

SOLAR CYCLE VARIATIONS IN THE INTERPLANETARY MAGNETIC FIELD

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Abstract

ISEE 3 interplanetary magnetic field measurements have been used to extend the NSSDC hourly averaged IMF composite data set through mid-1982. Most of sunspot cycle 20 (start:1964) and the first half of cycle 21 (start:1976) are now covered. The average magnitude of the field was relatively constant over cycle 20 with ~5-10% decreases in 1969 and 1971, when the sun's polar regions changed polarity, and a 20% decrease in 1975-6 around solar minimum. Since the start of the new cycle, the total field strength has risen with the mean for the first third of 1982 being about 40% greater than the cycle 20 average. As during the previous cycle, a ~10% drop in IMF magnitude accompanied the 1980 reversal of the solar magnetic field. While the interplanetary magnetic field is clearly stronger during the present solar cycle, another 5-7 years of observations will be needed to determine if cycle 21 exhibits the same modest variations as the last cycle. Accordingly, it appears at this time that intercycle changes in IMF magnitude may be much larger than the intracycle variations. The magnitude of the interplanetary field is not highly correlated with solar wind speed, the sunspot cycle, or magnetograph measures of the total solar magnetic flux. However, the B_z component was well correlated with smoothed sunspot number over both cycles. The solar cycle variation in B_z and the cycle to cycle changes in IMF intensity may be of considerable importance to the study of long term cycles in geomagnetic activity.

Introduction

Routine measurements of the interplanetary magnetic field (IMF) from earth and sun orbiting spacecraft have been carried out since the early 1960's. Given the strong periodic variations in the strength and polarity of the solar magnetic field on a time scale of 11 years, it is not surprising that a number of studies have searched for similar changes in the IMF. The identification and successful modeling of such variations could provide important insights into the configuration of the inner heliosphere and the low altitude sites from which the solar wind emanates.

While the reversal in the dominant polarity of the IMF near solar maximum has been observed for both cycles 20 and 21 (Fairfield, 1974, Hedgecock, 1975, Smith et al., 1982), no clear variation in the strength of the IMF was detected prior to the 1975-6 solar minimum (Hedgecock, 1975; Mariani et al., 1975, King, 1976). At that time a 10-20% drop in the interplanetary field intensity occurred (King, 1979). Following this interval of low field strength, the magnitude of the IMF was seen to rise with the approach of cycle 21 maximum (King, 1981).

In this study we have used the ISEE 3 vector helium magnetometer observations to extend the IMF database through day 126 of 1982. Our analyses of this 1966-1982 set of measurements have confirmed the findings of the earlier studies through 1979 and determined that the IMF has remained strong following cycle maximum in 1979-80. These results are examined in comparison with recent studies of the solar magnetic field.

IMF Observations

For the years 1966-1977, our investigation has used the same National Space Science Data Center hourly averaged interplanetary composite data set as most of the previous studies (King, 1976; 1981). While a large number of different earth orbiting satellites have contributed to the observations, IMP 8 was the only source of IMF measurements between 1975 and the launch of ISEE 3 in 1978. ISEE 3 is particularly well suited to this purpose because of its unique orbit about the forward earth-sun Lagrange point which keeps it always in the solar wind. For these reasons we have used ISEE 3 observations for 1978-1982 to update the NSSDC data set and enhance its temporal coverage.

Following Burlaga and King (1979), the log-normal nature of the IMF field strength has been noted and yearly averages of the logarithm of the hourly average total field computed as displayed in Figure 1. Autocorrelations were performed for each year and used to compute the standard errors (Bell and Glazer, 1957). Between 1966 and 1974 only weak variations are present with statistically significant small decreases of ~5% in 1969, 1971 (King, 1979) and a maximum in 1974. The total field shows a ~20% decrease that is nearly symmetric about solar minimum, June-1976. By 1978 the IMF intensity has again reached its previous 1974 maximum of just over 6 nT. Since that time, the total field strength has continued to climb, with the exception of a ~10% dip near solar maximum, to almost 8 nT during the first third of 1982. This increase corresponds to a 40% enhancement over the cycle 20 average and a 55% climb from solar minimum.

