Long-term Variations of Open Flux in the Solar Corona (The Open Flux Has Been Constant Since at Least 1840s)

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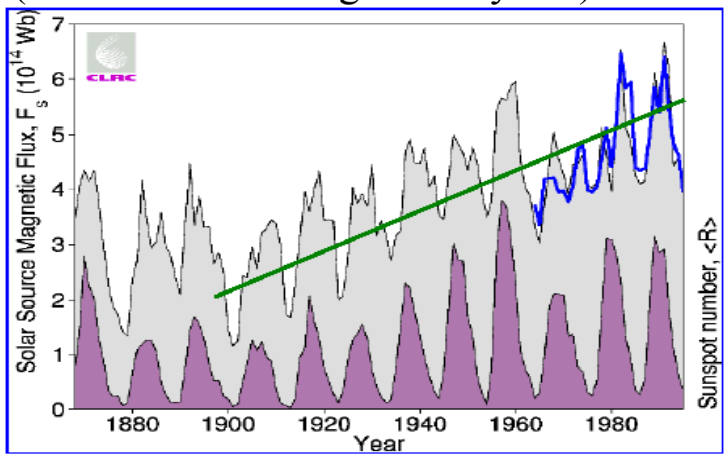
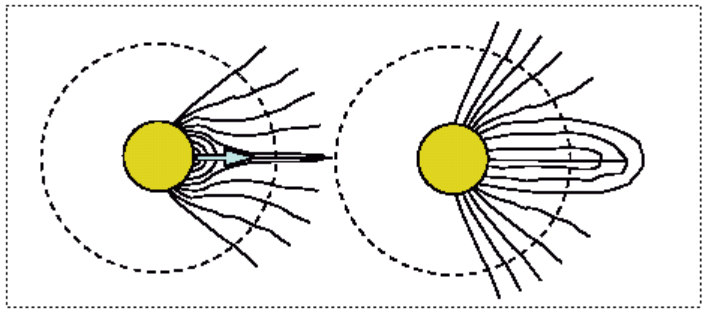
Abstract: The geomagnetic record allows us to infer the strength of the Interplanetary Magnetic Field, $|\boldsymbol{B}|$, at Earth for the past ~175 years. We find B to be $4.5 + 0.28\ (\mathrm{SSN})^{1/2}$ nT, where SSN is the sunspot number. We interpret the SSN-dependent part to be closed flux related to CMEs and flare ejecta, effectively riding on top of a constant minimum of open B of 4.5 nT. At each solar minimum as SSN goes to near zero, the field strength B approaches the same constant value of 4.5 [±0.5] nT (plus a small SSN-related residual if the SSN didn't go all the way to zero), corresponding to a nearly constant open flux of $\sim 4 \times 10^{14}$ Wb. We review the evidence (and the growing consensus) for this startling conclusion. As the sun's polar fields vary considerably from cycle minimum to cycle minimum, it seems that the Heliospheric field is not determined by the polar fields, contrary to what is commonly held. As the open flux apparently has stayed close to constant over the past ~175 years, it means that it, in particular, did not double during the past century. In fact, the IMF during the current cycle 23 is very much the same as it was during cycle 13 a century ago. The above conclusions are consistent with GCR-based determinations of B under the assumption that transients play a major role in GCR modulation.

What is "Open Flux"?

All open flux (*e.g.* M. Lockwood):
(more than doubling in 100 years)



Some open, some closed (*e.g.* P. Riley):



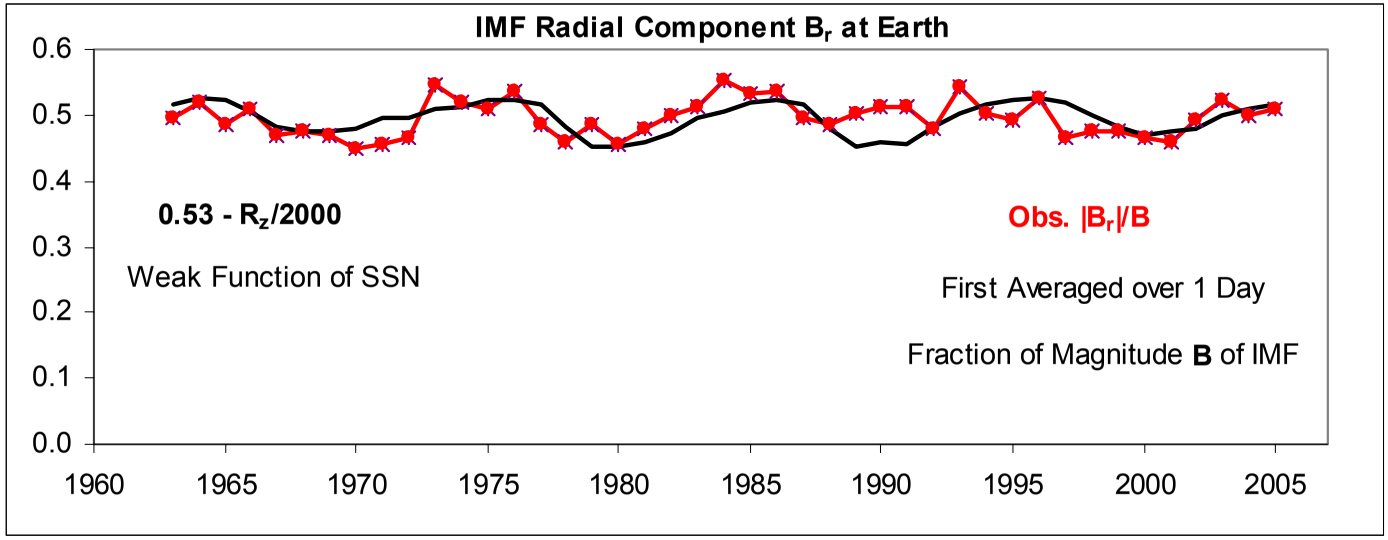
No open flux (Maxwell):

$$\nabla \cdot \mathbf{B} = 0$$

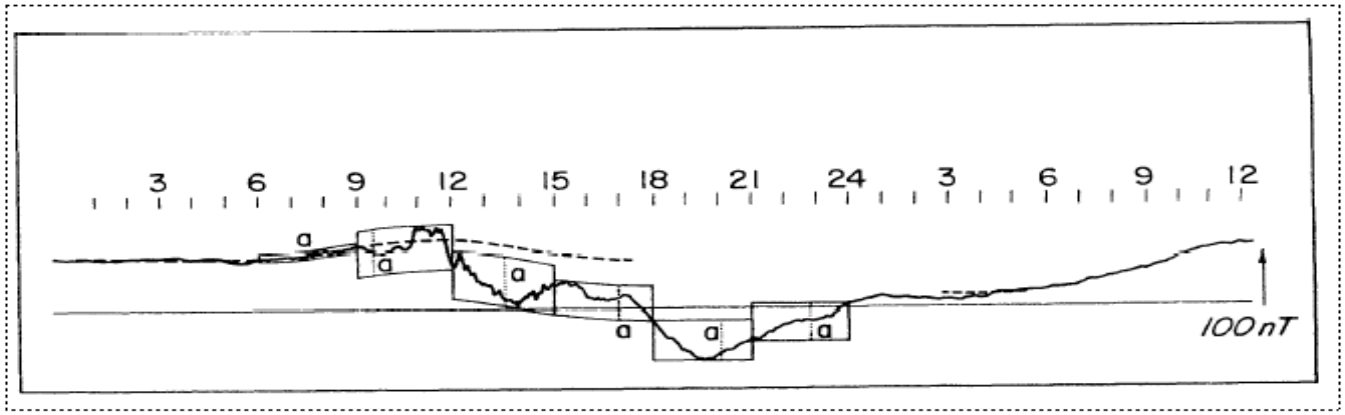
The (unsigned, to circumvent Maxwell) magnetic flux, F, in the Heliosphere is calculated by integrating the unsigned radial component, $|B_r|$ of the IMF over a surface ("effective" radius R_F) enclosing the Sun. There are some disagreements over whether to count the flux twice (once for each polarity), so we write

$$F = |B_r|\ 4\pi\ R_F^{\,2} / k \qquad \text{where } k = 1 \text{ or } 2.$$

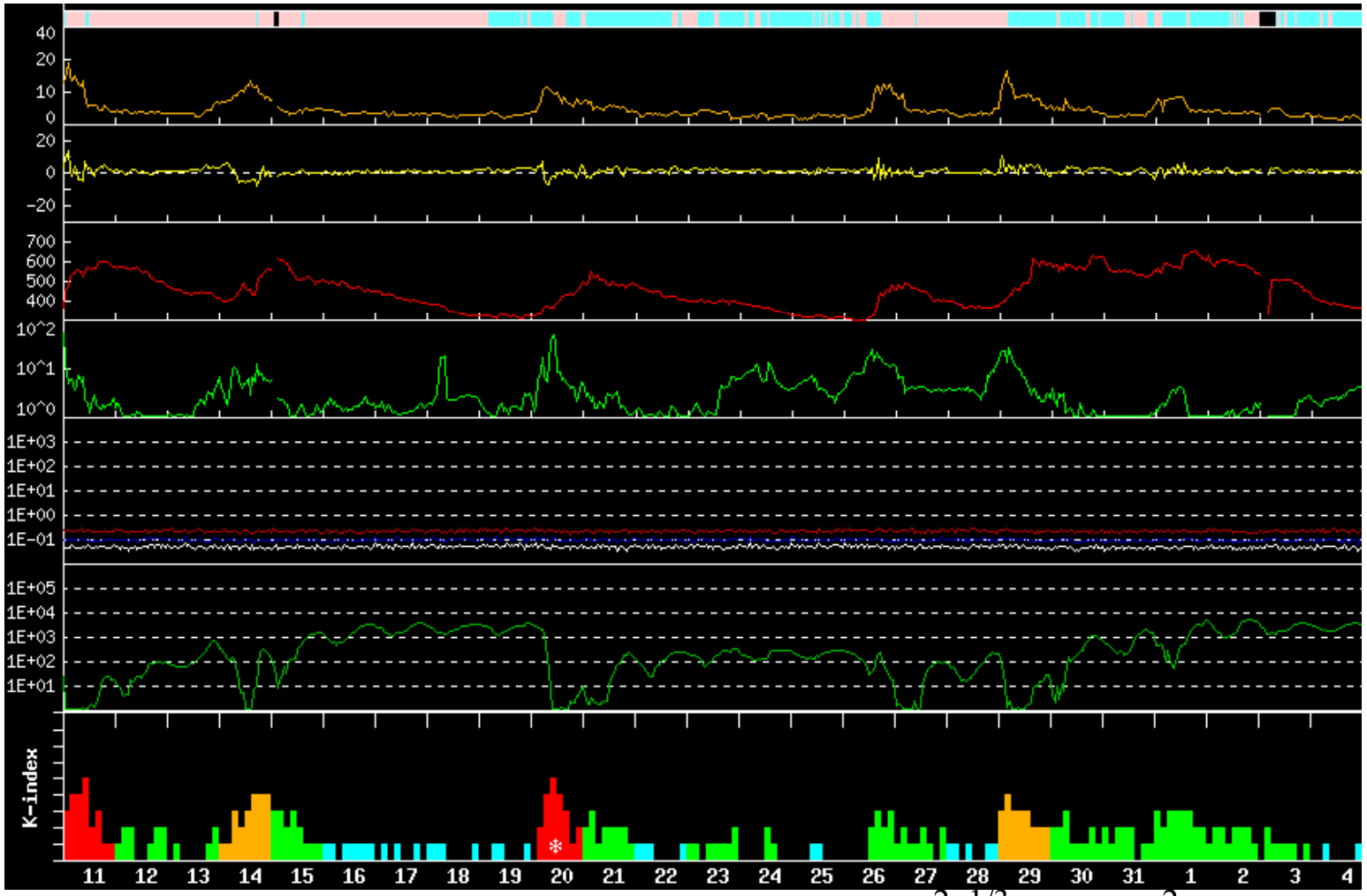
Calculating the radial component is tricky as the IMF varies considerably in direction on many time scales and B_r thus depends on the averaging interval. Often, as we are interested in the large-scale structure) one day is used. One finds that the ratio B_r/B is about 0.5 with a small (weak) variation with the SSN: more solar activity makes the direction vary more and thus lowers B_r/B slightly. To first order we can thus determine B_r from B. From geomagnetic activity we can determine B and thus estimate the long-term behavior of the flux.



