Reprinted from "Physics News" Vol. 10 No. 2, June 1979

LARGE SCALE STRUCTURE OF THE INTER-PLANETARY MAGNETIC FIELD*

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ABSTRACT :

The macrostructure of the interplanetary magnetic field which is stable over a few solar rotations is reviewed. The radial dependence of the IMF as well as its sector structure are briefly discussed.

I. INTRODUCTION

The solar terrestrial relationship has become a major preoccupation of space scientists in recent days. With the advent of the satellite era, huge amounts of information have been collected on the physical state of space not only in the immediate neighbourhood of our earth but in the interplanetary space as well. The magnetic field is one of the most important physical quantities in space which controls, apart from the sun-earth interaction, various phenomena involving charged particles and fields. In this article we shall study the gross features of this magnetic field in the interplanetary space, popularly abbreviated as the IMF.

The expanding solar corona, known as the solar wind, consists chiefly of equal numbers of electrons and protons of very low density of the order of one to ten particles per cubic centimeter at the earth's orbit. The mean free path of collision is, therefore, very large—being about 1 A.U. (A.U. = sun — earth distance). As a result, the conductivity of this plasma is so high that it can be mathematically treated to be infinity.

It is well-known that this highly conducting solar wind plasma forces the planetary magnetic fields to be confined within a cavity around the planet called its magnetosphere. Therefore, the contribution of the planetary fields to the IMF is virtually nil. The solar plasma, on the other hand, carries a part of the solar magnetic field in the interplanetary space — the intensity decreasing with increasing distance from the sun.

Long before the satellite era, the intensity of the galactic cosmic rays was found to decrease suddenly usually a day or two after some large solar flare. The existence of magnetic fields in space was conjectured from this phenomenon, known as 'Forbush decrease'. The latter was explained by assuming that the solar magnetic field was carried to the interplanetary space and that this field deflected the cosmic rays way from the earth. In later days, however, the existence of a persisting magnetic field of the order of a few γ ($\gamma = 10^{-5}$ gauss) was first confirmed by direct measurements in space by the spacecraft Pioneer 1, in 1958. Afterwards, a series of satellites measuring the IMF at various distances led to the understanding of the gross feaures of this field.

We have seen that the conductivity of the solar wind is very high. A characteristic property of a plasma with infinite conductivity is that the plasma motion carries the magentic field along with it. In other words, the field is 'frozen' inside the plasma. One interesting consequence of this property is that any magnetic field which is exterior (or interior) to the plasma will always remain so. Consequently, the streaming solar plasma will exclude even the galactic magnetic field from the inner solar system. The distance at which the galactic field is prevented from entering the solar plasma can be calculated from the pressure balance equation $(8\pi)^{-1} B_g^2 = r_h^{-2} P^2$. Here r_h is the heliocentric distance of the interface between the interplanetary plasma and the glactic medium with magnetic field B_g and P is the solar wind pressure at 1 A.U. Depending on various models of the solar wind, r_h ranges from 10 to 100 A.U. Despite the numerrical uncertainty in r_h, it can be regarded as the physical definition of the radius of the heliosphere which may be considered to be the domain of the interplanetary space over which we intend to study the structure of the magnetic field.

As already mentioned, the source of the IMF is in fact the large-scale solar magentic field (the planetary fields being confined within the respective small cavities, the magnetospheres) which is carried away from the solar surface by the streaming plasma. It must be remembered that the field on the solar surface itself is very complicated, irregular and fluctuating. Most of the field lines, particularly those associated with very strong magnetic fields, close themselves on the sun itself before they can reach the interplanetary space. However, some of the field lines are weak enough to be pulled away from the sun by the high kinetic energy of the coronal plasma and to be connected to the interplanetary space. Thus the magentic field at any point in space is related to that at some point on the solar surface (generally some distance away from the photosphere) where pulling took place. Because of solar rotation, these field lines look like spiral rays emitted by the sun as shown in Fig. 1.

