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Radial and Latitudinal Variations of the Interplanetary Magnetic Field

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This paper presents observations of the radial and latitudinal variations of the interplanetary magnetic field measured by the Voyager 1 (V1) and Voyager 2 (V2) spacecraft from mid-1977 to mid-1985. The data extend from 1 to 20 AU and from −5° to 26° in heliographic latitude. Data obtained at 1 AU are used to separate temporal variations from radial variations, and plasma measurements from V2 are used to consider the effect of temporal variations in the bulk speed. Observations of the radial variation of the large-scale magnetic field strength in the ecliptic agree with the predictions of Parker's model when temporal variations in the magnetic field and bulk speed are taken into account. The latitudinal variation of the magnetic field observed by V1 is in agreement with the predictions of Parker's model to first approximation. The magnetic field strength at higher latitudes is somewhat lower than expected on the basis of observations made in the ecliptic, but this could be due to an increase in bulk speed and/or a decrease of solar magnetic field strength with latitude. Fluctuations in the strength of the magnetic field are small compared to the large-scale field itself, and they decrease in amplitude with increasing distance approximately as $R^{-1/4}$. Fluctuations in the components are relatively large, and they make a significant contribution to the mean field that is not described by Parker's model.

INTRODUCTION

Voyager 1 (V1) and Voyager 2 (V2) have been making observations of the interplanetary magnetic field since their launch in August 1977. Data are available for at least two thirds of most days, and the coverage is ~90% for the months preceding encounters with Jupiter, Saturn, and Uranus. The V1 and V2 data sets complement those of Pioneer 10 and Pioneer 11 which were launched in 1972 in orbits which take them through the outer heliosphere, and those of ISEE 3 and IMP 8 which have been making observations of the solar wind near 1 AU. Voyager 2 has been moving near to the ecliptic, but Voyager 1 departed northward from the ecliptic after its encounter with Saturn in 1980, and it is currently approaching 30° above the solar equator. The latitude and the radial distance from the sun of V1 and V2 are shown as a function of time in Figure 1. By comparing the Voyager 2 observations of the interplanetary magnetic field with those made near 1 AU it is possible to separate the effects of radial variations of the magnetic field from those associated with temporal variations. In addition, the effects of temporal changes in the bulk speed can be investigated using bulk speed observations from V2. The Voyager magnetometer is described by *Behannon et al.* [1977], and the Voyager plasma analyzer is described by *Bridge et al.* [1977]. Additional information on the trajectories of V1 and V2 and a discussion of the coordinate systems used in the analysis of Voyager magnetic field data may be found in the review by *Burlaga* [1984].

The interplanetary magnetic field was modeled by *Parker* [1958, 1963] prior to the availability of in situ measurements, and his model has remained the standard for a description of the large-scale field to this day. Early work on the radial variations of the interplanetary magnetic field between 0.5 and 1.5 AU was reviewed by *Behannon* [1978]. Several studies of spacecraft data obtained beyond 1 AU have found measurements of the interplanetary magnetic field to be in good agreement with the predictions of Parker [*Thomas and Smith*, 1980, 1981; *Burlaga et al.*, 1982, 1984; *Burlaga*, 1986]. However, some recent papers [*Smith and Barnes*, 1983; *Slavin et al.*, 1984; *Thomas et al.*, 1986] infer that the magnetic field has a steeper radial gradient than that predicted by Parker and that the magnetic field is consequently weaker at large distances from the sun than expected. They suggest that the agreement with Parker's model found in the earlier studies was a coincidence, owing to an increase in the strength of the solar magnetic field during the years in which measurements of the radial variation were made, which just happened to equal the decrease in the field strength associated with the departures from Parker's model.

Thomas et al. [1986] suggest that the discrepancy between their observations of the azimuthal component of the magnetic field $B_T(R)$ and Parker's prediction of this quantity is associated with meridional transport of magnetic flux, a concept originally introduced by *Winge and Coleman* [1972]. Recently, *Suess et al.* [1985] calculated that meridional flux transport in a steady axisymmetric model could account for the reported "deficit," but *Pizzo and Goldstein* [1987] point out that the results of Suess et al. are based on unrealistic solar wind conditions. Pizzo and Goldstein conclude that axisymmetric expansion alone is unlikely to account for the reported deficit. They constructed three-dimensional flow configurations that could produce a 10% B_T deficit, but these special configurations should be observed only in the late declining and maximum phases of the solar cycle.