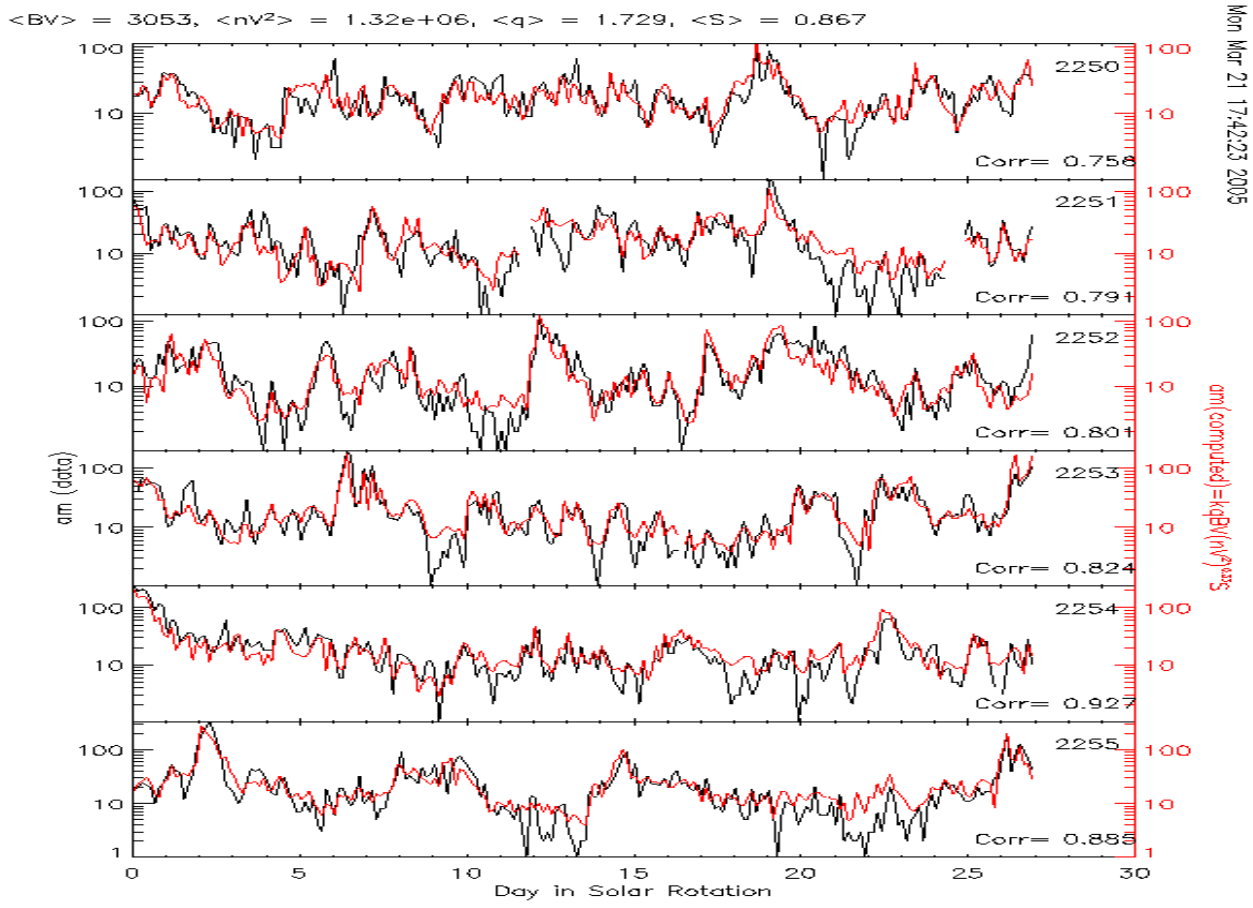
The Earth's magnetic field is confined by the solar wind to a "magnetosphere", which is sensitive to the interplanetary magnetic field and the kinetic energy of the solar wind impinging upon it. The resulting continual adjustment to the ever-changing solar wind conditions is called "geomagnetic activity". Here is a typical example (as measured at the surface of the Earth):



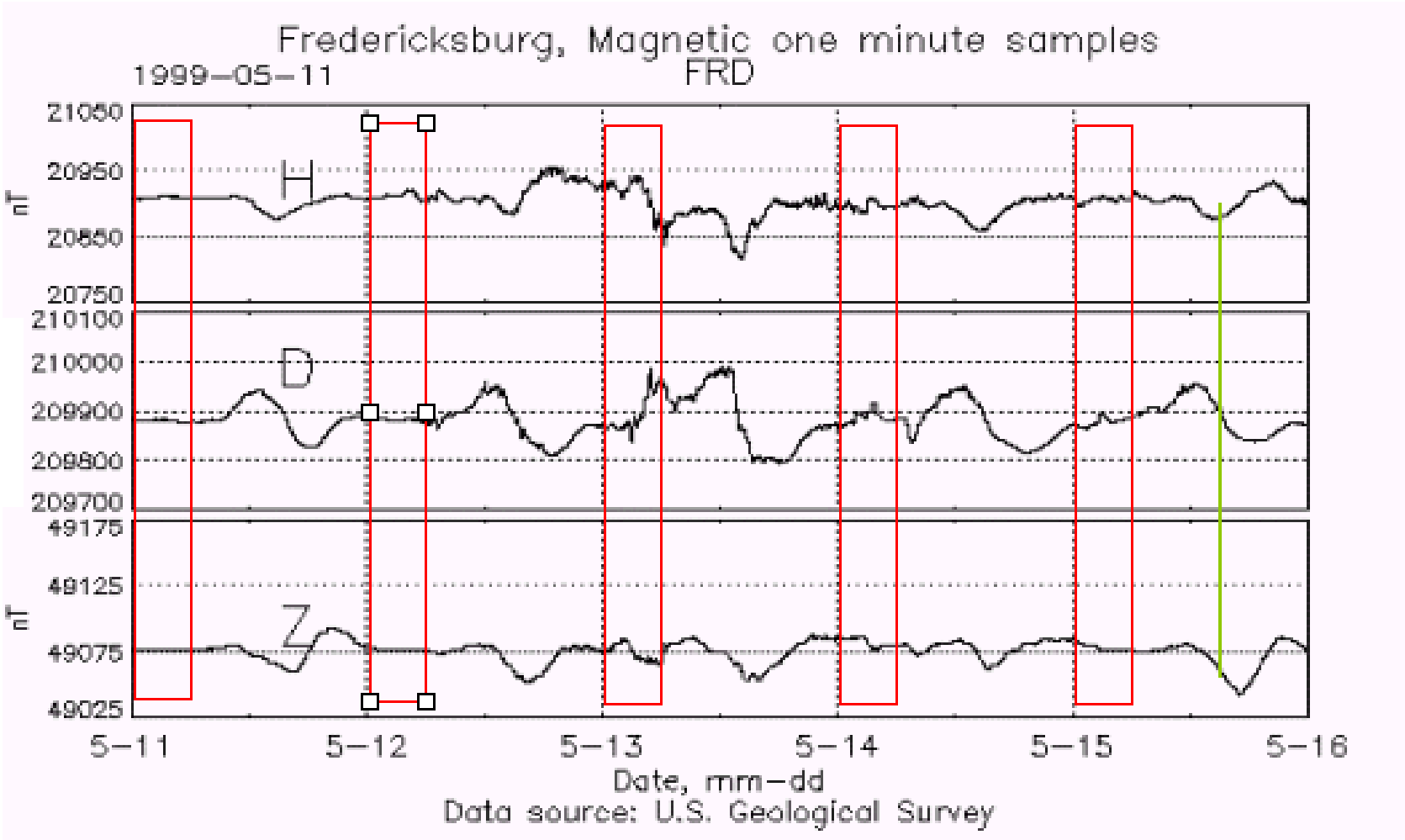
From the amplitude of the variation of the field within a certain interval (three hours in the above example) one constructs a geomagnetic "index" that codifies that variation and can be used as a proxy for solar wind conditions during the interval.



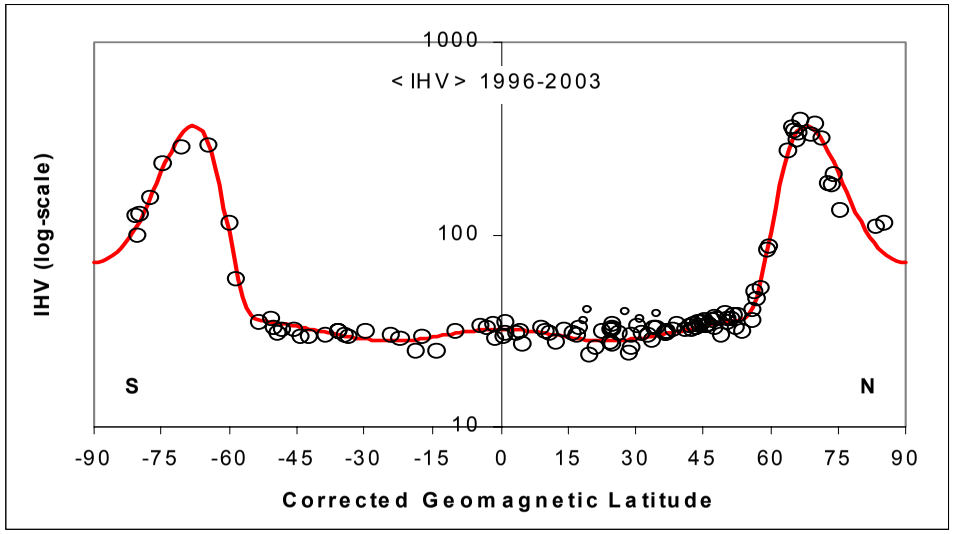
$$A = k\, q(a,f(V))\, (B\, V)\, (n\, V^2)^{1/3} \sim B\, V^2$$



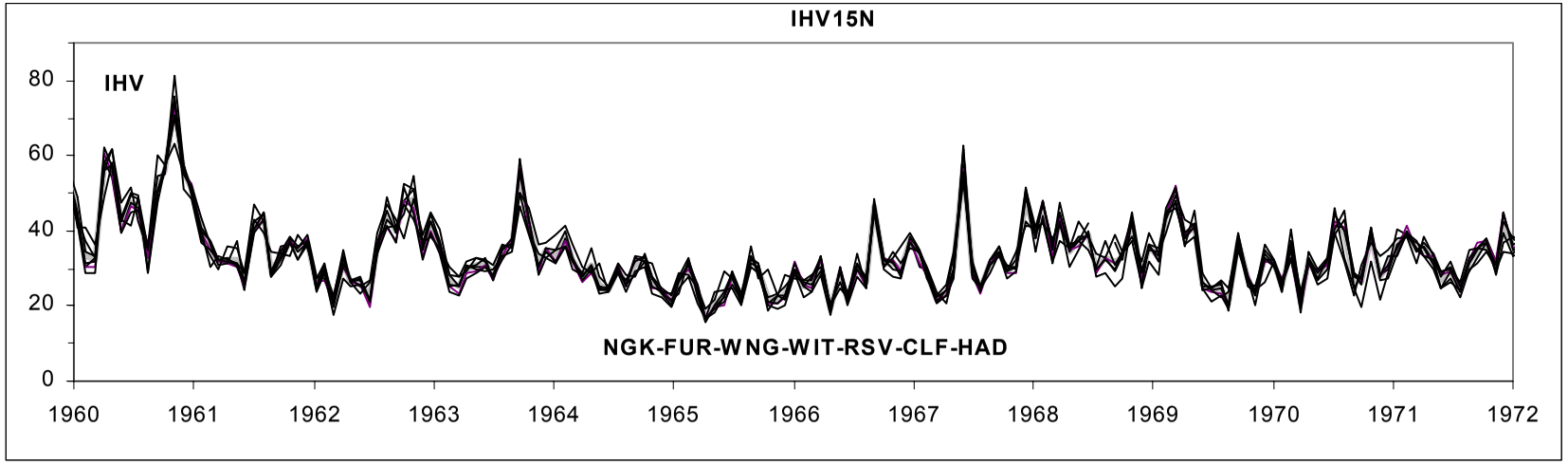
$$Cq = 13.22\exp(-1.090\cos\alpha+1.232f+0.417\cos^2\alpha+1.733f\cos\alpha+0.601f^2+0.141\cos^3\alpha-1.214f\cos^2\alpha$$
$$-2.033f^2\cos\alpha-2.044f^3+0.089\cos^4\alpha-0.116f\cos^3\alpha+0.801f^2\cos^2\alpha+1.262f^3\cos\alpha+1.050f^4)$$