The field strength distributions themselves have also been examined to determine the nature of the cycle 21 maximum increase. As shown in Figure 2 the log-normal distribution of IMF intensity about solar minimum, defined here as Bartels Rotations 1920-1965, is very similar to the solar maximum distribution, Bartels Rotations 1988-2022, save for a larger mean value. Accordingly, it does not appear that the increase is associated with any particular phenomenon, such as interplanetary shocks or magnetic bubbles, producing a skewed distribution at cycle maximum. The shape and width of the log B distributions are comparable at solar maximum and minimum.

The idealized interplanetary magnetic field model of Parker (1963) gives the total field strength, B, at a distance from the sun, R, where the radial field strength is B_x as

$$B = (B_x^2 + B_y^2)^{1/2} = B_x (1 + \Omega^2 R^2 / V^2)^{1/2} \quad (1)$$

Changing solar wind velocity influences the field in two ways: (1) by affecting the source field strength, and hence B_x , and (2) by varying the magnitude of B_y and the tightness of the spiral. King (1981) investigated the latter of

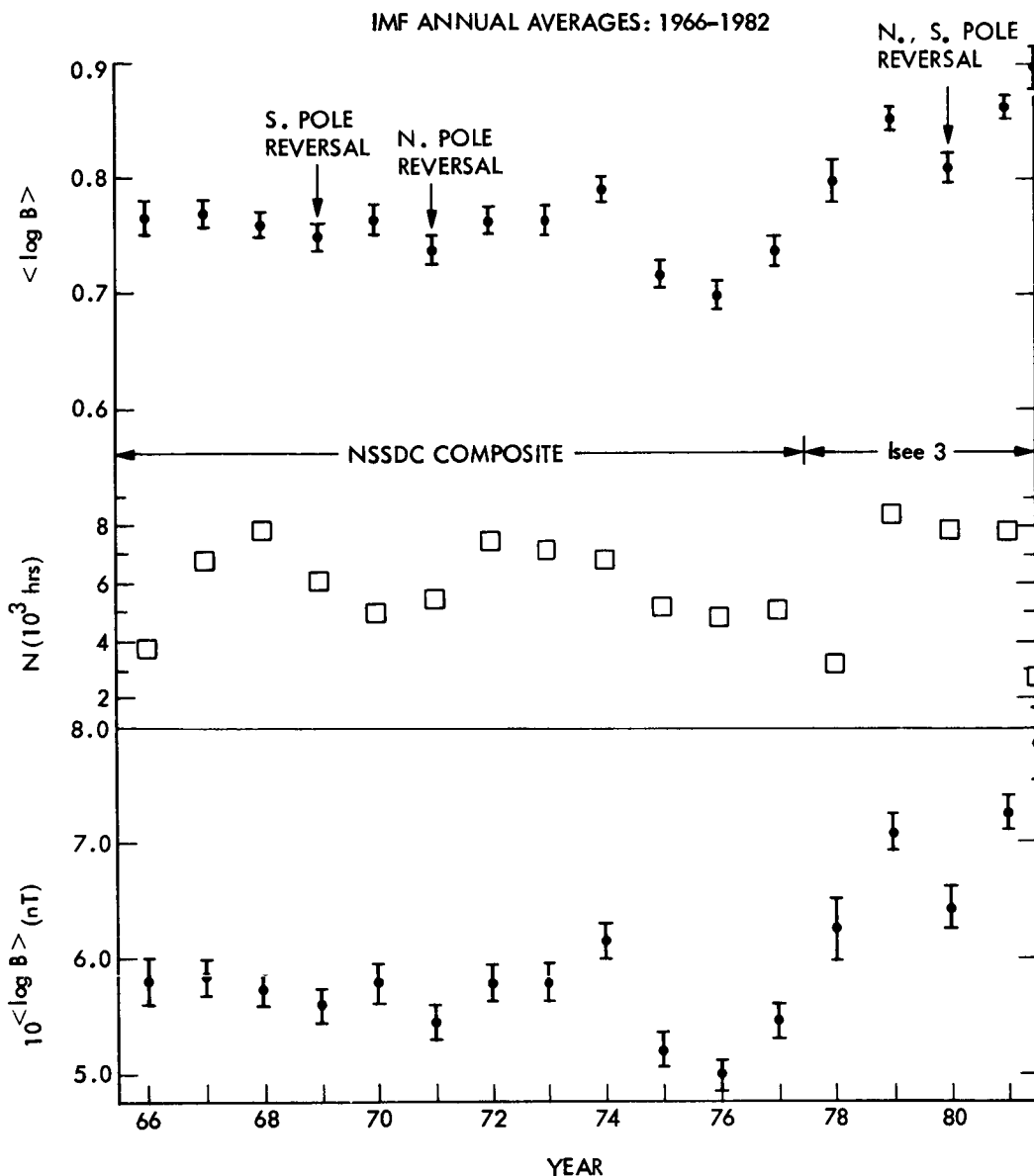


Figure 1. Yearly averages of the logarithm of the total interplanetary magnetic field strength, the number of hourly averages per year, and the inverse log of the annual averages are all plotted as a function of time. The intervals of solar polarity reversal are indicated.

these two effects by comparing annual averages of the solar wind speed and IMF strength. The yearly average solar wind velocities for 1966-79 all fell between about 400 and 460 km/s except for the high speed years 1973-5 which spanned 480-520 km/s. For a constant radial source field, the Parker model, equation (1), would predict a ~10% drop in field strength during the high speed years. However, as shown in Figure 1 the total field magnitude stayed constant from 1972 to 1973, increased from 1973 to 1974, and fell only in 1974-5 as the solar wind speed decreased. The more typical 10-20 km/sec changes in the annual mean solar wind velocities produce only ~1-2% changes in the field strength by varying B_y magnitude. We therefore conclude, in agreement with King (1981), that the long term changes in the interplanetary magnetic field are largely due to variations in the solar source fields.

