SHORT-TERM VARIATIONS IN SOLAR ROTATION RATE AND SOLAR WIND PARAMETERS

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ABSTRACT

The components of the interplanetary magnetic field (IMF) at the Earth's orbit are described by the model of Parker [1958]. In it, the solar rotation rate is assumed constant. In the present paper we compare in-situ measurements of the azimuthal IMF component B_y to the model predictions taking into account the variable solar rotation. A very good and highly significant correlation is found between the calculated and the measured B_y both on longer time-scales and – in most cases – on day-to-day basis. The difference between the observed and calculated yearly averaged IMF azimuthal component can be both positive and negative, with its sign determined by the solar magnetic polarity. In periods of interplanetary shocks, B_y doesn't obey Parker's model, and in almost half of the observed cases is instead highly correlated to the solar rotation rate.

INTRODUCTION

The basic geometry of the heliospheric magnetic field is described by the Archimedian spiral model under the assumptions of a purely radial solar wind with a constant velocity emanating from a uniformly rotating Sun, with the magnetic field frozen in the flow (Parker, 1958). In-situ measurements confirmed this general picture, and some correction have been made to the model. Smith and Bieber (1996) found a systematic deviation of the predicted winding angle of the heliospheric magnetic field from 0.7 to 16 AU with a 10° variation between solar minimum and solar maximum, and showed that this is in part a direct result of the solar cycle variations of solar wind speed. However, even after taking into account the measured solar wind speed, they found that the winding angle still remained overwound by several degrees beyond the theoretical value, and suggested as a possible reason a small azimuthal component of the magnetic field at the source surface which might result from solar differential rotation. Bruno and Bavassano (1997) confirmed this result for 0.3 – 1 AU and found a definite dependence of the winding angle on the solar wind speed. Fisk (1996) pointed out that the azimuthal velocity of the solar wind is not simply due to the rigid uniform rotation of the Sun. Due to the solar differential rotation, the nonradial expansion of the polar coronal hole magnetic field around solar minimum, and the offset between the axis of symmetry for the expansion of the magnetic field and the solar rotation axis, magnetic field lines move in heliographic latitude creating also a polar component to the heliospheric magnetic field. Schatten (2001) suggested the idea of streak lines to explain the differences between the solar wind plasma trajectory and the magnetic field lines geometry taking account of the horizontal movements of the field lines' foot points.

In all models solar rotation is assumed constant. However, it has been shown to vary on different time-scales (Javaraiah and Gokhale, 1995). In the present paper we compare observed By component of the IMF to the one calculated from Parker's formula with the measured solar rotation.

DATA AND RESULTS

For the equatorial solar rotation rate, we use the Mt. Wilson velocity data for the period 1967-1994, and for solar wind parameters – OMNI database of the National Space Science Data Center provided through their web-site http://nssdc.gsfc.nasa.gov/omniweb/ for the same period, both daily values. We calculate By according to the formula (Giacalone, 2001)

$$B_\theta(r,\theta,\varphi,t) = B_r(r_0)\frac{-r_0\Omega\sin\theta + V_\phi(\theta,\phi',t')}{V_\omega}$$

$$B_r(r_0) = B_r(r)\left(\frac{r}{r_0}\right)^2$$

where B_θ is the azimuthal (=By), and $B_r(r)$ the radial (=B_x) IMF component at the Earth orbit r = 1 AU, r_0 is the source surface radius, Ω is the solar rotation rate, V_ω is the solar wind radial velocity and V_ϕ the azimuthal velocity, and $t'=t-(r-r_0)/V_\omega$. We assume a zero velocity azimuthal component $V_\phi=0$, but a non constant solar rotation rate, $\Omega=\Omega(\theta',t')$. Further, we confine our study to the ecliptic plane, so $\cos\theta=1$, and $\Omega(\theta',t')=\Omega(t')$ is the solar equatorial rotation rate. As $V_\omega \approx V$ (plasma bulk speed), we use V instead of V_ω to

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reduce the data gaps. The yearly averages of the difference between the obsereved and the calculated IMF azimuthal component, $dBy=By-B_\theta$ (5-year running means) are presented in figure 1.