In this paper we consider measurements of the large-scale interplanetary magnetic field made between 1 and 20 AU and up to 26° in latitude, taking care to consider variations in the

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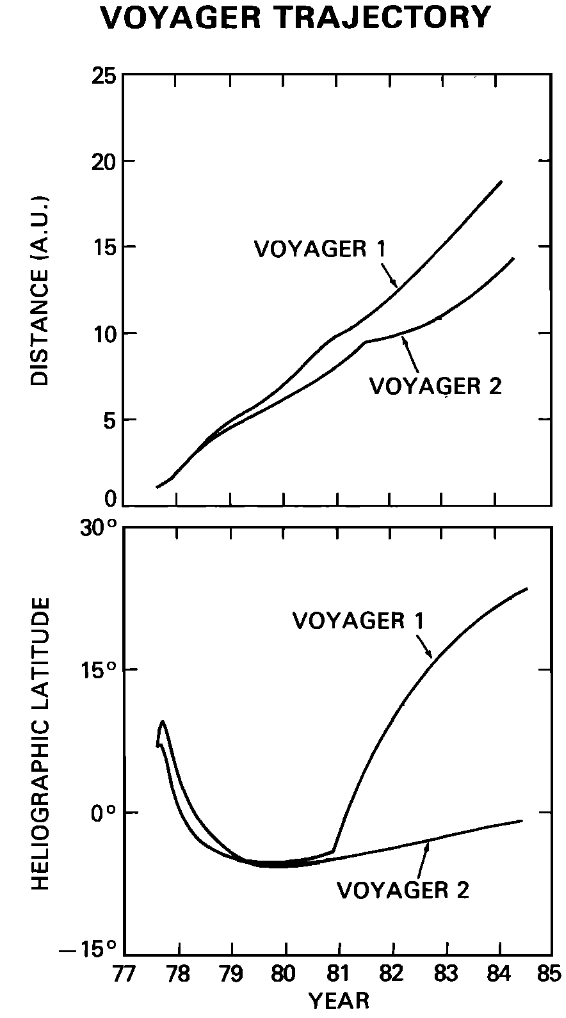

Fig. 1. The trajectory of Voyager 1 and Voyager 2. The top panel shows radial distance from the sun as a function of time, and the bottom panel shows the spacecraft latitude relative to the solar equator.

bulk speed as well as in the solar magnetic field strength. We also consider radial variations of the fluctuations in the strength and direction of the interplanetary magnetic field and their effect of the large-scale field.

PARKER'S MODEL FOR THE LARGE-SCALE MAGNETIC FIELD

Parker derived equations for the magnetic field as a function of radial distance R from the sun, heliographic latitude θ, and heliographic longitude ϕ, assuming a steady state flow with speed V_0 which may change with θ and ϕ but is independent of R and t. The assumption of a steady state requires only that the speed be constant during the time required for a volume element to move a distance R, namely R/V, which is of the order of 80 days for $R = 20$ AU and $V = 400$ km/s. Since we shall be considering averages over one or more solar rotations and a time series extending over 7 years, we may allow the speed in Parker's equations to be a function of time t, and we may allow the strength of the magnetic field at the source to vary on a time scale greater than a few months.

Parker's expressions for the radial, tangential, and normal components of the magnetic field, B_R, B_T, and B_N, respectively, modified to allow for slow temporal variations in the source field strength and bulk speed, and averaged over, are as follows.

$$B_R(R, \theta, t) = B_R(R_0, \theta, t)\,(R_0/R)^2 \quad (1)$$

$$B_T(R, \theta, t) = B_R(R_0, \theta, t)C(R_0/R)\cos\theta = B_T(R_0, \theta, t; V)(R_0/R) \quad (2)$$

$$B_N(R, \theta, t) = 0 \quad (3)$$

here R_0 is an initial radial distance which we shall take as 1 AU and,

$$C = C(\theta, t; V) = R_0\,\Omega/V(\theta, t) \quad (4)$$

where Ω is the rotation rate of the sun at the footprints of the magnetic field which we take as 360°/26 days.

The magnitude of the magnetic field is, accordingly,

$$B_p(R, \theta, t; V) = B_R(R_0\,\theta, t)(R_0/R)((R_0/R)^2 + C^2\cos^2\theta)^{1/2} \quad (5)$$

Note that at small distances from the sun, B_p is nearly independent of V, but at large distances from the sun, B_p is inversely proportional to V. Thus far from the sun the magnetic field strength is very sensitive to the value of the bulk speed, and variations in the bulk speed with time cannot be neglected.

If both the speed and the strength of the solar magnetic field are independent of time and θ is small, then (2) and (5) reduce to the following useful approximations for the radial variation of the magnetic field, which may be regarded as the zeroth order approximation to Parker's model:

$$B_{T0}(R) = A_0\,(R_0/R) \quad (6)$$

$$B_{p0}(R) = A_0\,R^{-1}\,(R^{-2} + 1)^{1/2} \quad (7)$$

where $A_0 = B_R(1)$. It is only in this case that RB_T and $R(R^{-2} + 1)^{-1/2}B_{p0}$ are invariants. In (6) and (7) we have used $V = 400$ km/s which implies $C \sim 1$.

A higher order approximation that has been used in analyzing data allows variations in the strength of the solar magnetic field but assumes that (1) the bulk speed is constant; hence $C = C_0$, (2) the source field is independent of latitude, and (3) θ is small. In this case,

$$B_{T0}'(R, t) = A(t)\,C_0\,R^{-1} \quad (8)$$

$$B_{p0}'(R, t) = A(t)\,R^{-1}\,(R^{-2} + C_0^{\,2})^{1/2} \quad (9)$$

where

$$A(t) = B_R(1, t) \quad (10)$$

OBSERVATIONS OF THE LARGE-SCALE MAGNETIC FIELD

The basic data set used for this study consists of hour averages of the magnetic field from V1 and V2. We consider observations made in the interval from mid-1977 to mid-1985, during which V1 moved from 1 to 20 AU and V2 moved from 1 to 14 AU. Figure 2 shows daily averages of B, B_R, and B_T versus distance R for V1 and V2.

