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Reply to the comment by M. Lockwood et al. on "The *IDV* index: Its derivation and use in inferring long-term variations of the interplanetary magnetic field"

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[1] From an analysis of geomagnetic and solar wind data, *Lockwood et al.* [1999] (hereinafter referred to as LSW99) reported that the solar coronal magnetic field had increased by more than a factor of two during the last century. If true, this would be an important discovery. Recently, *Svalgaard and Cliver* [2005] (hereinafter referred to as SC05) reported an analysis based on our newly developed interdiurnal variability (*IDV*) index of geomagnetic activity which indicated that cycle averages of the solar field varied no more than ~25% over the same time interval and are now decreasing. Here, we answer the criticisms of *Lockwood et al.* [2006] (hereinafter referred to as LRFS06) to our paper. In sum, we find their objections without merit. If our prediction that the next solar cycle will be the smallest in 100 years [*Svalgaard et al.*, 2005] bears out, this debate may be settled by direct solar wind measurements within the next few years. In the following sections we respond to the various points raised by LRFS06: percentage change, B_r versus B, regression technique (including the effect of missing data), and analysis procedure.

1. Long-Term Variation of IMF *B*

[2] Our *IDV* paper [SC05] showed that B follows the sunspot number (or rather a constant plus the square root of the sunspot number). The key new result of the LSW99 paper was the finding that the Sun's coronal magnetic field had an underlying component that increased independently of the sunspot number. *Parker* [1999, p. 416] commented on this point in the same issue in which LSW99 appeared: "Lockwood, Stamper and Wild use records of geomagnetic activity [...] to show that the weak (~0.5 millitesla) general magnetic field of the Sun has more than doubled over the past 100 years. [...]. The new finding complements the well-known fact that the number of sunspots [...] has also doubled over the same period of time. The general field varies much less with the 11-year sunspot cycle than does the number of sunspots, and appears to have a different origin."

[3] The basic finding of LSW99 would be of fundamental importance, if substantiated. It is illustrated in Figure 1. There are other features of Figure 1 to which we shall return but the point which we wish to emphasize now is that for a fixed sunspot number (say 40) on the rising branch of all solar cycles during the 20th century, the quantity F_s, calculated by LSW99 exhibited a steady increase. Figure 1 shows the crux of our disagreement with LSW99. In a preliminary report, *Svalgaard et al.* [2003, p. 15] noted that there was no long-term trend in B "other than a general correlation with the sunspot number." The absence of an underlying long-term trend in B implies the absence of such a trend in F_s, contrary to the central result of LSW99. The sunspot correlation with B is no surprise [e.g., *Wang and Sheeley*, 2003].

[4] In SC05 we noted that the temporal evolution of IMF B near the Earth seemed to exhibit the ~100 year Gleissberg cycle often seen in the sunspot number (see *Li et al.* [2005] for a recent analysis). This is not surprising because most (>70%, see Figure 8 of SC05) of the variation of B is explained by the variation of the number of sunspots and their magnetic fields. Let us write the long-term variation of B with time t as $B(t) = M + A \cos(2\pi\, t\, f_o + \varphi)$ where A is the amplitude of the ~100 year cycle, f_o its frequency, φ its phase, and M is the overall mean on which the Gleissberg cycle rides. A conservative estimate of the amplitude is half the range from the mean of cycle 14 to the mean of cycle 19 yielding the relative amplitude of the ~100 year cycle of $A/M = 0.13$, for a total range of ~25% as quoted in SC05.

[5] We contrast this view with that of LRFS06 who interpret their result as a secular increase, although the "100 years" of LSW99 has now become ~50 years, perhaps reflecting the fact that direct measurements of the solar magnetic field do not show any increase in the calculated source surface flux since 1974 [*Arge et al.*, 2002] nor in the solar mean field since 1968 [*Kotov and Kotova*, 2001]. LRFS06 calculate an 11-year running mean to quantify the secular increase, but a running mean is too simple a filter to completely remove the sunspot cycle. Because of remaining cycle signal, ε (including some plain noise), the difference between the cherry-picked absolute maximum of the running mean (in 1956) and the absolute

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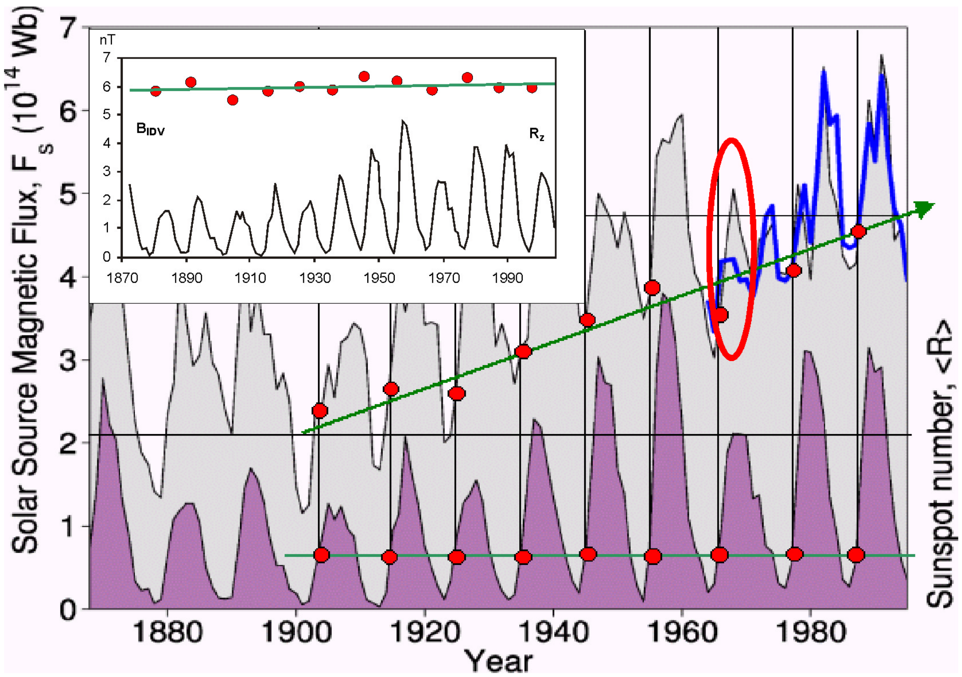

