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The *IDV* index: Its derivation and use in inferring long-term variations of the interplanetary magnetic field strength

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[1] On the basis of a consideration of Bartels' historical *u* index of geomagnetic activity, we devise an equivalent index that we refer to as the interdiurnal variability (*IDV*). The *IDV* index has the interesting and useful property of being highly correlated with the strength of the interplanetary magnetic field (*B*; $R^2 = 0.75$) and essentially unaffected by the solar wind speed (*V*; $R^2 = 0.01$) as measured by spacecraft. This enables us to obtain the variation of *B* from 1872 to the present, providing an independent check on previously reported results for the evolution of this parameter. We find that solar cycle average *B* increased by ~25% from the 1900s to the 1950s and has been lower since. If predictions for a small solar cycle 24 bear out, solar cycle average *B* will return to levels of ~100 years ago during the coming cycle(s).

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1. Introduction

1.1. Motivation

[2] How does the solar wind vary over timescales of a century or more? The question bears on topics ranging from the nature of the solar dynamo to the effect of the Sun on climate change. Various authors [e.g., *Feynman and Crooker*, 1978; *Cliver et al.*, 1998; *Lockwood et al.*, 1999] have used *Mayaud*'s [1973, 1980] geomagnetic *aa* index to constrain or deduce the variation of solar wind parameters over extended intervals. In particular, Lockwood et al. suggested that the interplanetary magnetic field (IMF) more than doubled during the 20th century. In the present paper, we revisit Bartels' long-abandoned *u* measure and show that it can be used to obtain a check on *aa*-based studies of the long-term evolution of the solar wind. This is particularly important now that the calibration of *aa* has been called into doubt [*Svalgaard et al.*, 2004; M. Lockwood et al., submitted manuscript, 2005]. A preliminary report of our results has been published elsewhere [*Svalgaard et al.*, 2003].

1.2. The *u* Measure and the *IDV* Index

[3] *Bartels* [1932] introduced the *u* measure of geomagnetic activity as a station-weighted mean of the interdiurnal variability *U* of the horizontal intensity (*H*) at each station, calculated as the absolute value of the difference between the mean values for a day and for the preceding day. The weight-factor took into account the dipole-latitude of the station by dividing by the cosine of the latitude. The *u* index was computed using only low to midlatitude stations and was normalized to the German station Niemegk (IAGA-code: NGK) and its predecessor stations Seddin (SED) and Potsdam (POT). Bartels' goal in deriving the *u* index was to establish "*a homogeneous series for all the time since consistent terrestrial-magnetic observations were begun*" (italics in the original). He added that "it will be sufficient ... to devise such a measure only as averages for intervals of months or years" as short-term indices already existed. The concept of the interdiurnal variability was introduced by *Moos* [1910].

[4] *Mayaud* [1980] evaluated the degree of contamination of the *u* index by the regular daily variation S_R by using only the first and the last 6 hours of the local day instead of all 24 hours. This elimination of the daytime hours should remove most of the effect of S_R. (For a 35-day solar minimum interval examined, Mayaud was "astonished" by just how small a contribution S_R made to the *u* index (~2 nT out of 7 nT).) We take Mayaud's lead but further limit the time interval to only 1 hour (taken to start 1 hour after the UT hour closest to local midnight) and construct the interdiurnal variability index (*IDV*) for a given station as the unsigned difference between 2 consecutive days of the average value of a field component measured in nT (usually, and in the present paper, *H*, although, in principle, we can do this for any of the components) for that hour and assigned to the first day. The individual daily values are then averaged over longer intervals, e.g., 1 year (minimizing various geometric and seasonal effects). The *u* measure was expressed in units of 10 nT ("in order to make the index of the order of

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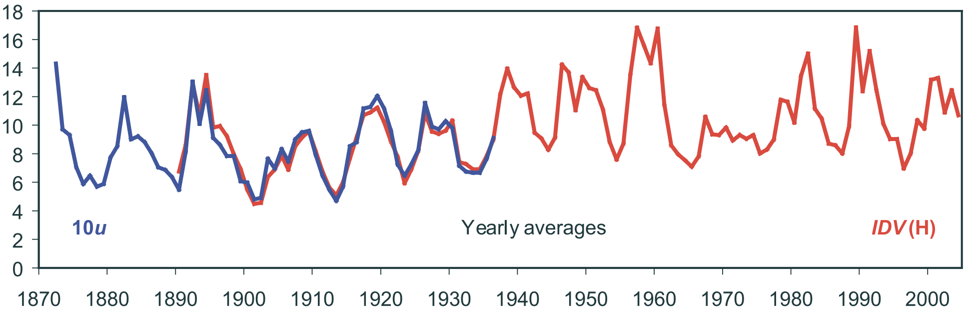


Figure 1. Ten times the *u* measure (blue curve) for 1872–1936 compared to the *IDV* index (red curve, derived as described in the text) for 1890–2004. For the time of overlap, the linear cross correlation coefficient is 0.95. Yearly averages of both indices are plotted.

magnitude 1, and therefore comparable with the C-index,'' *Bartels* [1932]). We have chosen to use 1 nT units for *IDV*.