Constant speed and source strength. Let us first consider fits to the data used on the simplest approximation to Parker's equations, which is that for constant speed and constant source field strength. The observations of B versus R were

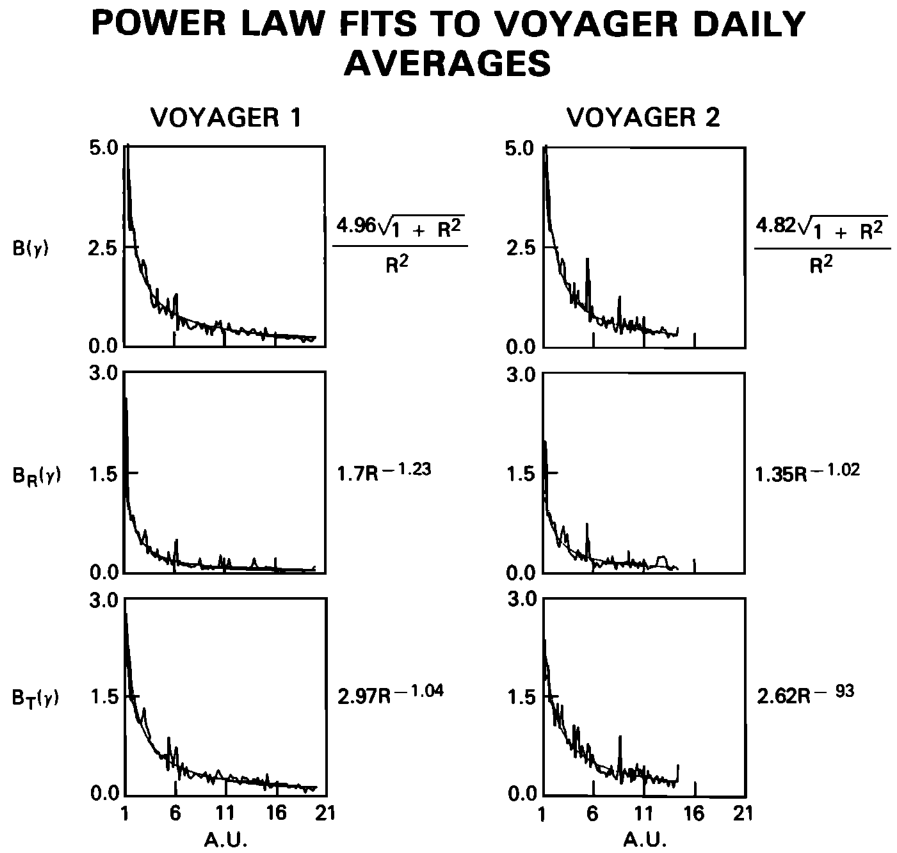

Fig. 2. Daily averages of B, B_R, and B_T as a function of radial distance from the sun. The solid curves are fits to the data based on Parker's model, based on the assumption that the source field strength and bulk speed are constant.

fitted to the approximate theoretical formula for $B(R)$ given by (7), using the method of least squares to determine the constant A_0. The resulting curve, shown as solid curves in the top panels of Figure 2, provide very good fits to the V1 and V2 observations, with $A_0 = 4.96$ and $A_0 = 4.82$, respectively. Fits to observations of B_T were obtained using the function dR^{-a}, where the constants d and a were obtained by the method of least squares. Again, the equation provides a good fits to the observations, as shown by the solid curves in the lower panels of Figure 2. From the fits to B_T we obtained $a = 1.04 \pm 0.04$ for V1 and $a = 0.93 \pm 0.5$ for V2, in good agreement with Parker's prediction, $a = 1$ (see equation (6)).

Fits to the observations of B_R using the equation $B_R = fR^{-b}$ suggested by (1) gave $b = 1.23 \pm 0.06$ for V1 and $b = 1.02 \pm 0.08$ for V2, whereas Parker's model predicts $b = 2$. A similar discrepancy was noted by *Burlaga et al.* [1982], who attributed it to the fluctuations which are always present in the solar wind but which are not included in Parker's model. The amplitude of the fluctuations decreases more slowly with R than the radial component of the magnetic field, so that beyond a few astronomical units the observations of B_R in Figure 2 are dominated by fluctuations rather than the large-scale magnetic field.

Variable source strength and constant speed. Since the launch of the Voyager spacecraft, the magnetic field strength at 1 AU has been changing, presumably in response to changes in the strength of the sun's magnetic field [*King*, 1979, 1981; *Burlaga et al.*, 1982; *Slavin et al.*, 1984]. As several authors have noted [*Burlaga et al.*, 1982; *Smith and Barnes*, 1983; *Thomas et al.*, 1986], this temporal variability in the magnetic field must be considered when making detailed comparisons with the predictions of Parker's model for the radial variations of the magnetic field.