Figure 1. Quantity F_s calculated by LSW99 from $\langle aa \rangle$ and $\langle I \rangle$ and inferred from interplanetary measurements (heavy blue line); adapted from LSW99. The red dots in the main plot highlight years when the sunspot number R_z was near 40 on the ascending branch of the cycles (away from recurrent high-speed streams). F_s shows a marked increase independent of the sunspot number while B derived from *IDV* does not, as shown by the inset (see text). Discrepancies between the calculated and observed flux are marked with the red oval.

minimum (in 1903) overestimates the long-term variation. Dividing this difference by the minimum value (as done in LRFS06) calculates this curious quantity

$$\{[M + (A + \varepsilon_{\max})] - [M - (A + \varepsilon_{\min})]\}/[M - (A + \varepsilon_{\min})]$$
$$= (2A + \varepsilon_{\max} + \varepsilon_{\min})/(M - A - \varepsilon_{\min})$$

that, with unknown ε, does not seem to have a useful, simple interpretation.

2. Estimating the Radial Component, B_r, of IMF B

[6] LRFS06 fault SC05 for misrepresenting the results of LSW99 by conflating B with B_r, the radial component of the IMF in the ecliptic plane at the Earth, which is assumed (by LSW99) to be proportional to the total coronal source flux. We counter that there is no confusion on this point, as LSW99 themselves assume B_r to be proportional to B.

[7] Physically, *IDV* does not depend on B_r, but on the southward component, B_s, in a coordinate system where seen from the Sun the north-south plane contains the Earth's dipole axis, or more precisely on B (draped around the "nose" of the magnetosphere) times some function of the angle between the Earth's field and the draped IMF. By *positing* a constant ratio (called s_B by LSW99, who found $s_B = 0.56$ based on solar wind data) between B_r and B, you can "transfer" that dependency from B to B_r. It does therefore not make sense to regress *IDV* against B_r directly as done by LRFS06. However, let us follow their lead and see where it takes us.

[8] As LRFS06 point out, magnetic clouds, coronal mass ejections, stream-stream interactions, and the generally higher variability associated with solar activity will tend to cancel some of the radial flux so that $|B_r|$ for such conditions will be underestimated. This may be seen in Figure 2, where we have plotted (red curve) the ratio, L, between (yearly means of) $|B_r|$ and B (both first averaged over the 1-day interval advocated by LRFS06) as observed by spacecraft. There is the expected clear solar cycle dependence in the ratio, L being smaller at solar maximum and larger at solar minimum, approximated by a simple expression (black curve): $L = 0.53 - R_Z/2000$, where R_Z is the International Sunspot Number on the Zürich scale. Under the assumption that the processes that cause cancellation of $|B_r|$ operated similarly 100 years ago we extend the black curve back in time. Also shown in Figure 2 (blue curve) is the ratio, L (LRFS06) = $|B_r|/B$, calculated from the correlations of B and $|B_r|$ for *IDV* derived by LRFS06 using their preferred method B and given in their Table 1. Not only does L(LRFS06) vary oppositely to L(observed) during the spacecraft era, but it also approaches the physically unreasonably low value of 0.2 during the very quiet years at the beginning of the 20th century when there were almost none of the factors present that lead to cancellation of flux. We therefore do not find any of the conclusions based of the calculation of $|B_r|$ by LRFS06 to be valid. The *IDV* index stands on its own, has a simple definition, and does not need

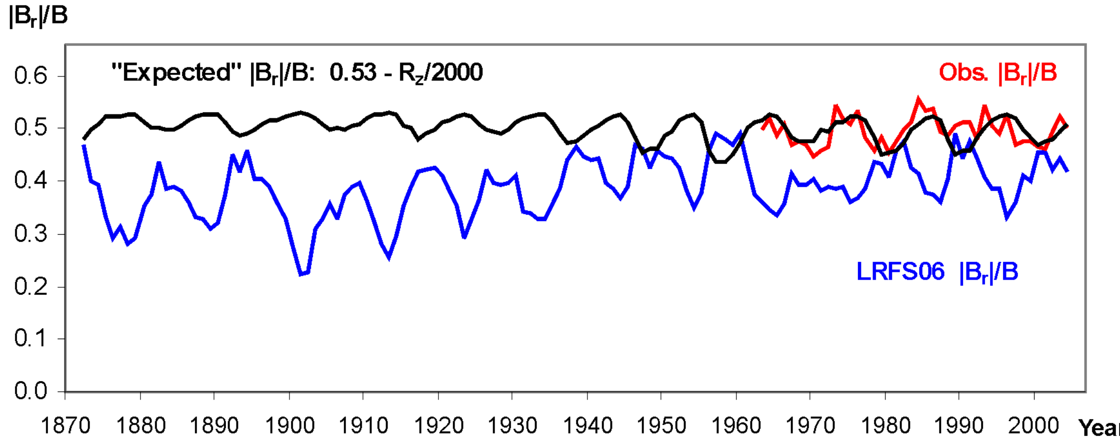

Figure 2. Ratio, L, between (yearly means of) $|B_r|$ and B (both first averaged over a 1-day interval) as observed by spacecraft (red curve), extrapolated from its observed solar cycle dependence (black curve), and calculated from the predictive correlations of B and $|B_r|$ derived by LRFS06 from *IDV* using their method B.

to be "predicted" (LRFS06 Figure 11) or corrected using proxies for B_r or the *aa* index.