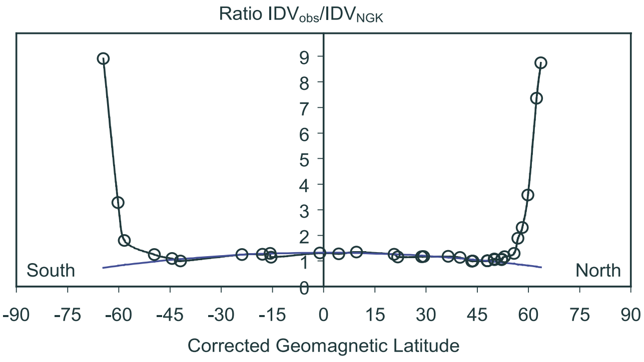
[5] *Van Dijk* [1935] criticized the *u* measure because it failed to register the very high activity in 1930, resulting from extensive recurrent storms and clearly shown in the daily character figure, the C_i index [see *Feynman*, 1980]. This problem was so severe that Bartels (after some struggle [*Bartels*, 1950]) abandoned the *u* measure and went on to invent the very successful *K* index [*Bartels et al.*, 1939] that we use to this day. As we shall see, the lack of sensitivity of the *u* index to recurrent activity caused by high-speed streams (also noted by *Nevanlinna* [2004]) from coronal holes [e.g., *Neupert and Pizzo*, 1974; see also *Crooker and Cliver*, 1994] is an unexpected advantage of the index.

[6] Figure 1 shows yearly averages of the *u* measure (in 1 nT units) from 1872 through 1936 [*Joos et al.*, 1952] and of the *IDV* index since 1890. The *IDV* index was derived as described below. It is clear that the *IDV* index also does not register the recurrent, high-speed solar wind streams that were so prevalent in 1930, 1952, 1974, 1994,

Table 1. Observatories (Stations) Used for Computation of *IDV*[a]

Observing Station	Geographic Latitude	Geomagnetic Latitude	Corrected Geomagnetic Latitude	Ratio IDV OBS/NGK 1965–2003
SOD	67.37	63.68	63.63	8.7422
MEA	54.62	61.88	62.40	7.3532
SIT	57.07	60.31	59.85	3.5731
LER	60.13	62.15	58.18	2.2992
OTT	45.40	56.37	56.96	1.8796
LOV	59.35	57.84	55.78	1.2901
ESK	55.32	58.04	53.00	1.1592
RSV/BFE	55.85	55.56	52.25	1.0668
SVD/ARS	56.73	48.64	52.12	1.0476
WNG	53.75	54.22	50.08	1.0454
FRD	38.20	49.13	50.04	1.0755
HAD	50.98	54.17	48.03	1.0054
NGK	52.07	51.94	47.95	1.0000
CLF	48.02	50.06	43.74	0.9947
FUR	48.17	48.48	43.42	0.9868
TUC	32.25	40.37	39.96	1.1301
MMB	43.90	34.61	36.54	1.1728
SJG	18.38	29.36	29.36	1.1693
KAK	36.23	26.62	28.75	1.1594
HON	21.32	21.46	21.74	1.1488
MBO	14.40	20.68	20.68	1.2591
ABG	18.63	9.64	9.64	1.3397
BNG	4.43	4.45	4.45	1.2697
HUA	−12.05	−1.06	−1.06	1.3079
VSS	−22.40	−12.53	−15.38	1.1430
API	−13.80	−15.61	−15.61	1.2900
PIL	−31.67	−20.73	−17.92	1.2536
TAN	−18.92	−23.85	−23.85	1.2433
HER	−34.42	−33.73	−41.94	0.9975
GNA	−31.78	−42.71	−44.36	1.0901
AIA	−65.20	−54.20	−49.57	1.2422
PAF	−49.35	−57.31	−58.37	1.7935
SNA	−70.30	−64.23	−60.20	3.2781
MCQ	−54.50	−60.50	−64.51	8.9059

[a]Geographic latitude, geomagnetic latitude (epoch 1985) and corrected geomagnetic latitude (CGML epoch 1985) as shown are used (calculated using the NSSDC web-based form). The average ratios (over 1965–2003) of yearly average *IDV* for each station to that of NGK as shown are used in Figure 2.



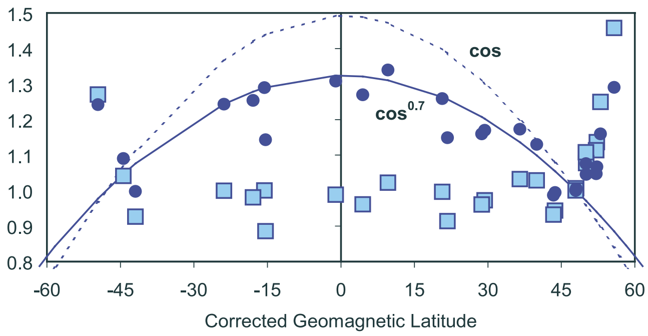


Figure 2. (top) Mean ratios between yearly average *IDV* for the 34 observatories listed in Table 1 and yearly average *IDV* for NGK over the interval 1965–2003 as a function of corrected geomagnetic latitude (CGML). (bottom) Expanded lower part of the above panel. Filled circles show the observed ratios. The dashed-line curve is the function cos(CGML) normalized to go through the datapoint for NGK (*IDV* ratio = 1.0000 at CGML = 47.95°). A better fit to the observed ratios is the somewhat flatter function $\cos^{0.7}$(CGML) also normalized to go through NGK and shown by the full-line curve. The squares show the result of dividing the ratios by the better fit: (*IDV* ratio)/$\cos^{0.7}$(CGML). For a useful normalization these points should cluster on a horizontal line at an ordinate value of 1.0.

