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Heliospheric magnetic field strength out to 66 AU: Voyager 1, 1978–1996

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Abstract. We discuss Voyager 1 (V1) observations of the heliospheric magnetic field strength from 1978 through 1996. During this period the distance of V1 from the Sun increased from ≈3 AU to 66 AU and its heliographic latitude increased from ≈5°S to 33°N. The magnetic field strength profile observed by V1 is consistent with Parker's spiral field model when one considers (1) the solar cycle variation of the observed magnetic field strength at 1 AU, $B_1(t)$ (which is a measure of the source field strength) and (2) the latitudinal and solar cycle variations of the solar wind speed, $V(t, \theta)$. Both $B_1(t)$ and $V(t, \theta)$ make significant contributions to the variation of the magnetic field strength variations observed by V1. There is no evidence for a "magnetic flux deficit" increasing with distance from the Sun. There is a solar cycle variation of the magnetic field strength in the outer heliosphere, which will affect the modulation of cosmic rays.

1. Introduction

The radial variation of the strength of the interplanetary magnetic field, B, has been the subject of numerous studies. Early work is reviewed by *Smith* [1979, 1989], *Mariani and Neubauer* [1990], and *Burlaga* [1984, 1995]. *Parker* [1958, 1963] provided the basic theoretical framework for studies of B versus R. The model shows that one must consider the latitude and solar cycle variations of the source magnetic field strength and the solar wind speed.

The analysis of Voyager and Pioneer 11 data by *Burlaga and Ness* [1993a] shows that the radial variation of the magnetic field strength out to 19 AU is consistent with Parker's model when one considers the latitudinal and temporal variations of the source magnetic field strength and the solar wind speed. On the other hand, several studies of Pioneer 11 data suggest that the magnetic field strength decreases more rapidly with distance than predicted by Parker's model [*Smith and Barnes*, 1983; *Winterhalter and Smith*, 1989; *Slavin et al.*, 1984]. *Slavin et al.* [1984] interpreted their result as evidence for a flux deficit, the flux being lost from the low-latitude heliosphere by "meridional transport" from the equator toward the poles. *Thomas et al.* [1986] found a flux deficit in both the radial and the azimuthal components of the magnetic field increasing with distance from the Sun, equal to 25% at 10 AU. *Winterhalter et al.* [1988] reported a deficit in the magnetic field strength increasing with distance from the Sun and equal to 29% at 20 AU. *Winterhalter et al.* [1990] suggested a "deficit" as large as 1%/AU between 1 and 20 AU. Finally, *Smith et al.* [1997] reported a flux deficit in the Ulysses data, although they did not consider temporal variations in the source field strength.

Little was known about the latitudinal variations of the heliospheric magnetic field prior to the launch of Ulysses [*Smith and Barnes*, 1983; *Klein et al.*, 1987; *Luhman et al.*, 1988]. The Ulysses magnetic field observations showed that the radial component of the magnetic field B_r is independent of latitude from the heliographic equator to 80° during its first latitude scan [*Smith et al.*, 1993, 1997; *Forsyth et al.*, 1996; *Balogh et al.*, 1995; *Smith and Balogh*, 1995; *Suess and Smith*, 1996; *Suess et al.*, 1996; *Wang and Sheeley*, 1995]. This result implies that the source magnetic field strength in Parker's model is effectively independent of latitude. *Smith* [1997] suggested that the constant B_r is a consequence of magnetic flux transport from the pole to the equator.

The aim of this paper is to discuss the variations of the magnetic field strength from ~3 to 66 AU, with consideration of latitudinal and solar cycle variations in the source magnetic field strength and solar wind speed, using the data obtained by Voyager 1 (V1) and spacecraft at 1 AU from 1978 to 1997.

2. Trajectory

The yearly averages of the distance from the Sun, R, and the heliographic latitude θ of V1 from 1978 through 1996 are shown in Figure 1. The radial distance increased monotonically from 1 AU at launch in August 1997 to 66 AU on day 365, 1996. The latitude varied between 7°N and 5.5°S from 1 AU to 6 AU, and thereafter it increased monotonically to 33°N on day 365, 1996.

