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ABSTRACT

The magnitude of the interplanetary magnetic field (IMF) exhibits an enhancement during 1978 - 1979 relative to all years back to 1963. It is shown that IMF magnitude variations over the 1966 - 1979 period represent the combined effect of variations in both the radial flux density of the IMF and the degree of spiraling of the IMF, consistent with the theoretical model of Parker. The 1978 - 1979 IMF magnitude enhancement is due to an enhancement of radial flux which was in turn related to an increase of magnetic flux leaving solar active regions. It is also shown that during the corotating stream dominated years 1973 - 1976, the IMF was less wound up than during other years, and that 1973 - 1974 were years of enhanced radial flux.

INTRODUCTION

In an earlier paper (King, 1979a), I showed that the IMF magnitude exhibited an $\sim$ 15% decrease during the solar quiet period 1975 - 1977 after having exhibited no systematic variability over the broad interval 1966 - 1974. I now want to point out that over the 1978 - 1979 period of increased solar activity, the IMF magnitude was enhanced by $\sim$ 15% relative to the 1966 - 1974 mean value, and by $\sim$ 30% relative to the 1976 minimum.

The yearly averaged IMF magnitudes are shown in Figure 1. Averages of logarithms were used since, as explained in the earlier paper, the IMF magnitudes are log-normally distributed. The data are from several Imp and Heos experiments, and most are found in the compilations of King (1977, 1979b). All the 1976 - 1979 data are from the Goddard Space Flight Center Imp-8 magnetometer. Note especially the significant 1978 - 1979 enhancement.

The ideal spiral IMF has the form (Parker, 1963)

$$\underset{\sim}{B}(\underset{\sim}{r}) = B_r(\underset{\sim}{r})\ (\hat{r} + \hat{\phi} \tan \phi \sin \theta) \tag{1}$$

The angle θ is the solar colatitude of the observer and will be neglected because $\sin \theta$ varies between .99 and 1.0 in the ecliptic plane. B_r is the radial flux density crossing a heliocentric sphere at $\underset{\sim}{r}$. The angle ϕ is the spiral angle between the magnetic vector and the radial direction, and is given theoretically by $\tan^{-1} r\Omega/V$ (radial distance times solar rotation frequency, divided by solar wind speed). As V increases, ϕ decreases and the degree of spiraling decreases. From Eq. 1 it follows that the magnitude of the ideal spiral field is given by

$$B(\underset{\sim}{r}) = B_r(\underset{\sim}{r})/\cos \phi, \tag{2}$$

which implies that the field magnitude depends only on the radial flux density and on the degree of spiraling. (Since $V > 0$, $\cos \phi > 0$ and no singularity is encountered in Eq. 2.)

Now the real, instantaneous IMF can deviate significantly from the ideal IMF just discussed. For instance, 58% of the 84,577 hourly IMF vectors in the 1963 - 1979 IMF compilation are inconsistent with tan ϕ = $r\Omega/V$ for any V between 200 and 800 km/s. Nevertheless, sufficiently long term averages of the IMF do adhere to the ideal spiral field configuration (e.g., Ness et al., 1964). Thus we shall examine variations in long term averages of real field magnitudes in terms of the two contributors to the ideal field magnitude, namely the radial flux density and the degree of spiraling.

In the ideal field model, variations in radial flux density follow only from variations in magnetic flux drawn off the sun. For the real field, the radial flux density can vary due to changes both in magnetic flux drawn off the sun and in the effects of coronal and interplanetary current systems. Such current systems include those associated with helio-latitudinal pressure gradients and stream interaction regions. It is not our intent to assess the effect of each contributing current system, although the dominant, relevant effect of the current is likely to be the transport of field lines from higher latitude to the ecliptic plane. (Higher order effects are mentioned later.) Latitudinal transport may be more significant near the sun than near 1 AU. As the distinction is not significant for our analysis, we group together coronal and interplanetary effects as "interplanetary" hearafter.

SOLAR CYCLE PHASES

In anticipation of attributing differing behavior to differing solar cycle phases, I show in Figure 2 yearly averaged sunspot numbers and solar wind speeds. The sunspot number profile was compiled from numerous issues of NOAA's Solar Geophysical Data bulletins. These values, which reflect transient solar activity, exhibit a 1968 - 1970 maximum, a 1975 - 1976 minimum, and a 1979 maximum about 50% greater than the earlier maximum.