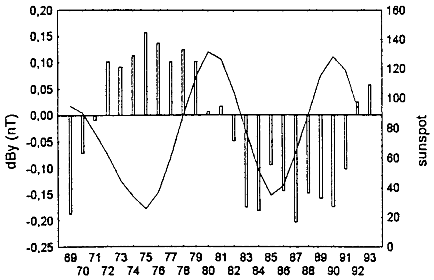
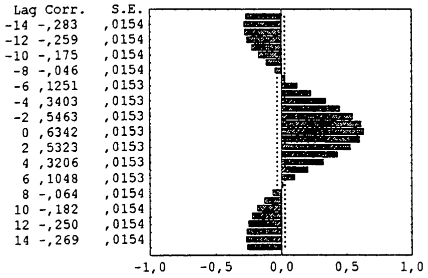


Figure 1: Yearly averages (5-year running means) of the difference between the observed and calculated IMF azimuthal component (vertical bars) and the sunspot numbers (solid line).

Unlike the IMF winding angle which is always "overwound" with respect to the theory predictions, the difference between the calculated and measured IMF azimuthal component can be both positive and negative. Moreover, the sign of this difference shows a distinct systematic behavior governed by the solar polarity cycle rather than by the solar activity cycle as suggested by Smith and Bieber (1996) and Bruno and Bavassano (1997) for the IMF winding angle. In positive (negative) polarity cycles, By is larger (smaller) than predicted.

When studying the relation between the shorter-term (day-to-day) variations of B_y and B_θ we should keep in mind that both OMNI and Ω data-sets have numerous gaps. Nevertheless, for the whole available period 1967-1994, the correlation between them is reasonably good and highly statistically significant, R=0.52. And if we focus on the period after 1981 due to the reduced instrumental noise and relatively better coverage of Ω data (Javaraiah and Komm, 1999), this correlation increases to 0.63 (figure 2).



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Lag Corr.   S.E.
-14 -,283   ,0154
-12 -,259   ,0154
-10 -,175   ,0154
 -8 -,046   ,0154
 -6 ,1251   ,0153
 -4 ,3403   ,0153
 -2 ,5463   ,0153
  0 ,6342   ,0153
  2 ,5323   ,0153
  4 ,3206   ,0153
  6 ,1048   ,0153
  8 -,064   ,0154
 10 -,182   ,0154
 12 -,250   ,0154
 14 -,269   ,0154
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Figure 2: Cross-correlation function of By and B_θ. The dotted lines present the 0.95 significance level.

For comparison, the correlation between the predicted and observed values of the IMF winding angle is only 0.16, though statistically significant.

However, in shorter intervals (determined by the data availability), the correlation between B_y and B_θ can vary substantially. Figure 3 demonstrates the behavior of B_y and B_θ in two periods.

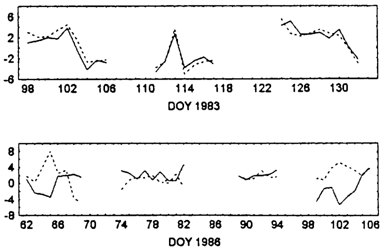


Figure 3: Daily averages of B_y (solid line) and B_θ (broken line) in two periods of 1993 and 1996.

Very often periods in which B_y doesn't obey Parker's prediction are characterized by a jump in solar wind magnetic field magnitude, plasma temperature, number density and flow velocity. An example is presented in figure 4.

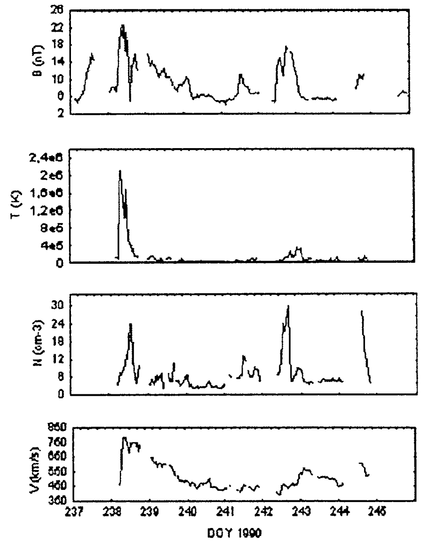


Figure 4: IMF total magnitude, plasma temperature, number density and flow speed from day 237 to 245, 1990.