3. Parker's Spiral Field Model

Parker [1958, 1963] introduced a model for the basic structure in the interplanetary magnetic field based on the following

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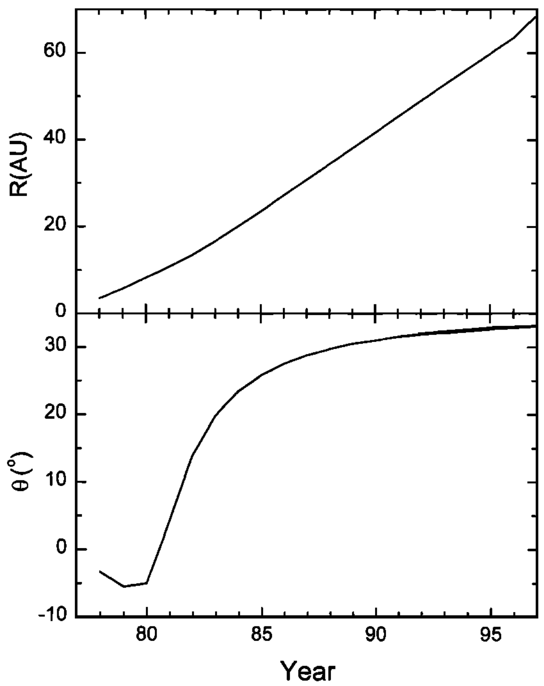

Figure 1. Trajectory of Voyager 1 from 1978–1997. Radial distance from (top) the Sun and (bottom) heliographic latitude.

assumptions: (1) The solar wind moves radially away from the Sun at a constant speed V; (2) the Sun rotates at an angular speed Ω; (3) the solar wind is azimuthally symmetric about the solar rotation axis; and (4) the interplanetary magnetic field is frozen-in the solar wind and anchored at the Sun.

A magnetic field line at a heliographic latitude θ has form of a spiral wrapped on a cone whose axis is the solar rotation axis and whose angular half-width is $90° - \theta$. According to Parker's model the strength of the magnetic field varies as

$$B_p(R, t, \theta) = B_{r1}(t, \theta)R^{-2} \cdot \{1 + [419.5\ R \cos(\theta)/V(t, \theta)]^2\}^{1/2} \qquad (1)$$

when the rotation period of the Sun is assumed to be 26 days independent of latitude, and the units of θ, V and R are degrees, km/s, and AU, respectively. The time t in this equation refers to the epoch of the solar cycle. The factor $B_{r1}(t, \theta)$ is the radial component of the magnetic field at 1 AU as a function of θ and time, which in this paper is in units of a year. The functions B_p and V refer to measurements at the spacecraft. Some care is required when using V determined from solar observations, as discussed below. The first term in the brackets on the right-hand side (RHS) of (1) is from the radial component of the magnetic field, which decreases as R^{-2}, and the second term is from the tangential component, which varies as R^{-1}.

Since the Ulysses data referenced above indicate no latitude dependence of the radial component of the magnetic field during the first latitude pass, we shall assume that there is no latitude dependence in the source term at all phases of the solar cycle, i.e., we take $B_{r1}(t, \theta) = B_{r1}(t)$. From (1) with $R = 1$ and $\theta = 0$ we obtain $B_{r1} = B_1(t)\ \alpha(t)$, where $\alpha(t) \equiv \{1 + [(419.5)/V_1(t)]^2\}^{-1/2}$. $V_1(t)$ and $B_1(t)$ are the speed and magnetic field strength, respectively, measured at 1 AU over the course of a solar cycle. Thus, in the absence of a latitude dependence of B_{rl} Parker's equation (1) becomes

$$B_p(R, t, \theta) = \{B_1(t)\ [1 + (419.5)/V_1(t))^2]^{-1/2}\}R^{-2} \cdot [1 + (419.5\ R \cos(\theta)/V(t, \theta))^2]^{1/2} \qquad (2)$$

Note that (2) has no free parameters, since $B_1(t)$, $V_1(t)$, and $V(t, \theta)$ can be determined from measurements, as discussed below.

Since *Burlaga et al.* [1984] and *Burlaga and Ness* [1993a] showed that (1) provides a good fit to the data out to 9.5 and 19 AU, respectively, we shall focus on the region beyond a few AU, where (1) has the simple form

$$B_p(R, t, \theta) = B_1(t)\alpha R(t)^{-1} \cos(\theta)[419.5/V(t, \theta)] \qquad (3)$$

In particular, beyond 3.5, 5, and 7.5 AU the difference between (3) and (2) is only 4%, 2%, and 1%, respectively. This means that beyond several AU the radial component of the magnetic field is negligible and the magnetic field strength is determined by the azimuthal component of the field. The magnetic field strength would vary with heliocentric distance as R^{-1}, if all other factors were constant. In general, however, the magnetic field strength at a spacecraft such as V1 will vary with time t (in particular, with the solar cycle) and with θ, because it is proportional to the source term $B_1(t)$ and inversely proportional to the speed $V(t, \theta)$.