One can separate temporal and radial variations by comparing observations which were made in the ecliptic beyond 1 AU by Voyager 2 with observations made in the ecliptic at 1 AU by IMP 8 and ISEE 3. In view of the form of (9) we remove the theoretical radial variation by dividing each hour average of the field by $A_0R^{-1}(1 + R^{-2})^{1/2}$, where A_0 is from the best fit described above. We take 26-day averages of the resulting $B(t)$, and we "corotate" the Voyager data to 1 AU by transforming from the time t' that a plasma element passed Voyager 2 to the time t that the corresponding plasma element moved past 1 AU, $t = t' - (R - 1)/V_0 - (\phi - \phi_0)/\Omega$, where $V_0 = 400$ km/s. The results are plotted in Figure 3 as solid curves together with the IMP 8/ISEE 3 data which are shown by the dashed curves and shading. If Parker's model is accurate and if the bulk speed were constant, then the Voyager 2 and ISEE 3 curves in Figure 3 should coincide. One can see that the magnetic field strength at V2 is generally less than the corresponding field strength at ISEE 3 after 1983. A similar effect was inferred by *Smith and Barnes* [1983] and *Thomas et al.* [1986], which is the basis for their conclusion that the field strength decreases more rapidly than Parker's model predicts. The V1 data are also shown in Figure 3 in the same format as the V2 data, and again one sees that the field strengths at ISEE 3 are larger than those at V2 in the later years. This cannot be taken as evidence against Parker's

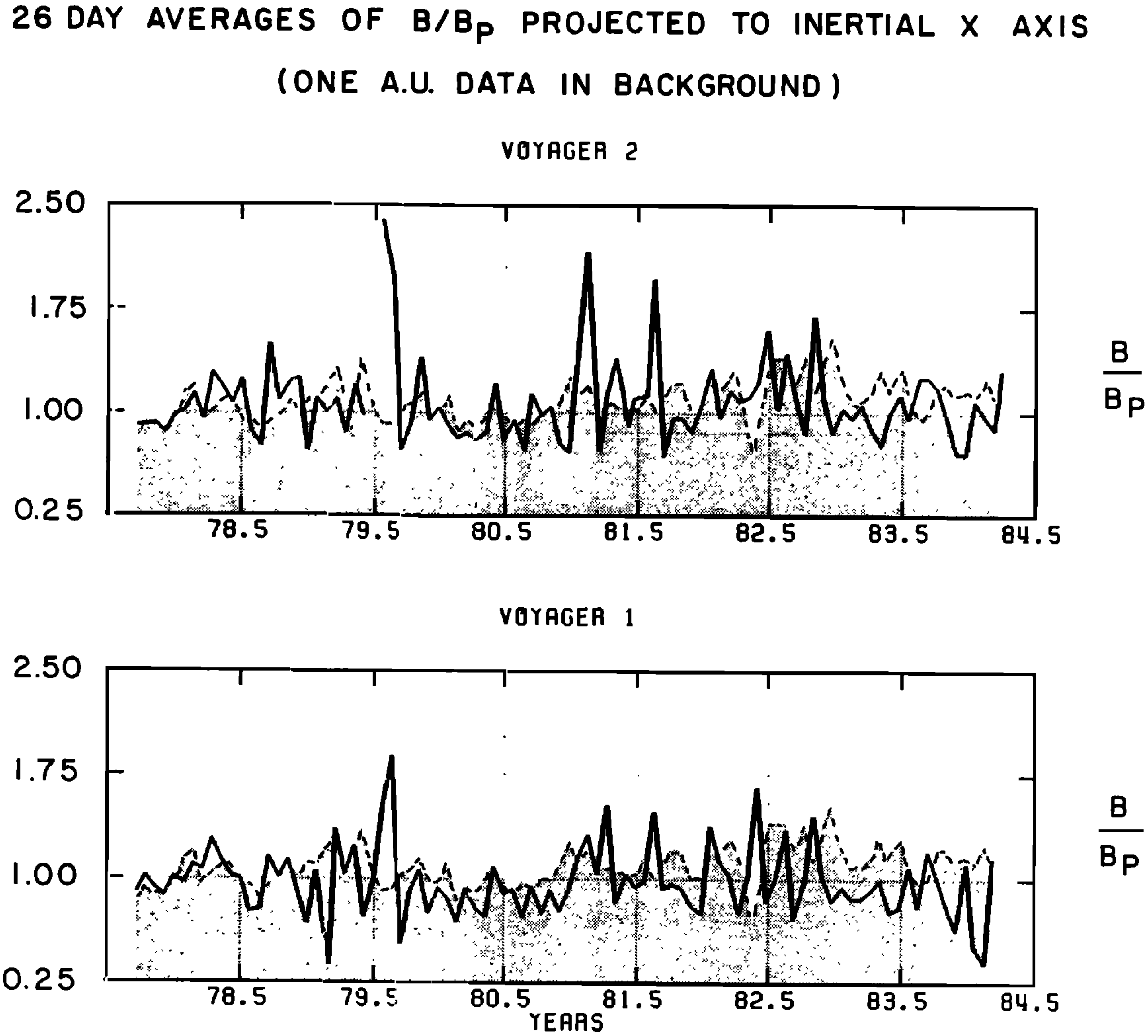

Fig. 3. A comparison of the magnetic field strength observed by Voyager with that observed by ISEE 3/IMP 8. The Voyager data are normalized to remove the effects of radial variations, and they are corotated and projected to 1 AU as described in the text.

