8 April 1966, Volume 152, Number 3719 SCIENCE

Solar and Interplanetary Magnetic Fields

Space probes can observe the extension of the sun's magnetic field by the solar wind.

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Much of our quantitative information about the sun's magnetic field has come from observations of the photosphere (the visible layer of the sun) made with the solar magnetograph, in measurements which utilize the Zeeman effect. The observations at the Mount Wilson Observatory with this instrument have recently been described by Bumba and Howard (*1*). With the advent of space probes it has become possible to make measurements in the interplanetary medium and to observe the extension of the solar magnetic field out into interplanetary space. The physical principle involved is simply this: the solar wind—the continual expansion of the outer solar corona—stretches out some of the lines of the sun's magnetic field into interplanetary space (*2*); at the same time, the solar rotation twists the lines so that the resulting form of the interplanetary magnetic field is an Archimedes spiral. This picture, which was developed by Parker (*3*) in the late 1950's, has been confirmed by recent satellite observations.

The spiral streaming angle of the interplanetary field (the average angle between the field direction and the earth-sun direction) is determined by a vector combination of the solar wind velocity in the radial direction and the quantity ΩR in the azimuthal direction, where Ω is the angular velocity of the solar rotation and R is the distance from the sun. At the earth the magnitude of ΩR is 435 kilometers per second, and if the solar wind velocity is also approximately 435 kilometers per second (as it frequently is), then the spiral streaming angle would be approximately 45 degrees. As the solar wind velocity increases the spiral angle decreases, until, in the limit of a very large solar wind velocity, the effect of solar rotation is small and the interplanetary field lines are stretched out toward the radial direction.

This spiral configuration is expected in most of the region between the earth and the sun, in which the kinetic energy density of the streaming plasma is considerably greater than the energy density of the interplanetary magnetic field. Within a few solar radii of the sun the situation is reversed: the energy density of the magnetic field may be considerably greater than the energy density of the plasma. The magnetic field then may be capable of controlling and guiding the flow of the plasma. This region close to the sun is not very well understood at present. For example, a region on the sun in which the magnetic field is stronger than average might be expected to contain hydromagnetic waves and shocks of higher-than-average intensity which might make an important contribution to the coronal heating. The resulting higher-temperature corona would be expected to be a source of a greater flux of solar wind. At the same time, however, the stronger magnetic fields could have an inhibiting effect on the flow of the solar wind. Thus it is not clear whether an active region on the sun, with its concomitant stronger magnetic fields, would or would not tend to be an important source of solar wind flux.

In the region close to the sun the strong magnetic fields can force the local plasma to rotate as a unit with the sun (*4*). At an elevation of a few solar radii the field becomes too weak to compel the plasma to rotate with the sun, and a transition occurs to the condition finally observed by space probes (*5*) near the earth—that in which the solar wind velocity is nearly radial from the sun most of the time (*6*).

Interplanetary Field Measurements

Because of the complexity of the intervening regions, until recently it was not clear whether there was any simple relation between the pattern of the photospheric magnetic fields observed with the solar magnetograph and the pattern of the interplanetary magnetic fields near the position of the earth. This problem has been investigated in terms of the large-scale direction of the fields. The solar magnetograph measures the line-of-sight component of the photospheric magnetic field, so that one knows whether the field at a given region on the sun is directed toward the sun or away from the sun. In the interplanetary field the direction is, on the average, along the spiral streaming angle described above, but the sense of the field can be either predominantly away from the sun or toward the sun. For comparison with the photospheric field, the interplanetary field is analyzed from the excellent observations obtained by Nor-

