UNIFIED THEORY OF THE INTERPLANETARY MAGNETIC FIELD

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Abstract. A simple model is used to present a unified picture of the polarity pattern of the interplanetary magnetic field observed during the solar cycle. Emphasis in this paper is on the field near solar maximum. The heliographic latitude dependence of the dominant polarity of the interplanetary magnetic field is explained in terms of weak poloidal (dipolar) field sources in the sun's photosphere. Unlike the Babcock theory, the author hypothesizes that the dipolar field exists at equatorial latitudes (0–20°), too, (as well as in polar regions) and that the major source of the interplanetary magnetic field observed near the ecliptic plane is the dipolar field from equatorial latitudes. The polarity of the interplanetary field data taken in 1968 and in the first half of 1969 near solar maximum may possibly be explained in terms of a depression of the dipolar field boundary in space. The effect on the solar wind of the greater activity in the northern hemisphere of the sun that existed in 1968 and in the first half of 1969 is believed responsible for this hypothesized depression, especially near solar maximum, of the plane separating the + and − dipolar polarity below the solar equatorial plane in space. Predictions are made concerning the interplanetary field to be observed near the ecliptic plane in each portion of the next solar cycle.

Rosenberg and Coleman (1969) have found evidence from an analysis of measurements of the interplanetary magnetic field taken mostly from 1965 through 1967 that the dominant polarity of the field was inward (negative, toward the sun) at heliographic latitudes above the solar equatorial plane and outward (positive, away from the sun) at latitudes below this plane during that time. The measurements used were taken mostly in the rising portion of the present solar cycle (a period of usually low geomagnetic and solar activity compared with the 1962–1964 time interval) between $\pm 7.3°$ in solar heliographic latitudes as measured from the solar equatorial plane and between 0.7 and 1.5 AU (see also Rosenberg, 1970).

The observed hemisphere-dependent dominant polarity followed the direction (and $1/r^2$ extrapolated magnitude by the Parker model (1958)) of the sun's dipolar field as measured by Babcock (1955) and Livingston (1966). That is to say, interplanetary magnetic field data taken in the ecliptic plane above the solar equatorial plane (in December to June, if near the earth in space) had a dominant negative polarity. Data taken below this plane (in June to December, if near the earth) had a dominant positive polarity. For near-earth interplanetary measurements the negative polarity dominance was greatest in September and the positive polarity dominance was greatest in March, the extreme points, $\pm 7.3°$, of the sinusoid in heliographic latitude that the earth follows. Thus, the phase relationship between the time of year and the percentage of negative polarity recorded by magnetometers on spacecraft following the ecliptic plane was in accordance with this low activity poloidal model. The author theorizes the lines of force from areas containing a weak, widespread dipolar field of one

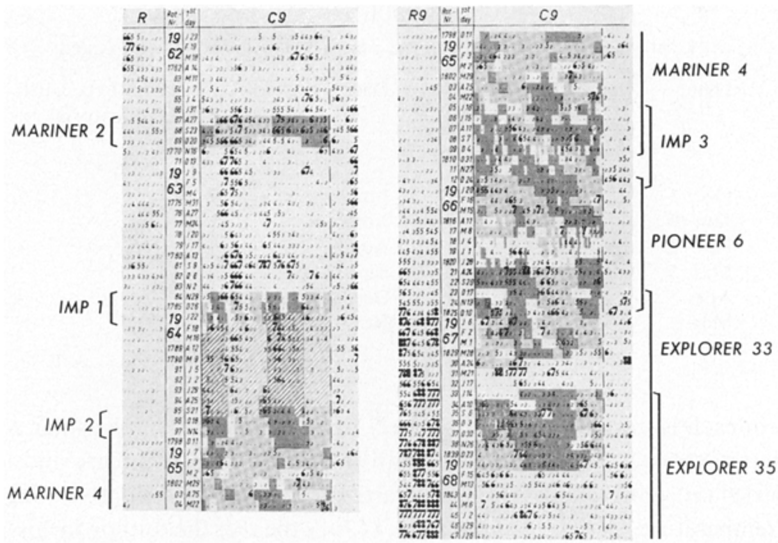

Fig. 1. Interplanetary magnetic field sector structure observed by spacecraft at a given latitude, overlayed on the daily geomagnetic character index C9, alongside the Zurich sunspot number R. Light shading indicates sectors with fields predominantly away from the sun (positive polarity). Dark shading indicates fields predominantly toward the sun (negative polarity). Diagonal bars indicate an interpolated sector pattern. (From Wilcox and Colburn, 1969).

