THE ELECTROMAGNETIC STRUCTURE OF INTERPLANETARY SPACE

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ABSTRACT

A method to calculate the three-dimensional structure of the interplanetary magnetic field is presented. The integrations are based on magnetograph recordings of longitudinal magnetic fields in the solar photosphere. The program by *Altschuler and Newkirk* [1969] is used to calculate the radial component of the magnetic field on the "source surface," situated at $r = 2.6r_{\odot}$. This determines the inner boundary conditions for the integration outwards of the interplanetary field equations by means of the method that is described.

Computer-drawn plots of the interplanetary field lines out to the earth's orbit are presented for the periods around the total solar eclipses of November 12, 1966, and March 7, 1970. During the former period the interplanetary field exhibited a clean, dipole-type structure, while during the latter period the field was more complicated and had four sectors in the equatorial plane. A movie has been presented, showing how the interplanetary field structure rotates as seen by a magnetometer in the sun's equatorial plane.

METHOD OF CALCULATING INTERPLANETARY MAGNETIC FIELDS

The two principal assumptions made are:

1. The magnetic-field structure is stationary in a frame rotating with the sun.
2. The solar wind velocity has no component in the θ direction (θ is the colatitude), but only in the radial and azimuthal (ϕ) directions. If we neglect the effect of space charges, assumption (1) implies, that the magnetic field vector and the flow velocity are parellel in the rotating frame. From this and assumption (2) it follows that the magnetic field has no component in the θ direction. Hence the interplanetary field lines will lie on conical surfaces of constant θ. This simplifies the problem considerably.

   As $\mathbf{v} \times \mathbf{B} = 0$ in the rotating frame, the relation between the ϕ and r components of the field is

$$B_{\phi} = \frac{(\omega - \Omega)\, r \sin\theta}{v_r} B_r \tag{1}$$

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where ω is the angular velocity of the solar wind, Ω the angular velocity of the footpoints of the field lines (the angular velocity of the rotating frame), and v_r the radial component of the solar wind velocity.

The condition div $\mathbf{B} = 0$ can be written

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 B_r) + \frac{1}{r\sin\theta}\frac{\partial B_{\phi}}{\partial \phi} = 0 \tag{2}$$

Equations (1) and (2) together with some boundary conditions are sufficient to determine the field structure if v_r and ω have first been determined or specified throughout space. If v_r and ω are assumed to be known, the procedure adopted for calculating the field is the following:

As boundary conditions we assume that the radial component of the field is given on an inner spherical surface. Using equation (1) we can calculate the B_{ϕ} component. Thus knowing the B_{ϕ} distribution on the boundary surface, we can determine $\partial B_{\phi}/\partial\phi$. According to equation (2), this determines how B_r changes with r. Hence we can calculate the value of B_r on a spherical surface that lies a step Δr farther out and, using (1), calculate the B_ϕ component on that surface, and so forth. In this way we can proceed from the outer corona to beyond the orbit of earth.

Turning to the determination of the angular velocity ω of the solar wind, we can proceed in a manner similar to that of *Weber and Davis* [1967], except that our calculations have to allow for any variation of B_r and B_ϕ with θ and ϕ, and we want to determine what happens outside the sun's equatorial plane. It can be shown [*Stenflo*, 1971] that

$$\omega = \Omega \frac{(r_A/r)^2 - \overline{M_A^{-2}}}{1 - \overline{M_A^{-2}}} \tag{3}$$

where

$$M_A = v_r \sqrt{\frac{\mu_o \rho}{B_r}} \tag{4}$$

is the Alfvénic Mach number, μ_o the permeability of vacuum, ρ the mass density, and r_A the distance at which $M_A = 1$. A line above a symbol means that it is averaged over all ϕ.

It has been assumed above that all physical quantities except the magnetic field are independent of ϕ. This assumption is not physically consistent, since fluctuations in the magnetic field will lead to fluctuations in the other physical parameters as well. It is only used, however, to derive an approximate expression for ω. As it turns out, ω according to equation (3) drops off very rapidly with distance and thus will be small compared to Ω. Hence, errors in the determination of ω will not affect the field structure seriously.

