

# DETERMINATION OF INTERPLANETARY MAGNETIC FIELD STRENGTH, SOLAR WIND SPEED, AND EUV IRRADIANCE, 1890-2003

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## ABSTRACT

A newly constructed long-term geomagnetic index, the interdiurnal variability (the IDV index; defined to be the unsigned difference between hourly averages of the H-component of the field near local midnight at a mid-latitude station for consecutive days), has the useful property that its yearly averages are highly correlated with the solar wind magnetic field strength ( $B$ ) and are independent of solar wind speed ( $V$ ). Existing geomagnetic records allow us to construct IDV since 1890 and thus to determine solar wind  $B$  over that period. Once  $B$  is known, we use other long-term indices with known dependence on  $B$  and  $V$  to determine the variation of  $V$  since 1890. Average  $B$  during 1872-2003 was 6.4 nT with no long-term trend (other than a general correlation with the sunspot number) and average  $V$  for the interval 1890-2003 was 433 km/s also with no apparent trend. These results are confirmed using polar cap data available from 1926 to the present and magnetic observations of the Amundsen and Scott polar expeditions for years near 1900. Focusing on geomagnetic activity at local midnight hours cleanly separates the EUV-regulated regular variation ( $S_R$ ) of geomagnetic activity from the solar wind driven component, allowing us to determine EUV variability since 1901. Using older data, all these time series might be extended possibly back to the 1780s.

## 1. THE IDV INDEX

Bartels [1] introduced the  $u$ -measure of geomagnetic activity as a station-weighted mean of the interdiurnal variability  $U$  of the horizontal intensity at each station given as the difference between the mean values for a day and for the preceding day taken without regard to its sign. The basic idea is due to early work by Moos [2] at Colaba in India. The  $u$ -measure could be criticised of being possibly contaminated by the regular daily variation  $S_R$ , since the day-to-day variability of  $S_R$  should contribute to the interdiurnal variability of  $U$ . Mayaud [3, p.13] tried to evaluate the importance of the contamination by using only the first and the last

six hours of the local day instead of all 24 hours. Thus the daytime hours are eliminated and most of the contribution of  $S_R$  should be eliminated as well. He was astonished at how small the contamination actually was. We take Mayaud's lead, but further limit the time interval to only one hour (taken to start one hour after local midnight), and construct the InterDiurnal Variability index (IDV) for a given station as the unsigned difference between two consecutive days of the average value of the field component (usually H, although, in principle, we can do this for all three components) for that hour and assigned to the first day. The  $u$ -measure was expressed in units of 10 nT. We have chosen to use 1 nT units throughout.

A further criticism [4] of the  $u$ -measure was that it clearly failed to register the very high activity in the year 1930, resulting from extensive recurrent streams, much as we observed in 1974 and actually right now as well, and clearly shown in the daily character-figure, the  $C_i$  index.. This problem was so severe that Bartels eventually (after some struggle [6]) abandoned the  $u$ -measure and went on to invent the very successful  $K$ -index that we use to this day. His parting shot [5, p.394] was:

“In conclusion, we may roughly classify solar phenomena according to their effects on the earth's magnetism as follows: (1) Individual flares of ultra-violet light: these produce brief geomagnetic effect simultaneous with radio fade-outs. (2) The general change of ionizing wave-radiation in the course of the sunspot cycle; this governs the general intensity of the solar daily variation. (3) Moderate corpuscular radiation: this produces ordinary aurora and minor magnetic disturbances, and is the main factor governing the daily character-figure  $C$ . (4) Intense corpuscular radiation: this produces magnetic storms, and aurorae outside the auroral zone. It is the main factor affecting the  $u$ -measure of magnetic activity.”

Fig. 1 shows yearly averages of the  $u$ -measure (in 1 nT units) from 1872 through 1936, and of the IDV-index

since 1890 (normalized as described in the Figure caption). 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, and 1994. 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.

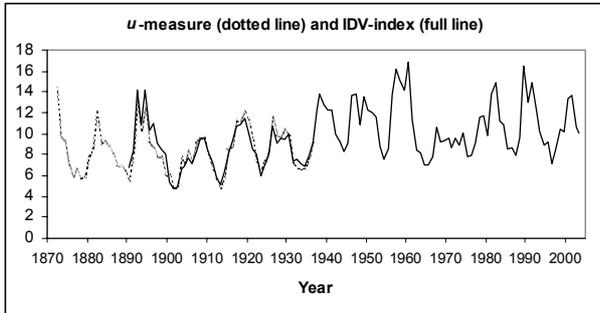


Fig. 1. Yearly means of the  $u$ -measure (in 1 nT units) for 1872-1936 (dotted line) and of the IDV-index (also in 1 nT units) for 1890-2003 (full line; the data for 2003 goes only through May). The IDV index was derived as the simple mean of values from several midlatitude stations normalized to have the same mean as the IDV values for Niemegek (NGK) for the interval 1943-73.