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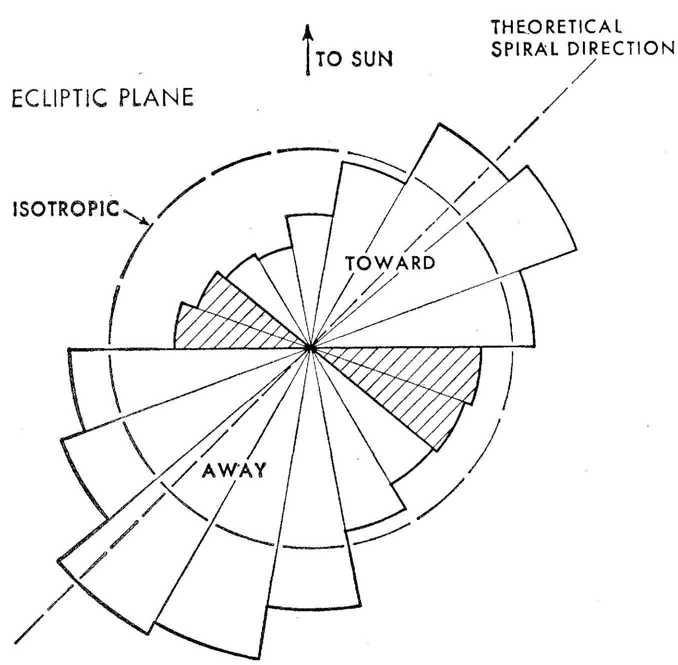
man F. Ness (7) with the magnetometer experiment on the IMP-1 satellite.

This satellite was launched on 27 November 1963 and observed the interplanetary medium during three solar rotations. The orbit was highly elliptical, with apogee at 31.4 earth radii, so the satellite could observe the interplanetary medium undisturbed by the presence of the geomagnetic field. Vector measurements with an uncertainty of ± ¼ gamma (1 gamma = 10^{-5} gauss) were obtained every 20 seconds, and these were averaged at 5.46-minute intervals. The distribution of the direction of the component of these vectors parallel to the ecliptic is shown in Fig. 1. The dashed line shows the average direction of the spiral magnetic field discussed above. It may be seen that the observed distribution is indeed stretched out along the directions predicted by the spiral-field model.

The range of angles labeled "away" in Fig. 1 is considered to represent a field directed predominantly away from the sun, and the range of angles labeled "toward" is considered to represent a field directed predominantly toward the sun. The total time of the observations (81 days) is divided into 12-hour intervals, and each such interval is characterized as "away" or "toward," depending upon the predominant direction of the field within that interval. This is a meaningful approximation because, during most of the 12-hour intervals, the field direction remains almost entirely within either the "away" range of angles or the "toward" range. Now that this description of the sense of the field, by 12-hour intervals, is available, the influence of the sun on the interplanetary magnetic field can be investigated. The rotation period of low latitudes on the sun, as seen from the earth, is about 27 days. Thus, if features on the sun that are changing only slowly with respect to a solar rotation period are indeed influencing the interplanetary field, then this field should show a tendency to recur every 27 days. This possibility can be investigated by computing an autocorrelation (a correlation of the members of a series among themselves) of the function describing the sense of the interplanetary field at 12-hour intervals. This autocorrelation is shown in Fig. 2. The prominent peak at a lag of about 27 days is evidence for a solar influence on the interplanetary magnetic field.

Comparison with Solar Field

For comparison with this description of the direction of the interplanetary magnetic field, observations made with the solar magnetograph by Howard and Bumba at the Mount Wilson Observatory have been utilized. Since observations made with this instrument have recently been described in *Science* (1), only a short account of them is included here. With the solar magnetograph one can produce a synoptic chart of the photospheric magnetic field, such as that shown in Fig. 3 for the period 1 December to 11 December 1963. Field directed away from the sun is represented by solid contours; field directed toward the sun is represented by dashed contours. The isogauss levels range from 2 to 12 gauss. A strip 10 degrees of latitude wide centered at a given latitude is divided into longitudinal increments, each corresponding to the solar rotation that occurs in an interval of 12 hours. Each of the resulting increments of area is designated "away" or "toward," depending upon the predominant direction of the photospheric field within that area. Occasional ambiguous areas are ignored. If an area contains no con-