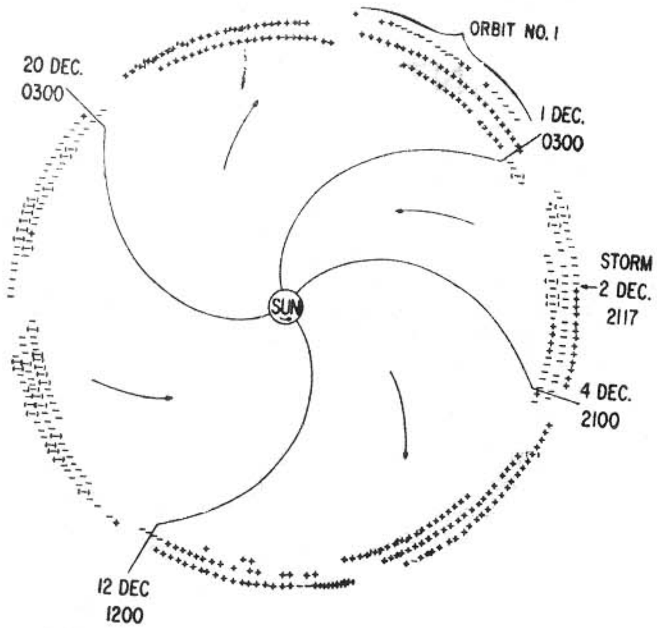

Fig. 1. Schematic representation of the interplanetary magnetic field measured by IMP1 satellite which was launched in Nov., 1963. The positive (negative) sign indicates that the spiral field lines are directed away from (towards) the sun.

II. PARKER'S SPIRAL MODEL

The first quantitative estimate of the IMF was given by Parker[2] (1958). We know that the sun rotates around its axis with an average period of 27 days. Hence the plasma which appears to be streaming radially out of the sun will have both a radial velocity v_s and an azimuthal velocity v_φ. Consequently, different portions of the plasma stream leaving the same region of the sun at different times will lie on a spiral (Fig. 2). Here ρ and φ define the heliocentric co-ordinate system and Ω is the angular velocity of the sun.

It is easy to see that

$$\frac{d\varphi}{d\rho} = \frac{\Omega}{v_s}. \qquad (1)$$

On the other hand, if ψ is the angle between the magnetic field which is parallel to the streamline and the radius vector, then

$$\frac{B_\varphi}{B_\rho} = \tan\psi = \frac{\rho\,\Omega}{v_s}. \qquad (2)$$

In fact, the streamline leaves the solar surface radially at some point (ρ_0, φ_0), so that equation (1) is slightly modified to be

$$\frac{d\varphi}{d\rho} = \frac{\Omega}{v_s}\left(\frac{\rho-\rho_0}{\rho}\right). \qquad (3)$$

Thus the equation of the streamline is simply

$$\frac{\rho}{\rho_0} - 1 - \ln\left(\frac{\rho}{\rho_0}\right) = \frac{v_s}{\rho_0\,\Omega}(\varphi-\varphi_0). \qquad (4)$$

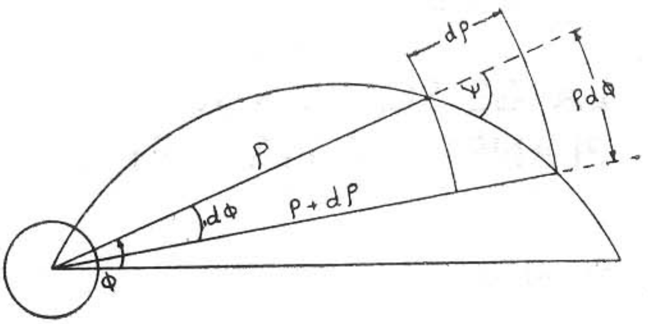

Fig. 2. The spiral interplanetary magnetic fields which are parallel to the streamlines. (ρ, φ) is the co-ordinate of an arbitrary point on the streamline and ψ is the angle between the radius vector $\vec{\rho}$ and the tangent to the streamline at this point.