## 2. CORRELATION WITH THE NEAR-EARTH INTERPLANETARY MAGNETIC FIELD

Although the IDV index fails to register the influence of the solar wind speed, there is a robust correlation between the IDV index (and therefore the  $u$ -measure, were its calculation continued to the present day) with the interplanetary magnetic field,  $B$ . This is shown in Fig. 2, using near-earth data from 1964 to the present.

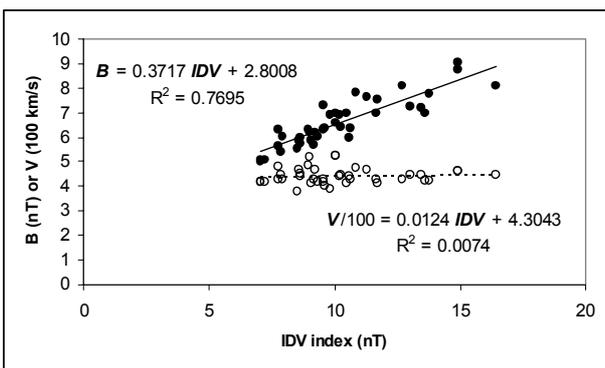


Fig. 2. Correlations between the IDV index (1964-2003) and the magnitude,  $B$  (filled circles), of the interplanetary magnetic field, and the solar wind speed,  $V$  (open circles) near the Earth.

The lack of correlation with  $V$  is also evident in Fig. 2. Using the regression formula we can calculate

$$B = 0.372 IDV + 2.8 \text{ nT} \quad (1)$$

Fig. 3 compares the calculated and observed yearly averages of the interplanetary magnetic field magnitude.

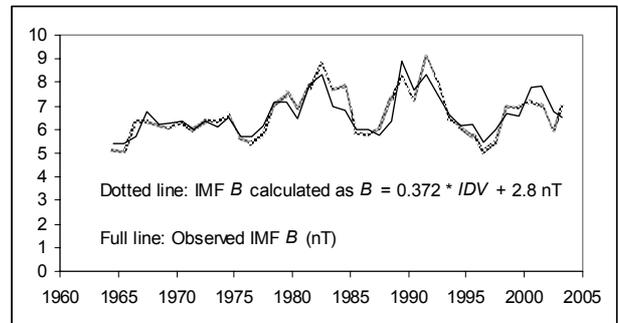


Fig. 3. Observed (full line) near-earth interplanetary magnetic field (yearly means) for 1964-2003. The dotted grey line shows values of  $B$  calculated from eq. (1).

If we assume that the same relationship holds in general (or at least within the range of IDV for which it was derived) we can infer the interplanetary magnetic field magnitude back to 1872. Fig. 4 shows the result.

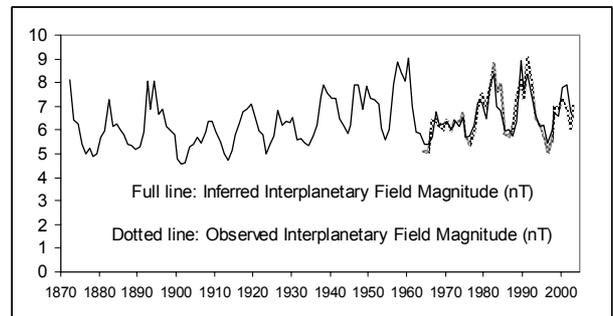


Fig. 4. Interplanetary magnetic field magnitude,  $B$ , near the earth inferred (full line) from the  $u$ -measure 1872-1889 and from the IDV index 1890-2003. The observed yearly means (since 1964) of  $B$  are shown with a dotted grey line.

## 3. CORRELATION WITH SUNSPOT NUMBER

It is clear from Fig. 1 that the IDV index exhibits a strong solar cycle dependence. This is expressed more explicitly in Fig. 5. A linear relationship does not do justice to the data as a clear “downturn” is indicated for low values of the sunspot number. The correct functional form (if any) is, of course, unknown. We arbitrarily assume a relation of the form  $a + bR^b$ . The Group Sunspot Number [7],  $R_G$ , and the Zürich Sunspot Number,  $R_Z$ , show the same dependency

within the accuracy of the data. The fit ( $R^2 \sim 0.7$ ) is best with an exponent  $\beta$  near 0.5. We choose  $\beta = 1/2$  and fit the coefficients  $a$  and  $b$ :