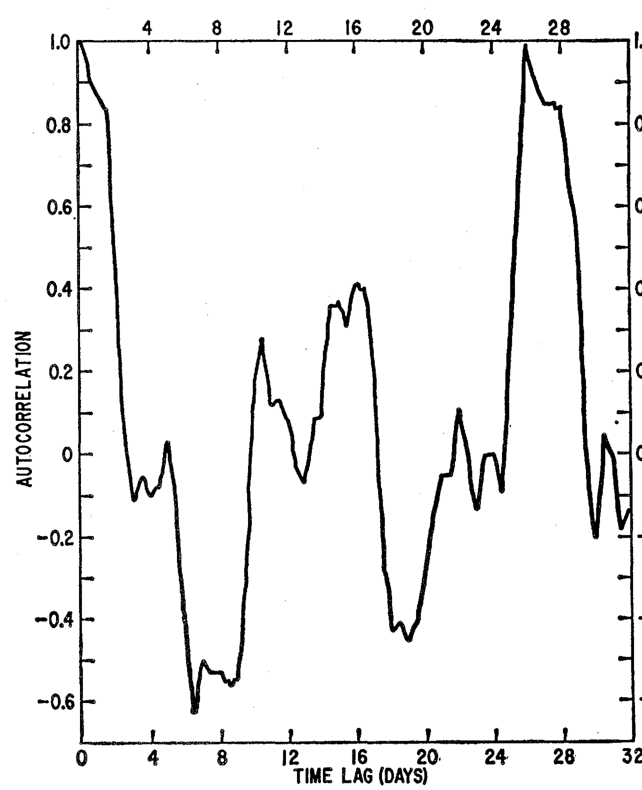


Fig. 1 (left). Distribution of direction of the measured interplanetary magnetic field component parallel to the ecliptic, averaged over 5.46-minute intervals. The dashed circle corresponds to an isotropic distribution of the same number of vectors. The dashed straight line shows the approximate direction of the theoretical spiral field. The origin of the coordinate system is the satellite. The direction of the sun is up, and the direction of the earth's orbital motion about the sun is to the right. Fig. 2 (right). Autocorrelation of the observed direction of the interplanetary magnetic field. The large positive peak at lag of about 27 days indicates that the interplanetary magnetic field structure rotates with the sun. The subsidiary peaks are related to the sector structure discussed later in the text.

tours but is closely surrounded by contours all of the same polarity, then the area is assumed to have a weak field of that polarity. Thus, a description of the direction of the photospheric magnetic field at a given latitude by 12-hour interval is obtained.

A cross-correlation between the direction of the photospheric magnetic field and the direction of the interplanetary magnetic field can now be computed. Cross-correlations corresponding to two latitudes near the center of the sun are shown in Fig. 4. A positive time lag is measured from the time a photospheric region passes the central meridian (day 0) to the time the field is observed by the IMP-1 satellite. A prominent positive peak in the correlation is obtained at a positive time lag of 4 to 5 days. This time interval is within the range of transit times for the flow of the solar wind plasma from the sun to the earth, as estimated from observations of the solar wind velocity made with plasma detectors on board the IMP-1 satellite. Thus, the appearance of a certain direction of field at the central meridian on the sun tends to be followed 4 or 5 days later by the corresponding direction in the interplanetary field near the earth. It is found that some of the magnetic lines of the photospheric field are dragged out by the solar wind in such a way that they flow past the earth. This result is consistent with a theoretical prediction by Ahluwalia and Dessler (*8*).

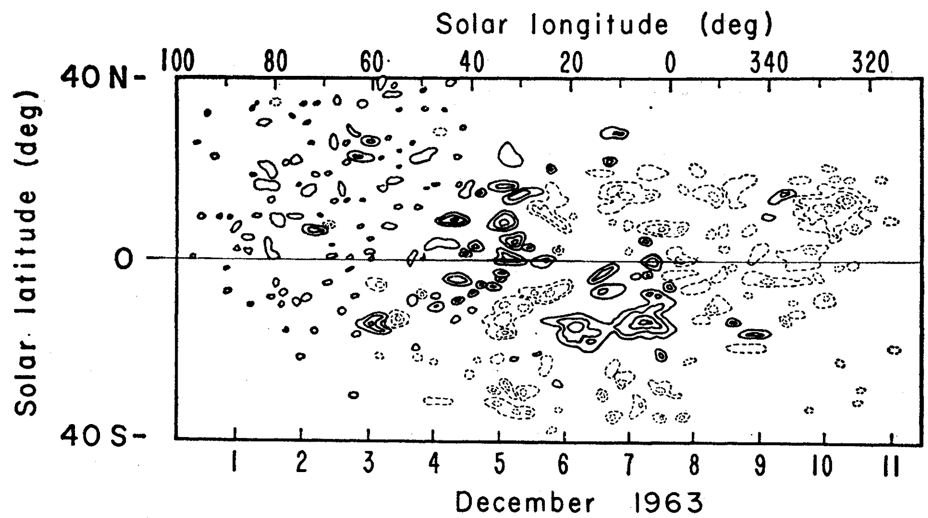


Fig. 3. Synoptic chart of the photospheric magnetic field during December 1963. Solid contours represent a field directed away from the sun; dashed contours, a field directed toward the sun.