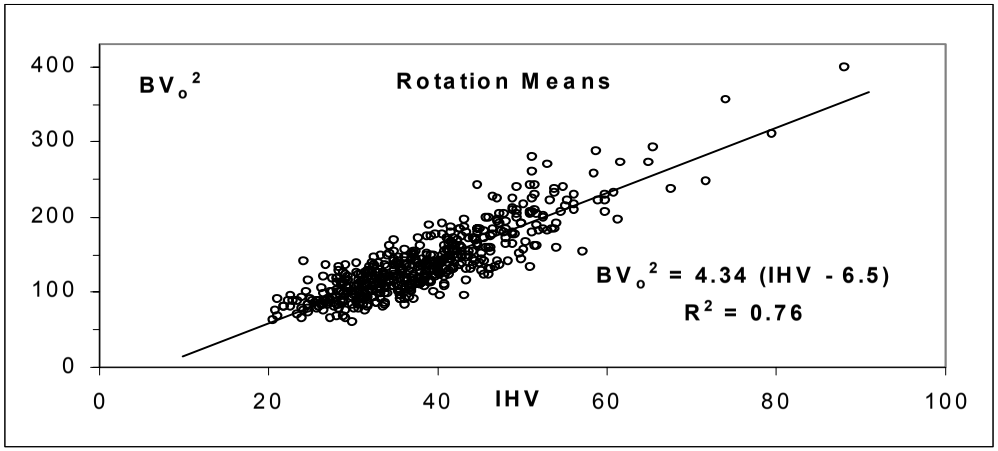


IHV = sum of unsigned differences between 7 hourly means centered at midnight

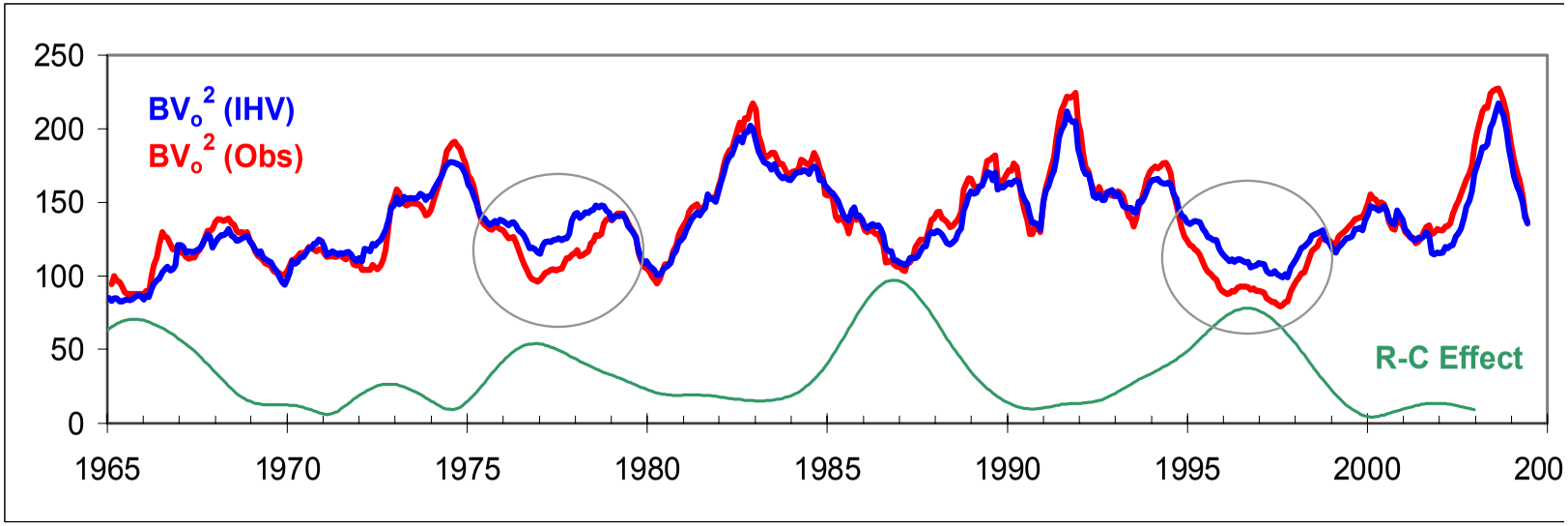


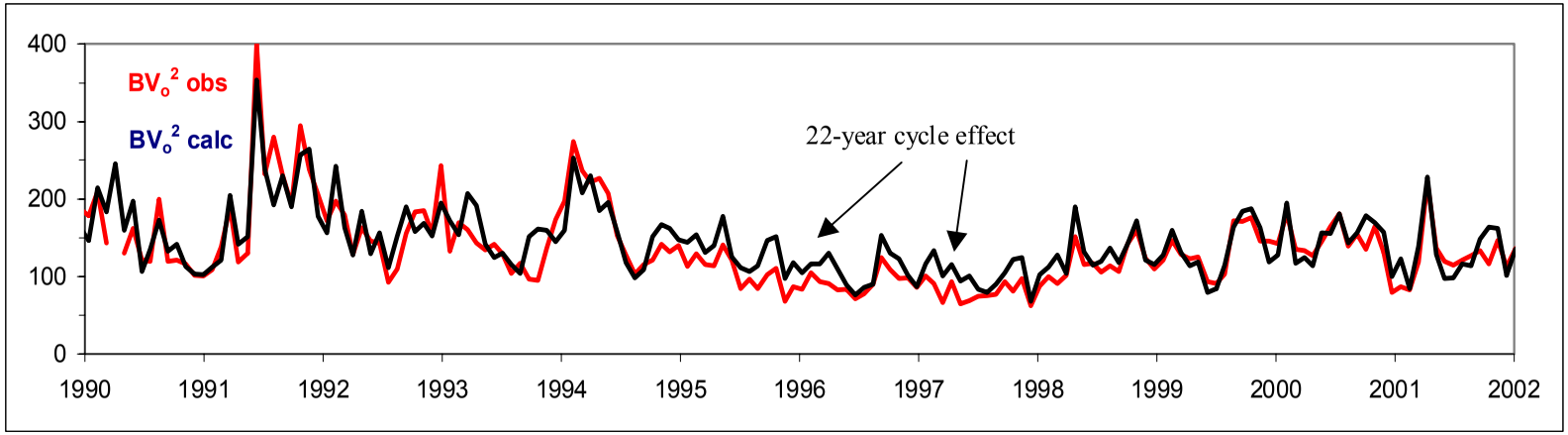
IHV-index is well-determined below 55 degrees geomagnetic latitude. For these mid-latitude stations the index is not very sensitive to secular changes in the geomagnetic field, e.g. the position of the poles.

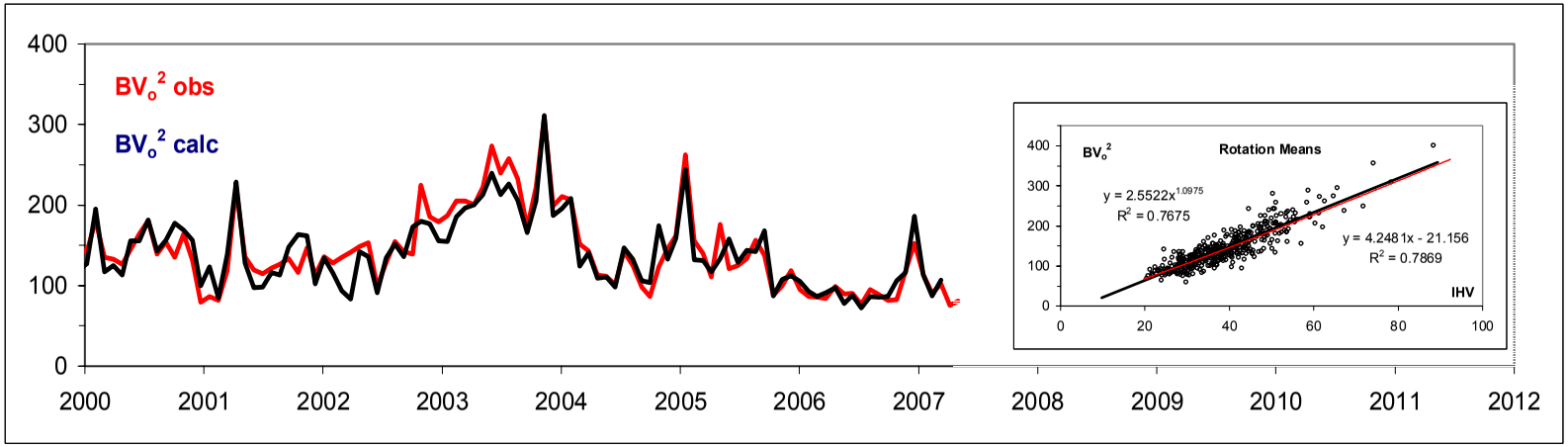


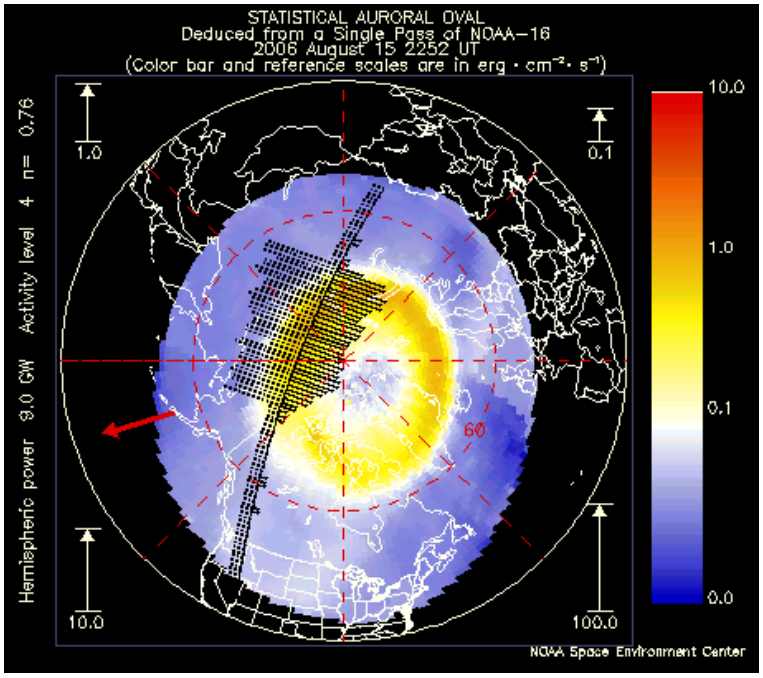


The IHV-index is strongly correlated with BV^2 on a 27-day rotation basis.
There are some second-order effects that we can either ignore (they are small) or correct for. Note high-speed streams in 1974 and 2003.