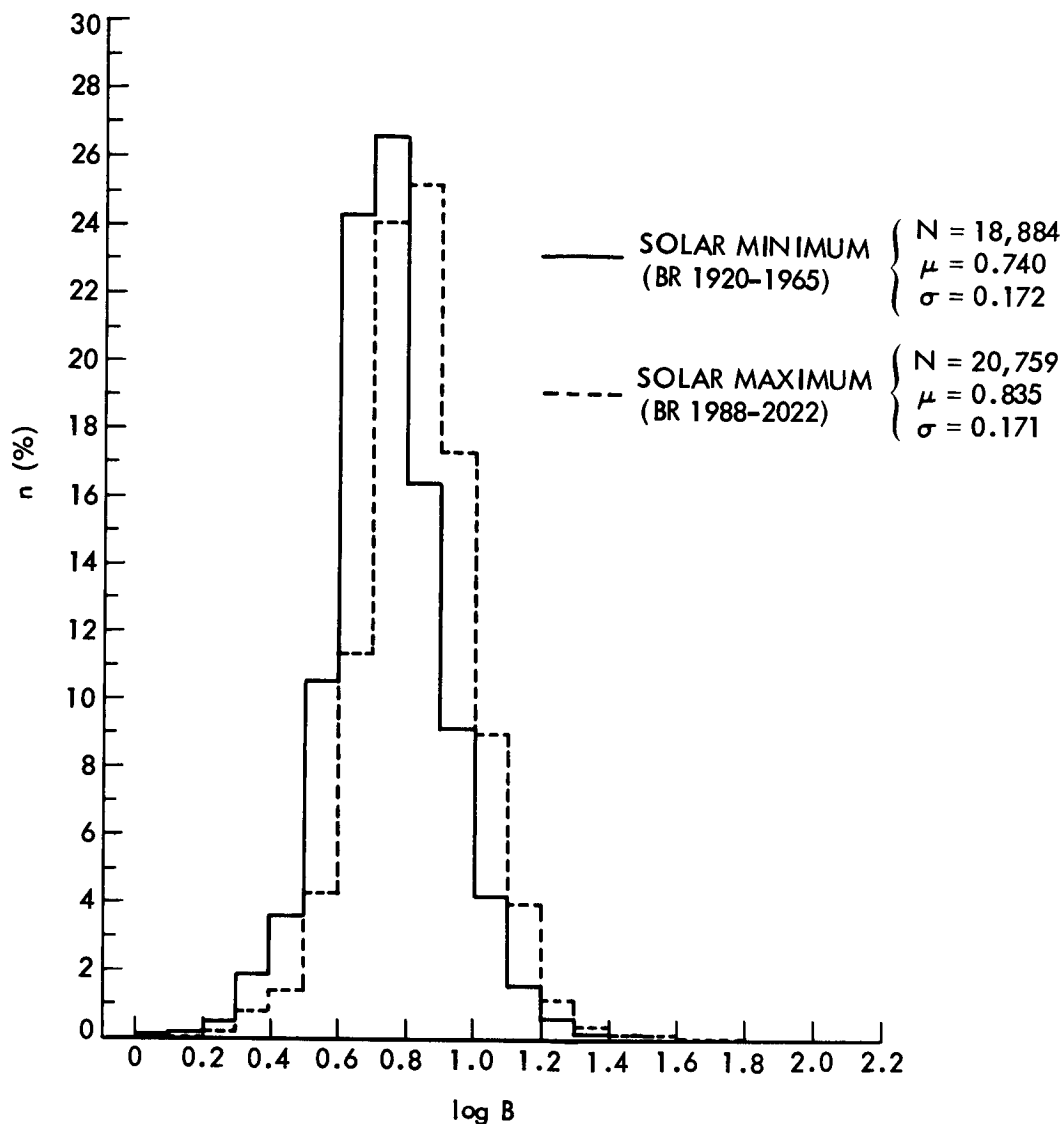


Figure 2. Histograms of $\log B$ during solar maximum and minimum are plotted as dashed and solid lines, respectively.

Solar Observations

Having examined the long term variations in the strength of the IMF, we investigated how the interplanetary field relates to the sunspot cycle and other ground based measures of the low altitude solar magnetic field. Figure 3 displays annual averages of the three GSE IMF components, the magnitude of the ecliptic component, the ratio of the field normal to the ecliptic to that in the ecliptic, the smoothed sunspot number (Solar Geophysical Data, 1982), and the years of solar polarity reversal (Howard, 1974, Howard and LaBonte, 1981, R. Howard, private communication, 1983). Overall the components of the interplanetary field are well correlated with the total field, albeit the correlation is weakest for B_z . All three components exhibit the same long term changes as the total field, but with the effects of changing solar wind conditions also evident in B_x and B_y . In particular, only during the the high speed years mentioned earlier was the ratio of $\langle |B_x| \rangle$ to $\langle |B_y| \rangle$ greater than unity in the annual averages.