The results for B_p presented below are based on (2), but essentially the same results were obtained from (3) with $\alpha = 0.72 \pm 0.02$. This value of α is obtained with $\langle V_1 \rangle = 446 \pm 32$ km/s, which is computed using measurements of speed at 1 AU during the interval of interest, 1978 through 1996. The value $\alpha = 0.72$ is consistent with a spiral angle of 45° at 1 AU. The small uncertainty in α indicates that it is not sensitive to variations of $V_1(t)$, which is why (3) is an excellent approximation to (2).

4. Observations

Our aim is to understand the variations in the yearly averages of the Voyager 1 observations of the magnetic field strength, $B_{V1}(t)$, from 1978 through 1996. In particular, we want to determine whether or not $B_{V1}(t)$ is consistent with Parker's model, as given by (2).

We begin by examining the validity of Parker's model in its simplest form, namely, with B_1 and V being constant, independent of time and latitude. In this case, B should vary as R^{-1}. The averages of B were computed from high resolution (of the order of a minute or less) averages of the magnetic field strength measurements. Determining averages of the magnetic field strength by averaging components would give artificially low values. The yearly averages of B measured by V1 between 5 and 66 AU are shown as a function of R in Figure 2 on a log-log scale. The yearly averages between 1 and 5 AU are not very meaningful because of the rapid decrease in B with increasing R in this region. The statistical error in the mean of the yearly averages is small, of the order of the size of the dots, since we are computing yearly means of hour averages. A power law fit to the data, shown by the dashed line in Figure 2 gives a slope $= -1.3 \pm 0.1$, i.e., $B \propto R^{-(1.3\pm0.1)}$. The simple spiral model (3) with constant α, B_1, and V describes the qualitative tendency of B to decrease with increasing R, but there are significant departures of the observations of B versus R from this model. We cannot neglect the temporal and lati-

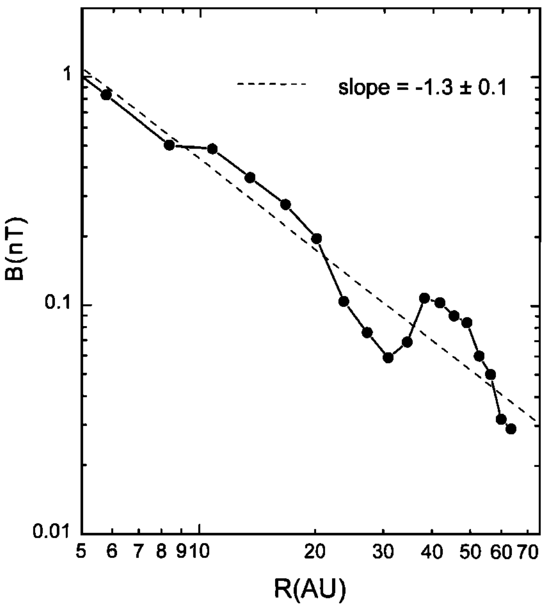

Figure 2. Yearly averages of the magnetic field strength observed by Voyager 1 (solid dots) versus radial distance from the Sun on a log-log scale. The dashed curve is a fit to $B \propto R^{\text{slope}}$.

tudinal variations of the functions in Parker's model, since the V1 observations were made over nearly two solar cycles and over a wide range of latitudes.

The scatter of the points about the dashed line in Figure 2 is systematic. The magnetic field is relatively strong from ~10 to 20 AU and from ~35 to 55 AU; it is relatively weak from ~20 to 35 AU and from ~44 to 68 AU. The two intervals with relatively strong fields were associated with high solar activity; and the intervals with relatively weak fields were associated with minimum solar activity.