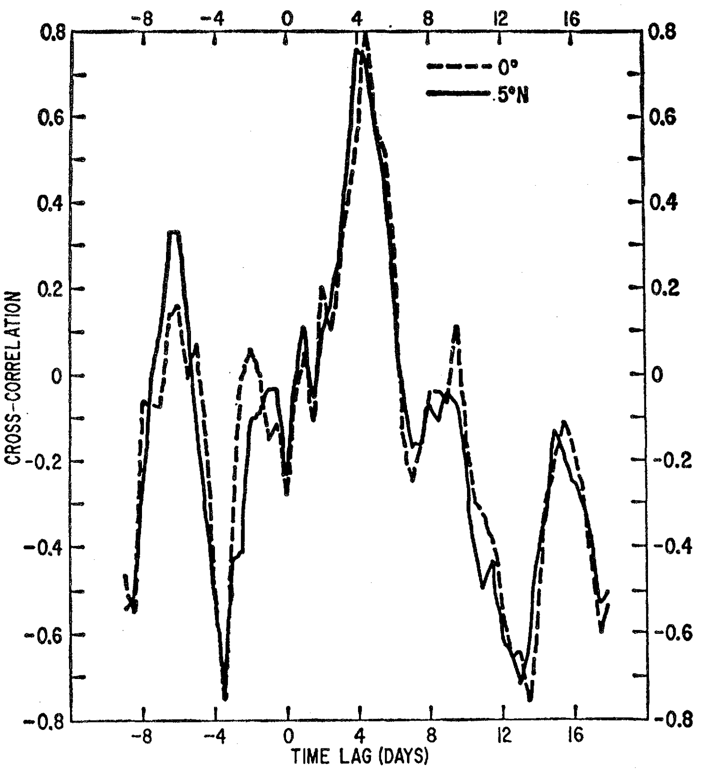
Latitude of the Solar Source

The latitude on the sun of the regions that constitute the source of the interplanetary magnetic field which sweeps past the earth has been investigated in terms of the solar differential rotation. As seen from the earth, regions near the solar equator rotate with a period of about 27 days, whereas regions at high latitudes have a slower rotation, with a period of about 30 days. First the period of recurrence of the interplanetary magnetic field is determined as accurately as possible, and then studies are made to find what latitudes on the sun rotate with this same period. The period of recurrence of the interplanetary magnetic field can be determined from the position of the large positive peak in the autocorrelation of Fig. 2. The differential rotation of the photospheric field is determined by computing autocorrelations, for each of the latitudes, of the functions describing the direction of the photospheric field, as described above. The results of two of these solar autocorrelations, for the latitude of the center of the visible disk (0°) and for latitude 25°N, are shown in Fig. 5. The dashed curve, corresponding to the autocorrelation for the higher latitude, clearly shows displacement toward a longer rotation period. The differential rotation of the photospheric field, as determined from such autocorrelations, is shown in Fig. 6. The solid curve of Fig. 6 was determined by Newton and Nunn (*9*) from observations of long-lived sunspots. The heavy arrow on the ordinate indicates the period of recurrence of the interplanetary field, as determined from the curve of Fig. 2. The lighter arrows indicate the uncertainty in this measurement. A comparison in Fig. 6 of the period of recurrence of the interplanetary field with the solar differential rotation suggests that the latitude of the solar source of the interplanetary field was within 10 or 15 degrees of the center of the visible disk. Future observations may help to establish this latitude more precisely. It is quite possible, for example, that the latitude of the solar source may change from time to time as the various kinds of photospheric magnetic field regions described by Bumba and Howard rotate past the central meridian. The correlation described here applies only to solar regions of considerable extent in latitude and longitude which have lifetimes at least comparable to the period of solar rotation. Transient effects such as flares are not included in this analysis, nor are the large but localized magnetic fields of sunspots, which are not significant in this context.