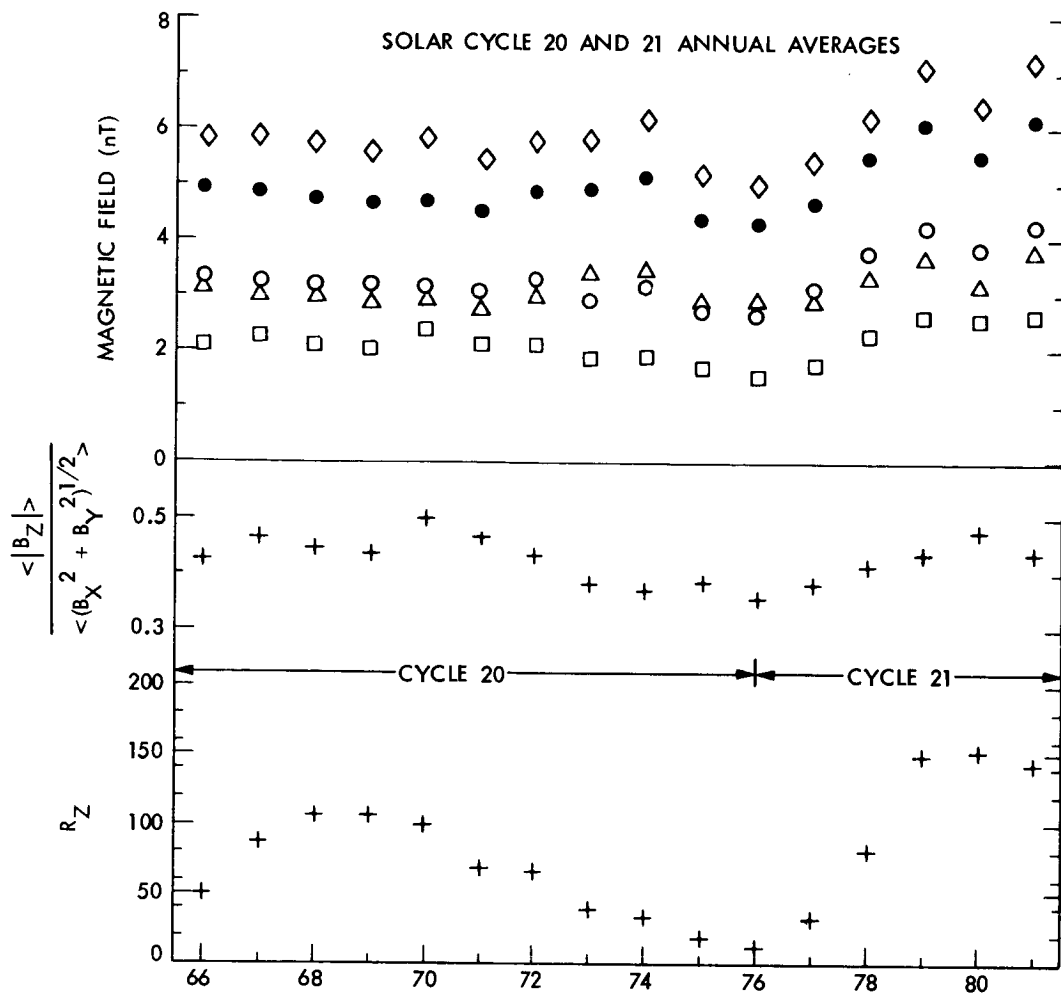


Figure 3. Annual averages of $|B_x|$, triangles, $|B_y|$, open circles, $|B_z|$, squares, $(B_x^2 + B_y^2)^{1/2}$, solid circles, the inverse log of the total field magnitude, diamonds, the relative magnitude of the component normal to the ecliptic, and the average sunspot number are all plotted as a function of time.

Cycle 21 maximum in sunspot number, December-1979, was about 50% higher than cycle 20 and possessed a more crested shape. Among the IMF quantities, the relative strength of the out-of-ecliptic component, $\langle |B_z| \rangle / \langle (B_x^2 + B_y^2)^{1/2} \rangle$, best reproduces the period of the sunspot curve with two peaks and one trough clearly visible. This parameter can be considered to be a measure of the ratio of the strength of the "ac" type waves/bubbles/turbulence that produce B_z to the steadier spiralled "dc" field in the ecliptic. However, the correlation is far from perfect with the low 1968 and 1969 values the most salient discrepancies. In addition, the cycle 21 maximum in the relative strength of B_z does not appear to have been any greater than during the weaker preceding cycle. It is not yet known how this result compares with the variation in the number of shocks, bubbles, and streams observed from cycle 20 to 21.