Since $\vec{B}$ is parallel to this streamline and since $\operatorname{div}\vec{B} = 0$, it follows naturally that B_ρ and B_φ at any point (ρ, θ, φ) are related to the radial reference field $B(\theta, \varphi_0)$ on the solar surface by the relation

$$\begin{aligned} B_\rho(\rho,\theta,\varphi) &= B(\theta,\varphi_0)\,(\rho_0/\rho)^2, \\ B_\varphi(\rho,\theta,\varphi) &= B_\rho \sin\theta\,(\Omega/v_s)\,(\rho-\rho_0), \\ B_\theta(\rho,\theta,\varphi) &= 0. \end{aligned} \qquad (5)$$

As stated earlier, the magnetic field either on the solar surface or in the interplanetary space exhibits a lot of fluctuations. Parker's model represents only the average large scale field which is fairly stable over a few solar rotations. Since the propagation and the generation of various hydromagnetic disturbances giving rise to these fluctuations presuppose the existence of a quasi-stationary long-range magnetic field, it is essential to study this large scale structure of the IMF first.

The magnetometer data obtained by various spacecrafts ranging a distance from about 0.26 A.U. (Mariner 10, Nov. 1973- April 1974) to around 5 A.U. (Pioneer 10, March 1972 - November 1973) were examined[3] by various analysts to check the validity of Parker's model. Attempts have been made to fit the data collected by individual spacecrafts as well as to seek a best fit of the composite data set from various spacecrafts (Mariner 4, Pioneer 6, Mariner 5, Pioneer 10, Mariner 10). The general conclusion is that the inverse-square radial dependence of B_ρ, predicted by Parker's model, is well satisfied within the experimental error as given by

$$B_\rho = (2.89 \pm 0.16)_\rho \, (-2.13 \pm 0.11) .$$

However, the solar-rotation-averaged $<B_\varphi>$ shows a steeper radial dependence compared to the theoretical expectation of an ρ^{-1} behaviour. The reason may be that the expression for B_φ contains the plasma velocity v_S which is a fluctuating quantity. A numerical solution to the hydromatnetic equations describing the solar wind plasma by Goldstein and Jokippi[4] led to the following conclusions : Nonlinear fluctuations at the base of the spiral due to steam-stream interactions in the solar wind can cause $< B_\varphi >$ to decrease faster than ρ^{-1}, although $< B_\rho >$ still follows the inverse square law. The basic reason is that the fluctuations may twist and turn a flux tube, but the conservation of flux demands that $\rho^2 B_\rho$ should remain constant. In fact, the analysis[5] of the Pioneer 10 data on $< B_\varphi >$, after taking into account the fluctuation of v_S, shows that the expected behaviour is indeed observed.

So far as the meridional componet B_θ of the IMF is concerned, Parker's theory predicts a null value. However, in situ measurements show a consistent although fluctuating B_θ of the order of few tenths of gamma ($\Upsilon = 10^{-5}$ gauss). The general obsrvation[6] is that $< B_\theta >$ is negative (positive) when the spacecraft is north (south) of the solar equator and it vanishes at the equator itself. To explain this, it has been conjectured that the meridional flow of the solar plasma at the base of the spiral itself (neglected in Parker's model) can cause this line of force to skew away from the euqatorial plane thereby producing a nonzero value of B_θ.

According to Coleman[7], the time dependnce of the base field $B(\rho_O, \varphi_O)$ at the reference level ρ_O will produce a non-zero B_θ at some other distance ρ. This is a consequence of the frozen-in-field line condition i.e.

$$\vec{E} = - \vec{v} \times \vec{B} ,$$

and the equations

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \vec{E} ,$$

$$\vec{\nabla} \cdot \vec{B} = 0 .$$

In case $B(\rho_O, t)$ has an intrinsic time dependence, then B_θ has to be non-zero if all the above three equations are to be statisfied simultaneously.

The radial dependence of the large scale interplanetary magnetic field is thus well described by the simple model of Parker[2] (1958). In fact, the introduction of more sophistication in the solar wind model as well as in the method of calculation does not generally lead to any substantially improved understanding. The exception is a non-zero value of B_θ which seems to aris from fluctuating boundary conditions at the foot of the field lines. Theories in this respect are quite cloudy and lack firm conclusion.