model, however, because the variation in bulk speed was not considered. Moreover, V1 was at significantly different latitudes than ISEE 3, and there may be latitudinal variations in the strength of the solar magnetic field which we cannot take into account.

Changes in both bulk speed and source strength. There is no a priori justification for considering only variations in the source field strength, while disregarding variations in the bulk speed, in view of our discussion concerning (5). The temporal variation in the bulk speed observed at V2 was significant in the interval from 1977 to 1984, as shown in Figure 4. In particular, the bulk speed was relatively high from mid-1982 to mid-1983, which would tend to make the predicted field lower than that obtained using the average speed for the entire 7-year interval. In order to test Parker's model we must use (2) and (5) with the observed values of bulk speed (that is $C \neq$ const). Parker's model predicts that the ratio $r = (B(R)/F_p(R)/(B(1)/F_p(1)) = 1$, where $B(R)$ and $B(1)$ are the magnetic field strengths measured by V2 and ISEE 3, respectively, $F_p(R) = R^{-1}(R^{-2} + C^2 \cos^2 \theta)^{1/2}$, and $F_p(1) = (1 + C^2 \cos^2 \theta)^{1/2}$. In this case, we take $C = C(V)$, where V is now the measured bulk speed. The top panel of Figure 5 shows the ratio r as a function of radial distance from mid-1978 to 1984. The average value of the observed ratios is 0.99 in excellent agreement with the predicted value of 1. In order to test for a radial dependence we performed a linear least squares fit to the points in the top panel, and the resulting line is superimposed. We find the ratio $r(R) = (-0.00185 \pm 0.00704)R + 1.00185$, where we have made a 1-parameter fit, since $r(1) = 1$ by definition. This result implies that there is a less than 2% deficit at 10 AU and is consistent with zero deficit within errors. Thus there is no indication that the observed field strength is weaker than the predicted field strength at large distances, and consequently, there is no evidence for

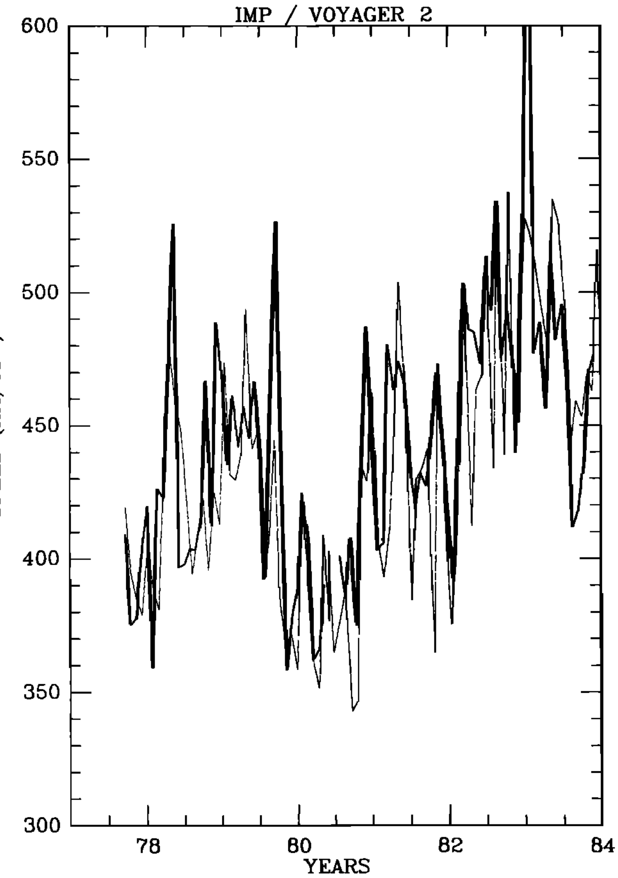

Fig. 4. Twenty-six-day averages of the bulk speed observed by Voyager 2.

meridional flux transport away from the ecliptic. The data are completely consistent with Parker's predictions for the radial variation of the strength of the magnetic field.

Similarly, one can compare Parker's predictions for the radial variations of the tangential component of the magnetic field by considering the ratio $r' = (B_T(R)/B_{T_p}(R))/(B_T(1)/B_{T_p}(1))$ as a function of time, which is shown in the middle panel of Figure 5. The average value of the observed ratios is $r' = 0.93$. We plot a least squares fit as in the top panel, again forcing $r'(1) = 1$. The result is $r'(R) = (-0.01082 \pm 0.00743)R + 1.01082$. This predicts an approximately 10% $\pm$ 7% deficit in B_T at 10 AU, which is smaller than the deficit reported by *Thomas et al.* [1986] and consistent with the theoretical result of *Pizzo and Goldstein* [1987]. However, the deficit in B_T could be associated with radial variations of the fluctuations in the magnetic field, to which the average of B_T is very sensitive. The effect of fluctuations was not considered by Pizzo and Goldstein.