3. Proper Regression Method

[9] LRFS06 state that B is better determined than *IDV* and therefore should be used as the independent variable "with no error." This does not take into account that 33% of the hourly IMF values are missing, for some years even in excess of twice that. We can simulate the effect of missing data by using the coverage pattern for the 13 years with least data (on average 42% covered) (excluding 1963–1964, where there was very little data) as a mask over the 13 years with the most data (on average 98% covered) to select data to throw away before calculating yearly means. We then calculate the RMS variation of the differences between the observed high-coverage years and simulated same years with coverage degraded according to the mask. Varying at random which years in both groups correspond, i.e., which low-coverage year to use as a mask for which high-coverage year, we get several such RMS values, clustering around 0.24 nT (or 3.5% of B). We take this as an estimate of the uncertainty of B as representative of the whole year for years with poor coverage (not, of course, of the inherent measurement or interspacecraft cross-calibration error of B). According to SC05 the standard error of a yearly mean of *IDV* is 0.20 nT or 2.0% of *IDV*. It is therefore clear that the errors are comparable, taking into account that some of the time B *is* well determined. This fact might argue for using method C, except that we are not exploring the functional relationship, but merely seek to predict B from *IDV*.

[10] Because of the missing IMF data we adopted a very careful procedure for calculating the means and gave a table (Table 3 in SC05) with the results. LRFS06 state that SC05 used a recurrence method to fill the gaps in the IMF data series and claim that this is not a valid technique because the autocorrelation function (for 1-day values) of the IMF is only 0.20 at a lag of 27 days. In fact, as clearly stated in SC05, we interpolated rotation averages for the few rotations with no data. For rotation averages the autocorrelation coefficient is 0.69 (for a lag of one rotation), high enough to justify our procedure for obtaining yearly averages utilizing the high positive conservation of the IMF data. The autocorrelation function for 1-day values is not relevant for this procedure. We have to confess that Table 3 in SC05 was constructed with a slight amount of additional data and that our Figure 6 and equation (2) were not updated to include the very latest data. The regression equation using the latest data up to the present, $B = (0.371 \pm 0.033)\, IDV + (2.92 \pm 0.34)$, is still within the error bounds of equation (1) of SC05, $B = (0.361 \pm 0.037)\, IDV + (3.04 \pm 0.35)$. For predictive purposes Method A is the proper regression method to use. The goal is to best predict or estimate the unknown B from the known *IDV* where the measure of the goodness of the prediction is how well (in the least squares sense) the empirical relation reproduces observed values of B, realizing that the relation is complex and involves other variables as well.

[11] The discussion of the *am* index showing that the shapes of the distributions for all days and for days with IMF data are nearly identical (LRFS06 Figure 3) does not demonstrate that there is a lack of bias due to missing IMF data for the single year averages with which we are concerned, only that over 40 years the biases are diluted out. In fact, LRFS06 Figure 4 shows that for some years the difference between $\langle am \rangle$ and $\langle am \rangle_W$ (for intervals with coincident IMF data) can reach 10%.

[12] LRFS06 goes into great detail about the effect of outliers. In SC05 we elected not to remove data points that did not "fit." By repeatedly removing data points that do not fit one can get the correlation as good as desired while eventually decreasing its statistical significance. From Figure 3 and from LRFS06 (e.g., Figure 9) it is clear that removing the five points with the greatest deviation between fitted and observed values of B results in a markedly improved correlation (R^2 goes from 0.75 to 0.89). We find for the years 1965–2006 (first 7 months) using ordinary least squares regression of B on *IDV*:

$$B = (0.445 \pm 0.026) IDV + (2.21 \pm 0.26) \qquad (R^2 = 0.89)$$

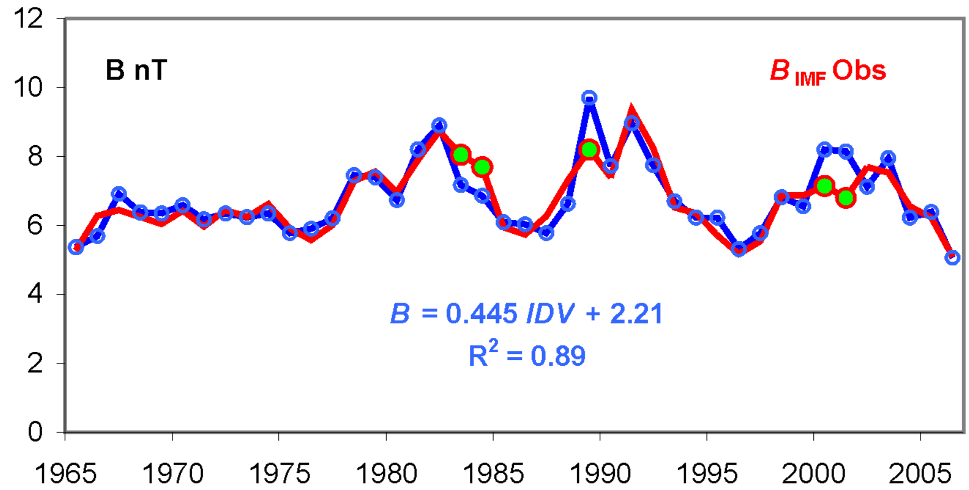

Figure 3. Identification of five "outliers" (marked with green dots) for the correlation between IMF *B* (red) and *IDV*. The regression fit (blue curve) was made omitting the outliers as advocated by LRFS06.