$$IDV = 4.67 + 0.721 R^{1/2} \text{ nT} \quad (2)$$

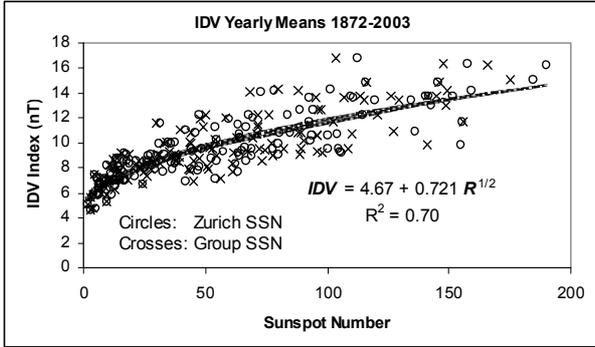


Fig. 5. The IDV index (1890-2003; 1872-89  $u$ -measure) dependence on the Zürich Sunspot Number (circles) and on the Group Sunspot Number (crosses). The relation (2) is shown with a shaded line.

Combining (1) and (2) we obtain an estimate of  $B$  solely from the sunspot number:

$$B = 4.54 + 0.268 R^{1/2} \text{ nT} \quad (3)$$

Armed with eq.(3) we can speculatively infer  $B$  from the Sunspot Numbers and compare the result (Fig. 6) with  $B$  inferred from IDV.

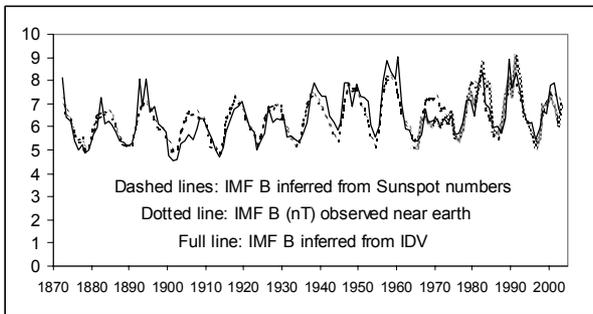


Fig. 6. Observed (nT) near-earth interplanetary magnetic field (dotted grey line) compared with  $B$  inferred from IDV (full line) using eq.(1) and from the Sunspot Numbers (dashed lines) using eq.(3). Both the Group and the Zürich Sunspot Numbers were used, but it is hard to tell the difference.

Although there are clear discrepancies (e.g. in cycles 20 and 14), the general agreement is encouragingly good. We speculate from eq.(3) that the interplanetary magnetic field results from two components, a relatively steady component ( $\sim 4.5$  nT) and a highly

variable, additional component that simply follows the total magnetic flux indicated by the sunspot number.

If this were the case, we would expect to see the influence of the variable component on time scales on the order of solar rotation or shorter. Monthly means of  $B$  should then correlate with monthly means of the sunspot number. Fig. 7 shows how well. On the shorter time scale the scatter is larger, but the agreement with eq.(3) is suggestive of some validity to our speculation.

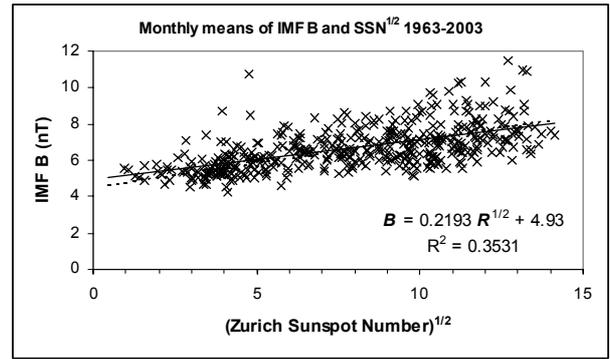


Fig. 7. Correlation between monthly means (since 1963) of the near-earth interplanetary magnetic field magnitude and the square root of the Zürich Sunspot Number. The dashed line indicate the relationship given by eq.(3).

There are indications [8, 9] that indeed active regions directly provide some of the IMF magnetic flux. That some kind of direct connection is involved may also be inferred (following Kotov [8]) from the very close relationship between the near-earth interplanetary magnetic field strength and the mean magnetic field of the sun-as-a-star (Fig. 8).

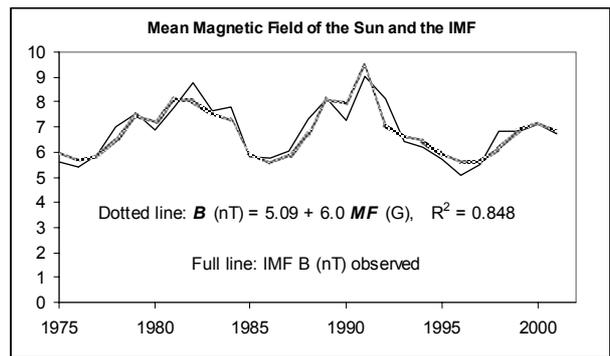


Fig. 8. The close relationship between the sun-as-a-star mean magnetic field measured at the Wilcox Solar Observatory ( $MF$  in Gauss) and the near-earth interplanetary magnetic field strength.