The power law fit shown in Figure 2, $B \propto R^{-(1.3\pm0.1)}$, indicates a more rapid decrease with increasing distance than predicted by Parker's model with constant α, B_1, and V. This result could be related to the monotonically increasing latitude of V1, since the solar wind speed increases with latitude throughout most of the solar cycle and the magnetic field strength varies as 1/V (see equation (3)). Such an increase of V with latitude was observed in situ by Ulysses [*Bame et al.*, 1993; *Phillips et al.*, 1994] and remotely by a number of observers (see the references in *Burlaga* 1995, page 39). An increase in the mean speed from 400 km/s near the ecliptic to 800 km/s at 35° would reduce B by a factor of 2 (see equation (3)), which is equivalent to doubling the distance of V1. The latitudinal dependence of V is a function of the solar cycle.

Let us now consider the functions $B_1(t)$ and $V(t, \theta)$ that should be used in (2) in order to compare this equation with the V1 observations.

The variation of $B_1(t)$ at 1 AU from 1978 through 1996, obtained from the NSSDC Omni data set, is shown in the bottom of Figure 3. A solar cycle variation of $B_1(t)$ is evident, as expected from previous studies [*King*, 1979, 1981; *Slavin et al.*, 1984, 1986]. The sunspot number during the same interval is shown in the middle of Figure 3 for comparison. The magnetic field at 1 AU, $B_1(t)$, had a minimum strength equal to ≈6 nT and a maximum strength of ≈9 nT. The two intervals with relatively strong fields observed by V1 were associated with relatively strong magnetic fields at 1 AU shortly after the sunspot maxima in 1979 and 1989, when the area of the open field regions was increasing and the strength of the magnetic field in these regions was still high [*Wang and Sheeley*, 1990]. The intervals with relatively weak fields observed by V1 were associated with relatively weak magnetic fields at 1 AU when the solar activity was low.

The speed $V(t, \theta)$ was not measured by Voyager 1 beyond 10 AU, and little is known about this function from direct measurement. Near the ecliptic, the solar wind speed varies by ~20% during the solar cycle (see the references in work of *Burlaga* [1995, p. 37] and *Wang and Sheeley* [1990]). The speed varies with latitude, as shown by remote sensing observations [*Coles et al.*, 1976, 1980; *Kojima and Kakinuma*, 1987, 1990; *Rickett and Coles*, 1991; *Watanabe*, 1989] and the Ulysses data [*Bame et al.*, 1993; *Phillips et al.*, 1994, 1995].

A method for estimating $V(t, \theta)$ from observations of the solar magnetic field was developed by *Wang and Sheeley* [1990] and *Wang et al.* [1990]. The method is based on the observation that the solar wind speed at Earth is inversely correlated with the flux tube divergence rate in the corona [*Levine et al.*, 1997; *Wang and Sheeley*, 1990]. The validity of the method was verified using interplanetary data from a wide range of distances and latitudes [*Sheeley et al.*, 1991, *Wang and Sheeley*, 1997]. Of special interest is the result of *Sheeley et al.* [1991] that from 1972 to 1989 the solar wind speed was calculated to be approximately 625 km/s at 30°N, except for a 4-year period around 1979 (near solar maximum) when it dropped to 425 km/s. This result was found to be consistent with IPS observations of the solar wind speed. A review of these and related results was published by *Sheeley et al.* [1997].

The method of Wang and Sheeley was used to determine

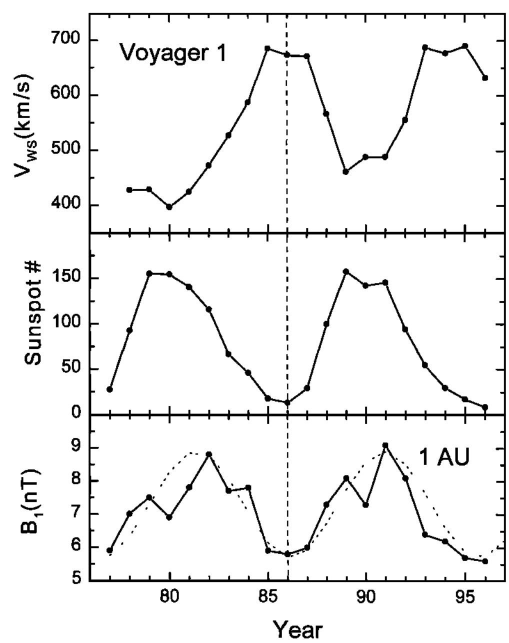

Figure 3. (top) The solar wind speed along the trajectory of Voyager 1 as a function of time from 1978 through 1996, calculated using the method of Wang and Sheeley. (middle) The sunspot number versus time. (bottom) The magnetic field strength observed at 1 AU versus time, together with a sine wave (dashed curve) to indicate the solar cycle variation. The vertical dashed line marks solar minimum.