In the whole period of 28 years we have identified 205 cases of such interplanetary shocks for which we have data for both solar wind parameters and solar rotation rate, and can calculate dB_y-B_y-B_θ. We have compared dBy for the periods of all such events (dB_y-e), for all other days (dB_y-*n*), and for all days in the 28-year periods (dB_y-*all*) by the method of the Principal Component Factor Analysis (Statistica for Windows, StatSoft Inc., 1999). Table 1 presents the factor loadings for the three variables, and they are plotted in figure 5.

Table 1: Principal component factor analysis of dB_y-*e*, dB_y-*n*, *and* dB_y-*all (see text).*

variables	Factor 1	Factor 2
dB_y-*e*	-,725644	,127191
dB_y-*n*	-,032744	,559851
dB_y-*all*	,031116	,814569

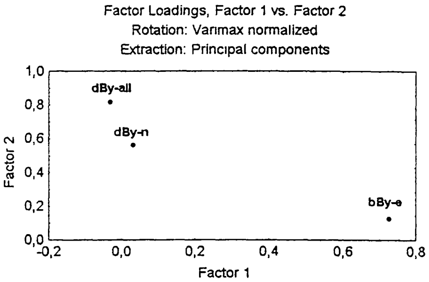


Figure 5: Plot of factor loadings for dB_y-*e*, dB_y-*n*, *and* dB_y-*all.*

A significant difference is obvious between B_y-*e* the one side, and B_y-*n* and B_y-*all* (in which periods of no events prevail) – on the other. We could therefore conclude that in periods of interplanetary disturbances Parker's formula doesn't describe well the observed B_y.

A curious feature which has been noted is that in some of the intervals of poor predictability of the observed IMF B_y, it is highly correlated to Ω, and with no time-lag. Such periods are short, typically 5-10 days. These correlations can be both positive or negative. In figure 6a an example is presented of a period from August 25 and September 2, 1990, with R=0.936, and in figure 5b – a period with a negative correlation, R=-0.801, from August 9 to 17, 1994.

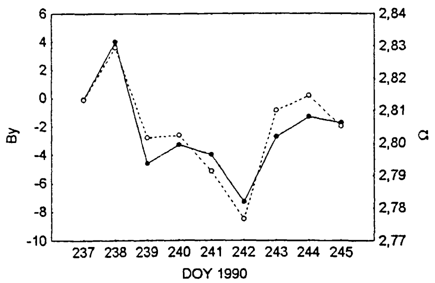


Figure 6a: IMF azimuthal component B_y *and solar rotation rate* Ω *from August 25 to September 2, 1990.*

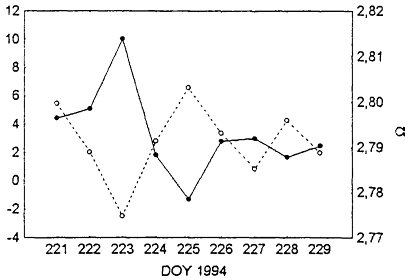
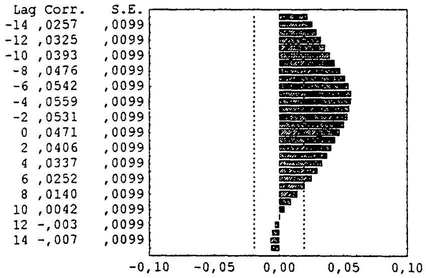


Figure 6b: The same as Fig.5a from August 9 to 17, 1994.

In the whole period of 28 years, we have found 97 intervals of such high correlations with zero time-lag, and the statistical significance of this finding has been tested with the Steepest Descent Method (Mathlab, Release 12). Practically all of these intervals (with only 3 exceptions) are associated with interplanetary shocks or tangential discontinuities. In other words, in almost half of the cases of such events (94 out of 205), the behavior of B_y doesn't obey Parker's formula, and is instead directly dependent on the variations of the solar rotation rate, Ω, as if the Sun and the solar wind rotated as a rigid body. The interval presented in figure 6a corresponds to the interval of figure 4. The dependence of B_y on Ω for the whole period is statistically significant, though weak, and with a maximum correlation r=0.056 when B_y is lagged with respect to Ω by 4 days, as expected from the time for the propagation of the solar wind from the Sun to the Earth – figure 7. Note the different scale as compared to figure 2.