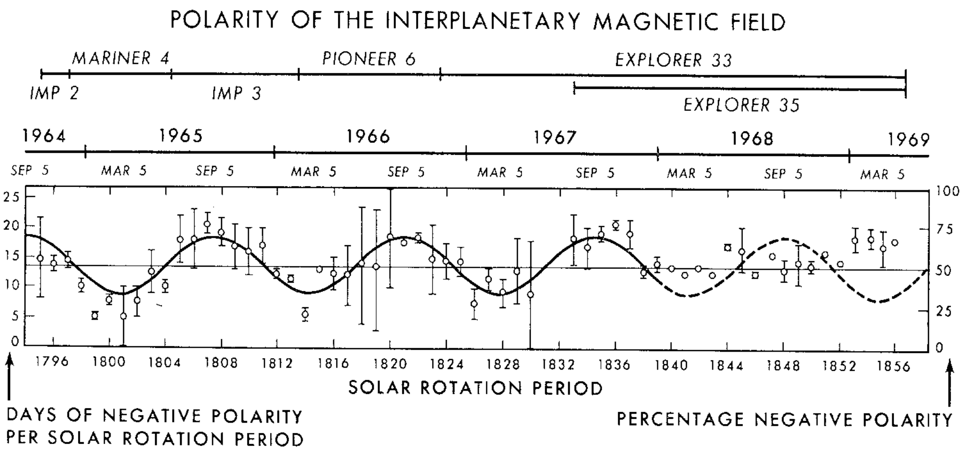

Fig. 2. Polarity observed by spacecraft having the earth's heliographic latitude. For each solar rotation period (SR) the lower bar is the actual number of days of negative polarity. The upper bar is 27 minus the number of days of positive polarity. The distance between the bars is the number of days of missing data. The sine function is the least-squares, best-fit function to the data (9.1% rms deviation) with a one-year period. The data for solar rotation periods 1795 through 1840 were used. This function is $50.9–17.6 \sin(\omega t - 0.171)$, where t is measured in terms of Bartels' solar rotations. This function leads by only 5° the heliographic latitude of the earth, $\beta(t) = 0.73° \sin(\omega t - 0.085)$. Some of the Mariner 4 and Pioneer 6 data were taken at latitudes differing somewhat from that of the earth. The original figure appeared in Rosenberg and Coleman (1969). This version with added Explorer 33 and 35 data past SR 1840 is from Wilcox (1970).

TABLE I

Latitude of the earth during the year in the solar equatorial system

Date	Latitude of the earth	Date	Latitude of the earth in solar equatorial system
Dec. 6	0°	June 5	0°
Jan. 4	−2.4°	July 3	2.4°
Feb. 2	−4.9°	Aug. 3	4.9°
Mar. 5	−7.3°	Sept. 3	7.3°
Apr. 5	−4.9°	Oct. 3	4.9°
May 5	−2.4°	Nov. 3	2.4°

polarity (in each hemisphere) are more likely to be carried out by the solar wind into interplanetary space on a regular basis than those of the more intense and localized fields (bottled up) which may explode outward infrequently with relatively high velocity and temperature. Unlike the Babcock (1961) theory, the author in his poloidal model presumes that the solar dipolar field exists at equatorial photospheric latitudes, too. See Figures 1 and 2 and Table I.

It is possible that different polarity sectors can come from different solar latitudes. The fact that the small, atypical positive polarity sector (which was associated with higher geomagnetic activity) in the second half of 1965 IMP-3 data appears to have come from 25 °N (Schatten *et al.*, 1969) does not mean that the other sectors (they were of negative polarity) came from that latitude.