The corresponding ratio for the radial component of the magnetic field is shown for completeness in Figure 5. This ratio increases with distance as the spacecraft moves away from the sun because at large distances the observations of B_R are dominated by the fluctuations.

LATITUDINAL VARIATIONS OF THE MAGNETIC FIELD

Because V1 moved out of the ecliptic up to a latitude approaching 30°, it is possible to study the latitudinal variations of the magnetic field and to compare them with the predictions of Parker's model. *Burlaga* [1986] has shown that to first approximation the observed variation of the strength of the magnetic field as a function of latitude is in agreement with (7), which is the prediction of Parker's model for constant speed and source strength.

We cannot determine whether or not Parker's model agrees to higher order with the observed latitudinal variation of the magnetic field strength, owing to insufficient data. The effect of temporal variations of the source magnetic field strength on the latitudinal variation of B cannot be determined because we do not have data from 1 AU at latitudes corresponding to those of V1. The effect of temporal variations of the bulk speed on the latitudinal variations of B cannot be determined because plasma data are not available from V1 after 1980. However, we can estimate the effect of changing speed by assuming that the speed at V1 is the same as the speed at V2, which is known. We remove the radial variation of the magnetic field by dividing the observed $B(t)$ by B_{p0} from (7) with the best fit value for A. We consider the ratio of the 78-day average of the normalized magnitude of the magnetic field observed by V1, B_1/B_{p01}, divided by the corresponding ratio observed at V2, B_2/B_{p02}, in order to eliminate temporal variations of the source field, to the extent that the temporal variations of the source are the same at the latitudes of V1 and V2. Figure 6 shows the ratio $(B_1/B_{p01})/(B_2/B_{p02})$ as a function

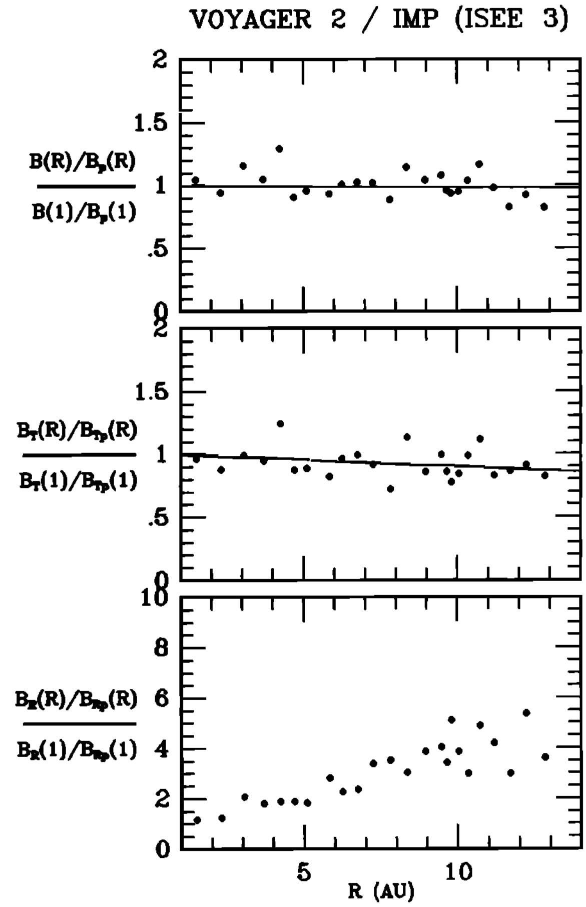

Fig. 5. Three solar rotation averages of the normalized Voyager 2 magnetic field data divided by the corresponding averages of ISEE 3 data.