Lag	Corr.	S.E.
-14	,0257	,0099
-12	,0325	,0099
-10	,0393	,0099
-8	,0476	,0099
-6	,0542	,0099
-4	,0559	,0099
-2	,0531	,0099
0	,0471	,0099
2	,0406	,0099
4	,0337	,0099
6	,0252	,0099
8	,0140	,0099
10	,0042	,0099
12	-,003	,0099
14	-,007	,0099

Figure 7 : Cross-correlation function of the observed azimuthal IMF component and the equatorial solar rotation rate, with the 0.95 significance level.

At present we cannot explain this phenomenon, neither can we explain why the correlation varies in sign. Our initial suspicion that in such intervals the frozen-in condition could not hold for some reason, was proven wrong. In 26 of these periods, the heliospheric current sheet is crossed. A comparison with the source surface synoptic maps from the Wilcox Solar Observatory web site shows that the time delay at 1 AU corresponds to the time for the solar wind propagation. However, the close association of these periods with interplanetary shocks implies that this may be a real phenomenon rather than random coincidence, and deserves a further study.

SUMMARY AND CONCLUSIONS

We compare the observed azimuthal IMF component B_y to the azimuthal B_θ calculated from the Parker's model taking into account the variable solar rotation. We find that the difference between the calculated and measured IMF azimuthal component can be both positive and negative, with its mean value very close to zero (0.004 nT, as compared to 0.03 nT if solar rotation rate is assumed constant), and its sign depends on the solar polarity cycle, B_y being larger (smaller) than predicted in positive (negative) polarity cycles. We have derived this result for the period 1967-1994 for which we have data for the solar rotation rate. To check it, we look at a longer interval, 1965-2000 for which solar wind data is available, calculating B_θ assuming a constant solar rotation – figure 8.

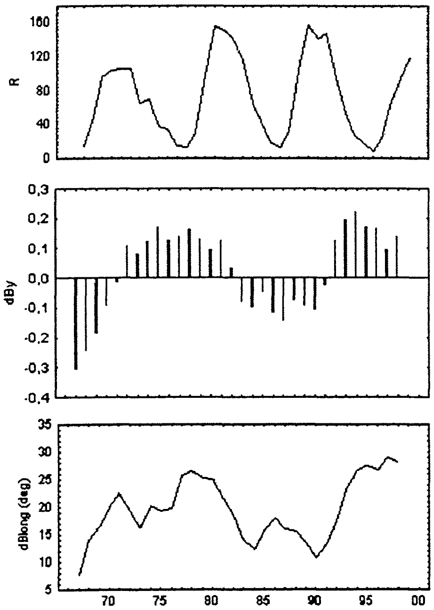


Figure 8: Yearly averages (5-year running means) of the international sunspot number (upper panel), the difference between the observed and calculated IMF azimuthal component (middle panel) and the between the observed and calculated IMF winding angle (bottom panel).

Figure 8 demonstrates that the difference not only between the observed and calculated IMF azimuthal component (middle panel) but also between the observed and calculated IMF winding angle (bottom panel) demonstrates a clear dependence on the 22-year solar polarity cycle rather than on the solar activity cycle as found for B_{long} by Smith and Bieber (1996) on the basis of data between 1965 and 1987. This is due to the fact that both the observed IMF azimuthal component and winding angle, as well as its radial component used in Parker's formulas demonstrate a clear 22-year periodicity (Kirov et al., present issue).

On day-to-day time scales, the calculated B_θ values are as a whole in a very good agreement with the observed B_y. However, in some intervals they can differ substantially. We have found that in periods of large-scale interplanetary disturbances Parker's formula doesn't describe well the IMF azimuthal component. In almost half of these periods, and only in these periods, B_y is highly (positively or negatively) correlated to the solar rotation rate, however the mechanism of this effect is not clear.

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