With our assumptions above, it can further be shown [*Stenflo*, 1971] that the mass flux and $(r^2 B_r)^2$ averaged over all ϕ are independent of distance. Hence

$$r^2 \rho v_r = F \tag{5}$$

and

$$\overline{(r^2 B_r)^2} = C \tag{6}$$

where F and C are constants. These constants can be fixed by the conditions at 1 AU. Since we can write

$$\overline{M_A^{-2}} = \frac{C}{\mu_o} F r^2 v_r \tag{7}$$

both the Alfvénic Mach number and ω can be calculated if we know the wind velocity v_r.

Our remaining task is therefore to specify v_r. As indicated by the work of *Weber and Davis* [1967], the magnetic field and solar rotation do not greatly influence the solution for v_r. Their v_r curve was almost identical to that of *Parker* [1958], which was derived neglecting magnetic fields and rotation. Accordingly, we have assumed that Parker's solution is a reasonably good approximation also for the case when the field varies with θ and ϕ.

THE BOUNDARY VALUES AND THE SELECTION OF FIELD LINES

In the method by *Altschuler and Newkirk* [1969] of calculating coronal magnetic fields it is assumed that the magnetic field is pulled out radially by the solar wind at a distance $r = r_S$. The surface at which this occurs represents a kind of "source surface" for the interplanetary field, a concept that has been introduced and used by *Schatten et al.* [1969]. According to *Altschuler and Newkirk* [1969], the best agreement between the calculated field lines and coronal structures seen on eclipse photographs is obtained for $r_s = 2.6\, r_\odot$. The inner boundary surface for integrating equations (1) and (2) outwards has therefore been placed at $r = 2.6\, r_\odot$. The program by Altschuler and Newkirk has been used to calculate from the recorded line-of-sight component of the photospheric magnetic field the B_r component of the field on our "source surface." This determines our inner boundary conditions.

The constants F and C in equations (5) and (6) have been fixed by assuming a mass density corresponding to 6 protons per cm^3 at 1 AU and an rms value of B_r of 4 γ at the same distance. For v_r we have assumed *Parker's* [1958] solution for an isothermal corona of 1×10^6 °K, with v_r normalized to 400 km/sec at 1 AU. The influence of the field structure of the choice of these parameters has been discussed elsewhere [*Stenflo*, 1971].

Two alternative methods of selecting the field lines have been used [*Altschuler and Newkirk*, 1969]. One is the "geometric" selection, for which the footpoints of the field lines are evenly distributed over the sphere independent of fluxes or field strengths. According to the other method, all weaker fields are suppressed and the number of field lines assigned to a region is proportional to the flux carried by the stronger fields through that region. Further details are given by *Stenflo* [1971].

RESULTS OF NUMERICAL INTEGRATIONS

Figure 1 is a computer-drawn plot of the interplanetary field as seen from the direction of the heliographic north pole. The footpoints of the field lines are selected on the "source surface" according to the "strong-field" method. The calculations are based on Mt. Wilson recordings of photospheric magnetic fields during the period February 17–March 16, 1970. All field lines are traced out to a distance of about 250 $r_\odot$ (1 AU = 215