Because of line-of-sight projection and limb darkening, the mean field measured by solar magnetographs is essentially the average flux over the central 25% of the solar disk that at solar maximum supplies an extra 50% of magnetic flux to the interplanetary magnetic flux at the earth. It seems likely that most of that additional flux is concentrated at low heliospheric latitudes and that therefore the flux measured near the earth is not always extrapolative to higher latitudes of the heliosphere.

It is tempting to use eq.(3) to infer  $B$  back to the start of the sunspot number time series. There are, of course, several problems with this, the first one being that we do not even have accurate sunspot numbers before about 1750. A second problem is that we do not have assurance that the relationship is even valid that far back, since conditions may have been different during the Maunder Minimum. It is quite possible that the constant term in eq.(3) was smaller, we simply do not know. On the other hand, sunspot maxima even during the interval 1650-1700 had sunspot numbers within the observed range on which eq.(3) is based. Fig. 9 shows the result of our extrapolation.

for speculation. If the next couple of solar cycles (as expected) turn out to be very weak, we may be able to constrain the estimates by real data.

#### 4. THE IHV INDEX

Svalgaard *et al.* [16] recently introduced the InterHour Variability (IHV) index defined as the sum of the differences, without regard to the sign, of hourly means (or values) for a geomagnetic component from one hour to the next over the six-hour interval around local midnight where the  $S_R$  variation is absent or minimal. They concluded that (1) a measure of geomagnetic activity could be constructed that on a statistical basis (e.g. monthly means) can be used as an accurate proxy for the  $am$ -index. (2) The index is objective in the sense that it is derived from simple hourly averages (or values) without any problematic attempt to eliminate the variations not caused by the solar wind. (3) IHV-indices derived from several stations substantially agree. (4) The IHV-index does not exhibit a secular increase over the last one hundred years. (5) The IHV-index disagrees with the  $aa$ -index before 1957. (6) The IHV-index agrees with the  $ap$ -index since 1932.

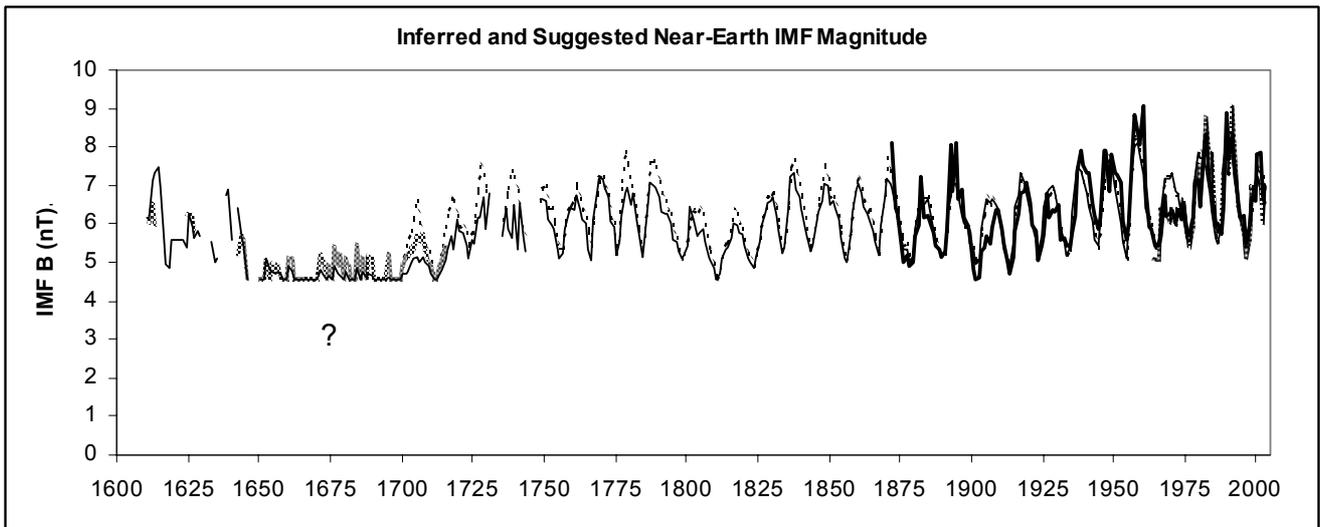


Fig. 9. The near-earth interplanetary magnetic field magnitude inferred from the IDV index (thick full line), and conjectured (based on eq.(3)) using the Group Sunspot Number (thin full line), the Zürich Sunspot Number (dashed line), and the sunspot numbers during the Maunder Minimum derived by Eddy [10] (dotted grey line). Observed values (yearly means) are shown using a thick dotted grey line since 1964.