The solar wind speeds are from the compilations of King (1977, 1979b) with some later MIT data added. All the data from 1972 onward are from the LASL and MIT instruments on Imps 6, 7, and 8. The speed profile shows an isolated peak in 1968 and a larger, broader peak in 1973 - 1975. These peaks were first shown in analyses of Gosling et al. (1971) and Gosling et al. (1976). The speed profile also shows that the average speed for the solar active years 1978 - 1979 was virtually the same as that for most of the active years of the previous solar cycle, despite the disparity of sunspot count.

Feldman et al. (1978) have shown that the years 1973 - 1976 were marked by recurrent high speed streams not found in the years immediately preceding or following. Their analysis showed that, as measured by average speed and by percent of time with speed above 600 km/s, the years 1976, 1975, 1973, and 1974 were increasingly stream dominated.

INTERPRETATION OF IMF VARIATIONS

In Figure 3 I show measures of radial flux density and of field line spiraling in the ecliptic plane at 1 AU, for the period 1966 - 1979. The period 1963 - 1965 is not included in Figures 2 or 3 because there is some uncertainty in IMF parameter values due to different averaging sequences (King, 1979a); the 1966 - 1979 period is adequate for our purposes.

The top panel of Figure 3 shows yearly averages of the absolute magnitudes of hourly IMF radial components. Because a small fraction of field lines may cross 1 AU more than once, owing to interplanetary kinematics, and because the magnitude of the hourly average is less than the average of finer time scale radial-component magnitudes for a few hours, the parameter of the top panel is only an imperfect measure of the number of field lines crossing 1 AU in the ecliptic plane. Nevertheless, I believe it provides an adequate first order estimate of variations in radial flux density. Note the radial flux density enhancements in the years 1973 - 1974 and 1978 - 1979.

The middle panel of Figure 3 contains reciprocal cosines (i.e., secants) of yearly averages of hourly spiral angles. Negative polarity hourly magnetic vectors (0° - 45°, 225° - 360° GSE longitude) were transformed to equivalent positive polarity for determining yearly averaged spiral angles. Figure 3 also shows values of this parameter as expected from the yearly averaged speeds of Figure 2 and the relation $\tan \phi = r\Omega/V$, with $r\Omega = 434$ km/s. Note the general agreement between the variations in the expected and observed spiral angles. This is despite the fact that the annual percentages of hours contributing to the $< \phi >$ averages which also contribute to the $< V >$ averages ranges from 100 down to 45%. The degree of spiraling is observed to be somewhat decreased during the high speed years 1973 - 1975, and also during 1976.

The bottom panel of Figure 3 contains the IMF magnitudes corresponding to the yearly averaged logarithms shown in Figure 1. This panel also shows for comparison the product of the observed parameters of the top two panels, normalized in such a way that the 14-year averages of the two bottom panel parameters are the same. While the agreement between the two bottom panel profiles is imperfect, with differences most notable in 1971 and 1978, there is a very good agreement between their general shapes. In fact, this agreement is clearly better than that between the observed magnitude variations (the x's of the bottom panel) and any profile of the upper two panels of Figure 3. This means that variations in both the radial flux density across 1 AU in the ecliptic plane and the degree of field line spiraling are important in accounting for observed IMF magnitude variations. This is as expected from our earlier discussion of Eq. 2.

Consider a few specific years. The IMF magnitude enhancement of 1978 is associated with greater radial flux density and somewhat enhanced spiraling, while the larger magnitude enhancement of 1979 is associated solely with greater radial flux density. While we cannot rule out changes in interplanetary processes as contributing to the 1978 - 1979 radial flux density enhancement, we note that the other source of such an enhancement, namely greater levels of magnetic flux being drawn off the sun, can be expected to be significant. This is because an enhanced level of solar active region magnetic flux, available for transport to the interplanetary medium, is expected (in a solar magnetic dynamo framework) to follow from the observation of greater levels of solar polar magnetic flux during the solar minimum preceding the 1978 - 1989 active years than during the previous solar minimum (Schatten et al., 1978). The 1978 - 1979 interplanetary radial flux density enhancement does not reflect a 1978 - 1979 solar polar magnetic flux enhancement; the latter fluxes were declining toward a 1980 minimum (P. Scherrer, private communication).