This result is very close to correlation three in Table 1 of LRFS06, obtained using the "least median of squares" method that is much less sensitive to outliers (equivalent to largely ignoring them). Whether or not it is permissible to remove outliers or greatly reduce their leverage is a different debate. Here we shall investigate the effect of using the above regression (or the almost identical one calculated by LRSF06). Figure 4 shows the result. Because the higher slope compared with the SC05 correlation is largely compensated by the lower offset, the result is almost identical to our Figure 7 in SC05. We approximate the long-term variation by a fourth-order polynomial shown by the red curve. The relative amplitude, *A*/*M*, determined from this curve is 0.113 corresponding to a total range of ~23%. Another fourth-order polynomial (black curve) is fitted to the data points for the sunspot minima only and shows a similar variation simply downshifted to match the lower values at minima. So, removing the outliers or downplaying their relevance by using a more "robust" regression technique does not change the long-term variation reported in SC05. LRFS06 note that the outliers do not appear in their calculation of the interhour variability (*IHV*) index. They are confusing the *IHV* index with the (very different) *IDV* index. *IHV*, *am*, and *aa* depend on solar wind speed squared while the *IDV* index does not vary with solar wind speed.

[13] To gauge the importance of outliers, we compare yearly averages of IMF *B* inferred in several different ways. Figure 5 shows the result. The red curve shows the magnitude of IMF *B* observed by spacecraft in the ecliptic plane near the earth. The blue curve shows *B* calculated from *IDV* using the regression derived by removing the five outliers (or the almost identical LMS correlation of LRFS06). Blue open circles show *B* calculated from *IDV* without removing the outliers. The purple curve shows *B* calculated from the mean magnetic field of the Sun as a star [*Kotov et al.*, 2002; *Svalgaard et al.*, 2003]. The green curve shows *B* calculated from negative only values of the *Dst* index [see SC05], which is what *IDV* really is a proxy for. All of these curves show occasional disagreements or "outliers." Instead of being classified as "errors" that should be removed or suppressed using "robust" methods, outliers tell us something of the processes that are behind the correlations and should be studied in their own right. For example we note that three of the five outliers occur for years where the IMF coverage was poor (less than 50%). If Johannes Kepler had used robust methods in dealing with the 8 arc min outliers in Tycho Brahe's Mars observations, he might not have discovered that the planets revolve in ellipses rather than in circles [*Monhor and Takemoto*, 2005].

4. Independent Confirmation From *Dst* Index

[14] SC05 noted and demonstrated that yearly averages of the *Dst* index calculated using negative values only is strongly correlated (R^2 = 0.89) with the *IDV* index and thus also with IMF *B* (R^2 = 0.72). J. J. Love (personal communication, 2006) has recently derived *Dst* back to 1905.

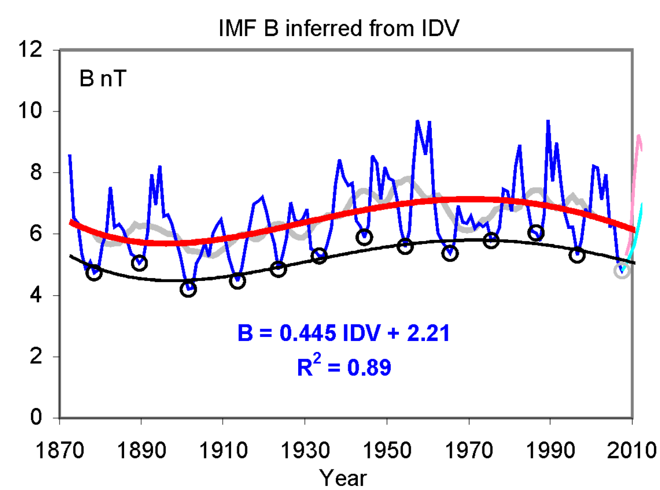

Figure 4. IMF *B* inferred from *IDV* using the regression with outliers omitted. Fourth-order polynomials fitted to all data (red curve) and sunspot minima data (open circles) only (black curve). The 11-year running mean (grey curve) still shows a weak solar cycle variation.