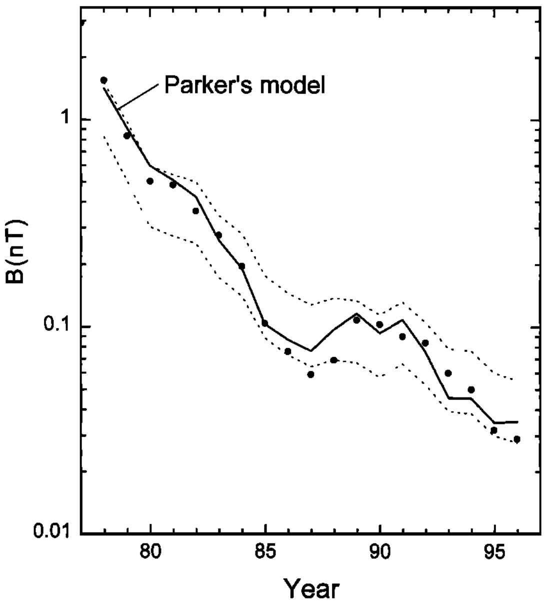

Figure 4. The Voyager 1 observations of the magnetic field strength versus time (solid dots) on a semilog scale, and the prediction of Parker's model (equation (3)) (solid curve) for variable source field strength and variable speed. The dotted curves show the predictions of Parker's model for a variable source field strength and constant speed, 400 km/s (top curve) and 800 km/s (bottom curve).

$V(t, \theta)$ along the V1 trajectory from 1978 through 1990. The potential field source-surface model (with source-surface radius $R_{ss} = 2.5\ R_{Sun}$) was applied to the Wilcox Solar Observatory (WSO) photospheric field maps for CR 1663–1920 in order to derive the "expansion factor," f_{ss}, the factor by which the "sub-Voyager" flux tube expands in solid angle between $R = R_{Sun}$ and $R = R_{ss} = 2.5\ R_{Sun}$. No attempt was made to include any stream interaction effects [*Wang et al.*, 1997], since we are dealing with 1-year averages. However, allowance was made for the considerable time lag between the dates of the solar magnetograph observations and the Voyager 1 observations times by assuming an average propagation speed of (1 AU/4 days). To convert the expansion factors f_{ss} (computed for every 5 degrees of Carrington longitude) into wind speeds V, the following table of correspondences was used:

$$[f_{ss}, V\ (\mathrm{km/s})] = [(<3.5, 775); (3.5\text{–}6, 700); (6\text{–}10, 600);$$
$$(10\text{–}20, 500); (20\text{–}50, 400); (>50, 300)].$$

Each yearly average is based on averaging some 72 × 13 individual V values. This table provides a "compromise" match to both the Ulysses and the near-Earth ecliptic wind speed patterns when no allowance is made for wind stream interactions. The computed speeds were maximal when Voyager 1 observed primarily a single polarity, i.e., during 1986/1987 and 1993/1994/1995 [see *Burlaga and Ness*, 1993b, 1997]. This is consistent with the fact that the speed is highest above the sector zone, lending further support for the method of Wang and Sheeley.

Let us now compare the V1 observations of 1-year averages of the magnetic field strength B with the predictions of Parker's model. Using the observations $B_1(t)$ and $V_1(t)$ at 1 AU and the speed profile $V[(t, \theta(t))]$ determined as described above, we calculated the magnetic field strength at V1 that is predicted from Parker's model using (2). The result is shown by the solid curve in Figure 4. The observations of B_{V1} are plotted in Figure 4 as dots. Parker's model, with consideration of the solar cycle variations of the source magnetic field strength and the latitude/solar cycle variations of the solar wind speed, provides a good fit to the data. The effects of the variations of the source magnetic field strength are of the same order of magnitude as those of the variations of speed, as one can see from Figure 3 and (1). The effects of the speed on the theoretical magnetic field strength are shown by the dotted curves in Figure 4, which show Parker's model for the cases $V[t, \theta(t)]$ = 400 km/s (top curve) and 800 km/s (bottom curve). Clearly, the speed variations have a significant effect on B_p. We conclude that Parker's model, without adjustable parameters, reproduces the basic features of the magnetic field strength profile, including the general tendency to decrease with increasing time, the two broad increases around 1980 and 1990, the minimum in 1989 and the very low values in 1995/1996.