Wilcox (1970) has published interplanetary magnetic field data for 1968 and 1969 obtained from Explorer 33 and 35 measurements. His Figure 1 is an extended version of Figure 6 from Rosenberg and Coleman (1969) and is reproduced here as Figure 2. The percentages of negative polarity in the first and second halves of 1968 are much closer to 50 % than in earlier data although it does appear to the author of this present paper that there is a preference for the latitude-dependent dominant polarity postulated earlier. We also note (to be explained later) that near 0° latitude in June, 1968, and in December, 1968, the percentage of negative polarity is greater than in the solar rotation periods at latitudes farther from the solar equator in the 1968 measurements. Also, for the data in the first half of 1969 the dominant polarity is negative and not positive as the extension of the sinusoid in Figure 2 shows.

Noting the disagreement between the early 1969 data and the extended sinusoid, Wilcox (1970) thought the early 1969 situation might have been explained if the interplanetary field came from sources near the poles and if the sun's dipolar field had reversed at the poles then. But he indicated that this dipolar field had the same directions at the poles in the first half of 1969 that it had had in 1965. The dipolar field in 1957–1958 at solar maximum reversed at the poles (Babcock, 1959) and should reverse at the poles (Babcock, 1961) at each solar maximum (and in much of the midlatitude regions before the maximum) and in the solar equatorial regions (±20° to 0° latitude) at each solar minimum (next in 1976) according to the theory presented later in this paper. The author of the present paper does not think that the interplanetary magnetic field lines observed near the solar equatorial plane came from sources near the poles (60° to 90° in latitude) because this would require cylindrical symmetry (radial component $B_r \sim 1/r$, east-west $B_\phi \sim$ constant) due to magnetic channeling. This cylindrical symmetry has not been observed for at least the part of the cycle observed from 1965 through 1967 (Coleman, 1969; Coleman and Rosenberg, 1970). Rather, the major part of the field may well be the dipolar field from equatorial sources ($\pm 20°$ in latitude) with some non-dipolar midlatitude sources (residual, unipolar magnetic background fields of bipolar magnetic regions) mixed in at high solar activity. The key to the 1968–69 situation may be a southward depression effect at high northern activity (caused by greater northern solar wind pressure) postulated by Wilcox (1965) in 1965 which he has not considered, in print, in examining the present situation.

It appears to the author that the 1968–69 situation can possibly be explained by a gradual depression, as the solar maximum approached, of the plane separating the two dominant polarity regions in space below the solar equatorial plane. Then in the first half of 1968 the measurements taken below the solar equatorial plane would be near the boundary of this separation plane and thus have nearer to 50 % negative polarity. The June, 1968, data taken at the solar equatorial plane in space would record the depressed, negative polarity dipolar field from the northern hemisphere of the sun and so be dominantly negative as, indeed, the polarity data were. The measurements in the second half of 1968 taken at northern latitudes would record not only the northern hemisphere dipolar field but also contributions from the southward depressed, northern mid-latitude nondipolar fields. This mixture would tend to decrease the dominance of the negative polarity observed. In early 1969 at the solar maximum, the postulated boundary plane might be expected to depress southward even more. Thus, in the first half of 1969 at latitudes below the solar equatorial plane, one might expect to observe the depressed northern hemisphere dipolar field and indeed the dominant polarity is unmistakably negative then and not positive.

Thus, the behavior of the dominant polarity data in 1968 and 1969 may be explained by a southward depression of the boundary plane separating the two poloidal regions. Wilcox (1965) himself postulated this southward depression of the solar wind and magnetic fields at times of high northern activity. Quoting Wilcox (1965): 'The resulting additional pressure would cause the average solar wind flow to 'bulge' out towards the south. The earth would tend to be connected to regions in the northern solar hemisphere.' For several recent solar cycles, including the present one up to mid-1969, the northern hemisphere of the sun has been more active and therefore hotter than the southern hemisphere (Bell, 1961; Livingston, 1966). At times of high northern activity the greater pressure of the hotter and faster northern midlatitude plasma allows it to expand more with distance from the sun than the cooler gas nearer the equator can. This could cause the solar wind flow toward the equator from the north and would tend to depress the poloidal field boundary in space below the solar equatorial plane (Wilcox, 1965). As the solar maximum approaches, the whole sun heats up and the northern hemisphere would heat up correspondingly more.