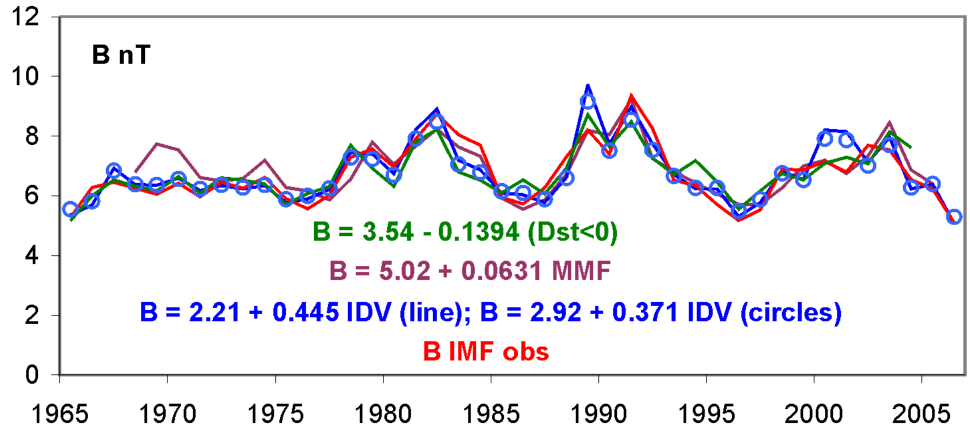

Figure 5. Several estimates of IMF B: Observed by spacecraft (red). Calculated from *IDV*, omitting outliers (blue curve), not omitting outliers (blue circles). Calculated from the Sun-as-a-star mean magnetic field (purple). Calculated from yearly means of negative *Dst* index values (green). Note that the *Dst* curve does not have the outliers in 2000–2001.

Figure 6 shows the substantial agreement between B inferred from *IDV* and from *Dst* (<0). The correlations between *IDV* and B and between *Dst* (<0) and B have different outliers and yet give substantially the same inferred B over the last 100 years, showing that with enough data straightforward analyses work well.

5. Residuals Versus Observed Values

[15] Figure 7 shows that the residuals, $B_{obs} - B_{fit}$, obtained from regression equation (2) in SC05, show no trend. We follow the standard (and correct) practice of plotting residuals (observed minus fitted) versus the fitted values. LRFS06 (Figures 6 and 10) also plot residuals versus observed values and make the statement "[n]ote how strong the bias is in SC05's plot [although it is LRFS06's]: the slope of the LMS regression fit in Figure 6 (right) [residuals versus observed values] is $s = 0.679$ [...]. If we use this regression to correct SC05's extrapolated values [...], this yields [...] by equation (1) a λ of 192%. [...] [T]his does serve to show the extreme sensitivity of λ to uncertainties and/or inadequacies in SC05's regression procedure." The inadequacy here is LRFS06's as it is inappropriate to plot residuals against observed values, as we show by the following precise argument.

[16] Consider the statistical model (using standard notation [e.g., *Draper and Smith*, 1998]):

$$\mathrm{E}(\boldsymbol{Y}) = c\,\mathbf{X}$$

$$\mathrm{Cov}(\boldsymbol{Y}) = \sigma^2\mathbf{I}$$

Then, provided that $\mathbf{X}^{\mathrm{T}}\mathbf{X}$ is nonsingular, the least squares estimate of $\boldsymbol{c}$ is

$$\hat{\boldsymbol{c}} = \left(\mathbf{X}^{\mathrm{T}}\mathbf{X}\right)^{-1}\mathbf{X}^{\mathrm{T}}\mathbf{Y}$$

The fitted $\boldsymbol{Y}$ is

$$\hat{\boldsymbol{Y}} = \mathbf{X}\hat{\boldsymbol{c}} = \mathbf{X}\left(\mathbf{X}^{\mathrm{T}}\mathbf{X}\right)^{-1}\mathbf{X}^{\mathrm{T}}\boldsymbol{Y} = \mathbf{C}\boldsymbol{Y}$$

where $\mathbf{C} = \mathbf{X}\,(\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}\,\mathbf{X}^{\mathrm{T}}$ is symmetric idempotent, that is, $\mathbf{C}\mathbf{C}^{\mathrm{T}} = \mathbf{C}$. The residual vector is

$$\boldsymbol{e} = \boldsymbol{Y} - \hat{\boldsymbol{Y}} = (\mathbf{I} - \mathbf{C})\boldsymbol{Y}.$$

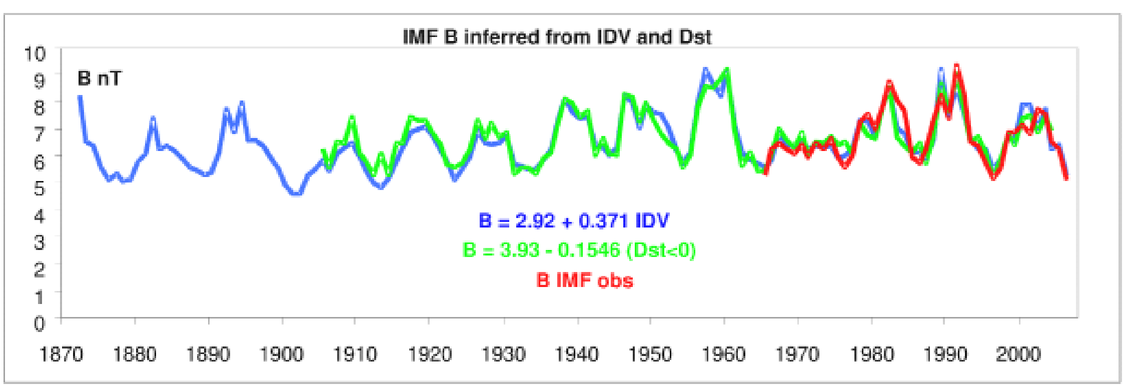

Figure 6. Magnitude B of the interplanetary magnetic field near the earth observed by spacecraft (red curve) and inferred from the *IDV* index (blue curve and regression formula). The green curve shows B calculated from an extension back to 1905 of the *Dst* index (J. J. Love, personal communication, 2006)