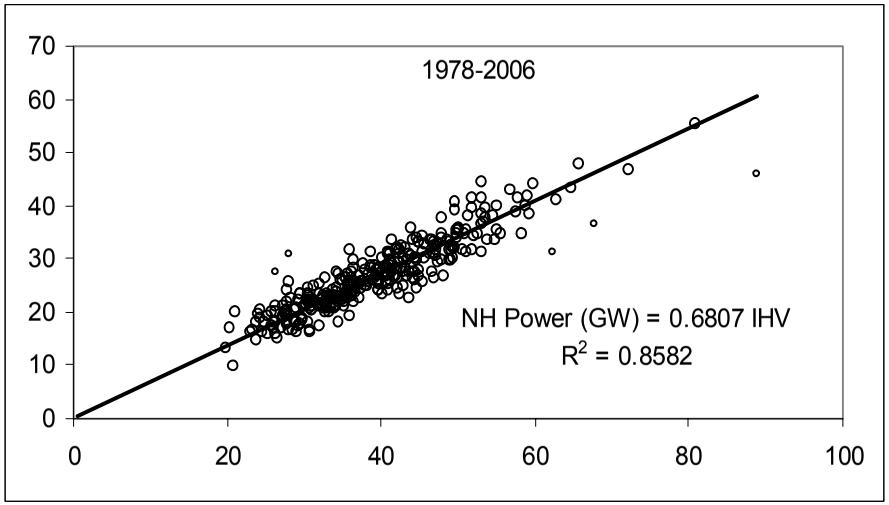


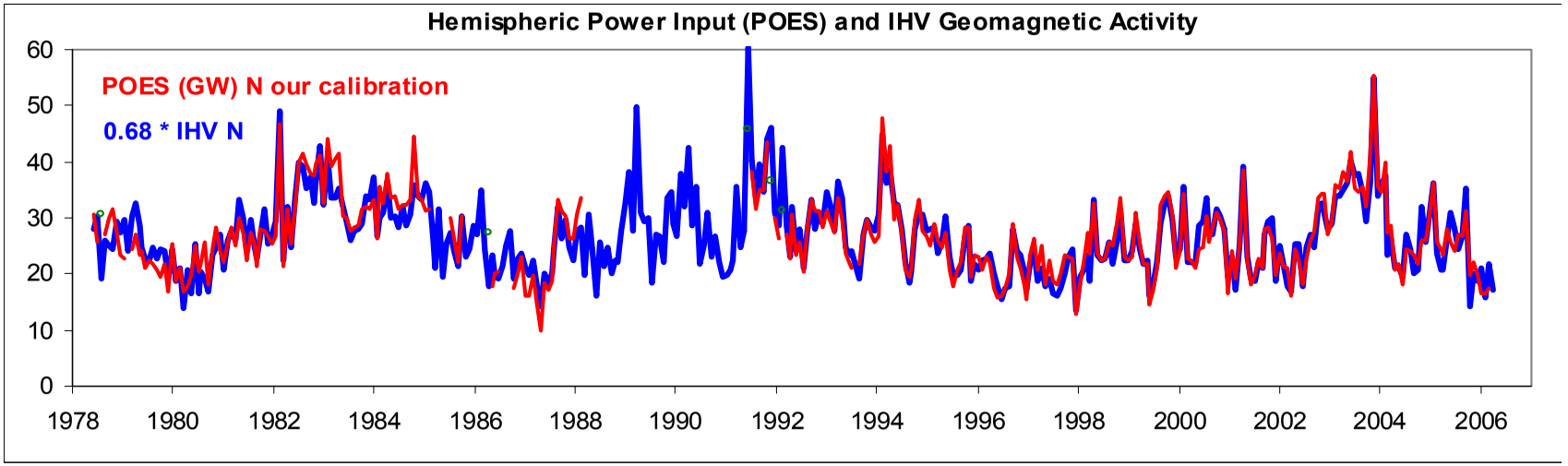

400
300
200
100
0
BV_o^2 obs
BV_o^2 calc
22-year cycle effect
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002


400
300
200
100
0
BV_o^2 obs
BV_o^2 calc
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
BV_o^2
Rotation Means
$y = 2.5522x^{1.0975}$
$R^2 = 0.7675$
$y = 4.2481x - 21.156$
$R^2 = 0.7869$
IHV
0
20
40
60
80
100

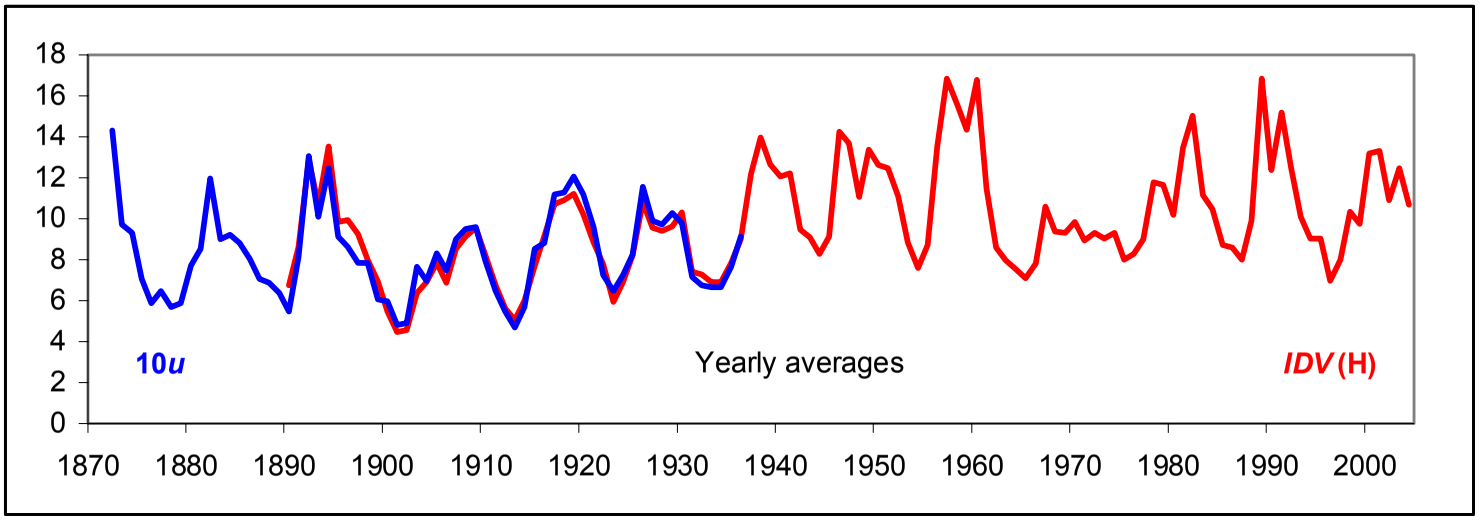


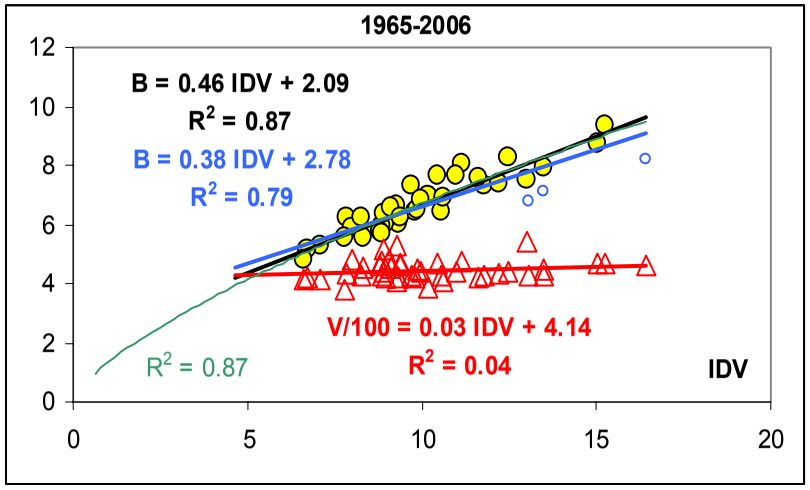
Physical meaning of the IHV-index = Energy input to upper atmosphere

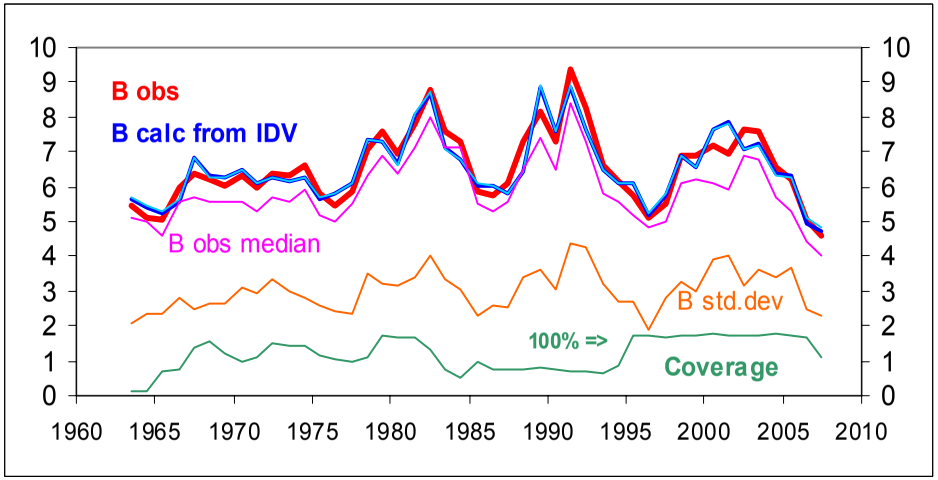




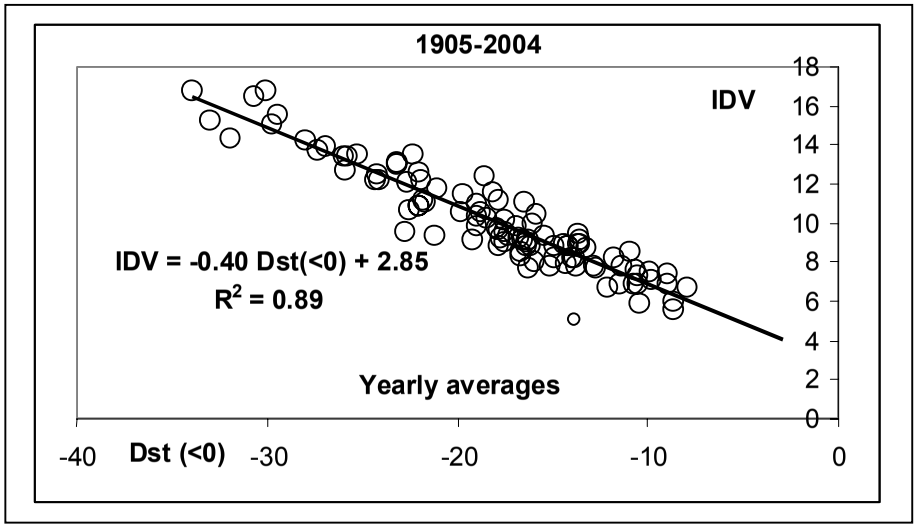
IDV = Average unsigned difference between the midnight hourly means from one day to the next.