Consider next the years 1973 - 1976 of stream-associated decreased IMF spiraling. The first two of these years have enhanced radial flux density which, in terms of IMF magnitude, is offset (fully in 1973 and partly in 1974) by the decreased spiraling. The years 1975 - 1976 have no radial flux density enhancement to offset the decreased spiraling; this results in the observed IMF magnitude decrease.

It is impossible to definitively attribute the radial flux density variations of the years 1973 - 1976 to a specific source (i.e., solar vs interplanetary). We note that solar polar magnetic fluxes increased from 1972 to 1974, but then showed no decrease through 1976 (Svalgaard and Wilcox, 1978). This is consistent with the IMF radial flux density increase from 1972 to 1973, but not with the decrease from 1974 to 1975. Relative to 1973, the year 1975 has decreased radial flux density at 1 AU, decreased transient solar activity (cf. sunspot numbers of Figure 2), similar levels of stream dominance (cf. Figure 2 and Gosling et al., 1978) and the above noted increased solar polar flux levels. Thus to the (indeterminate) extent that the 1973 to 1975 radial flux density decrease at 1 AU is due to differing amounts of drawn out solar flux, as opposed to interplanetary convergence of field lines towards the ecliptic plane, it seems that changes in solar active region fluxes are of more significance than solar polar changes.

SUMMARY AND DISCUSSION

Long term variations in IMF magnitude include enhancements in 1974 and 1978 - 1979, and a decrease in 1975 - 1976. These variations are to be understood in terms of varying levels of both spiraling of IMF lines and radial magnetic flux density at 1 AU in the ecliptic plane. We have confirmed the expectation that IMF lines should be less tightly wound up during recurrent stream dominated years of higher mean speed.

Changes in magnetic flux crossing 1 AU in the ecliptic plane may follow from changes in magnetic flux drawn off the sun, and from changes in convergence of field lines towards the ecliptic plane from higher latitude. Phasing arguments made in this analysis suggest the interplanetary variations in radial flux density may be more immediately related to variations in subpolar solar magnetic fluxes than to variations in polar fluxes. Transient solar activity and corotating streams, which are dominant at different solar cycle phases but which are not mutually exclusive in time (Burlaga and King, 1979), probably give rise to differing amounts of solar flux drawn out and of interplanetary latitudinal transport of field lines. Since these effects are not well understood, unique interpretations of long term variations in the magnetic flux density crossing 1 AU in the ecliptic plane are not presently possible. In particular, we have not attributed the 1973 - 1974 radial flux density increase to a specific source.

On the other hand, we have shown that the 1978 - 1979 enhancement of radial flux density has a likely source in enhanced levels of solar flux being drawn from solar active regions. If this is the case, then we would expect radial flux levels to decline as solar activity and sunspot numbers decline in the early 1980s.

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FIGURE CAPTIONS

FIGURE 1 — Yearly averaged values of logarithms of hourly IMF magnitudes. Numbers of hours in each year are given near the bottom of the plot. Vertical error bars show standard errors, with allowance for autocorrelation. Horizontal error bars show portion of year for which data are available.

FIGURE 2 — Yearly averaged sunspot numbers (top panel) and yearly averaged solar wind speed. Standard errors in speed averages, allowing for autocorrelations, are of order 10 km/s.

FIGURE 3 — Top panel: yearly averages of magnitudes of hourly IMF radial components. Middle panel: reciprocal cosines of yearly averages of hourly IMF azimuthal angles (denoted by crosses) and of $\tan^{-1}(r\Omega/\langle V \rangle)$ (denoted by dots). Bottom panel: product of the top panel parameter, the reciprocal cosines of the middle panel, and a normalization factor (dots), and field magnitudes corresponding to the average logarithms of Figure 1 (crosses). Error bars are minimum and maximum standard errors, with allowance for autocorrelation.