The magnitude of the IMF and its components, with the exception of B_z , show little correlation with sunspot number until the start of cycle 21. As reported by Siscoe et al. (1978), $|B_z|$ increased in phase with sunspot number

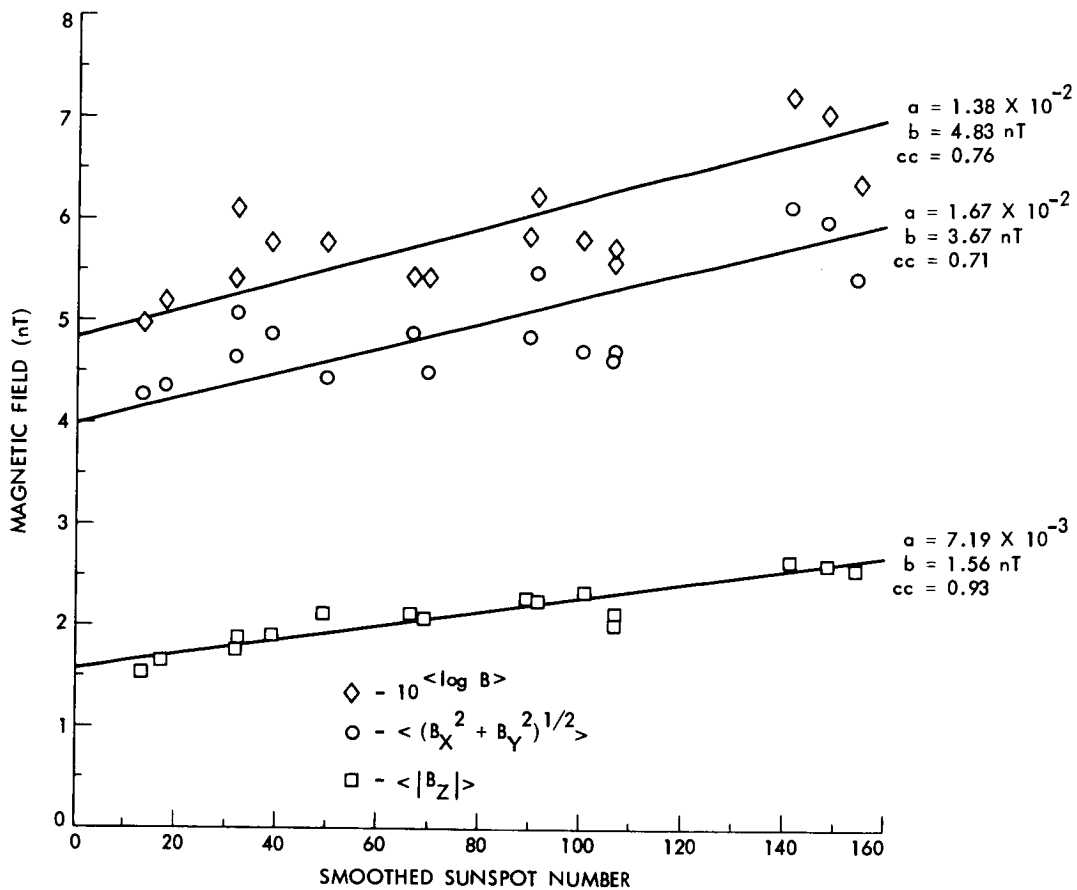


Figure 4. Annual averages of the total field strength and its components in and out of the ecliptic are correlated with smoothed sunspot number over the interval 1966-1982. Correlation coefficients, least square slopes, a , and intercepts, b , are also displayed.