A quantitative measure of the relative difference between the V1 magnetic field strength observations and the predictions of Parker's model is given by

$$X(t) \equiv (B_p - B_{V1})/B_p \tag{4}$$

Figure 5 shows $X(t)$ at 1-year intervals, using $B_p(t)$ from (2) and the V1 magnetic field strength observations from 1978 through 1996. The mean value of X is $\langle X \rangle = -0.04 \pm 0.03$, indicating that on average there is no significant difference between the predictions of Parker's model and the V1 observations.

If there were a flux deficit of 1 to 2.5%/AU as argued by Winterhalter, Smith and others in the references cited above, then $X(t)$ would decrease with increasing time (distance). The straight line in Figure 5 shows a linear least squares fit to $X(t)$. The slope of this line is 0.003 ± 0.006, where the uncertainty is the standard error. Since the slope is consistent with zero, there is no evidence for a flux deficit in the V1 data out to 66 AU. The standard deviation of $X(t)$ is 0.14. If there were a flux deficit equal to 1%/AU as suggested by *Winterhalter et al.*

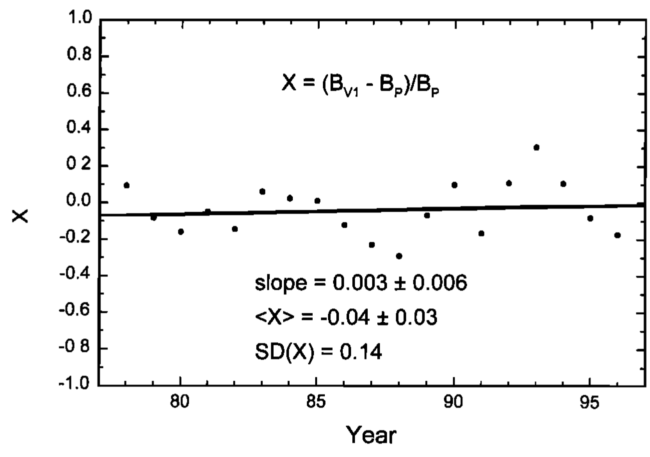

Figure 5. The relative difference between the magnetic field strength observed by Voyager 1 and predicted by Parker's model as a function of time. There is no significant difference between the observations and the model on average and there is no tendency for the difference to change with distance (time). In particular, there is no evidence for a flux deficit.

[1990], then during 1996 (when V1 was at 66 AU) X should be -0.65, which is clearly inconsistent with the observations in Figure 5.

Another way to address this issue of a flux deficit is to draw a best fit line through the data in Figure 5, constrained to give no flux deficit at 1 AU. The result is $X = (-0.002 \pm 0.003) \times (\mathrm{YR} - 77)$. Thus, when Voyager 1 was at 66 AU in 1996 (YR = 96), the "flux deficit" was $(B_p - B_{V1})/B_p = 0.038 \pm 0.057$ or $(0.06 \pm 0.09)\%/\mathrm{AU}$, which is again consistent with zero. The maximum flux deficit within the standard error is 0.15%/AU, an order of magnitude smaller than that derived from the Pioneer measurements.

For studies of cosmic ray modulation, it is of interest to know how B varies as a function of solar activity at a given distance in the outer heliosphere. This variation, in the solar equatorial plane, is given by $B_p\,R$, where B_p is found from (2) with $\theta = 0$ and $V(t, \theta) = V_1(t)$. The product $B_p\,R$ from 1978 through 1996 is plotted in Figure 6. A solar cycle variation of the magnetic field strength at a given distance in the outer heliosphere is apparent in Figure 6. The ratio of the maximum to minimum magnetic field strength is ≈ 1.7. The variation might be larger at higher latitudes where the variation of speed as a function of solar activity is greater. If the cosmic ray diffusion coefficient is inversely proportional to B as many authors assume, then the solar cycle variation of B shown in Figure 6 should contribute to the modulation of cosmic rays.