The method developed in Figs. 5 and 6 is an interesting new way to study the solar differential rotation. Textbooks often cite the results of Newton and Nunn (*9*) (represented by the solid line in Fig. 6), obtained by means of sunspots which were observed on one solar rotation and which were sufficiently long lived to be observable on the following rotation. These long-lived sunspots are almost always the preceding member of a sunspot pair. They may have a proper motion on the disk, which could distort the measured rotation period. The rotational velocity can also be measured directly from the Doppler shift of spectroscopic lines. In this procedure the influence of the local velocity fields must be removed. In obtaining measurement of the differential rotation of the photospheric magnetic field we are dealing with a large-scale fundamental feature of the sun. Such a measurement may be interesting in connection with the often-discussed but poorly understood relationships between stellar and planetary rotation and magnetism.

Interplanetary Sector Structure

An interplanetary-field structure that is suggested by the IMP-1 satellite observations is shown in the central area of Fig. 7. The field is directed predominantly away from the sun for an interval corresponding to about



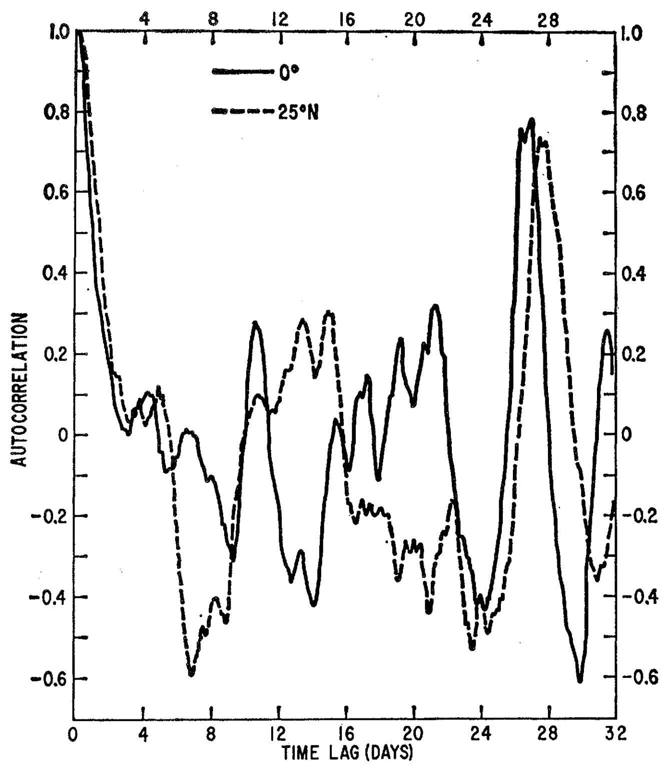


Fig. 4 (left). Cross-correlation of nearby interplanetary magnetic field direction and photospheric magnetic field direction for solar latitudes at the center of the visible disk (0°) and at 5°N. Fig. 5 (right). Autocorrelation of the photospheric magnetic field direction for latitudes at the center of the visible disk (0°) and at 25°N. The increase in period caused by differential rotation is apparent.

2/7 of the total circumference, then toward the sun for a 2/7-circumference interval, then away for a 2/7-circumference interval, and then toward the sun for an interval corresponding to about 1/7 of the circumference. The satellite observations that suggest this structure are shown on the periphery of Fig. 7. A plus sign designates a 3-hour interval during which the interplanetary field was predominantly away from the sun, and a minus sign designates a 3-hour interval during which the field was toward the sun. The position of the observations made during the first of the satellite's orbits is indicated, and subsequent observations follow in the clockwise direction.

This "sector" structure rotates with the sun, since, as Fig. 2 shows, it has a recurrence period of about 27 days, and, as Fig. 4 shows, it is rooted in the photospheric magnetic field. We must distinguish between the rotating magnetic *pattern* discussed here (the plasma velocity being radial from the sun) and the situation, mentioned above, in the region close to the sun where the *plasma* itself rotates with the sun. In the case of the rotating magnetic pattern of Fig. 7, the radially moving plasma slips along the rotating magnetic lines. This situation has been compared with a phonograph record in which the grooves (the magnetic lines) rotate as a unit and the needle (the plasma) slips along them and moves in the radial direction.