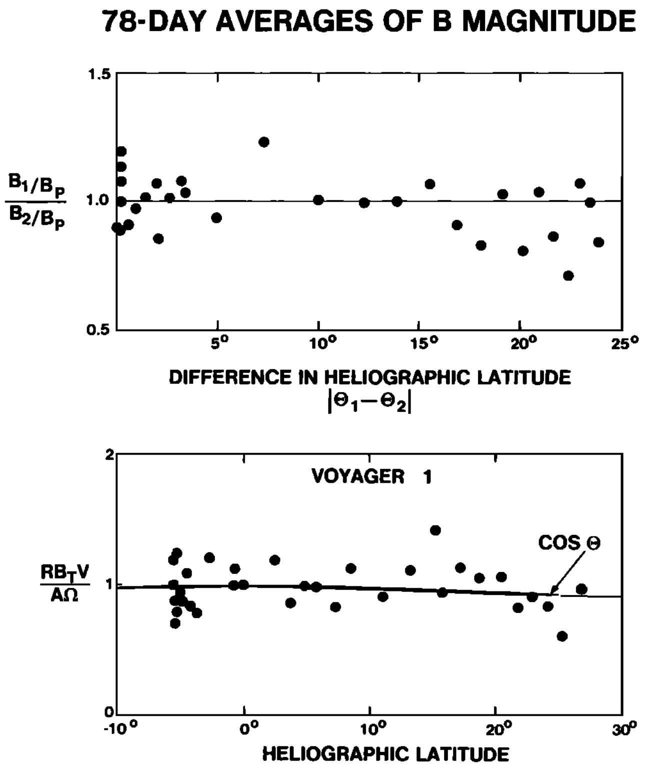

Fig. 6. Top, relative values of the normalized Voyager 1 and Voyager 2 magnetic field strengths as a function of latitude. Bottom, the latitudinal variation of the tangential component of the magnetic field observed by Voyager 1, together with a theoretical curve.

of the difference in latitude between V1 and V2. If Parker's model is valid and if the speed at V1 was the same as that at V2, then the ratio should be 1, but the observed ratio tends to be less than 1 above 15°. The discrepancy could be explained by postulating that the speed increased with latitude such that it was 20% higher at V1 than at V2 when V1 was above 15°. Such a gradient has been observed in the previous solar cycle [*Sime*, 1983], so we cannot conclude that the data are inconsistent with the latitudinal variation of the magnetic field strength predicted by Parker's model. We may conclude, however, that the magnetic field strength was weaker out of the ecliptic than in the ecliptic in 1982 and 1983.

Finally, let us consider the latitudinal variation of the tangential component of the magnetic field and compare it with the theoretical prediction, equation (2), neglecting temporal variations in speed and source strength. The bottom panel of Figure 6 shows $RB_TV/(A\Omega)$ for V1 as a function of latitude together with the theoretical variation, which is cos θ. The observed latitudinal variation of the magnetic field strength agrees to zeroth order with the theoretical variation.

FLUCTUATIONS IN THE INTERPLANETARY MAGNETIC FIELD

We consider the rms of fluctuations of daily averages of the interplanetary magnetic field relative to the best fit field $B_{(FIT)} = B_{p0}(R)$ in successive 26-day intervals, which is a measure of the amplitude of the large-scale fluctuations, σ. The radial variation of the relative amplitude of fluctuations in the strength of the magnetic field is shown in Figure 7 for V1 and V2. In both cases, the relative amplitude of the fluctuations is small compared to 1, and it decreases slowly with R. Best fits to a power law gave $\sigma/B_{(FIT)} = 0.26R^{-0.20\pm0.015}$ for V1 and $\sigma/B_{(FIT)} = 0.29R^{-0.27\pm0.018}$ for V2. Parker's model, which neglects fluctuations, provides a good description of large-scale variations of the magnetic field strength because fluctuations in the magnetic field strength are relatively small. The decrease in the relative amplitude of the fluctuations in the magnetic field strength with increasing distance from the sun is real, for the corresponding rms at 1 AU did not decrease with time.

The rms of daily averages of the tangential component of the magnetic field in successive 26-day intervals, relative to the best power law fit to values of that component, $B_T(R)$, is shown as a function of distance in Figure 8 for both V1 and V2. The rms of the tangential component is comparable to the best fit value at 1 AU, and it decreases slowly with R, as $R^{-0.31}$ and $R^{-0.41}$ for V1 and V2, respectively. It is for this reason that Parker's model, which does not consider fluctuations in the magnetic field, cannot be expected to provide a good fit to observations of $B_T(R)$, which does include a large contribution from the fluctuations for the averaging intervals that we considered.

The radial variation of the rms of the radial and normal components of the magnetic field relative to the corresponding best fit fields is shown in Figure 8 for V1 and V2. These results are more difficult to interpret because the best fit values of the

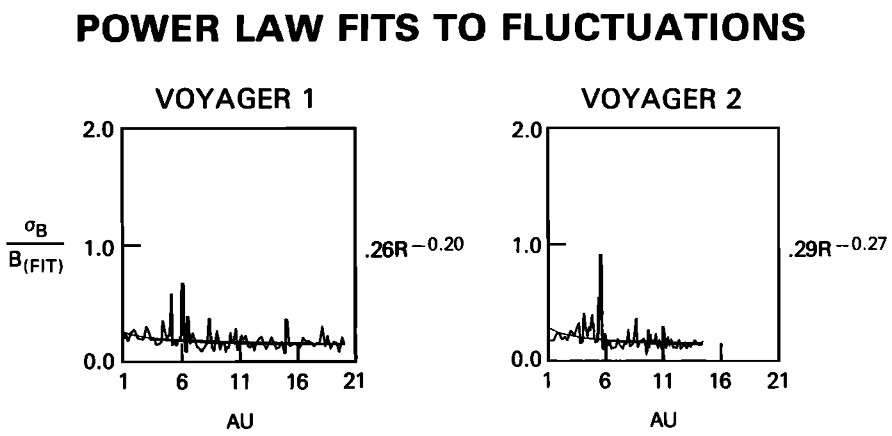

Fig. 7. The rms of daily averages of the magnetic field strength in successive 26-day intervals as a function of distance from the sun, and curves derived from least squares fits to the data.