during cycle 20. That behavior is reproduced, including a dip in strength near maximum, by the cycle 21 observations shown in Figure 3. This finding and the solar cycle to solar cycle variations in IMF strength may provide the ultimate explanation of the 11 and 22 years cycles in some components of geomagnetic activity (e.g Chernosky, 1966). Furthermore, the results may aid the studies of long term geomagnetic activity which often must infer interplanetary conditions from historic records of sunspot numbers. Figure 4 correlates IMF field intensity with annual average sunspot number over the years 1966-82 and confirms the close relationship between $\langle |B_z| \rangle$ and $\langle R_z \rangle$. The correlation between R_z , the component of the IMF in the ecliptic, and the total field is largely due to the stronger IMF fields and higher sunspot numbers during cycle 21 as opposed to any good agreement in the shapes of the curves over the two individual cycles.

In Figure 5 the annual averages of the IMF components parallel and perpendicular to the ecliptic have been compared to the Mt. Wilson magnetograph measurements of "total solar flux" compiled by Howard and LaBonte (1981). To within the limits of the instrument's aperture, daily measurements of the flux have been rectified and summed. The flux measurements refer to large scale magnetic fields. For example, a flux of $6 \times 10^{22} \text{ Mx}$ in Figure 5 would be produced by a uniform field of only 1 Gauss. Most of the magnetic flux is concentrated at lower latitudes with 69% being

found between $+28.1^\circ$. In examining 13 years of observations, they determined ratios of sunspot maximum to minimum total flux of 2:1 for cycle 20 and 3:1 for cycle 21. Using Kitt Peak magnetograms and He images, Harvey et al. (1982) have found that the enhanced solar fields near cycle 21's maximum are due to low latitude coronal holes similar in size to those existing at solar minimum, but possessing 3 times the magnetic field strength.