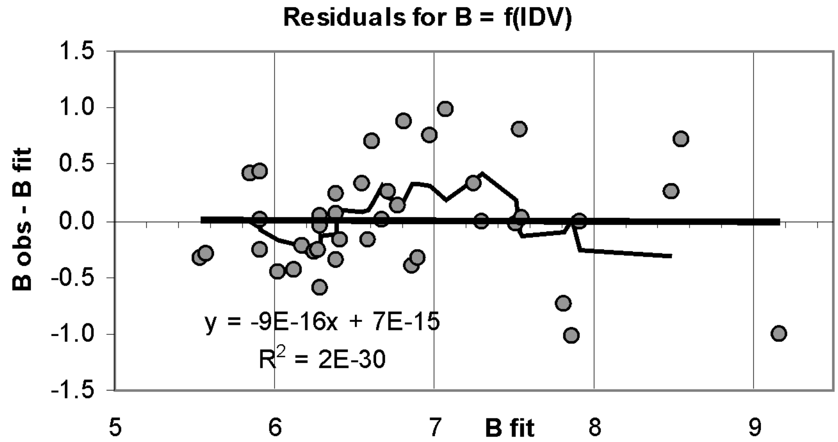

Figure 7. Residuals, $B_{\mathrm{obs}} - B_{\mathrm{fit}}$, of observed yearly means of IMF B from values predicted by the regression equation giving B as a function of *IDV* (method A) from SC05 plotted against the fitted values of B. Also shown is the seven-point running mean. No "outliers" have been removed.

The coefficient of determination R^2 for $\boldsymbol{e}$ versus $\boldsymbol{Y}$ (and similarly for $\hat{\boldsymbol{Y}}$) is defined as

$$R^2(\boldsymbol{e}, \boldsymbol{Y}) = [\mathrm{Cov}(\boldsymbol{Y}, \boldsymbol{e})/\mathrm{Cov}(\boldsymbol{Y}, \boldsymbol{Y})][\mathrm{Cov}(\boldsymbol{Y}, \boldsymbol{e})/\mathrm{Cov}(\boldsymbol{e}, \boldsymbol{e})]$$

[17] Now,

$$\mathrm{Cov}(\hat{\boldsymbol{Y}}, \boldsymbol{e}) = \mathrm{Cov}(\mathbf{C}\boldsymbol{Y}, (\mathbf{I} - \mathbf{C})\boldsymbol{Y}) = \sigma^2(\mathbf{C} - \mathbf{C}\mathbf{C}^{\mathrm{T}}) = \mathbf{0}$$

Therefore R^2 ($\boldsymbol{e}$, $\hat{\boldsymbol{Y}}$) = 0 and $\hat{\boldsymbol{Y}}$, i.e., the fitted $\boldsymbol{Y}$ is not correlated with the residuals $\boldsymbol{e}$. On the other hand,

$$\mathrm{Cov}(\boldsymbol{Y}, \boldsymbol{e}) = \mathrm{Cov}(\boldsymbol{Y}, (\mathbf{I} - \mathbf{C})\boldsymbol{Y}) = \sigma^2(\mathbf{I} - \mathbf{C}) \neq \mathbf{0}$$

Therefore R^2 ($\boldsymbol{e}$, $\boldsymbol{Y}$) $\neq 0$ and observed $\boldsymbol{Y}$ is correlated with the residuals. As a curiosum we note that the slope of the regression line through the residuals plotted against observed values equals the coefficient of determination.

[18] A nonmathematical argument: The residuals are uncorrelated with the fitted values; otherwise, they would not be the residuals of a least squares fit. The observed values are the (fitted plus residual) values; therefore the observed and residual values are correlated and it is not appropriate to plot residuals against observed values and then to claim that this correlation is an inadequacy of our analysis. In LRFS06'S Figure 6 it is clamed that the fit is that "given by SC05." They fail to mention that they do not use the yearly averages for B found in our Table 3 but instead use their own values for $\langle B \rangle$. A small matter, in the caption for their Figure 6 the intercepts quoted are switched around. We shall let the reader judge the difference in homoscedacity between Figures 6 and 10 of LRFS06 while noting that if the relative errors of a fit are approximately constant, which is typical for a relation between a driver and the ensuing response, the absolute errors automatically show heteroscedacity.