and 2003. In fact, for the years of overlap (1890–1936) the two indices agree closely (as should be expected) with a linear cross correlation coefficient of 0.95 (*IDV* = (9.96 ± 0.11) *u*). It is instructive to compare Figure 1 with Figure 1 of *Bellanger et al.* [2002], who investigated the spatial (and, as a by-product, the temporal) behavior of similar daily differences.

2. Details of Derivation of the *IDV* Index

2.1. Choice of Local Time Interval

[7] The choice of a 1-hour interval was dictated by the desire of being able to derive *IDV* indices from old geomagnetic data for which discrete values may be available for only certain hours of each day. Experimentation showed that little is gained by using longer spans of nighttime hours. This conclusion is implicit in Figure 1 that compared the *u* measure (based on 24 hours) and the 1-hour *IDV* index. We have chosen the interval 1 hour after local midnight but it does not make much difference precisely which night hour is used.

[8] A fine point is the distinction between an hourly mean and an hourly (instantaneous) value. Early magnetometer records often consist of hourly values which, having more variance than hourly means, result in a slight increase of *IDV* (a few percent, determined from simulated hourly values using 1-min modern data) compared to the same index derived from hourly means. POT changed from hourly values to hourly means in 1905, CLH, VQS, HON, and TUC changed in 1915, KAK in 1955, CLF in 1972, and other stations at other (known) times. There are no discernible discontinuities or "jumps" at these times (as evidenced by Figure 4 below), so we conclude that the effect is not significant for *IDV*.

2.2. Missing Data

[9] If either of the two values needed to calculate a daily *IDV* is missing, the *IDV* value for that day is missing. Similarly, if more than half of the *IDV* values needed for a long-term average are missing, the *IDV* value for the averaging interval is not computed. The ideal way of dealing with missing data when combining or comparing

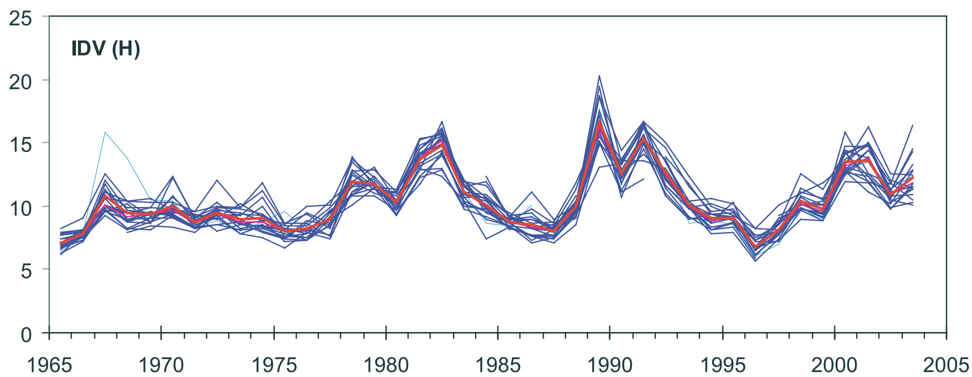


Figure 3. Yearly averages of normalized *IDV* for the stations with |CGML| < 51° for the interval 1965–2003 (thin blue lines). The (arithmetic) average over all stations is shown by the heavy red line. A thin pink line (largely masked by the red line) shows the run of the median value for each year. It does not make a significant difference which of the two is chosen.

Table 2. Observatories With Long Series of Data (as Covered by Available Hourly Values/Means From the WDCs) Used for Figure 4[a]

Observatories	Coverage
POT/SED/NGK	1890–2003
CLH/FRD	1901–2003
HON	1902–2003
DBN/WIT	1903–1984
VQS/SJG	1903–2003
TUC	1910–2003
KAK	1913–2003
WAT/GNA	1919–2003
VLJ/CLF	1923–2003
ABG	1925–2003
ABN/HAD	1926–2003
CTO/HER	1933–2002
FUR	1940–2003
WNG	1943–2003

[a]More data exist (even for these stations), but are not yet available in digital form.

several datasets is to limit the study to times where all contributing data sets have simultaneous high-resolution data. We did not do this but assumed that the distribution of missing data was random enough to make the averages comparable. This assumption is reasonable for modern data but is somewhat problematic with older data where recordings often go off-scale at times of large storms, resulting in an underestimation of the index.

2.3. Dependence on Latitude

[10] For each of the 34 stations in Table 1 we computed yearly averages of *IDV* for 1965–2003. As noted above, if data for over half of the days for a given station/year were unavailable (a relatively rare occurrence), we did not compute an average for that station/year. For each year for each station, we formed the ratio between the yearly averaged *IDV* for that station and for NGK. By considering ratios, we largely eliminate the effects of the placement of missing data caused by solar cycle and longer-term trends in the geomagnetic records. The average of the individual yearly *IDV* ratios for the 1965–2003 interval was determined for each station and is plotted in Figure 2 as a function of corrected geomagnetic latitude (CGML) which organizes the data better than does the dipole latitude.