It has been suggested [11, 12, and others] that the interplanetary magnetic field was very weak (by a factor from 5 to 10) during the Maunder Minimum. Evidence from some auroral counts [13] and a healthy  $^{10}\text{Be}$  modulation during the Maunder Minimum [14] suggest that perhaps the interplanetary magnetic field was not down by an order of magnitude, because the modulation strength seems to be roughly proportional to the open magnetic flux [15]. There is ample room

Fig. 10 compares yearly means of the IHV index with the  $aa$ -index. It is evident that the two indices agree well since 1957 (cross correlation coefficient 0.985, Fig. 11). We shall assume that the  $aa$ -index is in need of a recalibration before 1957 and that the IHV index is as good a proxy of such a recalibrated  $aa$ -index before 1957 as after 1957.

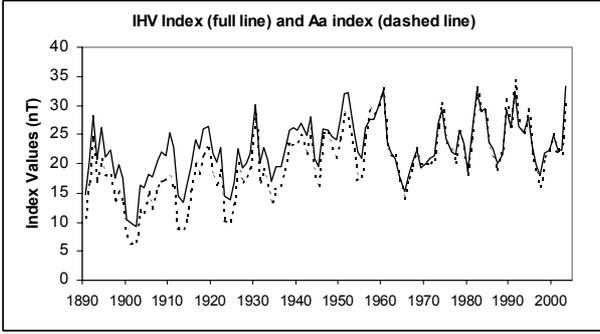


Fig. 10. The IHV-index (full line) and the  $aa$ -index (dashed line) since 1890.

Numerous studies [see *e.g.* 17 and references therein] indicate that the  $aa$ - and  $am$ -indices respond to the product of the square of the solar wind speed and the interplanetary magnetic field strength (mostly including a geometrical factor emphasizing the southward component in an appropriate co-ordinate system). Fig. 11 shows first how extremely well ( $R^2 = 0.9694$ )  $Aa$  and IHV correlate (since 1964), then how well  $BV_0^2$  correlates with IHV ( $R^2 = 0.8837$ ).  $V_0$  is  $V/100$  km/s.

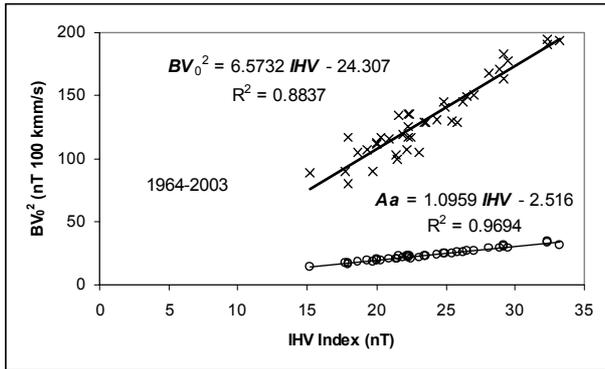


Fig. 11. Correlation between yearly means of  $Aa$  (circles) and IHV. And between  $BV_0^2$  and IHV (crosses), where  $V_0$  is  $V/100$  km/s. The data covers the interval 1964-2003.

It thus seems that  $BV_0^2$  with fair accuracy ( $R^2 = 0.88$ ) can be determined from the IHV index:

$$BV_0^2 = 6.573 IHV - 24.3 \quad (4)$$

The inverse relation can be approximated ( $R^2 = 0.85$ ) without an offset by an expression of the form:

$$IHV \sim Aa \sim (BV_0^2)^{0.8} \sim B^{0.8} V_0^{1.6}$$

very similar to the form deduced by Stamper *et al.* [17]. Within the dynamic range of the data there is no

significant difference between the various forms and either can be used. We shall use eq.(4).

Fig. 12 shows  $BV_0^2$  reconstructed from IHV using eq.(4) compared with observed yearly means.

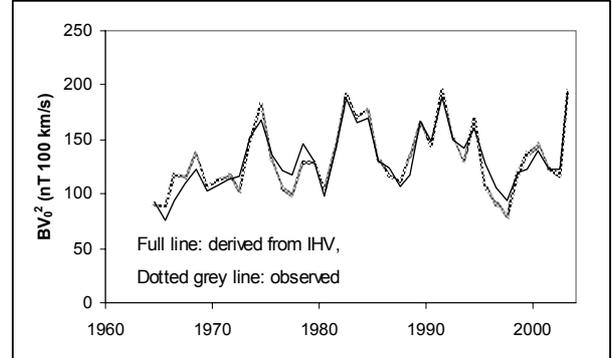


Fig. 12. Comparison of observed (dotted grey line) and reconstructed values (full line) of  $BV_0^2$  where for 1964-2003.

