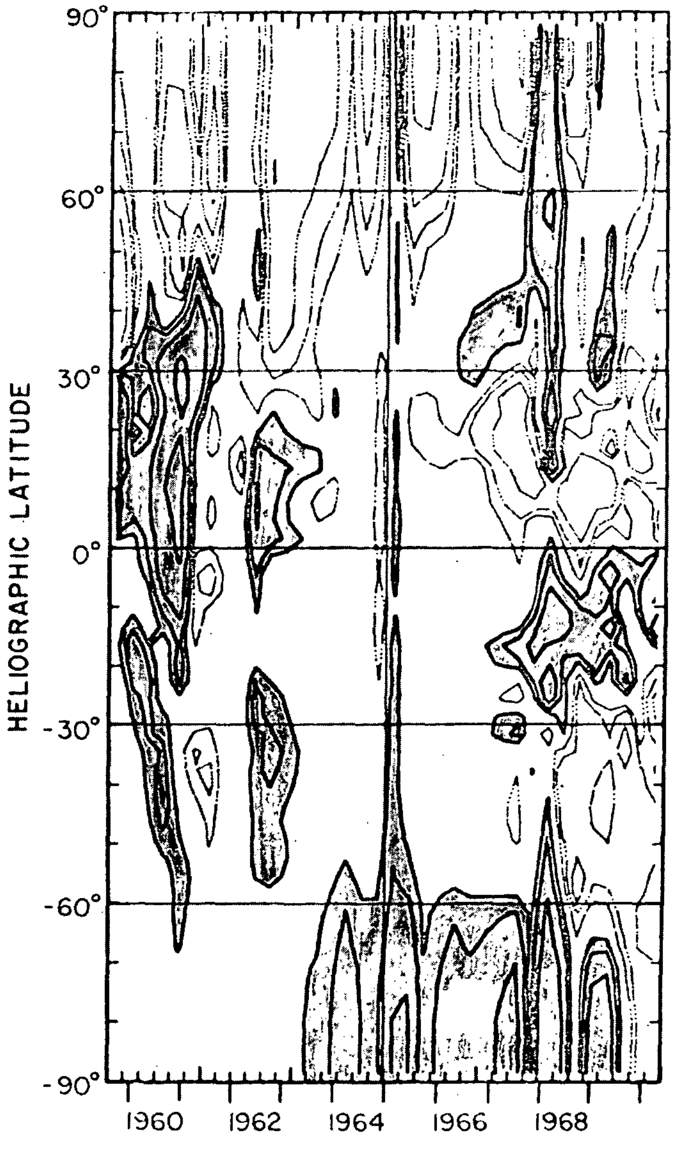
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Figure 2