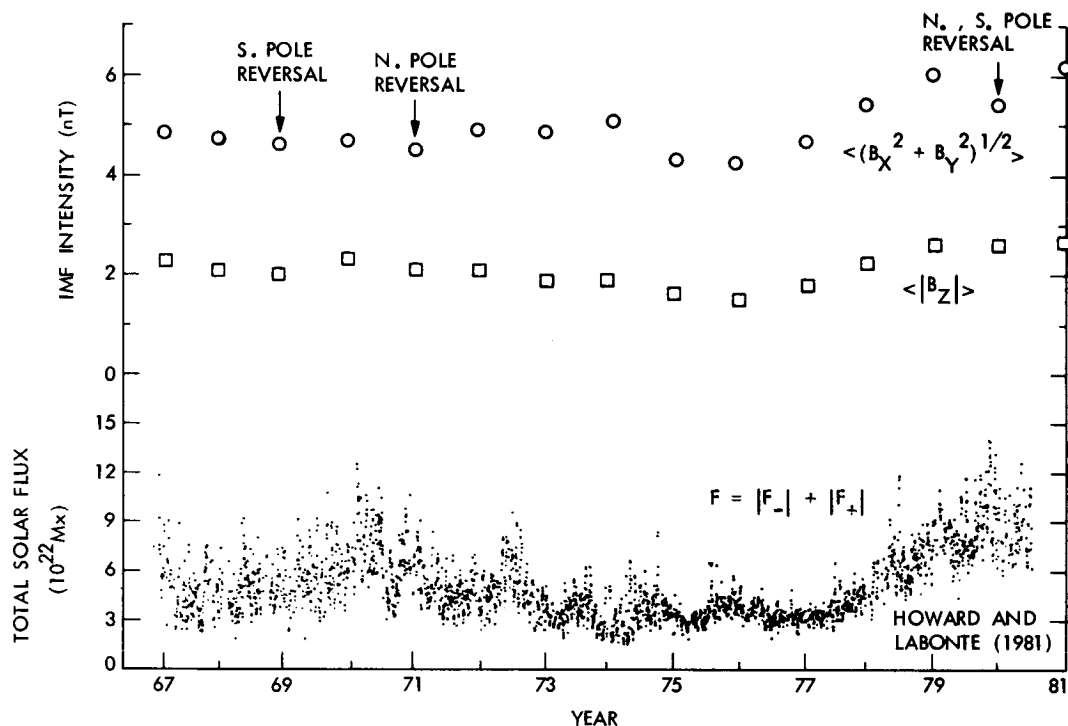


Figure 5. Yearly averages of the IMF components in and out of the ecliptic are compared with the daily total solar magnetic flux measurements of Howard and LaBonte (1981).

In general, the correlation between the magnitude of the IMF and full disk solar flux appears no better than for sunspot number. The factor of 2 total flux increase during cycle 20 maximum appears to have gone almost unnoticed by the IMF at earth orbit while the factor of 3 increase for the current cycle produced only a 55% change in the 1 AU field. Conversely, the enhanced interplanetary fields accompanying the high speed solar wind streams of cycle 20's declining phase, 1972-4, do not correspond to any overall increase in the total photospheric flux which continued its march toward minimum. For enhanced IMF to have been observed during the 1972-4 interval without any increase in the solar field strength, it is necessary that a greater than normal fraction of photospheric field lines have been "open" (i.e. not connect back to the sun as with, for example, sunspot pairs). Such a geometry is certainly consistent with the presence of large equatorward-dipping coronal holes. Similarly, the strong solar fields around cycle 21 maximum could not have produced so modest a rise in the IMF strength if the same fraction of the low altitude field lines were carried to 1 AU as during the decline of cycle 20. The lack of strong stream activity in 1978-80 supports the presence of a more closed solar field configuration.

For these reasons there must be very significant variations in the low altitude field geometry as well as the field strength during the solar cycle. In agreement with previous studies (Levine, 1977; Harvey and Sheeley, 1979), it appears that we do not yet possess sufficient knowledge of the sun's magnetic field geometry to be able to generally predict low latitude heliospheric magnetic field strength from coronal hole and magnetograph observations.

Concluding Remarks