The structure of Fig. 7 is evidently quasi-stationary, since, during most of the three solar rotations observed by IMP-1, it did not change. The first satellite orbit is an exception to this sector structure. It may be that the solar field was changing at this time. In the second orbit it appears that the positive field associated with the recurring geomagnetic storm of 2 December arrived "too soon." However, the solar wind velocity at this time was considerably higher than the average solar wind velocity during the entire period (*5*), and this brought the sector boundary associated with the beginning of the geomagnetic storm out to the position of the earth too soon. For the remainder of the observations, as may be seen from Fig. 7, the "sector" description is a very good approximation—that is, in a sector with field directed away from the sun the 3-hour observations are almost all designated "away" (+), and in a sector with field directed toward the sun the 3-hour observations are almost entirely designated "toward" (−). If one examines with the solar magnetograph the photospheric field region corresponding to an "away" sector one finds that the photospheric field is indeed predominantly directed away from the sun. However, one finds within this region a number of small areas with field directed toward the sun, and as the resolution of the solar magnetograph is improved, more and more such small areas are discovered. It appears that many of the magnetic lines leaving the photosphere loop around and return to it at rather low altitudes, and that the sense of the distant interplanetary field in a given sector is determined by the algebraic sum of the photospheric field lines in the many small areas that make up the corresponding region of the photospheric field.

Structure within the Sectors

The sector structure has been defined on the basis of the sense of the interplanetary magnetic field. We ask now if the magnitude of the field and the velocity and density of the solar wind plasma are related to the sector structure. A schematic answer is given in Fig. 8. Since the sector structure rotates with the sun, a 2/7-sector sweeps past the earth in 7¾ days, and the abscissa of Fig. 8 represents this time interval. The sector boundary (0 days in Fig. 8) is the position in Fig. 7 in which the direction of the field changes. (This change is observed by the satellite to occur within a period of a few minutes, hence the sector boundary is very narrow.) The solid lines represent the average value of the indicated quantities as a 2/7-sector passes the earth (for the original analysis, see *10*). Note that the field magnitude and solar wind velocity are represented by the same curve in Fig. 8, while the curve for solar wind density is quite different in shape. It appears that the solar wind is not just boiled off the sun at random, but instead is very much structured and guided in the region close to the sun. Presumably the solar magnetic field has a large influence here.

An analysis of geomagnetic activity as the sector structure sweeps past the earth yields a curve with a shape similar to that for the plasma velocity, as shown in Fig. 8. This result is consistent with the finding from Mariner II observations (*11*) that the solar wind velocity and the geomagnetic index K_p are linearly related.

Discussion

This analysis of the solar wind parameters in terms of the sector structure indicates that the sectors are a fundamental property of the interplanetary medium. The longitudinal structure and regularity thus revealed in the interplanetary medium will have important implications for the theory of the structure of the sun. It has been long known that certain longitudes on the sun are unusually active in terms of sunspots and flare production. Bumba and Howard (*1*) have observed a regularity in the background photospheric magnetic fields. One can perhaps distinguish an increasing order of characteristic dimensions associated with the sun. The classical granulation pattern has a typical cell size of about 700 kilometers. The supergranulation or chromospheric network pattern observed by Leighton (*12*) has a typical dimension of about 30,000 kilometers. The sector structure discussed here has a dimension to be measured in terms of a fraction of the solar diameter. No theoretical expla-