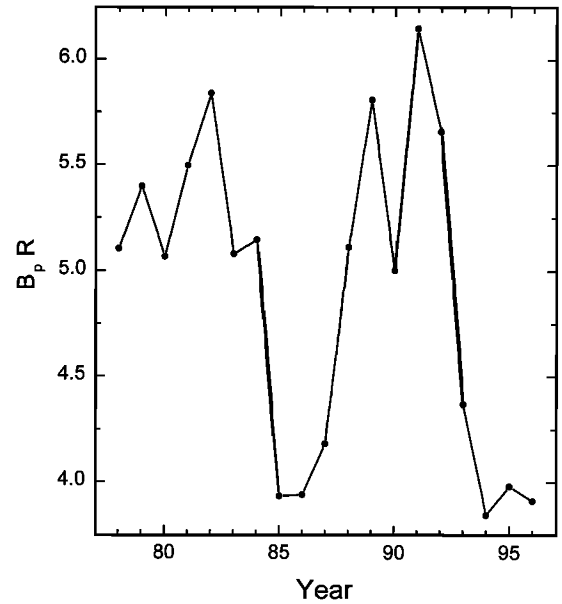

Figure 6. The product B_pR as a function of time computed from (2) with $\theta = 0$, $V = V_1(t)$, and $B = B_1(t)$, showing a solar cycle variation of B at a given distance that might affect the modulation of cosmic rays.

5. Conclusions

The variation of B observed by Voyager 1 (V1) from 1978 (≈ 3.5 AU) through 1996 (66 AU) can be attributed primarily to three effects. To zeroth order, the magnetic field strength tends to decrease as $B \approx 1/R$ beyond a few AU as a result of the expansion of the solar wind at a constant speed and the rotation of the Sun. A systematic decrease in B relative to $1/R$ is observed by V1, because the latitude of the spacecraft increased monotonically with time, and because V increases with latitude throughout much of the solar cycle. A decrease in the speed at midlatitudes near solar maximum contributes to an enhancement in B around 1980 and 1990. Finally, solar cycle variations in the strength of B by O(50%) contribute to the relatively strong fields observed when solar activity was high and the relatively weak magnetic fields observed when solar activity was low. Thus the V1 magnetic field strength observations are consistent with (2) using the measurements of $V_1(t)$ and $B_1(t)$ at 1 AU and using $V(t, \theta)$ determined by the method of Wang and Sheeley.

Parker's spiral field model should have wide applicability to stellar and protostellar objects, since it is based on simple and universal factors: a localized source, uniform dilation (expansion) and rotation. *Seaquist et al.* [1989] found evidence for the predicted $1/R$ variation of the magnetic field strength at large distances in the shell of the nova GK Per. It seems likely that many stellar and protostellar objects have winds that are latitude dependent. Hence the $1/V$ dependence of the magnetic field strength predicted by Parker's model and observed by V1 should be significant in astrophysical situations, just as it is in the solar wind. "Stellar cycle" variations in the magnetic field strength might also be present and observable.

During 1997, the magnetic field strengths measured by V1 were generally comparable to the measurement uncertainties, ~ 0.02–0.05 nT, so they could not be used for this study. Nevertheless, we do expect to obtain useful magnetic field measurements during the next few years at least, despite the increasing distance of V1 and the $1/R$ dependence of B. The results above show that as solar activity increases to a maximum during the next 2 or 3 years, the solar wind speed should decrease and the magnetic field strength at the source and 1 AU should increase. Both of these effects will tend to increase the magnetic field strength at V1. From (3) with $B_1 = 9$ nT (Figure 3, bottom) and with $V = 450$ km/s (Figure 3, top), we calculate that in the year 2000, the magnetic field strength at V1 (at 76 AU) will be ≈ 0.06 nT, which can be measured by the magnetometer on V1.

We conclude that the V1 magnetic field strength observations are consistent with Parker's model when one considers the solar cycle variations in the source magnetic field strength and the latitude/time variation in the solar wind speed, together with the uncertainties in the measurements. The results are not consistent with the simple spiral field model with V and B_1 constant. There is no evidence of a "magnetic flux deficit." A deficit as large as 1–2.5%/AU is ruled out, and our results indicate that any deficit is at least an order of magnitude smaller than this. We expect V1 to observe stronger magnetic fields approaching solar maximum during the next 2 or 3 years, despite the increasing distance of V1, owing to a decrease in the solar wind speed at 33°N latitude and an increase in the strength of the solar magnetic field. The magnetic field strength varies with solar activity in the outer heliosphere; this variation might contribute to the modulation of cosmic rays.

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