[11] *IDV* is smallest at |CGML| = 45°, increases slightly toward low latitudes, and increases dramatically above |CGML| of ~50°. At higher latitudes, the magnetic effects of the auroral electrojets begin to overwhelm the effect due to the ring current, which is the physical quantity measured primarily by *IDV*. We therefore only included stations with |CGML| less than 51° (see below for the reasoning behind this precise choice). This requirement reduces the number of stations used to 22. Empirically, the dependence on latitude for a given station "A" is somewhat weaker than the "theoretical" 1/cos(CGML) dependence that Bartels assumed for the *u* measure (and used today for the *Dst* index), namely:

$$IDV(\text{normalized to NGK}) = IDV(\text{Station A}) \\ /\left(1.324\ \cos^{0.7}(\text{CGML}(\text{Station A}))\right). \quad (1)$$

Physically, it would have made more sense to normalize to the equator, but we retain the historical choice of NGK (in any event, there is just a constant factor involved: $1.324 = 1/\cos^{0.7}(\text{CGML (NGK)})$). This weaker dependence on latitude is probably related to the fact that parts of the magnetic effects are caused by field-aligned currents rather than the traditional ring current [e.g., *Burch*, 2005].

2.4. Averaging Over Stations

[12] The final step is to (arithmetically) average the normalized *IDV* values over all stations with CGML between 51° north and 51° south. These boundaries were chosen to include the stations WNG and FRD (important because of their long series of observations). Figure 3 shows the result for 1965–2003, as well as the run of values for each individual station to allow assessment of the standard deviation (average 0.9 nT or 9%). The average standard error of the mean of the 22 stations is 0.2 nT.

3. Average *IDV* Index Since 1890 (and 1872)

[13] The World Data Centers archive machine-readable hourly means (or values) of the geomagnetic elements for several stations back in time. Fewer and fewer stations have data available as we go to earlier and earlier years.

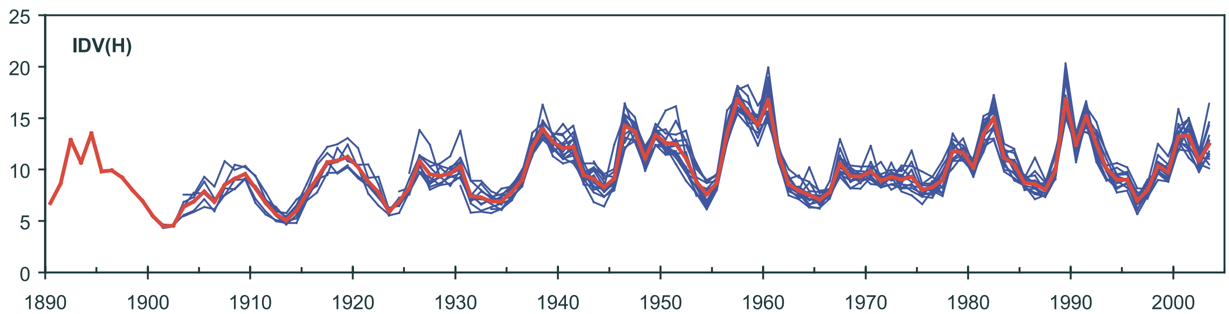


Figure 4. Combined *IDV* index (yearly averages) for the stations given in Table 2. The run of *IDV* for individual stations are shown as thin blue lines. The average *IDV* index for each year over all stations with data is shown as a heavy red line. Before 1901, only one station (POT) has data available from the WDCs and its thin blue line is hidden behind the average (red) curve. The average standard deviation is 0.7 nT.

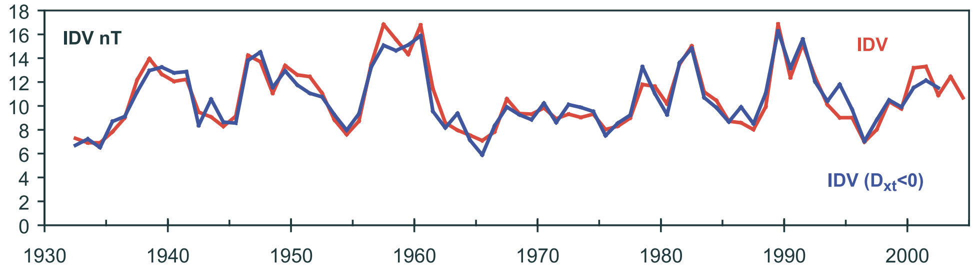


Figure 5. Yearly means of the *IDV* index (blue line) compared to IDV_{xt} computed from negative D_{xt} only using the regression equation given in section 4.