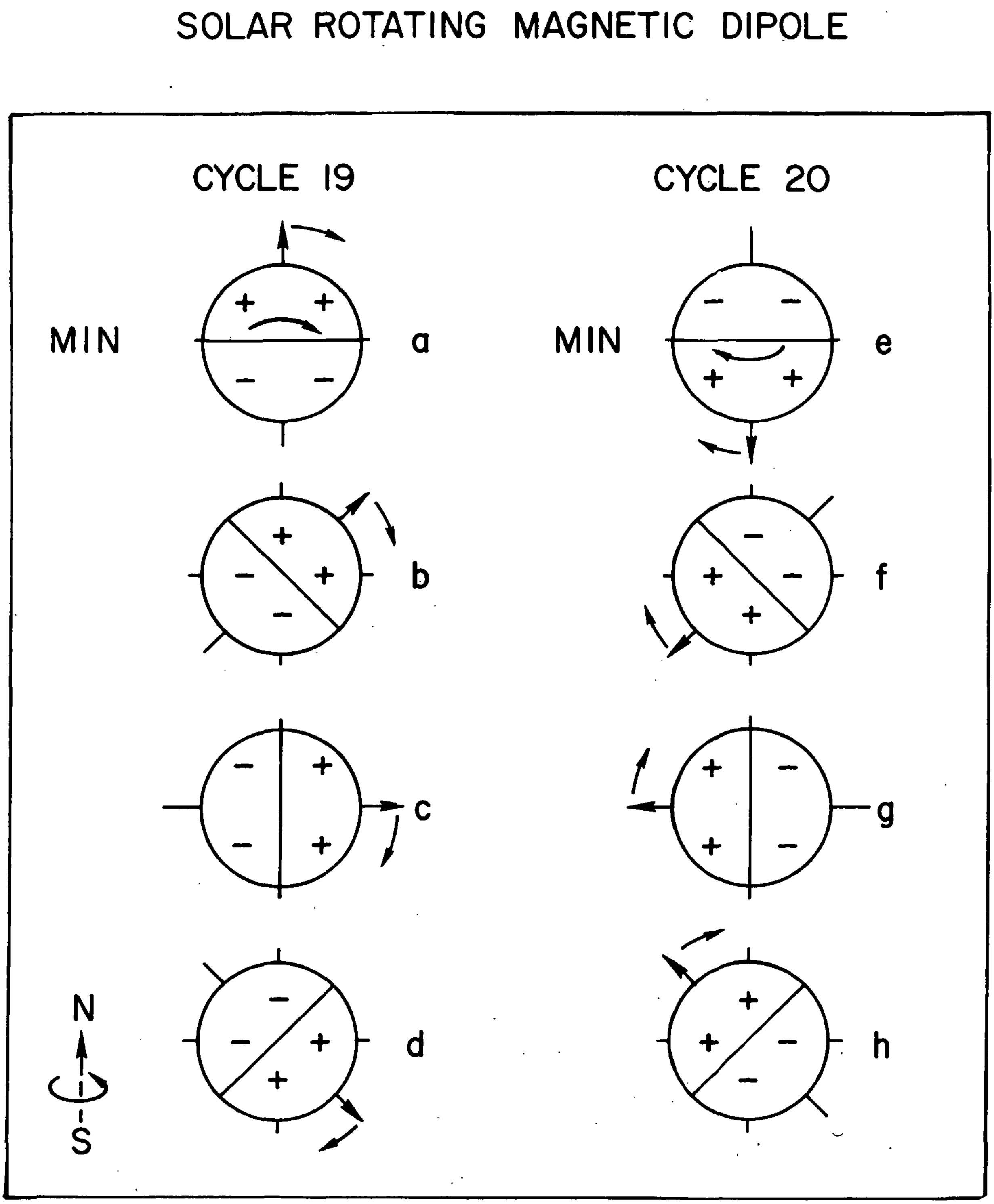
SOLAR ROTATING MAGNETIC DIPOLE
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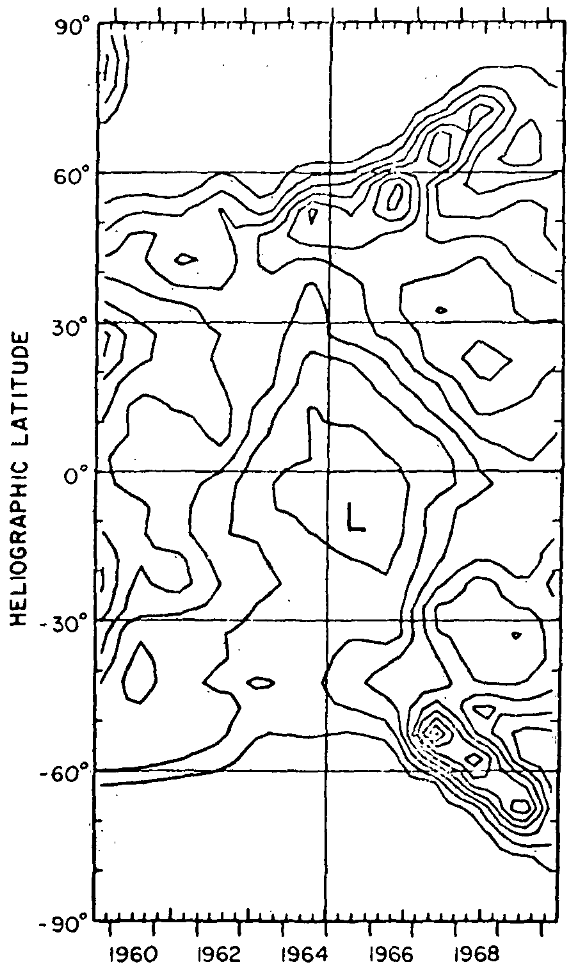
Figure 3



HELIOGRAPHIC LATITUDE
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Figure 4

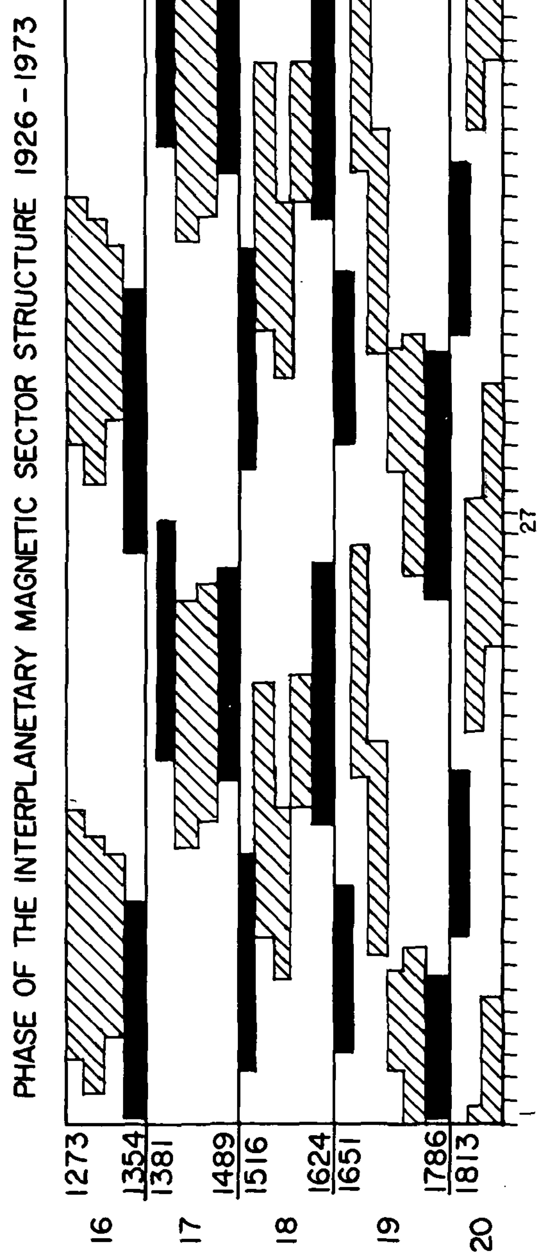
PHASE OF THE INTERPLANETARY MAGNETIC SECTOR STRUCTURE 1926 - 1973
16
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Figure 5

