The Open Flux Has Been Constant Since at Least 1840s

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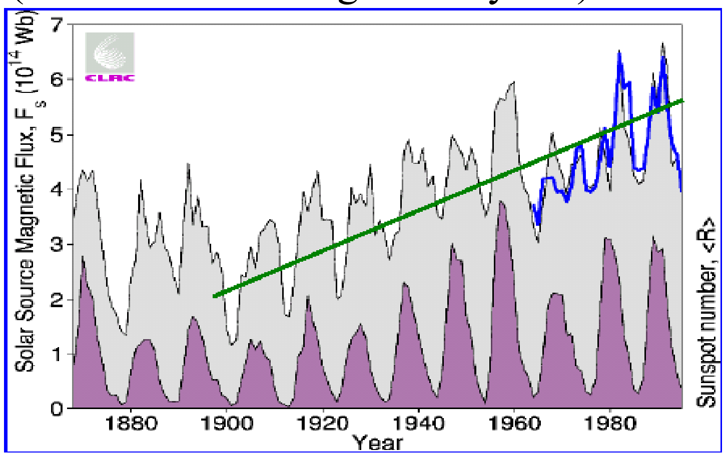
Invited paper in SHINE 2007 working group:
Is the Open Flux in the Heliosphere Conserved?

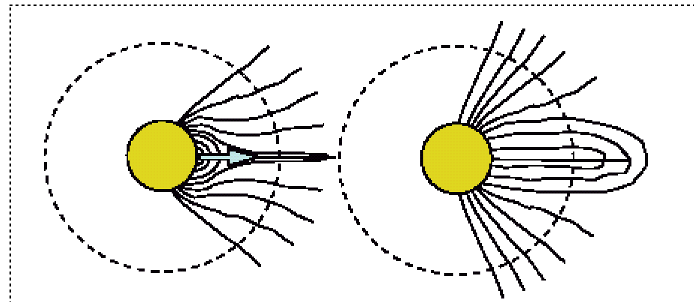
Abstract: The geomagnetic record allows us to infer the strength of the Interplanetary Magnetic Field, |***B***|, at Earth for the past ~175 years. We find B to be $4.5 + 0.28\ (SSN)^{1/2}$ nT, where SSN is the sunspot number. We interpret the SSN-dependent part to be closed flux related to CMEs and 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 ~4×10^{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, although inconsistent with one recent GCR re-calibration of pre-1950 ionization-chamber data.

What is “Open Flux”?

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



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



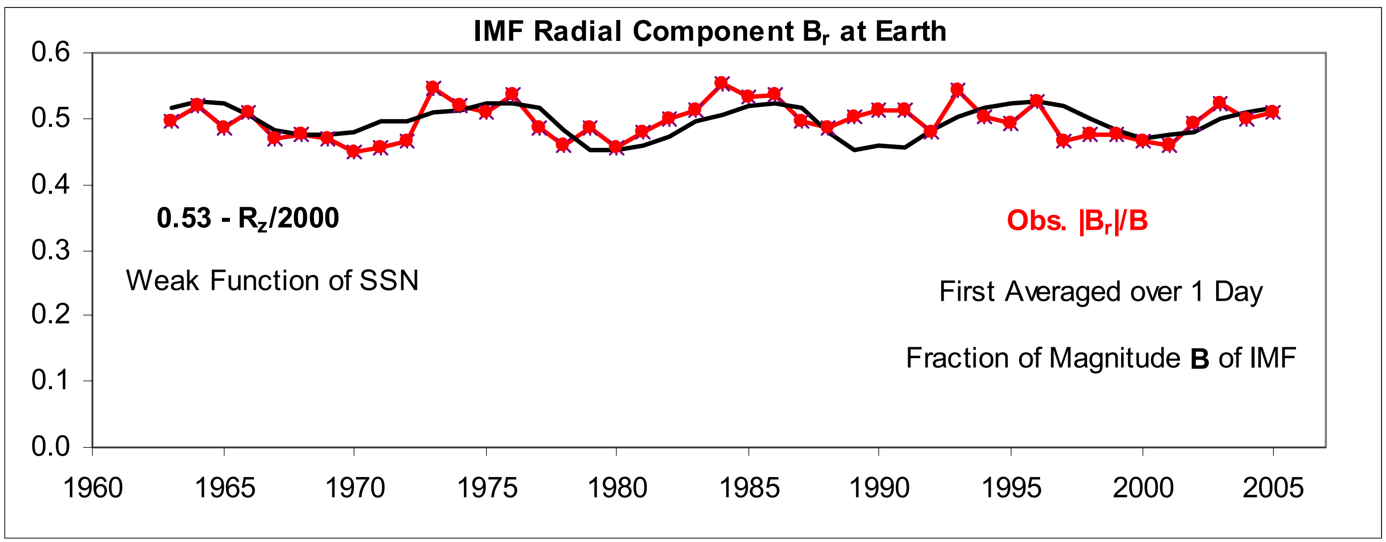
No open flux (Maxwell):