Recently, Dr. Robert Howard (private communication, Pasadena, 1970) told the author that he and others had observed that starting in the period from mid-1969 to mid-1970 (the latest available data) the activity in the southern hemisphere of the sun (as measured by the number of sunspot groups) was comparable and sometimes even greater than the activity in the northern hemisphere. He said this has not happened for at least the last 11 years and probably longer. When analyzing interplanetary field data from the second half of 1969 until late 1971 when solar activity is expected to decrease, one should find out which hemisphere was more active in each solar rotation studied. The postulated dipolar boundary plane may have been displaced one way and then the other way. When southern hemisphere activity dominated, the boundary plane would have been displaced northward in the theory outlined above.

Predictions concerning observations near the ecliptic plane are as follows. If the above theory is correct, observations in the years 1970 and 1971 (right after solar maximum) will probably be influenced by greater activity in one hemisphere in the manner outlined above. At low solar activity again in 1972 to early 1974, dipolar fields should be observed with the phase of the dominant polarity sinusoid the same (no displacement effect) as from 1965–1967. From late 1974 until the solar minimum in mid-1976 we shall probably observe a partly 'quasi-stationary' polarity pattern associated with high geomagnetic activity patterns (Sinno, 1956; Tandon, 1956) and high solar wind velocities because of contributions from very widespread, unipolar magnetic regions (Bumba and Howard, 1965; 1966) that will exist then at low latitudes under conditions similar to 1962–64 and, possibly, to the two years before every solar minimum. These new residual UMRs (from following BMR halves) are much weaker than localized fields but they are stronger than the old dipolar field at the equator formed at the last minimum.

At low activity in the next solar cycle, beginning after the solar minimum in 1976, the dominant polarity of the interplanetary field should be positive in the northern hemisphere and negative in the southern hemisphere in interplanetary space, a reversal of the 1965–67 sinusoid phase. This will be true if the sun's dipolar field reverses (should reverse in equatorial regions at solar minimum, see below), if solar photospheric equatorial latitudes provide the sources of the interplanetary field observed near the ecliptic plane, and most important, if the dipolar field does, in fact, supply the dominant contribution. The discovery of the phase relationship in the present cycle (the sinusoid of Figure 2) *at low activity* is good evidence that the dipolar field does indeed contribute major portions of the field.

In experimentally constructing averages of the background field of the sun, the following should be considered. Averages should be taken over at least 60-day periods. A reasonably wide aperture with the solar magnetograph should be used to insure that widespread background fields (on the order of 1 G or less) and not much stronger localized fields are being measured. Even when the above procedure is used, it is still possible that the field strength of the most widespread and weakest background field, probably the dipolar field, may be masked or below the limits of the magnetograph some of the time and in much of the photospheric regions.

When computing background field averages, each hemisphere should be divided into four regions in latitude: 0–15°, 15–40°, 40–70°, and 70–90° (the pole). At solar minimum at about 35° latitude new sunspot activity starts and the main sunspot distribution appears at progressively lower latitudes as the cycle progresses. Based on past experimental data (Aller, 1963; Babcock, 1959, 1961) the author would expect that by two or three years or even less after the solar minimum the background field in the 40–70° region in a given hemisphere would assume the polarity of the unipolar magnetic regions (UMRs) formed from the following halves of residual bipolar magnetic regions (BMRs). Most of the following BMR halves have the same polarity in a given hemisphere (this polarity is opposite in the other hemisphere). As these following UMRs migrate poleward, the average background field in the 70–90° region could assume for quite a few months their polarity but then as the effects of the individual UMR fields fade there the polarity of the 'original' dipolar field would be resumed in the average. However, by the solar maximum (or within 18 months later in 1957–8) the following UMRs would have reached a sufficient level at the poles to have changed and kept the background field there at the polarity (now that of the new dipolar field) of the following fields until the next cycle. Just before the next solar minimum the main distribution of sunspot-BMR fields is very near the equator. The author thinks the net cumulative effect of the collective wake of the following UMR background fields will be to reverse the background dipolar field in the equatorial regions (0–15° in each hemisphere) by about solar minimum.

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