Before 1901, only a single station (POT) has data readily available (back to 1890). Using the stations given in Table 2, we compute yearly values of the *IDV* index with the result shown in Figure 4. This directly derived *IDV* series starts in 1890. Because of the very high correlation with the *u* measure (the *IDV* index is really nothing more than a revived *u* measure), we can with some confidence extend the series back to 1872 (as shown in Figure 1) by setting $IDV = 10u$. The *u* measure is available back to 1836, but values before 1872 are unreliable, as they were derived from monthly or yearly values rather than from daily values [*Mayaud*, 1980].

[14] Because the CGML of a station changes slowly with time, the normalization divisor also changes. A 1° increase of CGML decreases the normalization divisor by from 0% at the equator to 1.5% at 50°. None of the stations used has changed CGML more than 1° during the last 150 years, so the effect of this is not large (especially since various stations have experienced changes of opposite signs). In future studies with very old data, it might be necessary to correct for the changing latitude to the extent this can be reliably done. The effect on the changing strength of the Earth's magnetic dipole moment might also be detectable, but it is not clear how to incorporate such a correction at this time, and we elect to minimize the number of empirical adjustments.

4. Comparison With D_{st} (and D_{xt})

[15] As we would expect, (yearly averages of) the *IDV* index and the D_{st} index [*Sugiura*, 1964; *Karinen and Mursula*, 2005, and references therein] are moderately correlated ($R^2 = 0.65$ for the years 1957–2002). The fact that positive and negative values of D_{st} are due to different physical processes (controlled roughly by solar wind pressure and magnetic reconnection, respectively) makes a simple yearly average of D_{st} a somewhat suspect physical quantity. If we include only negative values of D_{st} in the average, the correlation improves markedly to $R^2 = 0.89$. We conclude that the same physical processes are responsible for the correlation between *B* and both the *IDV* and D_{st} indices. The lack of correlation between D_{st} and *V* has recently been stressed by *Kane* [2005]. *Karinen and Mursula* [2005] have reconstructed D_{st} back to 1932. Their reconstruction, called D_{xt}, corrects several errors (e.g., in 1971) and inhomogeneities in the index. The regression equation $IDV_{xt} = 1.142 + 0.4078\ |D_{xt} < 0|$ ($R^2 = 0.89$ for negative values only over 1957–2002) can be used to calculate *IDV* from D_{xt} using only negative values of D_{xt}. Figure 5 shows the result.

5. Correlation With Interplanetary Magnetic Field Strength

[16] Figure 6 contains scatter plots of yearly averages of solar wind magnetic field strength (*B*) and speed (*V*) versus annual IDV indices for 1965–2003. Although the

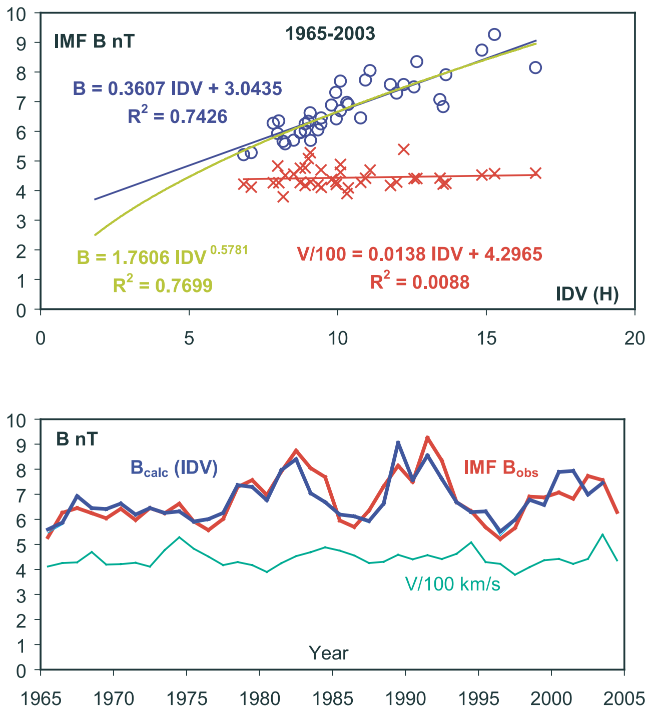


Figure 6. (top) Scatterplots of yearly average *IDV* and the strength of the total interplanetary magnetic field, *B* (open blue circles), and the solar wind speed, *V* (red crosses) for each year of the interval 1965–2003. There is no correlation (square of linear cross correlation R^2 effectively zero) beween *IDV* and *V*. There *is* a robust correlation ($R^2 \approx 0.75$) between *IDV* and *B*. There is no significant difference between a simple linear fit (blue regression line) and a power-law fit (green curve) within the range of the data. (bottom) Comparison between observed yearly averages of *B* (red curve) and reconstructed values of *B* (blue curve) using equation (2). The thin green curve shows the observed solar wind speed in units of 100 km/s.