III. SECTOR STRUCTURE

A very important structural feature of the IMF is that the large scale field is arranged in some well-defined sectors of a definite polarity. All the field lines in a given sector are directed either away from the sun (+ ve polarity) or towards the sun (− ve polarity). Fig. 1, showing data[1] taken by the IMP 1 satellite, shows a clear four-sector structure. The sectors have been observed[1] to change sharply even if the field is averaged over as short an interval as 5.46 min. Considering the azimuthal velocity of the spacecraft to be of the order of 440 km/sec, the upper limit to the thickness of the seetor boundary can be estimated to be about 1.48×10^5 km. However, the thickness of the transition layer is variable. Over a solar rotation, a two-sector structure and some times even a six-sector structure also have been observed.

Although the most direct way of observing the sector structure is via in situ measurements by a satellite, Svalgard[8] devised a method to infer the polarity of the IMF at one A.U. from an analysis of the nature and degree of geomagnetic activities. The interaction of the terrestrial magnetosphere with the solar wind plasma is much influenced by the polarity of the IMF. Magnetic observatories all over the world photographically record the geomagnetic fluctuating field almost continuously. These magnetograms, therefore, can provide the history of the IMF structure for times long before the satellite era. By analysing the magnetograms of a few high latitude stations for the period 1926-1971, Svalgard[8] tabulated the daily IMF polarity for that period. In order to see the semi-annual variation of the IMF sector structure, the proportion of solar rotations with four sectors for each month of the year has been counted using spacecraft data for the period 1962-1969 as well as Svalgard's data for the period 1926-71. The interesting conclusion[9] emerging from either analysis is that a four-sector structure occurs more frequently in May-June and in December when the heliographic latitude of the earth is almost zero. On the other hand, the probability of a two-sector structure is enhanced for the higher latitudinal position of the earth (the heliographic position of the earth varies between ± 7.3° over one revolution around the sun).

Although the IMF at one A.U. is arranged in definite sectors, there are some fluctuations even in a sector of given polarity. By calculating the percentage of time that a given polarity (say + ve) persists over a solar rotation, one can tell what the predominant polarity observed at one A.U. is. Analyses of the satellite data have led to the conclusion that the predominant polarity is positive (negative) when the position of the earth (or the spacecraft) is in a northern (southern) heliographic latitude during a period when the solar cycle has passed its maximum phase. The situation is reversed during the pre-maximum phase. There is confusion about the predominant polarity at the exact maximum phase. These are the facts about the sector structure near the orbit of he earth. Since the origin of the IMF is the solar magnetic field, a similar type of sector structure should exist in the sun also.

The solar photospheric magnetic field can be measured from observations of the Zeeman-splitting of the spectral lines emitted from different points on the solar disc. By determining the plane of polarisation of these lines, the line of sight component of the solar field can be measured. The analysis shows that the sector boundary of the large scale solar field is almost north-south. (This does not, in general, include the strong field associated with sunspots and other associated small scale structure; since the source-dimensions of these fields are much smaller, they die out very fast as one moves away from the sun). Apart from this mid-latitude field, there is the weak polar field which resembles a dipole aligned to the rotation axis of the sun. If this sector boundary is extrapolated to one A.U., then there should not be any change in the predominant sector structure as one proceeds from northern to southern heliographic latitudes: however, this is contrary to observation as we have seen earlier.