Over the last 16 years the interplanetary magnetic field has undergone a number of changes which appear related to the sun's magnetic cycle. The reversals in the dominant polarity of the IMF and the solar field have not been examined here, but are known to be well correlated (Smith et al., 1982). Minima in the intensity of the total interplanetary field and its radial component occur around solar minimum and, to a lesser extent, during the intervals of polarity reversal. The solar minimum decrease in the IMF can be directly ascribed to the weak source fields on the sun in Figure 5. However, the smaller decreases about the time of the polarity reversal in 1969, 1971, and 1980 are more difficult to interpret. These dips in the IMF do not correspond to any decreases in the magnetograph determinations of the solar field. For this reason it does not seem reasonable to attribute them to a decrease in solar dynamo action in association with the polarity reversal. In our opinion, a more likely hypothesis is that the intermingling of positive and negative oriented field lines during the reversal (e.g. Howard and LaBonte, 1981) produces enhanced reconnection which closes off a larger than usual fraction of the solar field lines and decreases the number being carried out to 1 AU by the solar wind.

It is not yet apparent whether the growth in IMF intensity over the years 1976-82 is associated with a solar minimum to maximum change or a cycle 20 to cycle 21 variation. However, the weak changes in interplanetary field magnitude during cycle 20 and the continued strength of the field after cycle 21 maximum suggest that the current solar cycle may simply have a stronger magnetic field than cycle 20. In this case the change in field strength from 1976-1982 is associated not with the 11 year sunspot cycle, but perhaps one of the longer 80-100 year cycles whose existence has been inferred from historic records (e.g. Feynman and Silverman, 1980). Finally, alternate solar cycles of stronger and weaker IMF could be the cause of the 22 year cycles in some measures of geomagnetic activity (Chernosky, 1966).

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