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

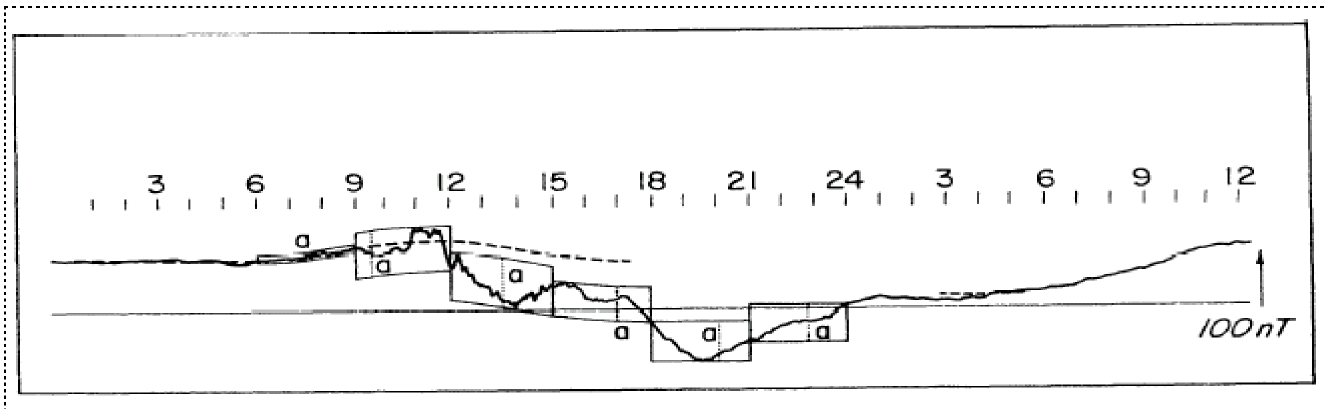
The (unsigned, to circumvent Maxwell) magnetic flux, F, in the Heliosphere is calculated by integrating the unsigned radial component, $|B_r|$, of the IMF over a surface (“effective” radius R_F) enclosing the Sun. There are some disagreements over whether to count the flux twice (once for each polarity),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