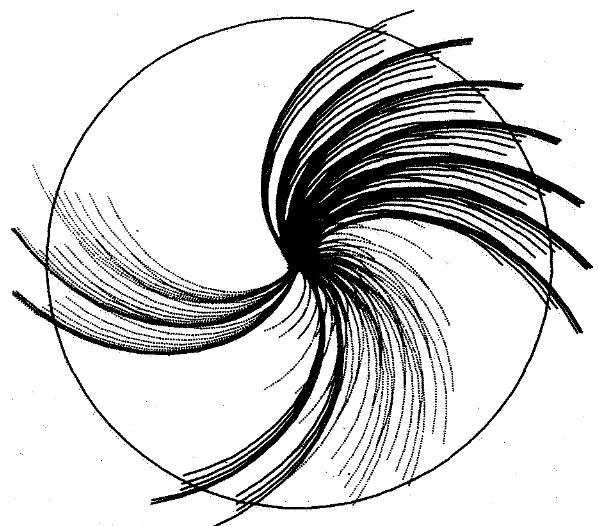


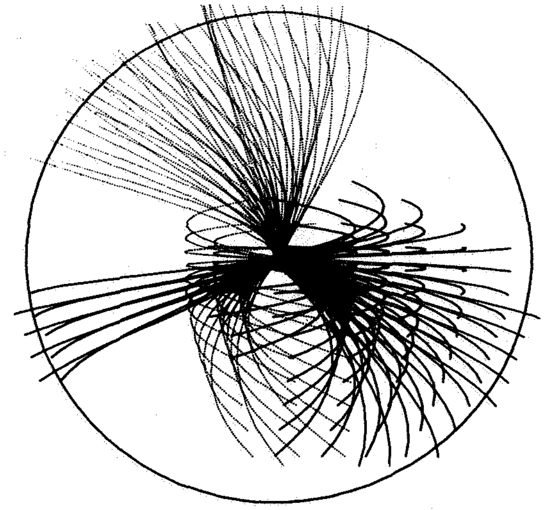
Figure 1. *The interplanetary magnetic field calculated out to a distance of 250 $r_\odot$. The calculations are based on Mt. Wilson recordings of photospheric magnetic fields during the period February 17-March 16, 1970. Solid lines: positive polarity. Dashed lines: negative polarity. View from the direction of the heliographic north pole. Zero longitude is toward the right.*

$r_\odot$). Some field lines appear to be shorter due to projection effects. They originate at higher latitudes. The field in the equatorial plane exhibits four sectors.

When viewed from a position far out in the equatorial plane, the structure appears to be much more complicated (fig. 2(*a*)). To obtain a stereoscopic impression of the structure, a movie has been produced (presented at the Solar Wind Conference at Asilomar), showing the whole field structure rotate as seen by an observer in the equatorial plane.

A considerable contribution to the interplanetary field comes from old, diffused active regions. Accordingly, we should expect a simpler structure to occur before the solar activity maximum. Such a case is shown in figure 2*b*, which is based on Mt. Wilson recordings from the period October 29–November 26, 1966. The interplanetary field shows a clean dipole-type structure with negative polarity in the north hemisphere and positive polarity in the south.

Figure 3 shows maps of the coronal field out to a distance of 17 $r_\odot$. The "geometric" procedure for selecting the footpoints of the field lines on the solar surface has been used. The circumstance that the field lines in figure 3 are almost straight has nothing to do



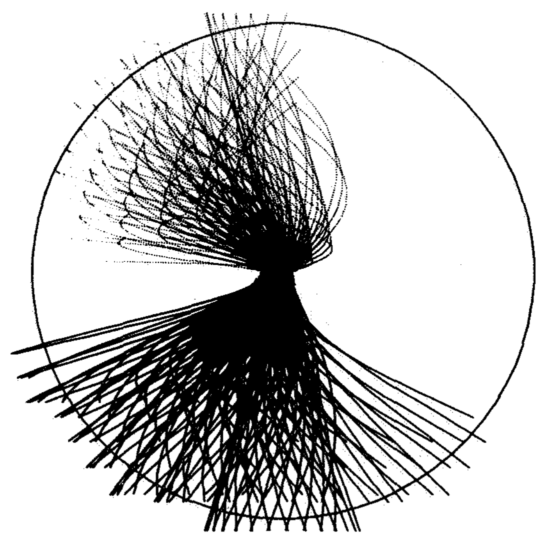


Figure 2. *(a) The same structure as shown in figure 1 viewed from the equatorial plane. North is upwards, east to the left. Longitude of central meridian 0°. (b) The same structure as in (a), except that the calculations are based on Mt. Wilson recordings from the period October 29-November 26, 1966, and that the longitude of the central meridian on the sun is 240°.*