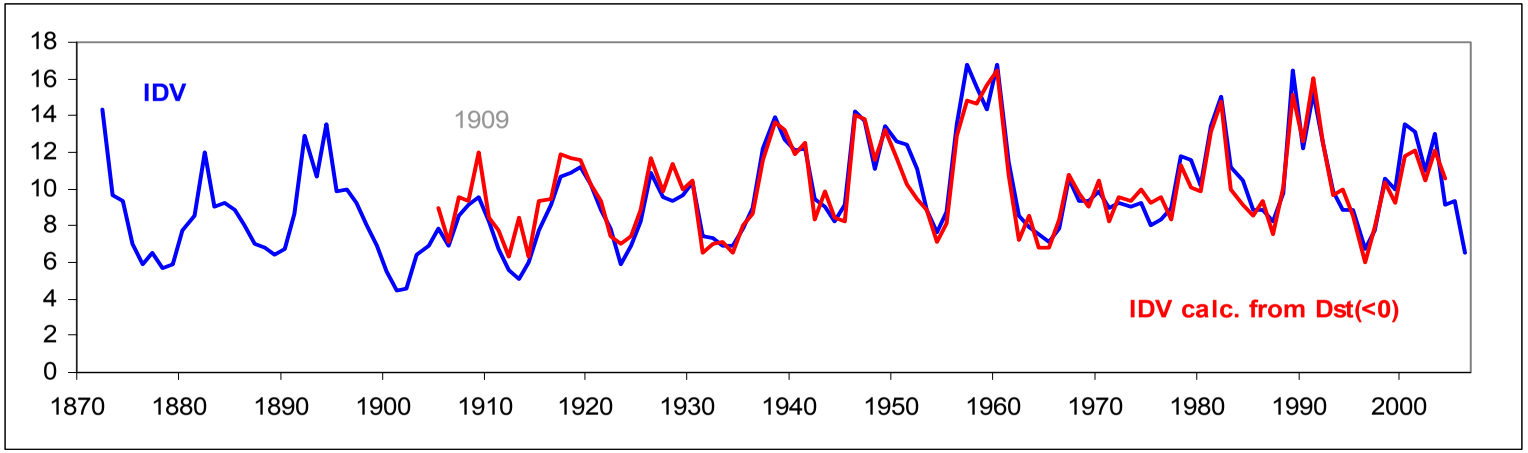


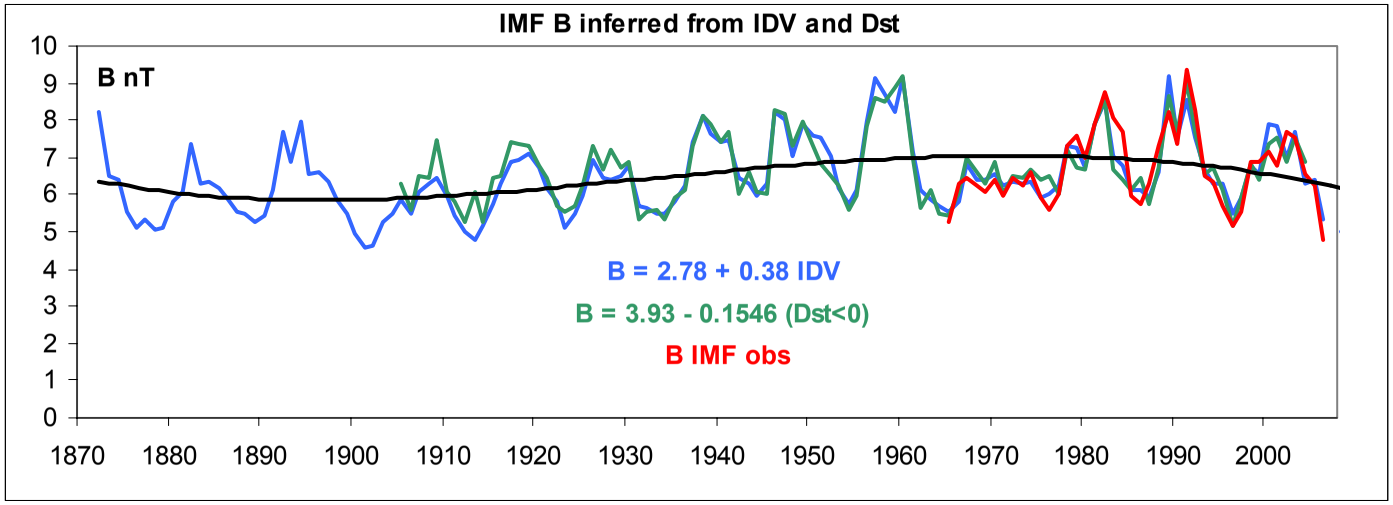
IDV is closely related to negative values of Dst:

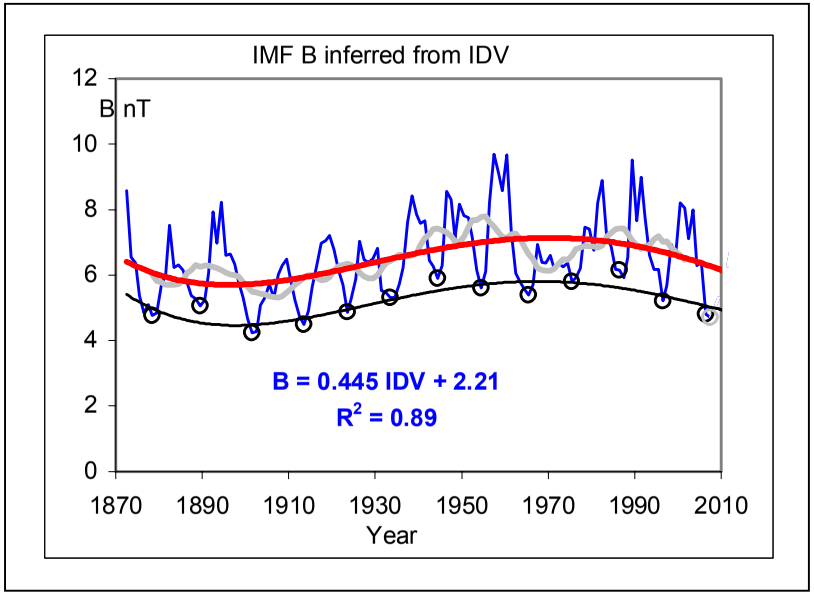


The difference in geomagnetic effect from one large storm to the next is largely due to different IMF strength (as the solar wind speed often follows almost the same pattern from storm to storm). So it is not a surprise that IDV is almost "blind" to the solar wind speed.

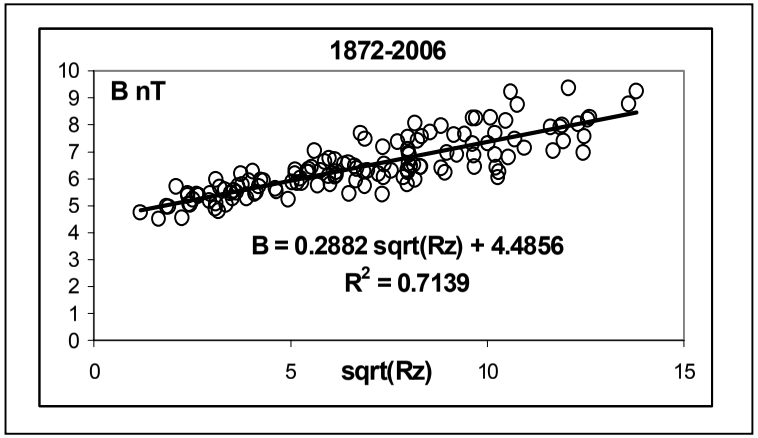
J. Love has calculated Dst back to 1905:



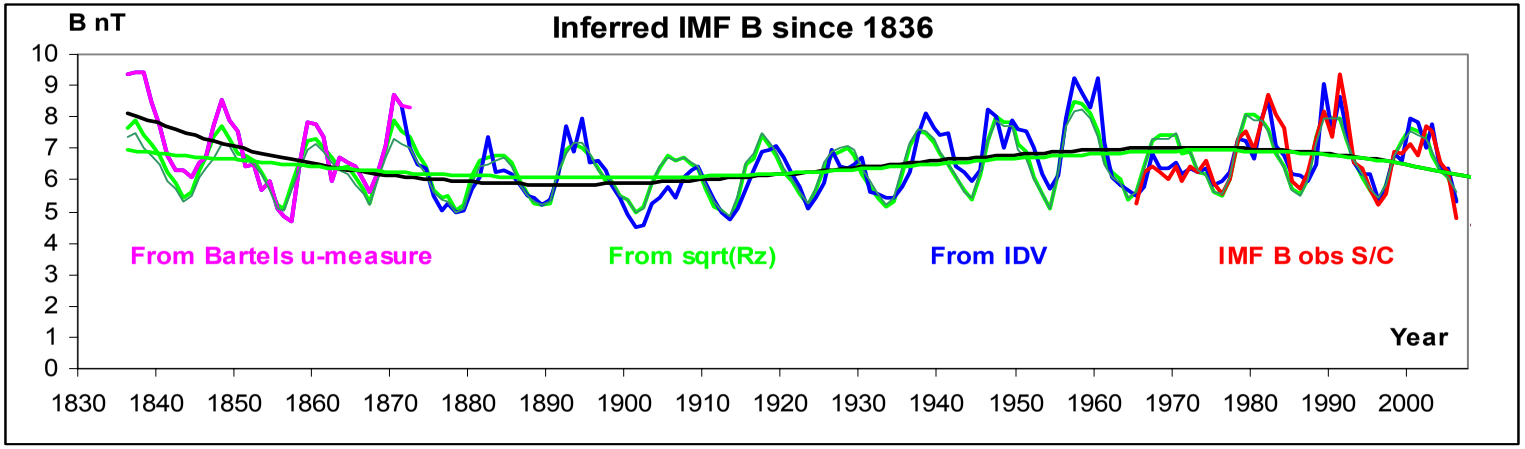




Using u-measure and IDV we can infer IMF B directly back to 1872. There seems to be a "Gleissberg"-type wave in IMF B. This is not a surprise because the sunspots show a similar wave. The IMF at solar minimum varies between 4.5 nT and 5.5 nT. Note that at present the IMF is close to what it was 107 years ago.

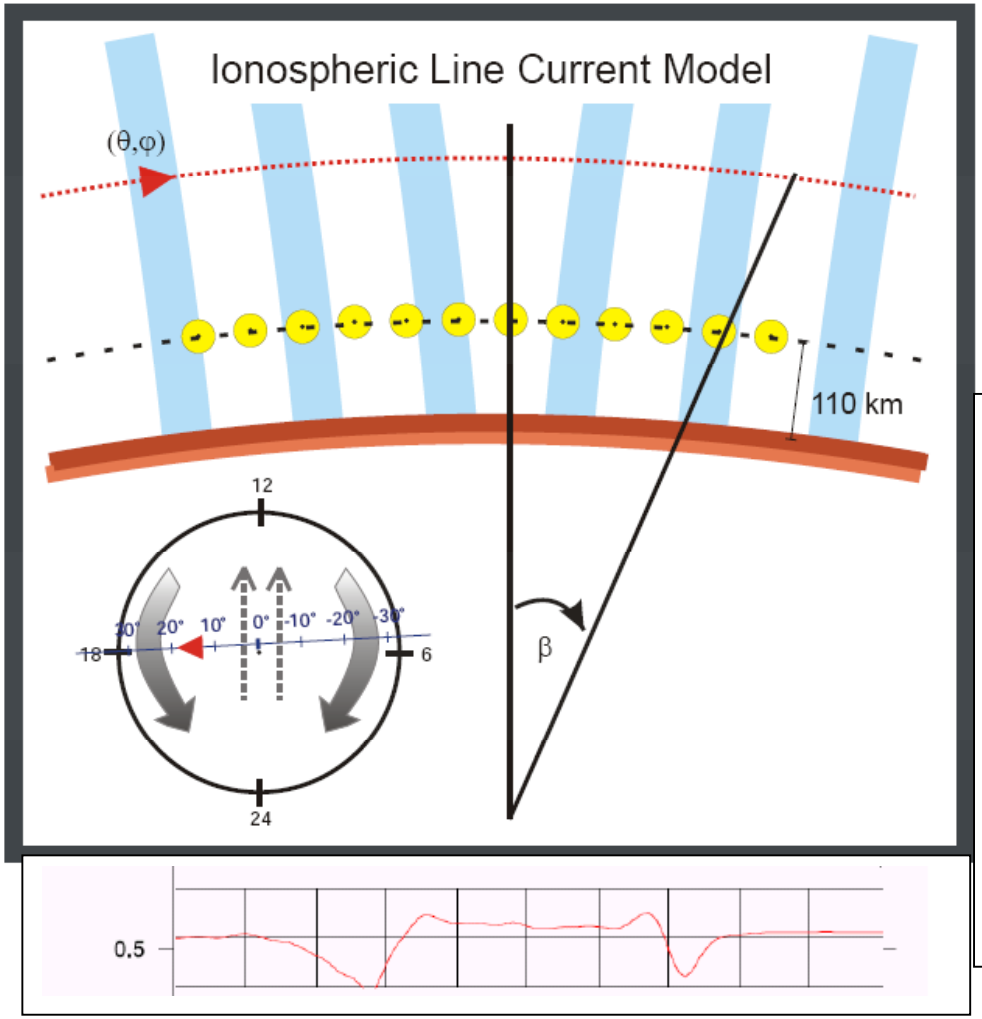


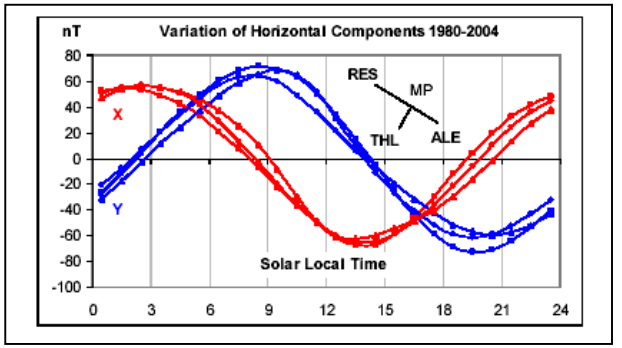
The main sources of the equatorial components of the Sun's large-scale magnetic field are large active regions. If these active regions emerge at random longitudes, their net equatorial dipole moment will scale as the square root of their number. Thus their contribution to the average IMF strength will tend to increase as $SSN^{1/2}$ which is what we observe (left).