6. Physics-Based Versus Empirical Approach

[19] The "physics-based" relationships used by LSW99 to calculate their quantity, F_{s}, have at their core an ad hoc parameter, their $f_{\mathrm{p}} = s_{\mathrm{f}}\,(\langle I \rangle\, \langle aa \rangle^{\,4.95})^{\,0.263} + c_{\mathrm{f}}$, where I is the Sargent recurrence index [*Sargent*, 1986], *aa* is the *aa* index, angle brackets denote yearly average values, and s_{f} and c_{f} are two empirical constants. The variation of f_{p} is dominated by that in the solar wind speed. Because of the constant c_{f}, the solar wind speed determined by LSW99 is bounded below at 334 km/s (for $\langle I \rangle = 0$). Should the actual solar wind speed fall below that, the result would be an artificial increase in B inferred from their method. LSW99 state that the primary justification for adopting this particular relationship was that it produces a good correlation for the interval 1964–1994. We have calculated I following Sargent's prescription using 27-day Bartels rotations. The cross correlation is often negative (23% of the time) and the yearly mean $\langle I \rangle$ is negative in 1956, 1969, and 1992. It is not entirely clear what is meant by $\langle I \rangle$. LSW99 (p. 437) state that they use "Annual means of Sargent's recurrence index, $\langle I \rangle$ (defined for the jth 27-day Carrington [sic] rotation period as $I_j = (1/13) \sum c_{(j+k,\,j+k+1)}$ from $k = -6$ to $k = +6$, where c is the correlation coefficient between two consecutive intervals of twelve-hourly *aa* values)." We calculated $\langle I \rangle$ over a year using the 13 rotations prior to the rotation whose first day belongs to the following year, but many other interpretations are possible, e.g., to choose as the jth rotation the one that contains the 183rd day of the year, or even calculating the yearly mean of the thirteen or fourteen 13-rotation running mean values within the year. We do not know how LSW99 calculate $\langle I \rangle^{0.263}$ for negative $\langle I \rangle$, nor do we reproduce their $\langle I \rangle$ values (we reproduce Sargent's values as precisely as his published figure allows us to determine).

[20] To illustrate the danger of applying ad hoc relations outside of the domain on which they are defined, we may note that the year 2003 had some of the most extensive coronal holes and high-speed streams on record ($\langle V \rangle_{2003}$ = 545 km/s, the highest yearly mean ever measured), yet $\langle I \rangle$ was only 0.055 versus the ~0.40 usually found for years with strong high-speed streams, leading to an underestimate (using the method described in LSW99) of V by ~70 km/s, and an overestimate of B by 3 nT (40%), a much larger error than even our largest residual (1 nT). We take this as an

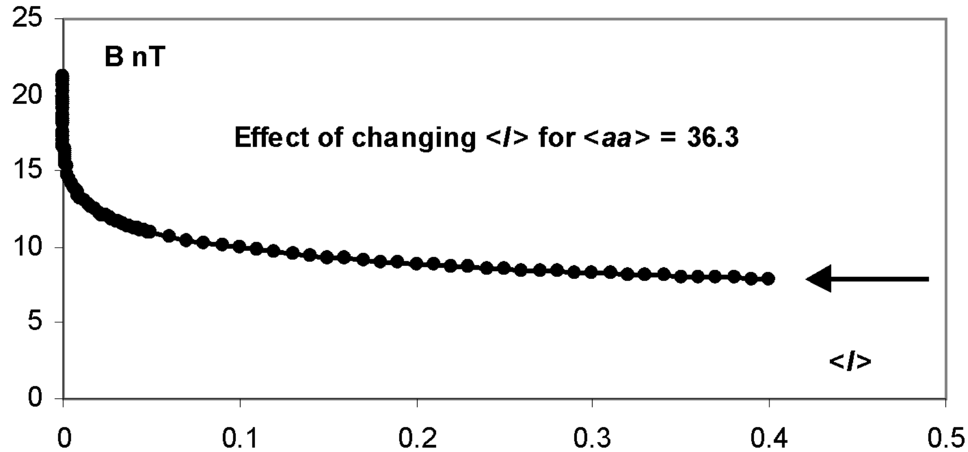

Figure 8. Effect of changing the yearly average $\langle I \rangle$ from 0.40 to 0 for the level of activity $\langle aa \rangle$ = 36.3 of the year 2003 on B calculated using the ad hoc f_p function of LSW99. The arrow shows the observed value of $\langle B \rangle_{2003}$.

indication that the LSW99 procedure is not inherently superior as claimed by LRFS06.

[21] With $\langle I \rangle$ as small as 0.055, it could easily by chance have been even nearer to zero (like $\langle I \rangle_{1956} = -0.002$ and $\langle I \rangle_{1968} = 0.009$). It is instructive to investigate the effect of $\langle I \rangle$ changing from 0.40 to 0 for the level of activity of the year 2003 shown in Figure 8. The arrow shows the observed value of $\langle B \rangle_{2003}$, which is incidentally what we would expect for the $\langle I \rangle = 0.4$ that is typical for this phase of a declining sunspot cycle. Note how strongly B grows as $\langle I \rangle$ approaches zero from 0.4, from 7.9 to 21.2, and that most of the change takes place very close to zero, e.g., from 13.2 to 21.2 as $\langle I \rangle$ changes from 0.01 to 0.00. Such extreme sensitivity is not the behavior of a real physical system but comes from wrapping what the authors considered to be a physics-based procedure around the core of an empirical, ad hoc relationship. LSW99 (p. 439) prudently stated that "we assume that all three correlations were valid at all times." We now know that at least, f_p fails the test of time, although its nonphysical extreme sensitivity for very small values of $\langle I \rangle$ should have been clear from the outset. Figure 3 of LSW99 should have given a warning signal as shown in Figure 1. The rather glaring discrepancies (highlighted in the red oval) between F_s calculated by LSW99, during 1967–1970 and that calculated from the IMF measured by spacecraft (heavy blue curve) are caused by very small values of $\langle I \rangle$ for that interval showing failure of the ad hoc relationship, despite the stated 99.999999999996% significance level of the correlation. There is a similar problem with 1992, for which we calculate $\langle I \rangle = -0.12$. If we set $\langle I \rangle = 0$ for this year (what else makes sense?), we find, using the method of LSW99, $\langle B \rangle_{1992} = 13.5$ nT, which is 64% larger than the observed value of 8.26 nT.