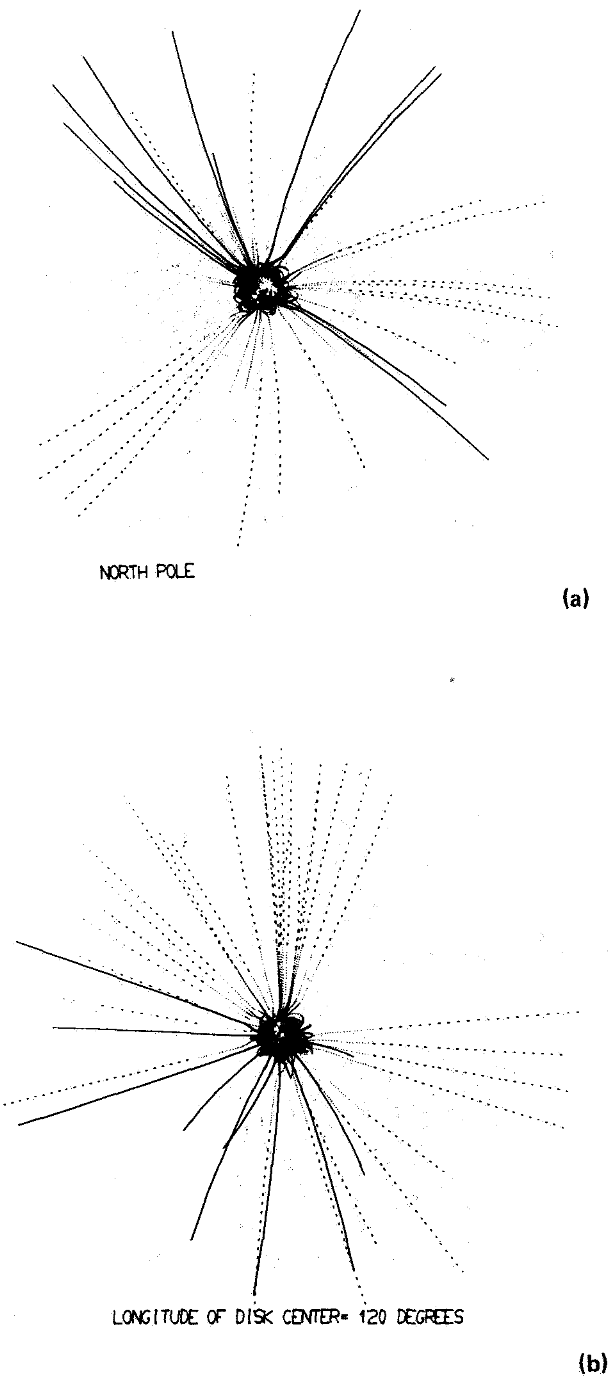


Figure 3. *Coronal magnetic fields calculated out to a distance of 17 $r_{\odot}$. The calculations are based on the same material as figure 1. (a) View from the direction of the heliographic north pole. Zero longitude is towards the right. (b) View from the equatorial plane. North is upward, east to the left. Longitude 120° of the central meridian corresponds to the time of the March 7, 1970, total solar eclipse.*

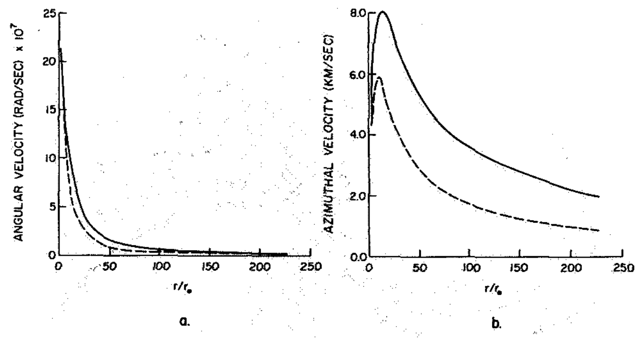


Figure 4. *(a) Angular velocity and (b) azimuthal velocity of the solar wind. The solid curves are determined from the numerical values given in the text. For comparison the dashed curves have been derived assuming that the rms value of the B_r component of the field at 1 AU is 2γ (instead of 4 γ for the solid curves).*

with corotation of the coronal plasma. The angular velocity decreases very rapidly with distance, as shown by figure 4*a*, which has been calculated from equation (3). The curvature of the field lines is so small because v_r is much larger than $r\Omega$ in most of the region.

The magnetic field at 1 AU calculated by the present method has been compared with actual spacecraft observations during the period around the March 7, 1970, solar eclipse (Ames Research Center magnetometer experiment on Explorer 35, *C. P. Sonett, D. S. Colburn, and J. M. Wilcox*). The correlations between the computed and observed field are 0.73 for B_r, 0.72 for B_ϕ, and 0.90 for the sign of B_r.

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