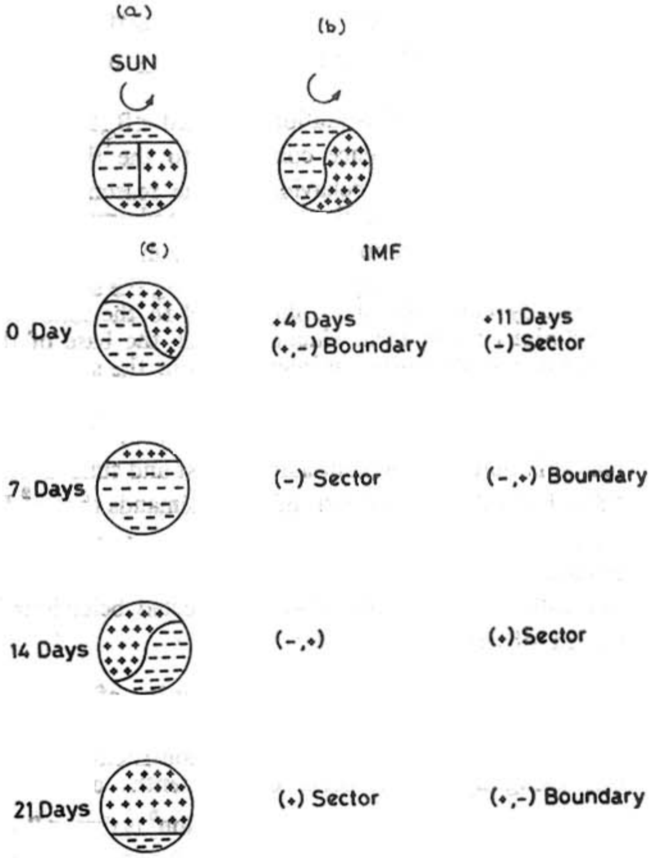

Fig. 3. The schematic representation of the phenomenological model of Svalgaard[9] et. al. to describe the sector structure of the solar magnetic field as well as the IMF. The + (—) sign indicates that the field lines are leaving (entering) the solar disc.

(a) The almost north-south sector boundary and the polar dipole-field are presented.

(b) The sector boundary of (a) is smoothed out to show a single curved line separating the field lines of opposits polarity.

(c) The left hand side diagrams show sector structure of the magnetic field on the solar disc at various phases of the solar rotation. On the right hand side the nature of the corresponding IMF at 1 A.U. is shown. On the average it takes about 4 days for the magnetic field to be convected from the sun to the earth.

In order to explain the relationship of the solar sector structure with that of the IMF, Svalgard[9] et al developed a phenomenological model representing the polar field of the sun and the solar mid—latitude north-south sector boundary by a smothed out curved line as shown in Fig. 3. This figure[9] gives a schematic representation of the polar field as a combination of a polar dipole field, north (south) having negative (positive) polarity, and a central sector structure with almost north-south boundary. The continuous sector boundary shown in Fig. 3 b is considered to be a realistic situation. When the earth is situated in northern heliographic latitudes, it is exposed to the negative sector longer than the positive sector over a solar rotation. Thus the predominant polarity is expected to be negative. In the southern latitudinal position the situation is reversed, in agreement with observation. During a post-maximum period the dipole field of the sun is reversed; therefore the above conclusion should also be reversed. On the other hand, the polar field of the sun becomes very weak during the period of solar maximum. Therefore, the solar sector boundary is just the extrapolated north-south line. As a result, the predominant polarity at one A.U. should be neither positive nor negative. In fact, observation shows that there is no clear cut predominant polarity during these periods. By observing the variation of the sector structure at one A.U. with the heliographic latitudes in the range of $\pm 7.3°$, the sector boundary is estimated to be inclined to the solar equator by about 15°. On the other hand, the same is found to be 90° on the photosphere, as mentioned earlier. Moreover, the structure of the coronal streamer during eclipses implies that the magnetic sector boundary ngle at about $6R_{\odot}$ ($R_{\odot}$ = solar radius) is approximately 25°. Similar observations of the K-Corona show the same ngle at $1.5 R_{\odot}$ to be about 45°. It follows from Maxwell's quations that there must be a current sheet between wo oppositely directed field lines. Thus the sector oundary in the interplanetary space must be characterised y a current sheet whose inclination is different at different listances or in other words this is a warped current sheet. The possible structure of this current sheet[10] is shown in ig. 4. Recent observations by Pioneer 11 support this iew. A warped current sheet is indeed observed: it is nearly parallel to the solar equatorial plane near the earth's orbit, but is inclined near the sun.

Since the solar equatorial plane is inclined to the earth's ecltiplic plane, the IMF should have a two-sectored structure at about one A.U. The occurrence of a four-sector structure is explained by the existence of a quadrupole type of solar magnetic field which will prouce an azimuthal asymmetry. Consequently, the neutral current sheet will be warped rather than planer which will be crossed four times during one solar rotation when the earth is near the solar equator (in June and December). This is consistent with observation. Furthermore, an observer at a higher heliographic latitude should see no sector structure in the IMF. In fact, Pioneer 11 has actually observed the absence of sector structure at a latitude of about 15°.