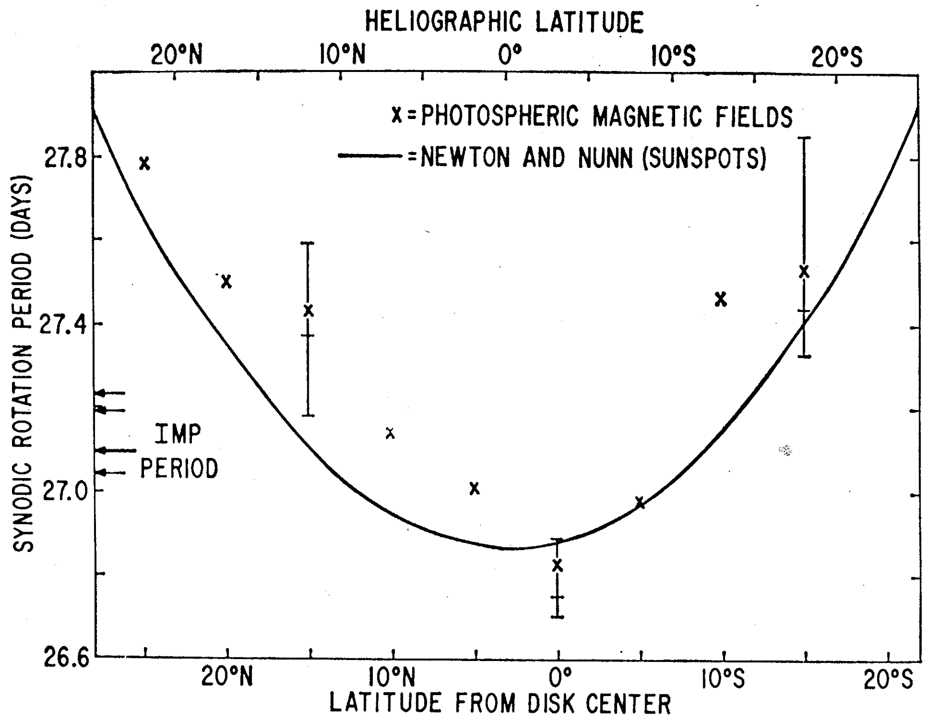


Fig. 6. Rotation period of the photospheric magnetic field as a function of latitude, as determined from autocorrelation analysis (see Fig. 5). (Solid line) Rotation period determined by Newton and Nunn (*9*) from analysis of long-lived sunspots; (heavy arrows) period of recurrence of nearby interplanetary field; (light arrows) uncertainty of recurrence period.

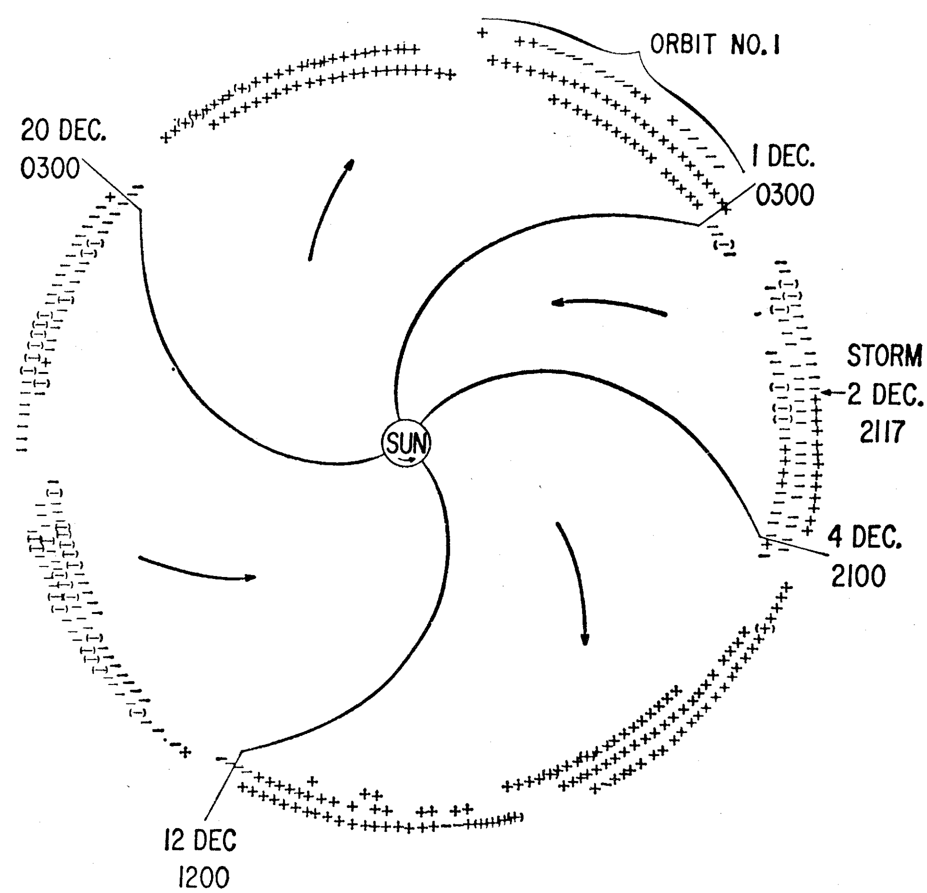


Fig. 7. Measured direction of interplanetary magnetic field for successive 3-hour intervals and a sector structure suggested by the data (see text). (+) Field away from sun; (−) field toward sun.