## 5. SEPARATION OF THE INFLUENCE OF MAGNETIC FIELD STRENGTH AND SOLAR WIND SPEED

The importance of the two new indices lies in the fact that they respond differently to the interplanetary magnetic field strength and the solar wind speed, thus allowing the influence from both of these factors to be separated and determined. From eqs.(4) and (2) we get

$$V_0^2 = BV_0^2 / B = (6.573 IHV - 24.3) / (0.372 IDV + 2.8)$$

$$V = 420 \text{ km/s} ((IHV - 3.7) / (IDV + 7.5))^{1/2} \quad (5)$$

Fig. 13 compares computed and observed values of yearly means of  $V$  since 1964.

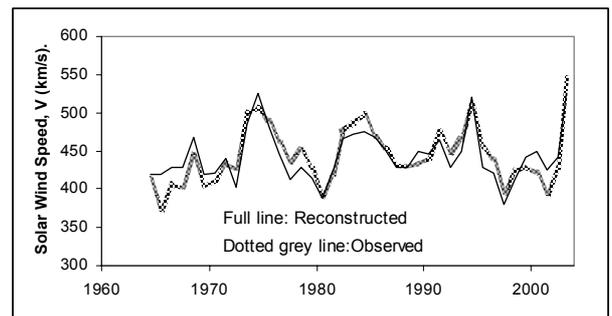


Fig. 13. Reconstructed (full line) and observed (dotted grey line) yearly means of solar wind speed since 1964. The linear cross correlation coefficient is 0.88 ( $R^2 = 0.770$ )

Under the usual assumption that the IHV and IDV indices are not in some way different before the space

age, we can reconstruct  $V$  back to 1890. Computing the hourly means is so straightforward that it is hard to claim that observers could not do this correctly before 1964, especially since absolute baseline problems are minimized by taking differences between hours. Fig. 14 shows the reconstructed solar wind speed back to 1890.

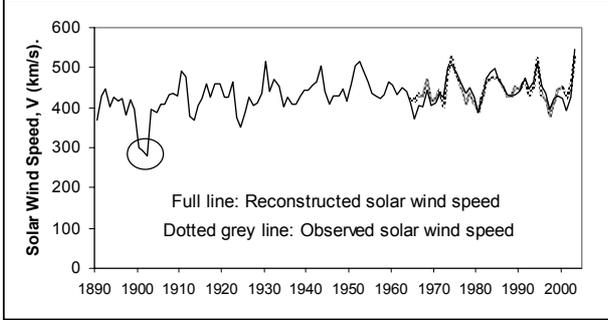


Fig. 14. Reconstructed solar wind speed (full line) using eq.(5). Observed yearly means are shown with a dotted grey line.

The years 1900-1902 seem to be in a class of their own with very low solar wind speed (275-300 km/s). No other years approach such low values. These years were also exceptionally quiet. Fig. 15 shows that in 1901 the number of intervals where  $aa = 2$  (its lowest possible value) was more than 50% of the total number of intervals, in other words, more than half the time there was no measurable geomagnetic activity *at all* (at least as given by the  $aa$ -index).

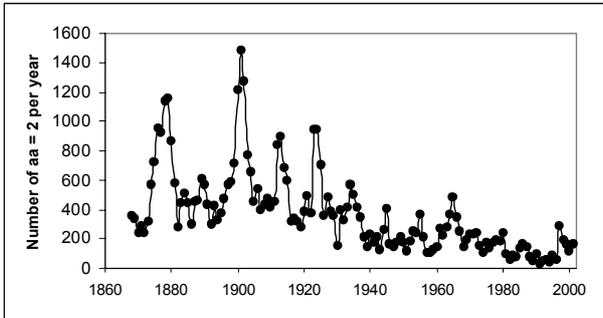


Fig. 15. The number of 3-hour intervals per year where the  $aa$ -index was at its lowest possible value ( $=2$ ). The abrupt change of the frequency of  $aa = 2$  in 1938 is likely due to a change of instrument at the northern  $aa$ -station, Abinger [18].

## 6. COMPARISON WITH THE STAMPER *et al.* [17] RECONSTRUCTION OF $B$ AND $V$

Reference [17] contains formulae for computation of  $B$  and  $V$  using yearly means of the  $aa$ -index and the

Sargent Recurrence Index,  $I$  [19]. We simplify their expressions by ignoring the secular change in the dipole moment of the earth (mostly because it is not clear what effect it has and also because the effect, if any, is small). They define a function  $f_p$  proportional to the solar wind speed:

$$V \text{ km/s} = 21.425 f_p \quad (6)$$

where  $f_p$  is given by

$$f_p = ((I aa^5)^{0.263} + 72.61)^{0.641} \quad (7)$$

The constant 72.61 is given in [17] as  $c_f/s_f$  where  $c_f = 1893000$  and  $s_f = 26070$ . Because of this constant,  $V$  is bounded below at 334 km/s (when  $I = 0$ ).