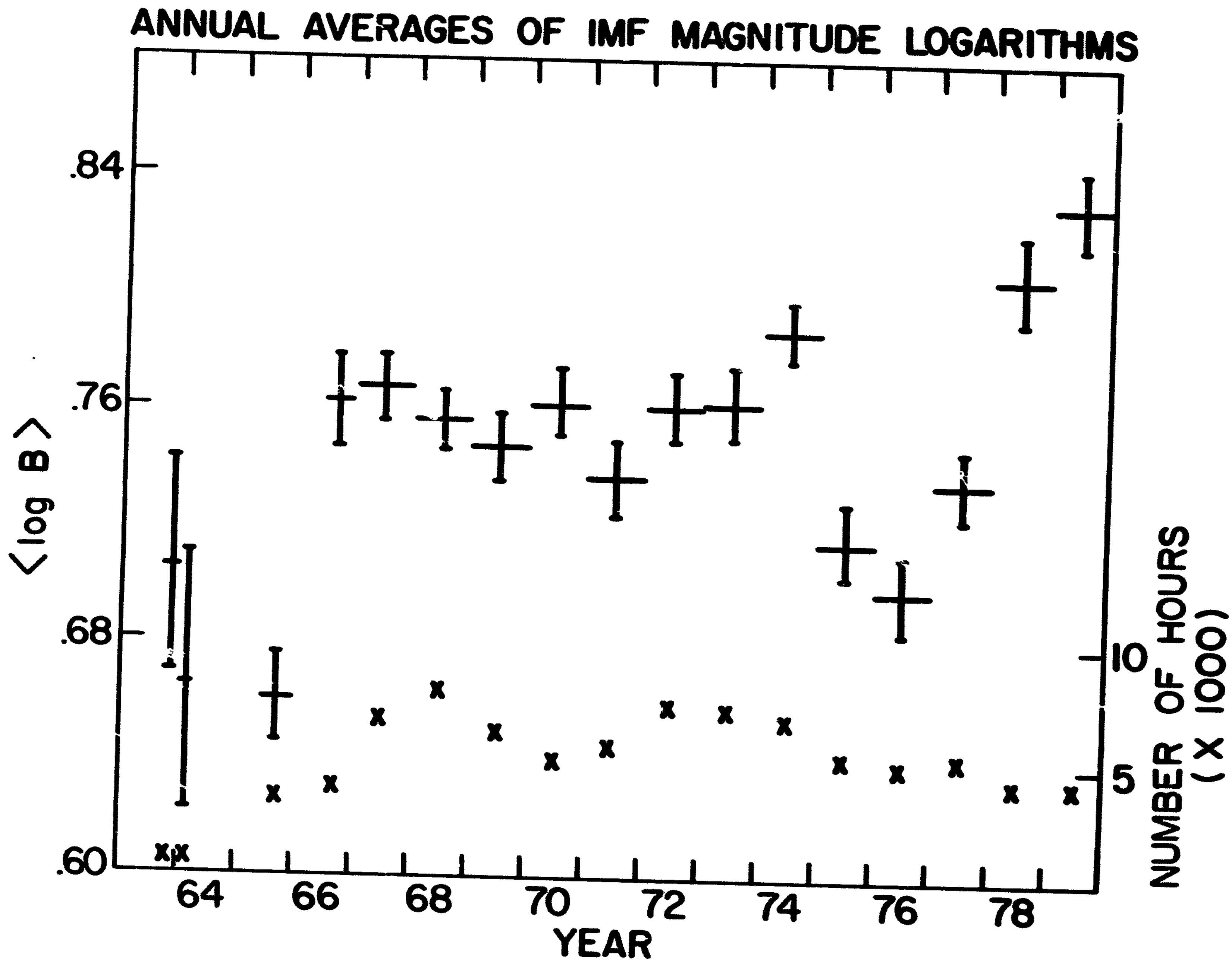

ANNUAL AVERAGES OF IMF MAGNITUDE LOGARITHMS
⟨log B⟩
.84
.76
.68
.60
64
66
68
70
72
74
76
78
YEAR
10
5
NUMBER OF HOURS
(X 1000)