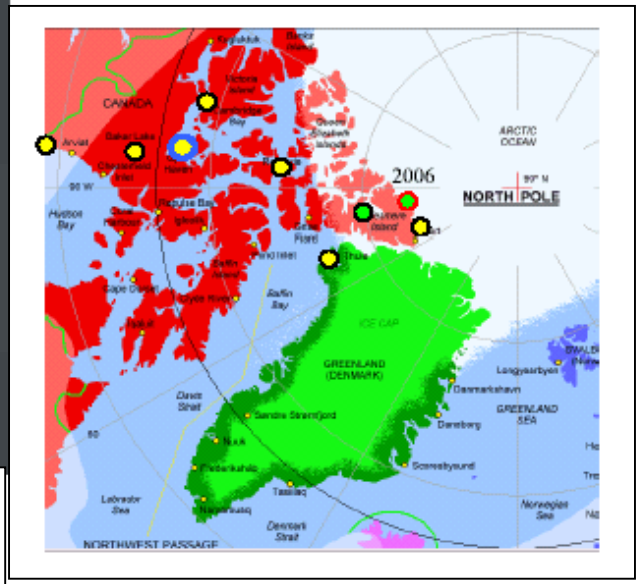


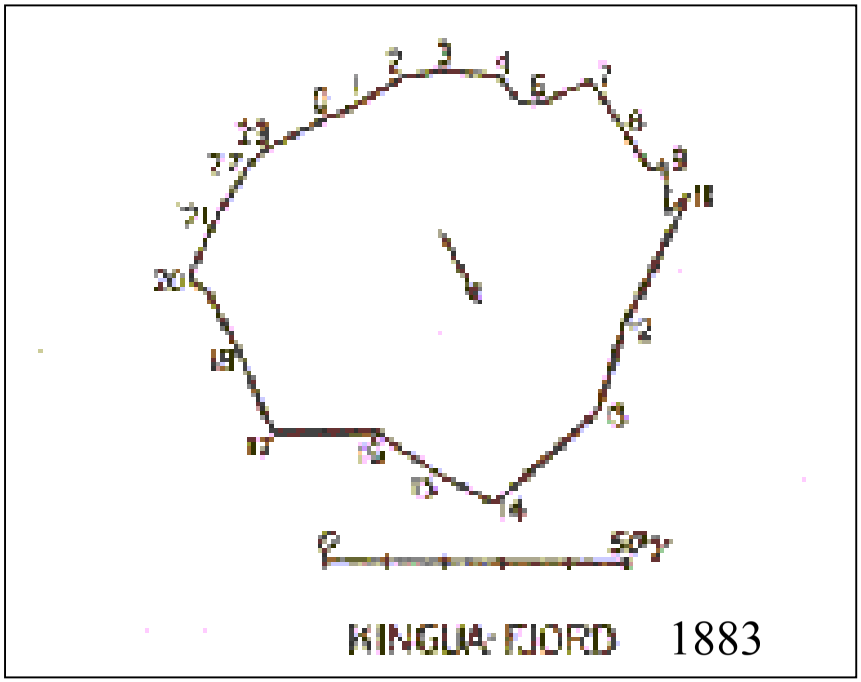
Yet another way…

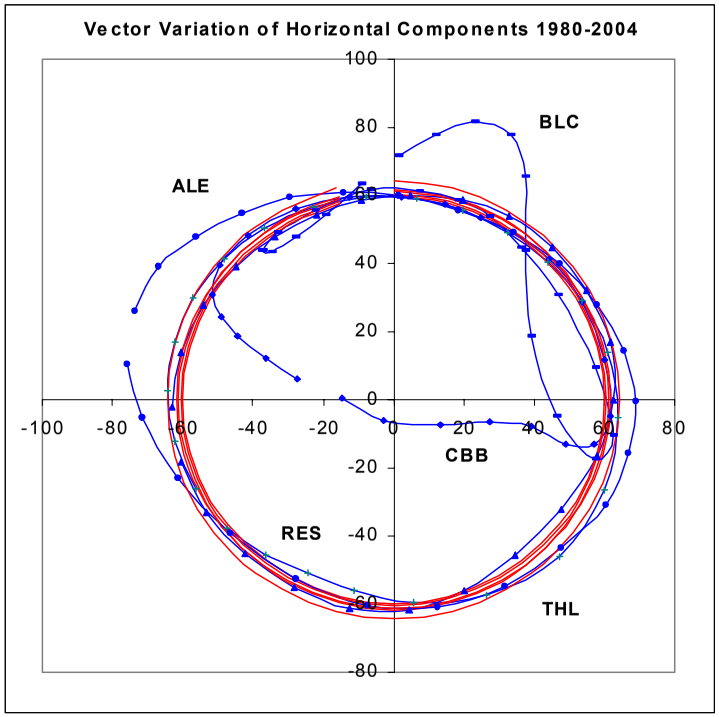
Polar Cap Current Sheet

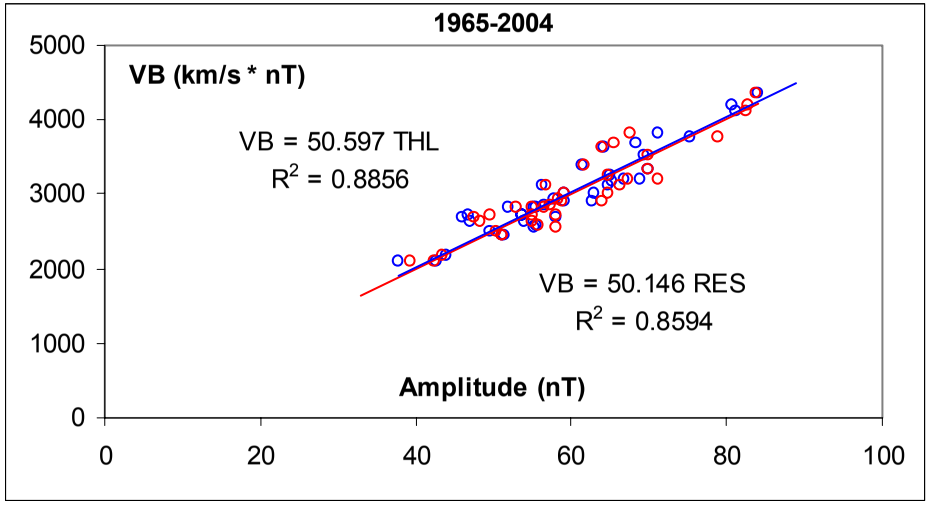




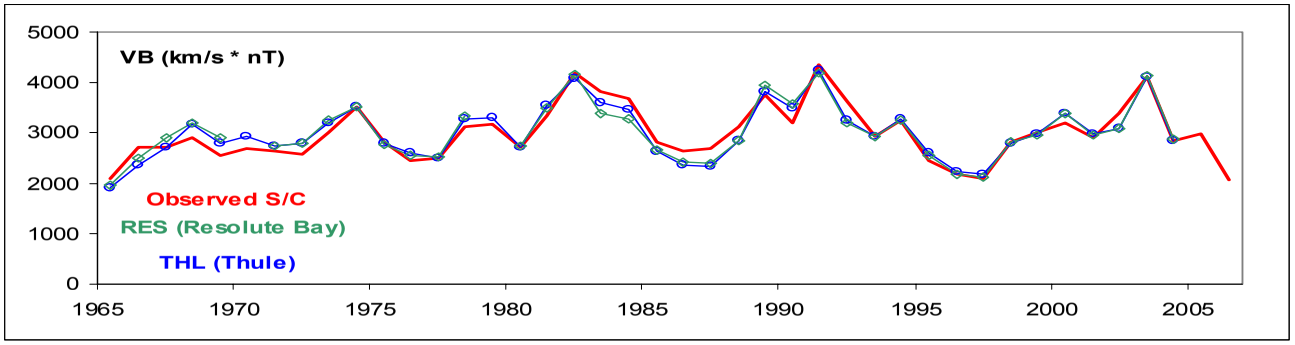




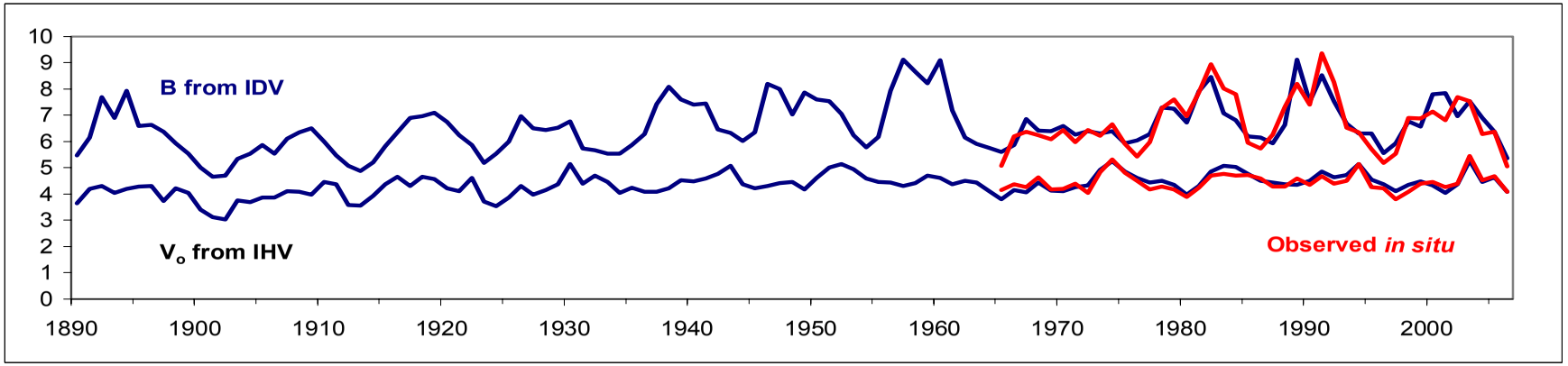


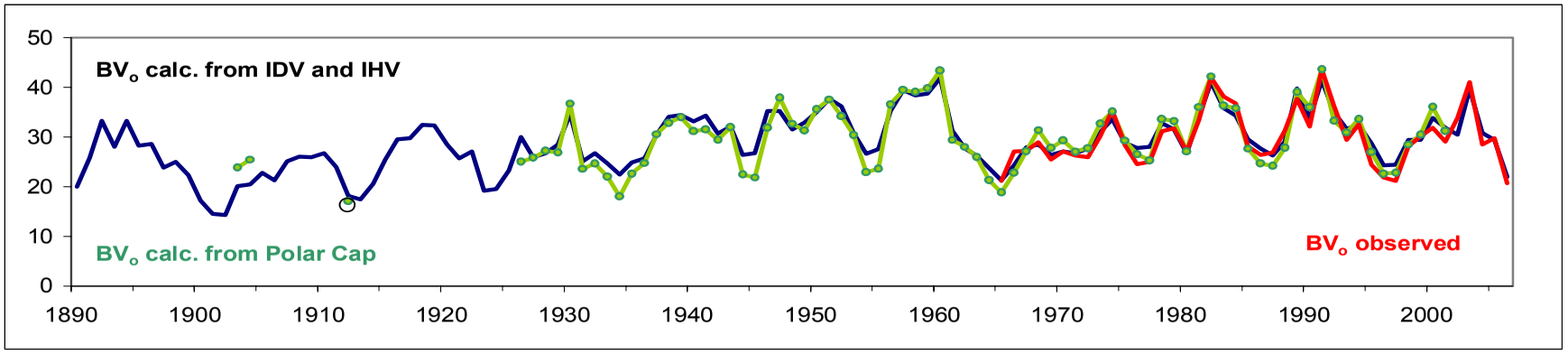


The Polar Cap Current is driven by the Polar Cap Electric Potential which in turn is given by the product of the solar wind speed V and the IMF B. There is a very direct relationship.