The field strength  $B$  can then finally be computed from

$$B \text{ nT} = 49.2 aa^{1.295} / f_p^2 \quad (8)$$

The constants in eq.(6) and (8) have been adjusted to match the observed values for 1964-2003. This assumes that the number density (that also enters into the original Stamper *et al.* expression) can be replaced by a constant.

When the solar wind does not show any recurrence tendency, the Sargent index,  $I$ , fluctuates randomly between +0.05 and -0.05. Clearly eq.(7) has a problem with negative values of  $I$ . We overcome this by setting all values of  $I$  that are smaller than 0.05 to 0.05 (nine years out of 114). We don't know how Stamper *et al.* handled this problem. Using  $IHV$  instead of  $aa$  (to overcome the calibration problem with the  $aa$ -index), we can now determine the solar wind speed using eqs.(6) and (7). Fig. 16 shows the result.

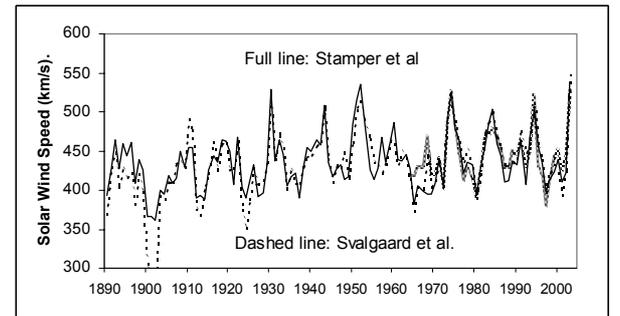


Fig. 16. Reconstructed solar wind speed using the Stamper *et al.* formulae (full line) and the result from the present paper (dashed line). Observed values are indicated by the dotted grey line.

In general, there is good agreement ( $R^2 = 0.8$ ) between our values and Stamper *et al.* suggesting some validity to their scheme in spite of the *ad hoc* functional form

of eq.(7). Stated in other words, the Sargent Index does fairly accurately indicate the presence of high-speed streams. The main areas of disagreement occur for the peak in 1968 and the deep minimum in 1900-1902.

Similarly, we can use eq.(8) to reconstruct  $B$ . Note that this Stamper *et al.* [17] reconstruction indirectly also involves  $V$  (through the  $f_p$  function). Fig. 17 shows the Stamper *et al.* reconstructed  $B$  compared to our reconstruction.

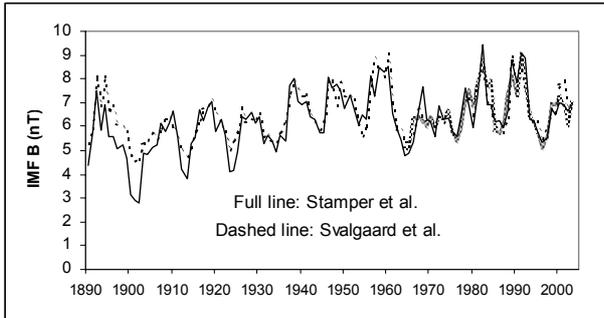


Fig. 17. Reconstructed interplanetary magnetic field magnitude using the Stamper *et al.* formulae (full line) and the result from the present paper (dashed line). Observed values since 1964 are indicated by the dotted grey line.

As for the solar wind speed, the agreement is generally good. The main disagreements are for sunspot minima before 1930, where the Stamper *et al.* reconstruction has sharply lower values of  $B$ . Comparison with Fig. 16 reveals that our values for  $V$  are low when Stamper *et al.*'s values for  $B$  are low. This is not surprising as the IHV index responds to  $BV^2$ . So  $B$  and  $V$  would tend to be anti-correlated for constant IHV.

It has been suggested [20] that the total open magnetic flux of the sun should tend to be constant in time since it can only be destroyed if open flux of opposite polarity reconnects, a process that may be unlikely since the open flux is ordered into large-scale regions of uniform polarity (especially at sunspot minimum). It is thus difficult to understand how the open flux (the IMF) could drop drastically for a couple of years at minimum. On the other hand, we know of no process that could lower the solar wind speed instead. Maybe the truth is somewhere in between the two extremes.

## 7. COMPARISON WITH POLAR CAP ELECTRIC POTENTIAL

The horizontal component of the geomagnetic field measured within the polar caps of the earth has a particularly simple average diurnal variation: the end point of the component vector describes a circle with a

diameter (the "range",  $E$ ) of typically 100 nT.  $E$  is controlled by season (ionospheric conductivity) and by the interplanetary electric field  $VB$ . Averaging over a full year eliminates the dependence on conductivity and yearly average ranges have a strong linear dependence,  $VB = kE$ , (correlation coefficient 0.95) on  $VB$  as measured by spacecraft. This relationship holds for any station within the polar caps with only a slight variation of  $k$ . We have determined [21]  $k$  for three polar cap stations: Thule (data back to 1932,  $k = 24.4$  for  $V$  in km/s,  $B$  and  $E$  in nT) and Godhavn (to 1926,  $k = 31.3$ ) in the northern polar cap and Scott Base (to 1957,  $k = 27.4$ ) in the southern polar cap.