Table 3. Yearly Averages of *IDV* (10*u* Before 1890) and the Inferred Near-Earth Interplanetary Magnetic Field Strength Calculated Using Equation (2)[a]

Year	⟨10u,IDV⟩	B_{calc}	B_{obs}
1872.5	14.308	8.21	
1873.5	9.702	6.54	
1874.5	9.310	6.40	
1875.5	7.056	5.59	
1876.5	5.880	5.16	
1877.5	6.468	5.37	
1878.5	5.684	5.09	
1879.5	5.880	5.16	
1880.5	7.742	5.83	
1881.5	8.526	6.12	
1882.5	11.956	7.36	
1883.5	9.016	6.29	
1884.5	9.212	6.37	
1885.5	8.820	6.22	
1886.5	8.036	5.94	
1887.5	7.056	5.59	
1888.5	6.860	5.52	
1889.5	6.370	5.34	
1890.5	6.736	5.47	
1891.5	8.622	6.15	
1892.5	12.876	7.69	
1893.5	10.682	6.90	
1894.5	13.507	7.92	
1895.5	9.834	6.59	
1896.5	9.925	6.62	
1897.5	9.235	6.37	
1898.5	7.993	5.93	
1899.5	6.938	5.54	
1900.5	5.479	5.02	
1901.5	4.485	4.66	
1902.5	4.561	4.69	
1903.5	6.377	5.34	
1904.5	6.903	5.53	
1905.5	7.854	5.88	
1906.5	6.876	5.52	
1907.5	8.512	6.11	
1908.5	9.137	6.34	
1909.5	9.575	6.50	
1910.5	8.198	6.00	
1911.5	6.753	5.48	
1912.5	5.641	5.08	
1913.5	5.080	4.87	
1914.5	6.012	5.21	
1915.5	7.688	5.82	
1916.5	9.142	6.34	
1917.5	10.697	6.90	
1918.5	10.894	6.97	
1919.5	11.230	7.09	
1920.5	10.230	6.73	
1921.5	8.857	6.24	
1922.5	7.793	5.85	
1923.5	5.928	5.18	
1924.5	6.891	5.53	
1925.5	8.204	6.00	
1926.5	10.833	6.95	
1927.5	9.553	6.49	
1928.5	9.390	6.43	
1929.5	9.626	6.52	
1930.5	10.322	6.77	
1931.5	7.427	5.72	
1932.5	7.276	5.67	
1933.5	6.906	5.53	
1934.5	6.911	5.53	
1935.5	7.834	5.87	
1936.5	8.992	6.29	
1937.5	12.165	7.43	
1938.5	13.960	8.08	
1939.5	12.665	7.61	
1940.5	12.062	7.39	
1941.5	12.220	7.45	
1942.5	9.480	6.46	
1943.5	9.081	6.32	
1944.5	8.274	6.03	
1945.5	9.137	6.34	
1946.5	14.254	8.19	
1947.5	13.690	7.98	
1948.5	11.059	7.03	
1949.5	13.382	7.87	
1950.5	12.603	7.59	
1951.5	12.455	7.54	
1952.5	11.084	7.04	
1953.5	8.839	6.23	
1954.5	7.598	5.78	
1955.5	8.714	6.19	
1956.5	13.533	7.93	
1957.5	16.825	9.11	
1958.5	15.574	8.66	
1959.5	14.327	8.21	
1960.5	16.766	9.09	
1961.5	11.460	7.18	
1962.5	8.590	6.14	
1963.5	7.960	5.91	
1964.5	7.542	5.76	
1965.5	7.090	5.60	5.28
1966.5	7.826	5.87	6.27
1967.5	10.583	6.86	6.45
1968.5	9.362	6.42	6.25
1969.5	9.308	6.40	6.05
1970.5	9.832	6.59	6.42
1971.5	8.919	6.26	5.97
1972.5	9.297	6.40	6.45
1973.5	9.044	6.31	6.25
1974.5	9.299	6.40	6.62
1975.5	8.016	5.93	5.92
1976.5	8.298	6.04	5.57
1977.5	8.983	6.28	6.02
1978.5	11.786	7.29	7.29
1979.5	11.638	7.24	7.57
1980.5	10.177	6.71	6.97
1981.5	13.468	7.90	7.91
1982.5	15.021	8.46	8.74
1983.5	11.162	7.07	8.05
1984.5	10.456	6.81	7.69
1985.5	8.719	6.19	5.95
1986.5	8.593	6.14	5.70
1987.5	8.017	5.93	6.35
1988.5	9.924	6.62	7.31
1989.5	16.846	9.12	8.15
1990.5	12.381	7.51	7.50
1991.5	15.182	8.52	9.26
1992.5	12.443	7.53	8.35
1993.5	10.093	6.68	6.69
1994.5	9.022	6.30	6.33
1995.5	9.023	6.30	5.69
1996.5	6.972	5.56	5.21
1997.5	8.019	5.93	5.66
1998.5	10.352	6.78	6.91
1999.5	9.753	6.56	6.88
2000.5	13.186	7.80	7.07
2001.5	13.310	7.84	6.83
2002.5	10.893	6.97	7.73
2003.5	12.451	7.53	7.57
2004.5	10.688	*6.90*	*6.16*

[a]The IMF *B* as observed by spacecraft is given for comparison.

IDV index seems to be "blind" to *V*, there is a robust correlation with *B*.

[17] The interplanetary data were obtained as hourly values from the OMNI-2 data set (*King and Papitashvili* [2005]; http://nssdc.gsfc.nasa.gov/omniweb/ow.html).