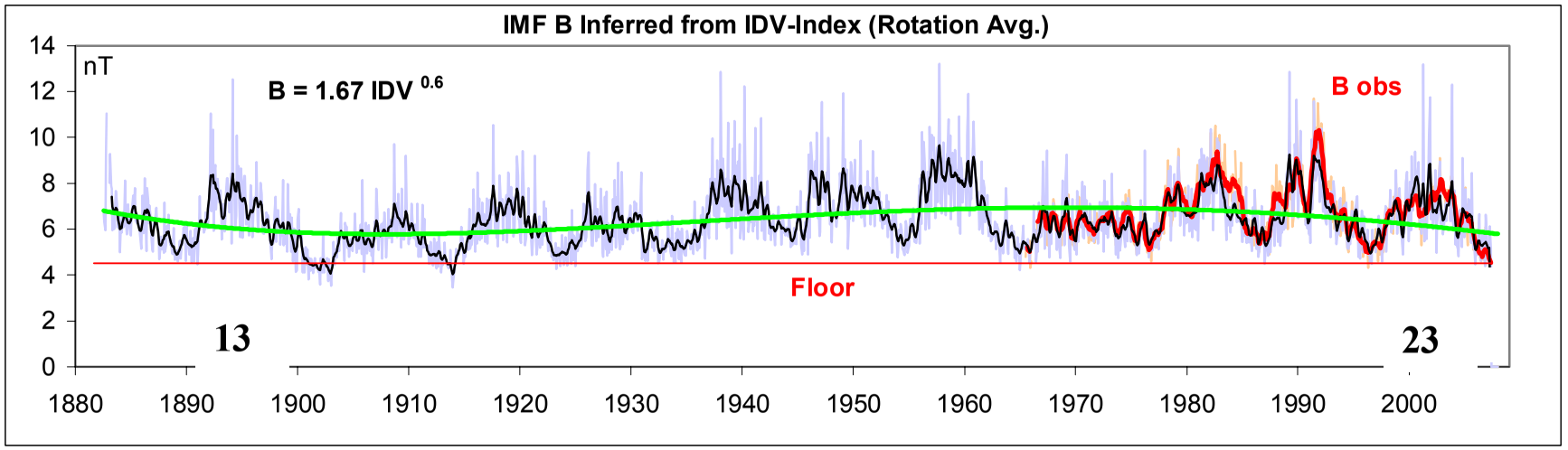


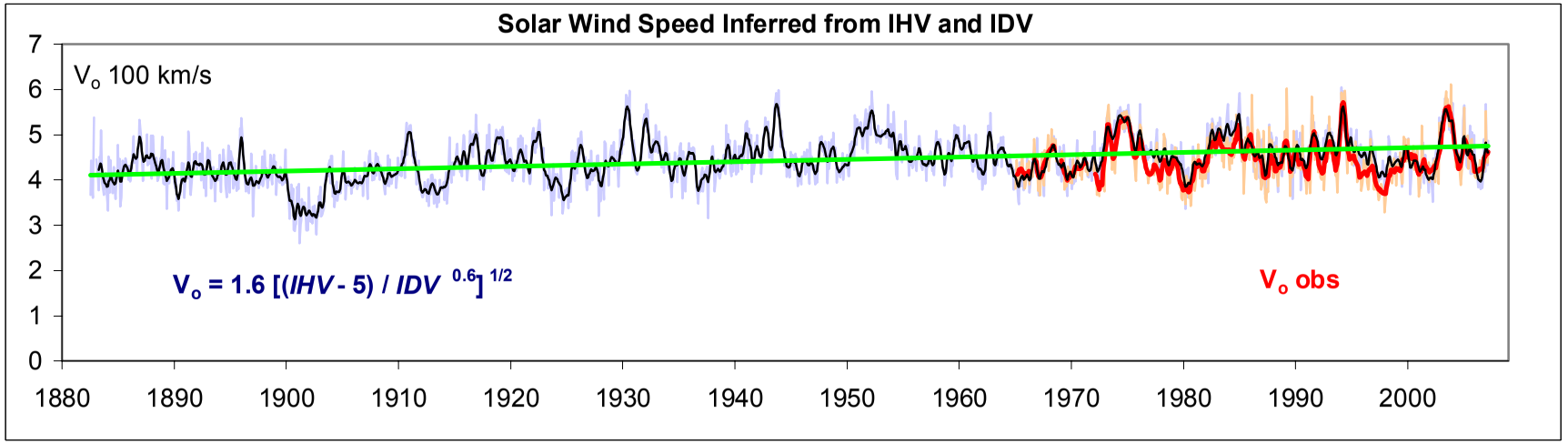
IDV gives us B, and IHV gives us BV^2, hence we can compute V, then BV and compare with polar cap BV.



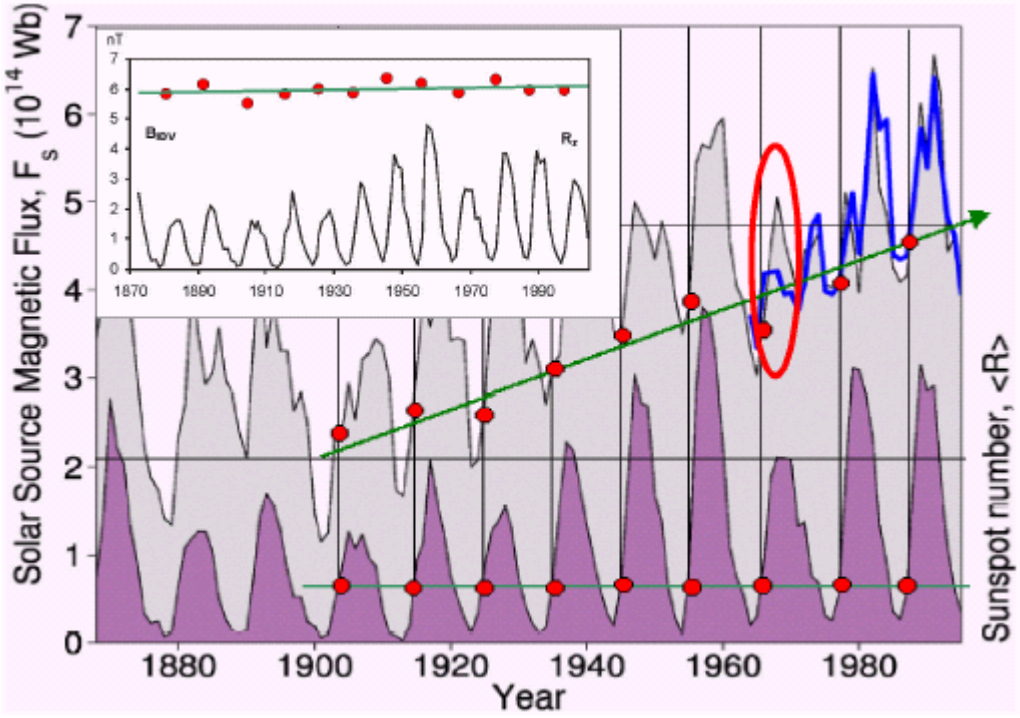


We can even do this on a 27-day rotational basis:



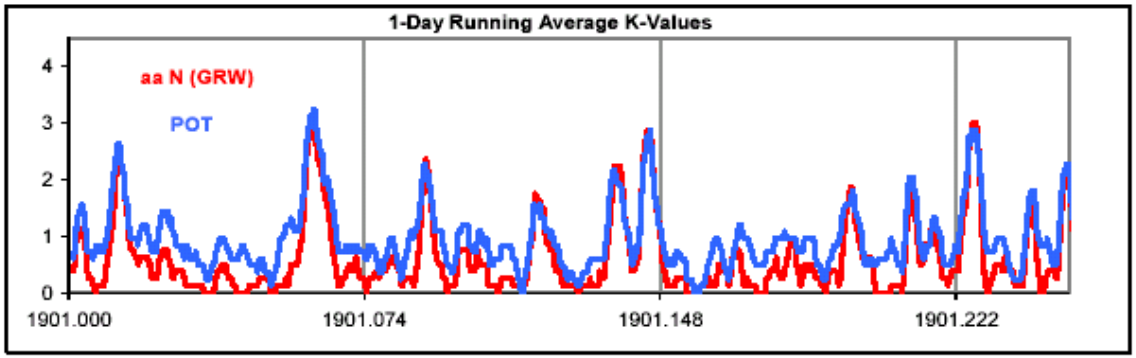


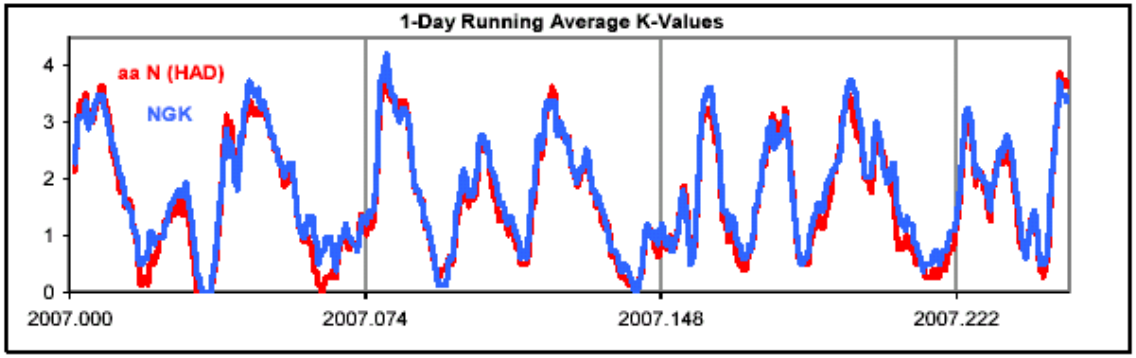
Back in 1978 I proposed that the Sun's "open" flux had doubled since the 1900s. Lockwood et al. in a famous 1999 paper extended the analysis to 1995 and inferred an increase by a factor of 2.3 independent of the sunspot number:



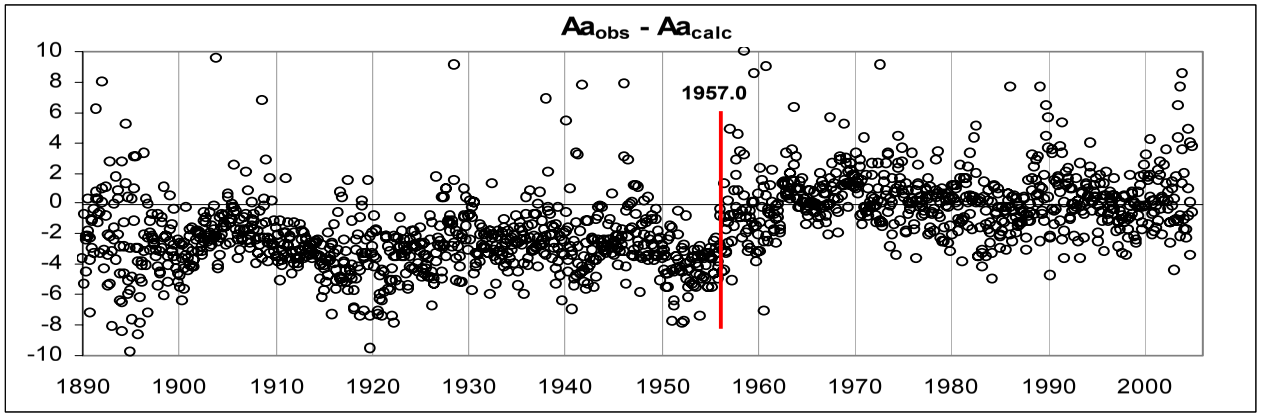
The analysis was based on the geomagnetic aa-index. Subsequent work by several groups has shown that the calibration of aa is too low before 1957. In addition, there is an inhomogeneity in about 1937. Before that time Mayaud [who constructed the aa-index] had himself scaled all the geomagnetic records, after that he used existing scalings by others.