The noted Norwegian explorer Roald Amundsen wintered over with his ship "Gjøa" at "Gjøahavn". Magnetic recordings began on November 1<sup>st</sup>, 1903 and continued through May 1905 [22]. The National (British) Antarctic Expedition of 1901-04 under Robert F. Scott operated magnetographs at the Winter Quarters of the Expedition for nearly two full years (1902-03) [23]. The range of the diurnal variation has been determined for these two sets of observations. Magnetographs were in operation at Cape Evans, the base station of the British (Terra Nova) Antarctic Expedition during 1911 and 1912. Cape Evans and Winter Quarters are co-located with Scott Base. The range was also determined for this station [23]. However, this value represents only a *lower limit* to the true range because disturbed days, where the trace was not complete, were excluded. We can calibrate these early ranges using  $k$ -values derived from the modern data (using the  $k$ -value for Godhavn for Gjøahavn as well, as these two stations have nearly the same geomagnetic latitude.

We can now compute the product  $BV$  from our reconstructed values of  $V$  and  $B$  and compare the result to  $BV$  determined from the polar cap stations. The result is shown in Fig. 18.

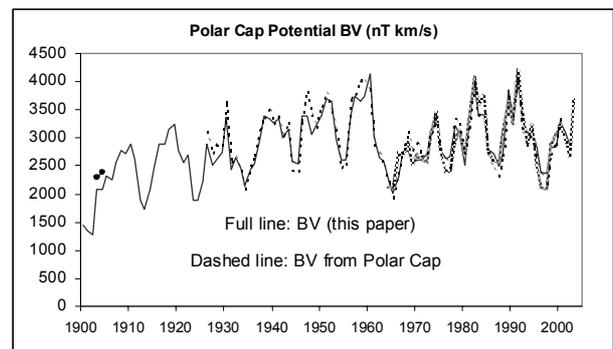


Fig. 18. Computed (full line)  $BV$  compared to  $BV$  determined from polar cap stations (dashed line). Two dots show the data from Gjøahavn and Winter Quarters.  $BV$  calculated from

observed yearly means of  $B$  and  $V$  are shown by the dotted grey line.

The agreement is substantial. It is worth stressing that the polar cap variations are due to different physical processes and that the polar cap data represents an independent check of our result.

## 8. THE SOLAR EUV FLUX

We have stressed the importance of using only local night hours to avoid contamination with the regular daily variation,  $S_R$ . On the other hand, the amplitude of  $S_R$  carries information about the solar EUV flux. Fig. 19 shows the amplitude of  $S_R$  at the stations Cheltenham/Fredericksburg since 1901. Also shown is the F10.7 radio flux since 1947. The cross correlation coefficient between the two is 0.97. To the extent that F10.7 is a proxy for EUV, we might say that the amplitude of  $S_R$  is too. We expect the amplitude of  $S_R$  to be a more direct measure of the EUV flux as it measures the effect of the EUV on ionospheric conductivity. The information in old geomagnetic records is tremendous and we are becoming better at extracting physical parameters from the old records.

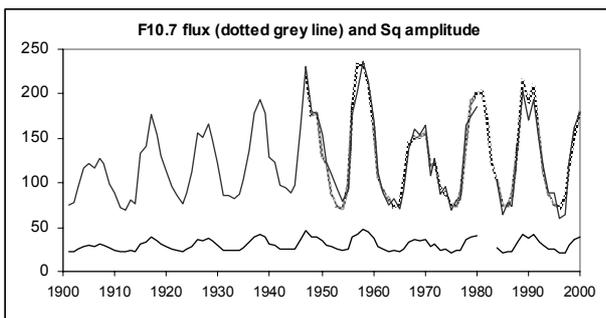


Fig. 19. The F10.7 radio flux (dotted grey line) and the amplitude of the  $S_R$  variation (full line, lower curve) at Cheltenham/Fredericksburg. The upper full-line curve is the amplitude of  $S_R$  scaled up using  $6.42(S_R) - 70.6$ .

## 9. CONCLUSION

We have shown that it is possible with fair accuracy to extract the solar wind speed and the interplanetary magnetic field strength near the earth from hourly means of the geomagnetic elements at midlatitude stations. Such records go back more than two hundred years. There is still much to be done, but it seems worthwhile to critically examine the old records and possibly extend the analysis reported here even further back in time.

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Acknowledgement : We are grateful to the World Data Centers for Geomagnetism for the availability of the hourly means of the geomagnetic elements.