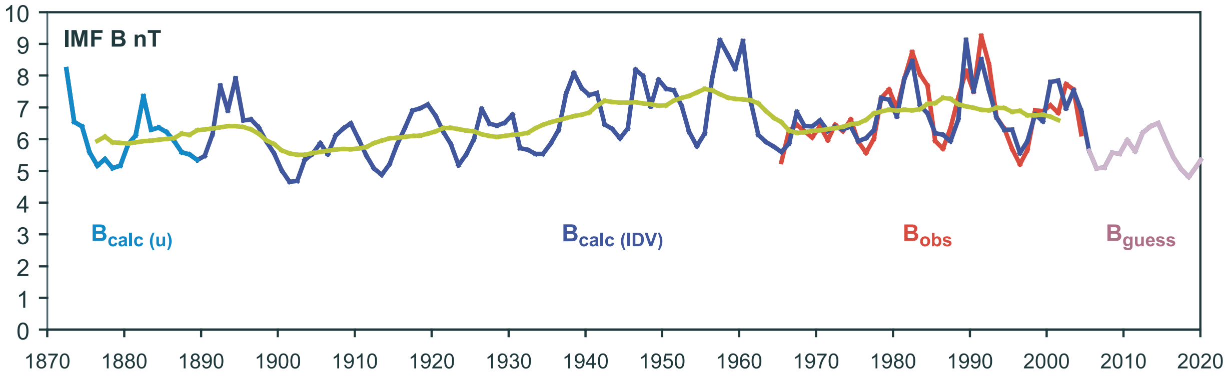


Figure 7. Inferred (reconstructed) near-Earth interplanetary magnetic field strength, *B* since 1872 (blue curve). Before 1890 (light blue), *B* is calculated using the *u* measure. After 1890 (medium blue), *B* is calculated from *IDV* using equation (2). The observed field strength is shown by the red curve. The purple curve shows a guess of what *B* might be during the coming solar cycle 24, based on cycle 14. The green line shows the 11-year running mean, suggesting a ~100-year wave.

Because significant amounts of interplanetary data are missing for certain years, we adopted the following procedure to deal with missing data: the (UT) daily mean was calculated from available hourly data (even if only one); the 27-day Bartels rotation mean was calculated from available daily means (even if only one); if there were no data for a rotation, its mean was linearly interpolated from surrounding rotations. The average for a year was then calculated from the Bartels rotations spanned by the year. Table 3 contains these averages.

[18] The linear regression fit (R^2 = 0.74) for yearly averages of *B* is

$$B(\mathrm{nT}) = (3.04 \pm 0.37) + (0.361 \pm 0.035) IDV. \quad (2)$$

The linear fit has an offset that limits *B* from below to ~3 nT for *IDV* = 0. The equally good power-law fit has *B* going to zero with *IDV*. We do not have values of *IDV* low enough to decide among the two cases. As always, it is problematic to extrapolate regression fits beyond their input data range. We opt in the present analysis for the simple linear fit and reconstruct *B* from *IDV* using (2) as shown in the lower panel of Figure 6. The average reconstruction error is about 5% (for monthly averages, R^2 drops to 0.50). The reconstruction using yearly averages appears good enough to permit a reconstruction of *B* for times before the availability of in situ interplanetary measurements. Thus the *IDV* index may be considered to be a proxy for the interplanetary magnetic field strength under the usual assumption that the response of the Earth's magnetosphere to solar storms has remained the same over time (at least over the last few centuries).

6. Inferred Interplanetary Magnetic Field Strength Since 1872

[19] Using the regression equation (2), we can convert the yearly averages of the *IDV* index to inferred interplanetary *B*. The result is shown in Table 3 and in Figure 7.

[20] The 11-year running mean (green line) of *B* over the period hints at the ~100-year wave (±15%) often seen in solar activity and proxies thereof [*Gleissberg*, 1939]. In addition, there is a strong ~11-year modulation of *B*, generally following the sunspot number. That *IDV* at sunspot minima shows the ~100-year modulation is a simple consequence of the fact that larger (and often, shorter) cycles have significant overlap during minima so clearly evidenced in the sunspot Butterfly Diagram.

7. Correlation Between *B* and Sunspot Number (R_Z)

[21] It has been suggested that the coming solar cycle 24 will be a small cycle (possibly the smallest in a 100 years (peak sunspot number R_Z = 75) [*Svalgaard et al.*, 2005, and references therein]). If so, we might speculatively plot the field strength inferred for cycle 14 (peak R_Z = 64) as a guess of what the field might be during cycle 24 (shown as a purple curve on Figure 7). This places the long-term trend in perspective.

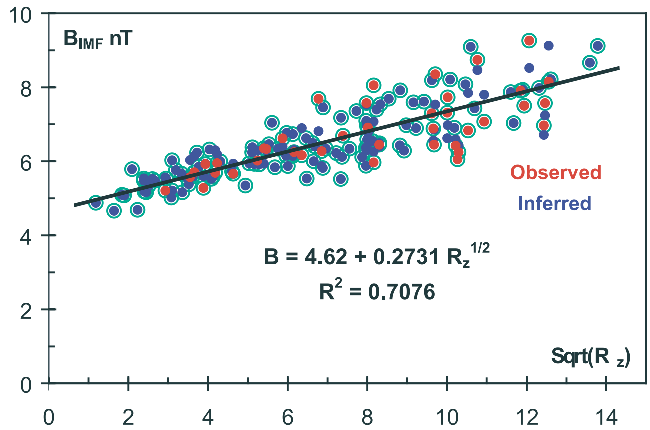


Figure 8. Yearly means of *B* derived from *u* and *IDV* (blue) and observed by spacecraft (red) as a function of the square root of the Zürich (International) sunspot number. Regression line is computed from a combined dataset (*B* inferred for 1872–1964 and observed thereafter) marked with green circles.