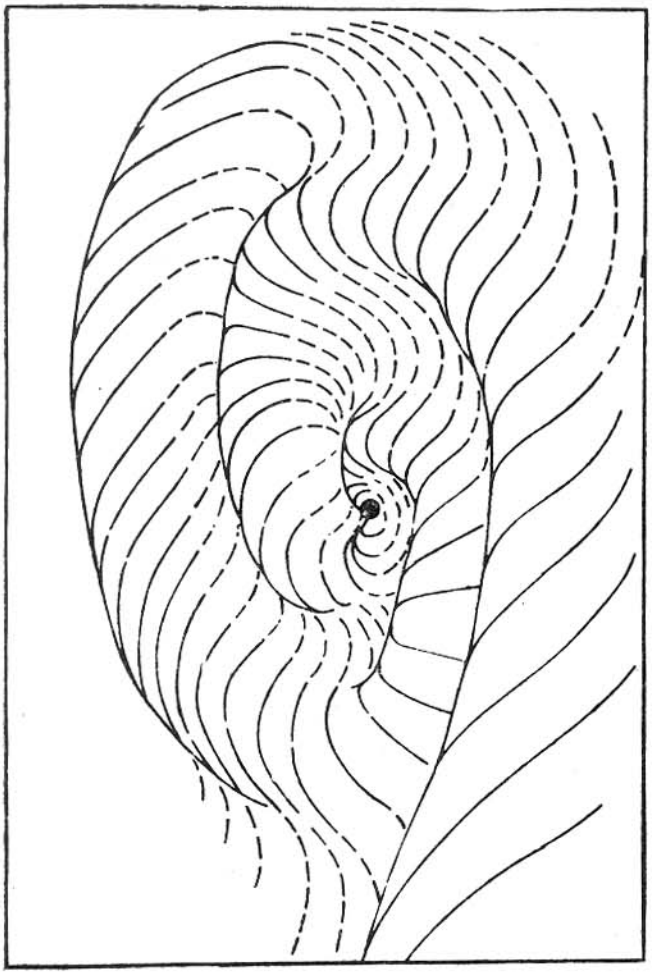

Fig. 4. The warped current sheet separating the IMF of opposite polarity. The dashed lines (full lines) indicate that the current sheet is below (above) the heliographic equatorial plane. The sun at the centre is not shown to scale.

The large scale macro-properties of the solar-rotation-averaged IMF can thus be summarised as follows :

1) The radial dependences of $\mathbf{B}_\rho$ and $\mathbf{B}_\varphi$ follow Parker's model of the spiral IMF.

2) The meridional component $\mathbf{B}_\theta$, although zero in Parker's model, exists mostly as a fluctuation.

3) The IMF is arranged in definite sectors of two or four regions where the magnetic field is directed away from or towards the sun. Sector boundaries are, on the average, well-defined regions and are characterised by a warped neutral current sheet, almost parallel to the solar equatorial plane at one A.U. Since this current sheet is warped, a four-sector structure is more probable when the earth is near the heliographic equator. There is no sector structure at higher latitudes of about 15°.

Apart from this large scale structure, the magnetic field in the interplanetary space is characterised by various types of discontinuities and shock fronts predicted by hydromagnetic theories. Hydromagnetic waves of different types have also been observed in the IMF. These micro-structures, superimposed on the long range spiral magnetic field, are actually responsible for constant fluctuations of the IMF. Because of the large length scales involved, some of these waves and discontinuities cannot be generated in the laboratory. Hence the study of the interplanetary magnetic field offers an excellent opportunity to test certain aspects of hydromagnetic theories. However, a detailed discussion of small scale fluctuations in the IMF is beyond the scope of the present article.

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* Based on invited talk delivered in the " National Symposium on Magnetospheric physics " at Banaras Hindu University on 22 March, 1979.