Figure 1

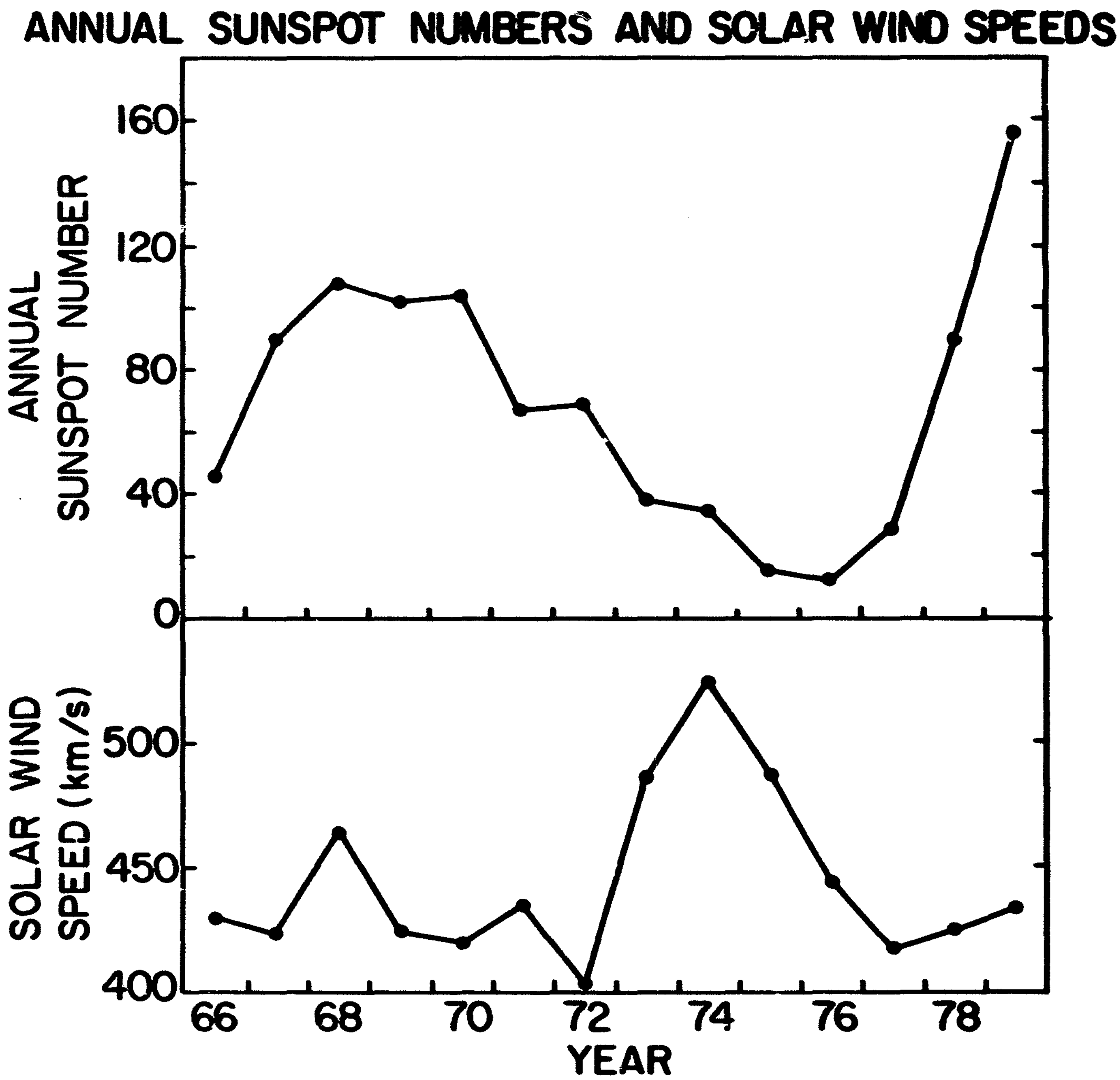
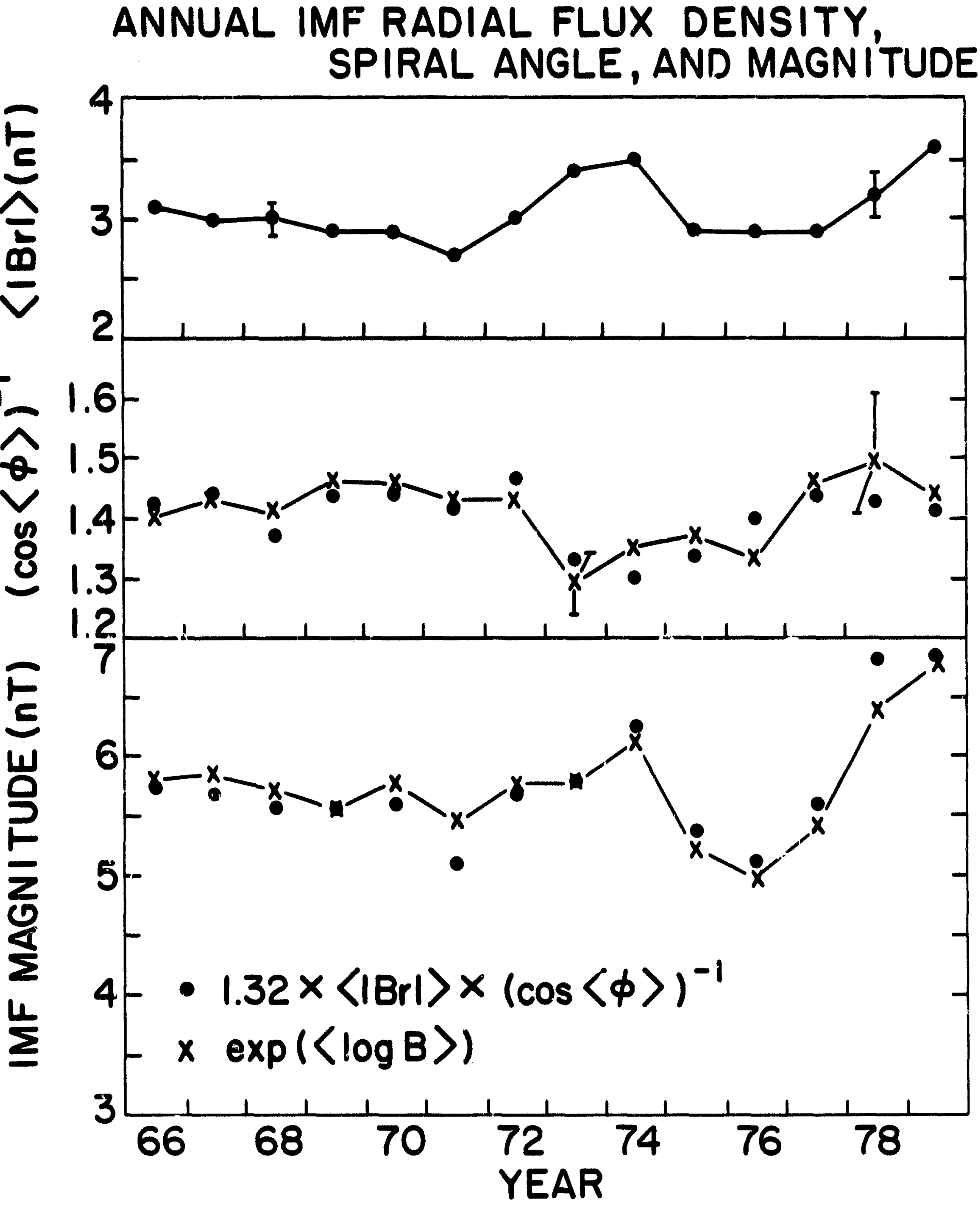

ANNUAL SUNSPOT NUMBERS AND SOLAR WIND SPEEDS
ANNUAL SUNSPOT NUMBER
160
120
80
40
0
SOLAR WIND SPEED (km/s)
500
450
400
66
68
70
72
74
76
78
YEAR

Figure 2



ANNUAL IMF RADIAL FLUX DENSITY,
SPIRAL ANGLE, AND MAGNITUDE
<|Br|>(nT)
(cos<φ>)^-1
IMF MAGNITUDE (nT)
• 1.32 × <|Br|> × (cos <φ>)^-1
x exp(<log B>)
YEAR

Figure 3