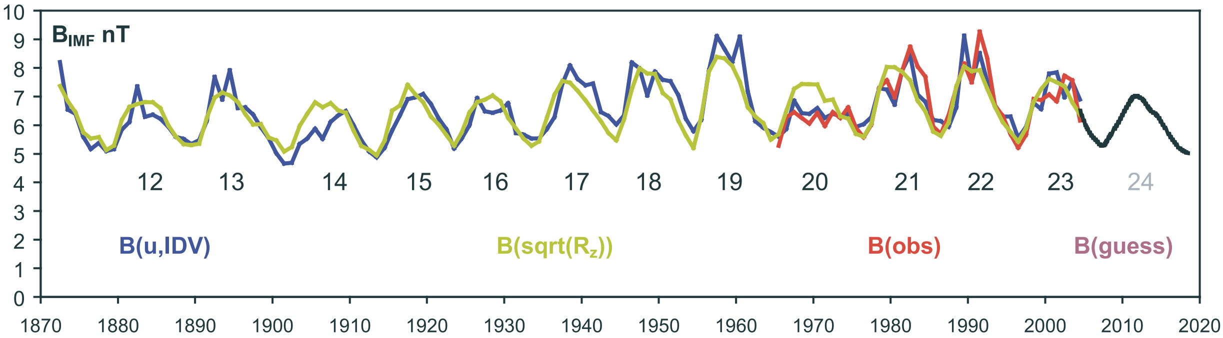


Figure 9. Variation of yearly averages of IMF B inferred from geomagnetic records (blue) and from sunspot numbers (green). Observed B is shown in red, while B predicted for cycle 24 is shown in black. Cycle numbers are indicated.

[22] Although it came as a surprise that there was no clear solar cycle dependence of IMF B during the first decade of spacecraft measurements [*King*, 1976], data from later cycles do show a strong solar cycle relationship. Having 13 cycles worth of B (inferred and observed) permits a study of this relationship with much improved statistics. The main sources of the equatorial components of the Sun's large-scale magnetic field are large active regions. If these active regions emerge at random longitudes, their net equatorial dipole moment will scale as the square root of their number. Thus their contribution to the average IMF strength will tend to increase as $R_Z^{1/2}$ (for a detailed discussion, see *Wang and Sheeley* [2003] and *Wang et al.* [2005]). We find, indeed, that there is a linear relation between B and the square root of the R_Z as shown in Figure 8.

[23] The best-fit ($R^2 = 0.71$) regression equation is

$$B(\mathrm{nT}) = (4.62 \pm 0.16) + (0.273 \pm 0.015)R_Z^{1/2}, \qquad (3)$$

where R_Z is the Zürich (International) Sunspot Number. Using the Group Sunspot Number gives essentially the same result. Using equation (3), we can then calculate B from R_Z for comparison with B derived from the geomagnetic record (Table 3). The result is shown in Figure 9. Although there are areas of disagreement, e.g., for cycles 14 and 20 (for the latter also seen in cosmic ray intensity correlations with B [e.g., *Wibberenz et al.*, 2002]), possibly due to ecliptic-only sampling of a global solar property, the overall fit is encouraging. As will be explored elsewhere, equation (3) permits the possibility of estimating B back to the beginning of the sunspot time series.

8. Conclusion

[24] It is pleasing that the u measure introduced by Bartels nearly 75 years ago (following *Moos* [1910]) as a long-term measure of geomagnetic activity is capable, in the light of modern knowledge, of providing insight on the variability of the solar wind for periods preceding the space age. The equivalent *IDV* index that we have derived suggests that the IMF B is the sum of a fixed amount and a component that varies with the square root of the sunspot number. We find that solar cycle average B increased by ~25% between the 1900s (cycle 14) and the 1950s (cycle 19) and is now again becoming smaller. This behavior stands in contrast to the more than doubling of B during the 20th century obtained from an analysis of the *aa* index by *Lockwood et al.* [1999]. If the coming cycle 24 is as small as predicted (peak R_Z = 75 [*Svalgaard et al.*, 2005]), the long-term average of B should be approaching its value circa 1900 of ~5 nT by ~2018. The B and *IDV* variations we obtain during the 20th century are consistent with the results of *Le Sager and Svalgaard* [2004], who found that there was no increase of the interplanetary near-Earth electric field since 1926, and with the reconstruction of D_{st} back to 1932 by *Karinen and Mursula* [2005, cf. Figure 5]. In contrast to the *IDV* index, midlatitude range indices such as *aa, ap,* and *am* are dependent on both solar wind speed (squared) and IMF, enabling one to determine V once B is known. Investigation of the evolution of V over time will be the subject of a future report.

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