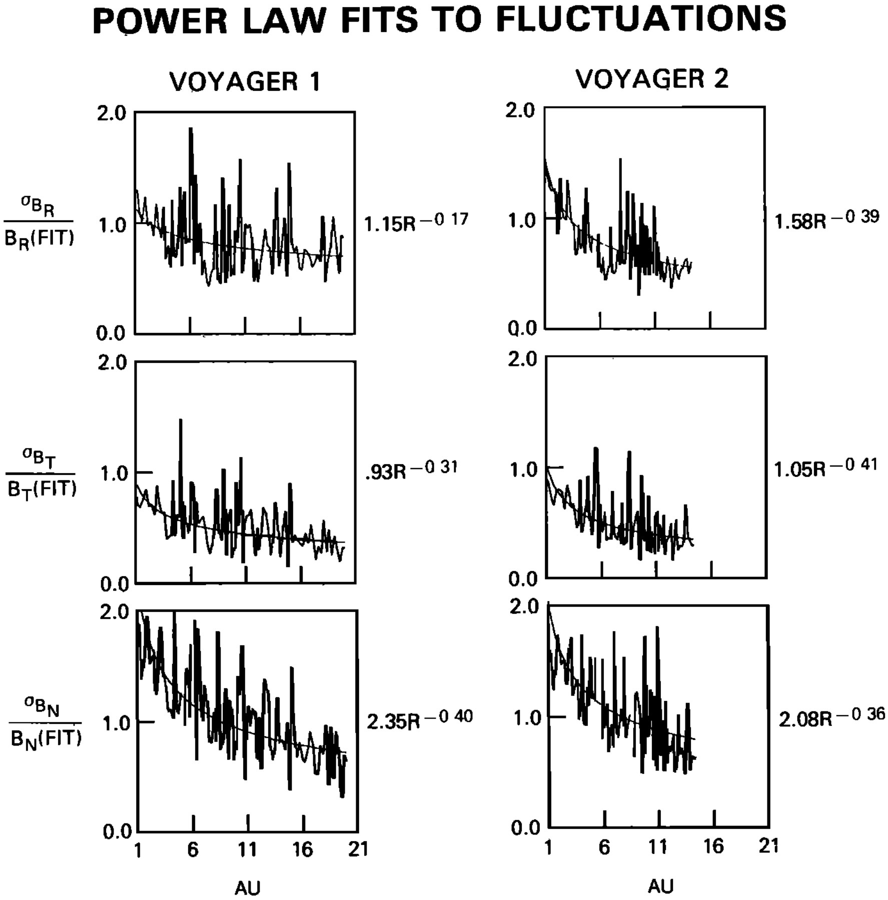

Fig. 8. The rms of daily averages of components of the magnetic field in successive 26-day intervals as a function a distance from the sun, and curves derived from least squares fits to the data.

components are themselves largely due to the fluctuations. Nevertheless, again Figure 8 shows that the fluctuations are relatively large and decay slowly with distance from the sun.

SUMMARY

We have presented observations of the interplanetary magnetic field made by Voyagers 1 and 2 as V1 moved from 1 to 20 AU from 1977 to 1985. Using ISEE 3 data obtained in the ecliptic at 1 AU to determine the effect of temporal variations in the solar magnetic field strength and using plasma measurements from Voyager 2 to determine the effect of temporal variations in bulk speed, we found that the Voyager 2 observations of radial variations in the magnetic field in the ecliptic are in good agreement with the predictions of Parker's model. We find no evidence that the magnetic field strength decreases more rapidly than predicted, in contrast to the conclusion of *Slavin et al.* [1984]. Hence there is no evidence for meridional flux transport. We believe that the discrepancy is due to the fact that these authors did not explicitly take into account either the temporal variations in the bulk speed, which are important at large distances from the sun, or the possible latitudinal variations in the strength of the sun's magnetic field, which would be important when comparing Pioneer 11 data obtained out of the ecliptic with the ISEE 3 and IMP data obtained in the ecliptic. Our results concerning the radial variation of B_T are consistent with the theoretical simulation of *Pizzo and Goldstein* [1987], but they did not consider radial variations of the fluctuations in B_T associated with waves and turbulence, which are in the observations.

The Voyager 1 data show that the magnetic field strength at higher latitudes was lower than that observed in the ecliptic by an amount which exceeded that predicted by the cos θ dependence. Since this effect could be due to higher speeds at higher latitudes, it cannot be regarded as evidence against Parker's model.

Fluctuations of the magnitude of the magnetic field are relatively small near 1 AU, and their value relative to the mean field decreases slowly with increasing distance from the sun. Thus Parker's model, which does not consider the effect of magnetic field fluctuations, should be applicable to observations of the radial variation of the strength of the magnetic field. On the other hand, fluctuations in the components of the magnetic field are relatively large, and one cannot expect Parker's model to accurately describe the measurements of the components, which include the fluctuations in the field as well as the average large-scale field itself.

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