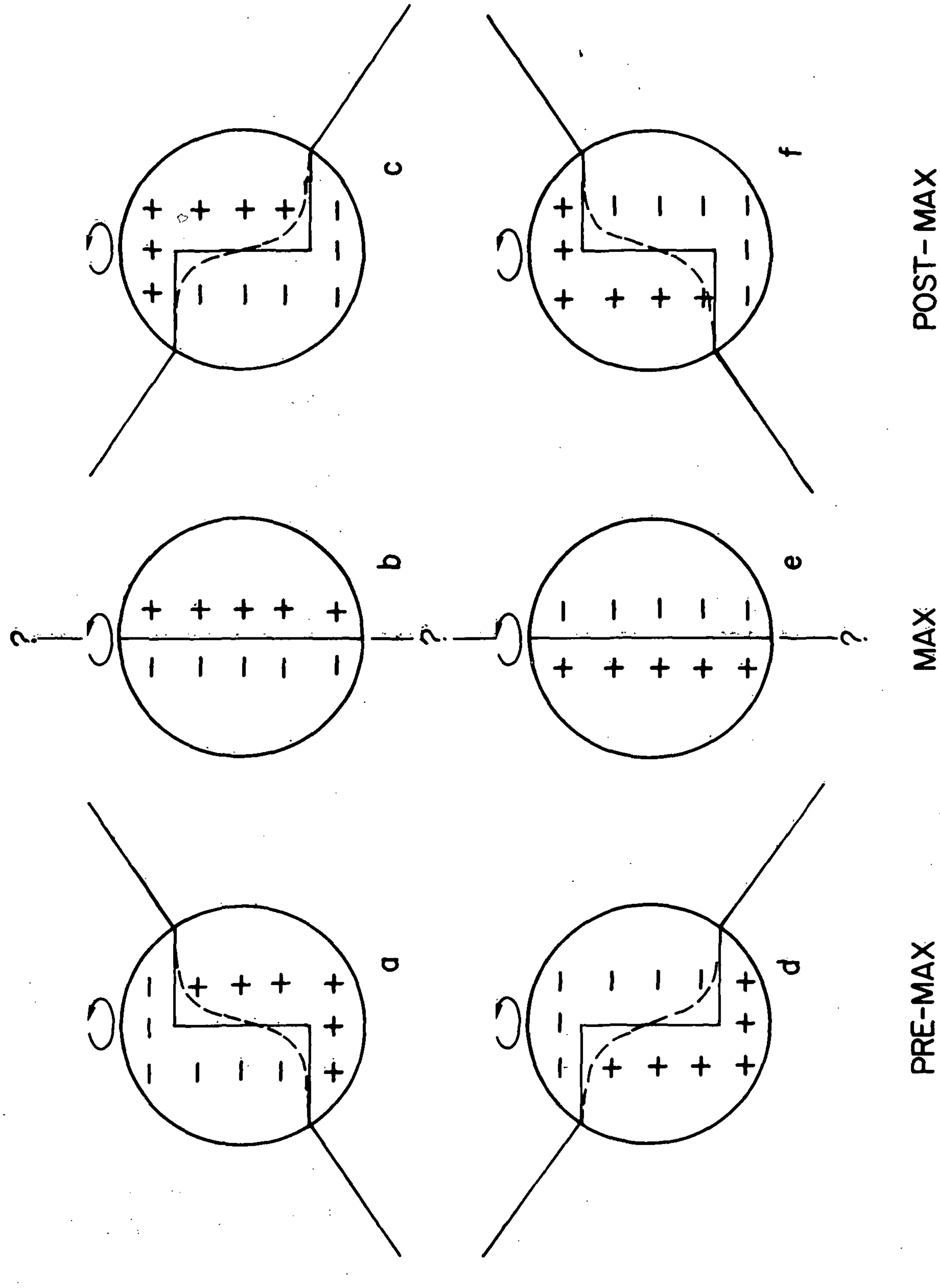

Figure 6

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A magnetic dipole rotating around an axis perpendicular to the rotation axis of the sun can account for the characteristics of the surface large-scale solar magnetic fields through the solar cycle. The polarity patterns of the interplanetary magnetic field, predictable from this model, agree with the observed interplanetary magnetic sector structure.

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