[22] When we first calculated $\langle I \rangle_{2003}$ and found it to be so low, we thought that there was a problem with the *aa* index data, so we redid the calculation using the *am* index and confirmed that there is no problem with the data. The reader may wish to compare our Figure 9 with Figure 1 of LSW99 to gauge some of the differences between $\langle I \rangle$ and the values calculated by LSW99 or at least shown in their figure. Because of the large variation of the cross correlation from rotation to rotation, the effect of $\langle I \rangle$ when $\langle I \rangle$ is close to zero is very sensitive to precisely how the annual means are calculated, as should be clear from Figure 9 that shows the cross correlation for each rotation pair and their 13-rotation running mean.

7. Conclusion

[23] LSW99 reported that the Sun's coronal magnetic field more than doubled during the last century. Our calculation in SC05 of B from *IDV* indicates no such increase in B, and therefore none in B_r and the coronal magnetic field. The situation is illustrated in Figure 1 where the inset gives our computed B values for years when the sunspot number was nearly constant near 40 on the rising part of the cycle, away from recurrent high-speed streams and with no lingering flux from the maximum phase, for comparison with the main part of the figure adapted from LSW99. Figure 8 of SC05 showed that 71% of the variation of B is explained by the varying sunspot number. For constant sunspot number we see no increase in the coronal magnetic field, while LSW99 do. Nothing in their comment on our paper leads us to doubt our technique or result. In fact, it has given us the opportunity to raise a serious question about their methodology, specifically, their use of the Sargent recurrence index to reconstruct solar wind speed (combined with an error in the calibration of the *aa* index prior to 1957 [*Svalgaard et al.*, 2004; *Jarvis*, 2005; *M. Lockwood et al.*, The long-term drift in geomagnetic activity: calibration of the *aa* index using data from a variety of magnetometer stations, submitted to *Annales Geophysicae*, 2006; L. Svalgaard and E. W. Cliver, Long-term variation of geomagnetic activity (the IHV-index) and its use in deriving solar wind speed since 1882, manuscript in preparation, 2006]), which, in our opinion, is the likely cause of the major increase in the inferred coronal field that LSW99 report, but which we cannot confirm.

[24] Both our method and that of LSW99 use extrapolations of correlations outside the range for which they were derived and thus both must be regarded with caution. For this reason, in SC05 we substantiated our *IDV*-based results

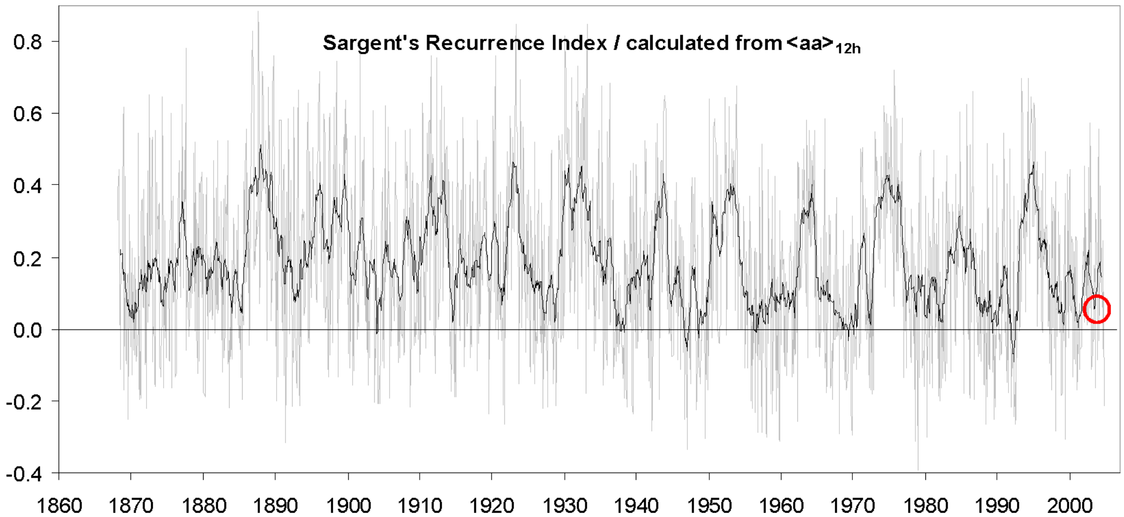

Figure 9. Sargent's recurrence index, *I*, calculated as the 13-rotation running mean (heavy black line) of the cross correlation for each pair of Bartels rotations since 1868 calculated from 12-hourly averages of the *aa* index (grey line). The value for 2003 is indicated by a red circle. Note that the "base level" of *I* is significantly higher before ~1925 than after that time. This has the effect of systematically decreasing the value of *B* calculated using the method of LSW99 before 1925 (compare Figure 8).

by using an independent method based on magnetic field measurements in the terrestrial polar caps, some of which were made during the crucial interval early in the last century for which LSW99 inferred very low coronal fields. Our debate with Lockwood and colleagues on the long-term evolution of the coronal magnetic field and the solar wind may be resolved within the next few years if our prediction [*Svalgaard et al.*, 2005] of a solar maximum with peak sunspot number comparable to that of cycle 14 bears out. If so, direct measurements of solar wind properties during conditions similar to those during the previous minimum of the Gleissberg cycle would take the estimates of IMF *B* out of the realm of extrapolation. It is noteworthy that the *IDV* index (and thus *B*, regardless of regression method) for 2006 (based on the first 7 months only, but expected to fall further as we approach solar minimum) is already the lowest in the last 94 years.

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