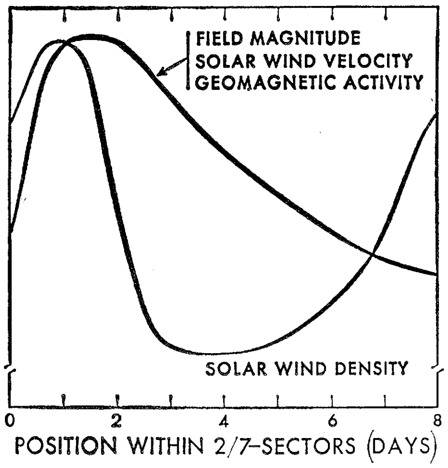


Fig. 8. Schematic representation of average interplanetary magnetic field magnitude, solar wind velocity, solar wind density, and geomagnetic activity as a function of position within the 2/7-sectors (see text). Range of field, about 3½ to 6½ gammas; velocity, 280 to 340 kilometers per second; density, 7 to 14 protons per cubic centimeter; 24-hour sum for the geomagnetic activity index K_p, 10 to 25.

nation for this sector structure has yet been proposed.

The sector structure could have interesting implications with regard to observations of stellar magnetism. Babcock (*13*) has observed many stars in which the field direction has irregular oscillations with a period of a few days. One suggested explanation for this effect is in terms of a magnetic oscillation similar to that observed in our sun. In each 11-year sunspot cycle the magnetic polarity of the preceding and of the following sunspots is opposite to their polarity in the previous cycle. The change from the 22-year period observed for the sun to the period of several days observed for the stars could be related to the change from an average field magnitude of a few gauss observed for the sun to an average field magnitude of a few kilogauss observed for the stars having variable magnetic field. A different suggested explanation for Babcock's observations is in terms of an oblique rotator (*14*). The star is assumed to have a dipole-like field similar to that observed in the polar regions of the sun, but with the magnetic axis considerably displaced from the rotational axis. It is suggested that when such a star is observed from an appropriate angle the field appears to oscillate. In a new suggested explanation it is postulated that a magnetic star might have a large-scale longitudinal pattern in the direction of its field, a special case of which would be the sector structure discussed in this article. Such a star would appear to have an oscillation of field direction of period half the star's period of rotation.

In the sector structure of Fig. 7, more magnetic field lines leave the sun than return to it, since the "away" sectors are bounded by arcs which comprise 4/7 of the circumference, and the "toward" sectors, by arcs which comprise 3/7 of the circumference. The average field magnitude is about 10 percent greater in the "away" sectors, and the average solar wind velocity is the same for the "away" and for the "toward" sectors. This net outward-directed field in the plane of the ecliptic must be balanced by an inward-directed field at other heliographic latitudes.

Protons of energy of a few million electron volts (*15*) have been observed to be largely confined to one "away" sector. This suggests that the outward magnetic lines in this sector do not connect in a smooth manner to the inward magnetic lines in the adjacent "toward" sectors, because, if they did, these protons would follow such lines and populate the adjacent "toward" sectors.

The three solar rotations discussed here represent a very short interval during the quiet portion of the 11-year cycle. About a year earlier the interplanetary field was observed (*16*) by Mariner II during its flight to Venus; the field was away from the sun for about half a solar rotation and toward the sun for the other half rotation. About a year after the observations discussed in this article Mariner IV, at the start of its flight to Mars (*16*), found that the direction of the interplanetary field was similar to the sector structure discussed here, but that the sizes of the individual sectors had changed somewhat. Further evolution of the structure occurred during the subsequent Mariner IV observations. Thus, elements of the sector structure persist over at least a few years. It will now be interesting to observe the interplanetary medium during the rising portion of the 11-year sunspot cycle, when the rather quiet conditions discussed in this article are perturbed by the plasma streams and shock waves associated with solar flares.

References and Notes

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17. I thank the director of the Mount Wilson Observatory for guest-investigator privileges at the observatory, and N. F. Ness, R. Howard, and V. Bumba for many valuable discussions. This research was supported in part by the Office of Naval Research, under contract Nonr-3656(26), and by the National Aeronautics and Space Administration, under grant NsG 243-62.