The most difficult K-value to scale is K = 0 [no activity at all] because it requires the correct removal of the [ever changing] daily variation due to solar FUV generated currents. Mayaud was the great expert at this and dared classify many intervals as K = 0 where other people conservatively opted for K = 1:





The net result was that aa was on the average 3-5 nT too low during the early years, which for the solar minima years 1901 and 1912 would amount to about 40%, so no wonder we all miscalculated the IMF B and the open flux.

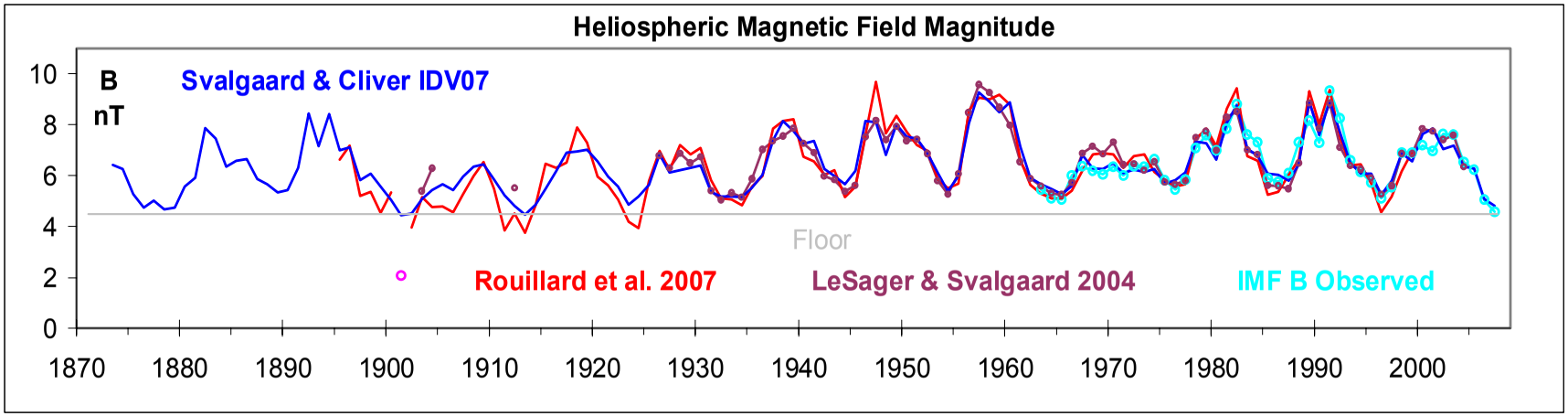


Difference between aa observed and aa calculated from IHV (for 1980-2004):

$$Aa = 0.36\ IHV^{1.1856}$$

$$R^2 = 0.9511$$

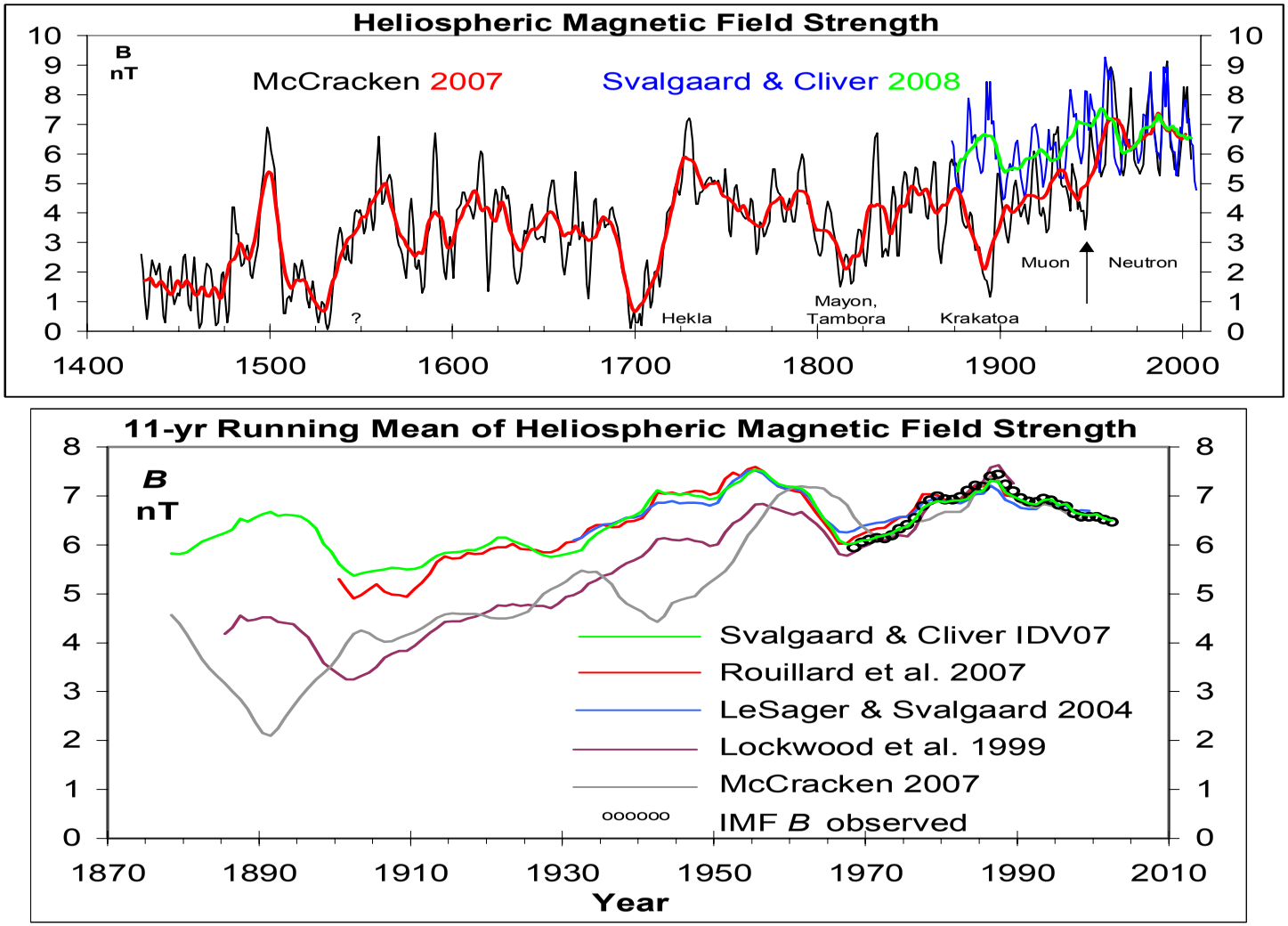
Using their new ‘m-index’ and the corrected aa-index, the Lockwood group (Rouillard et al., 2007) has recently recalculated IMF B and obtained results that are very close to ours, although Lockwood still maintains that the 1999 result is valid [c.f. Solanki at SORCE]…



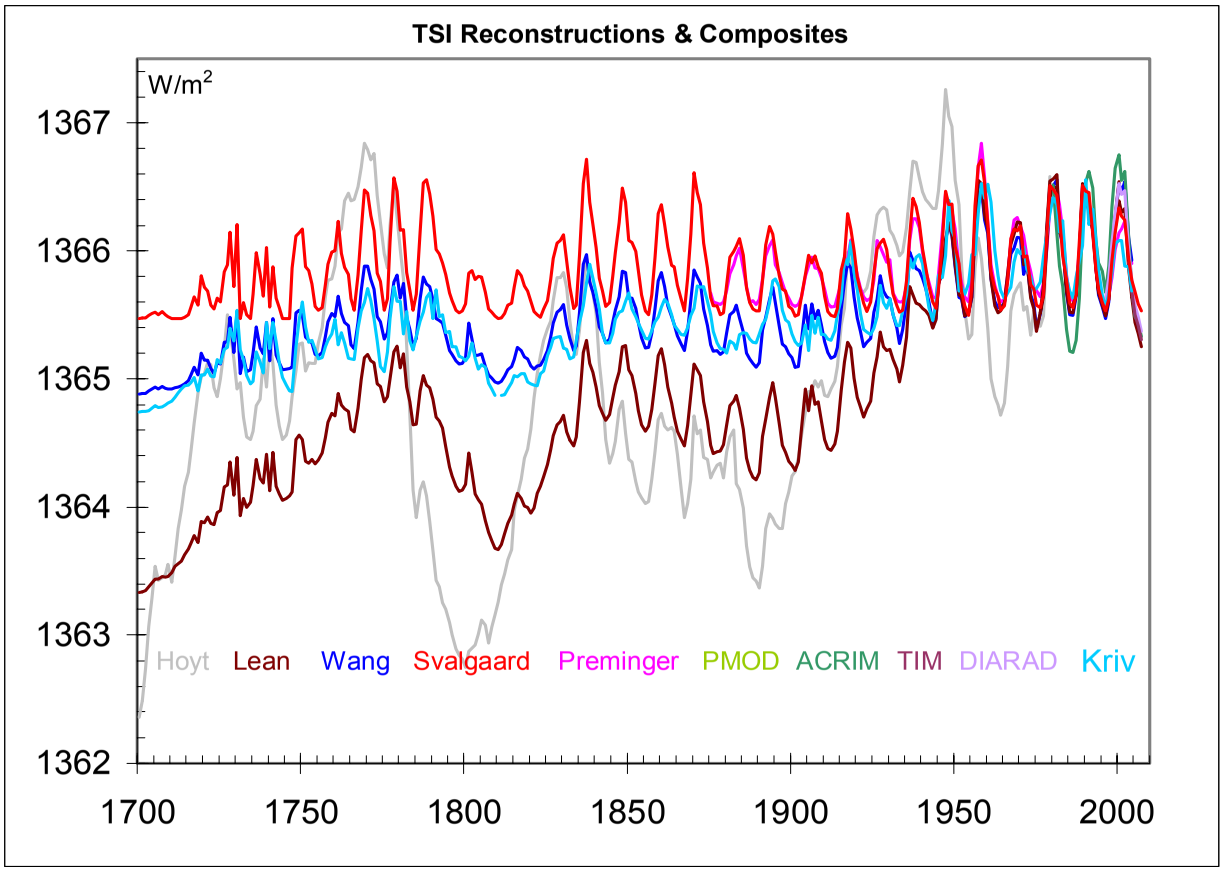
The point for 1901 is in error (Rouillard, Pers. Comm., 2007) and their result before 1910 is based on very few stations with resulting large error bar. Apart from such details, the various groups trying to reconstruct B and V are converging on a common position that should be taken into account now by other researchers, rather than relying on the superceded earlier results.

This re-assessment of the “open” flux calculated from B has implications for reconstructions of various solar proxies that postulate a secular increase of the “open” flux.

One example is McCracken [2007] who inverted the cosmic ray flux (inferred from ^{10}Be fitted to the secular change) to calculate the IMF B (or the HMF as he calls it):



Another example is reconstructions of TSI (Total Solar Irradiance) which often rely on an "open flux background":



Without the background "rise" 1900-1960, the TSI seems to have varied less than commonly assumed.

Conclusion

Geomagnetic activity has been used to infer the HMF [or the "open" solar magnetic flux] before the Space Age. Earlier, these inferences were discordant and controversial. In the last couple of years, the sources of these disagreements have been uncovered and corrected and a remarkable consensus is now emerging, with the result that the heliospheric magnetic field and the solar wind speed can now be considered to be well constrained to a level of ~10% or better.

The end