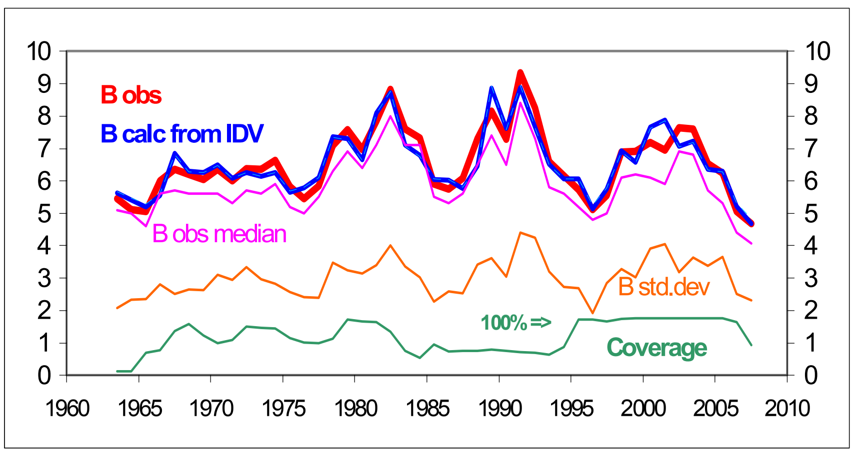


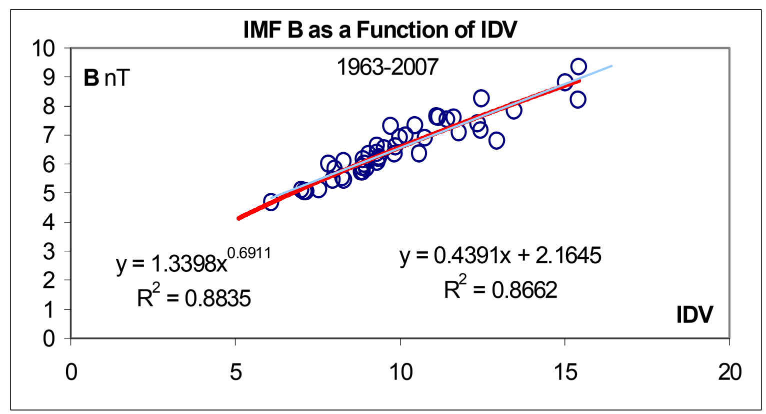
From the amplitude of the variation of the field within a certain interval (three hours in the above example) one constructs a geomagnetic "index" that codifies that variation and can be used as a proxy for solar wind conditions during the interval.

Several new indices of geomagnetic activity have recently been introduced.

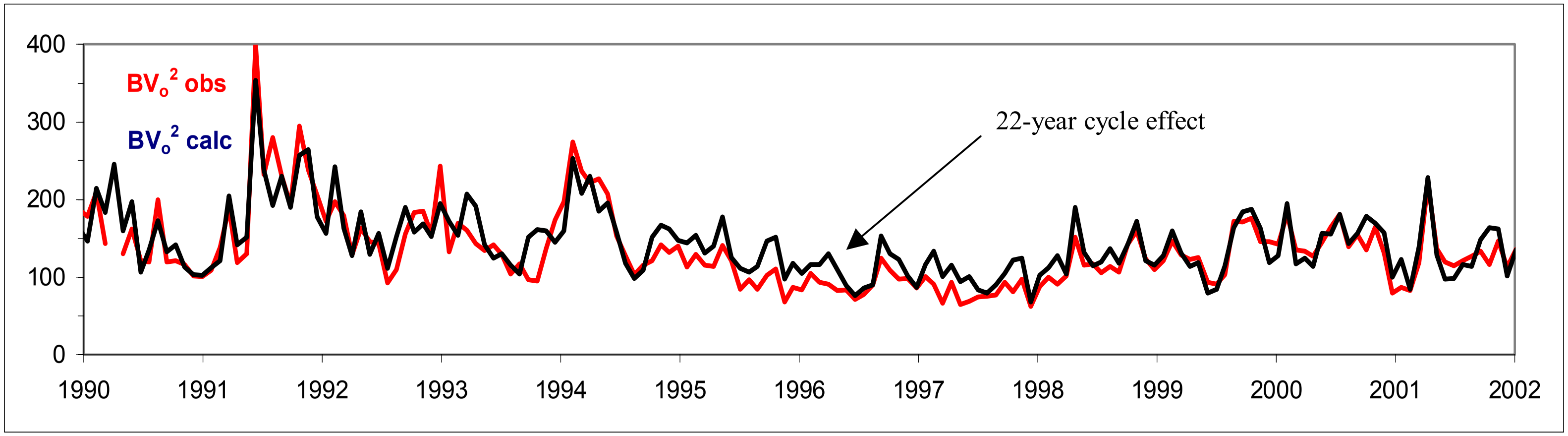
Geomagnetic index	**Function of**	$B V^{\alpha}$	**Proponents**
IDV, [D_{st}<0]; u	B	$\alpha = 0$	Svalgaard & Cliver; Bartels
m	$B V^{0.5}$	$\alpha = 0.5$	Lockwood et al.
PCP	$B V$	$\alpha = 1$	Le Sager & Svalgaard
IHV	$B V^2$	$\alpha = 2$	Svalgaard & Cliver
aa, am; ap	$B V^2$	$\alpha = 2$	Mayaud; Bartels

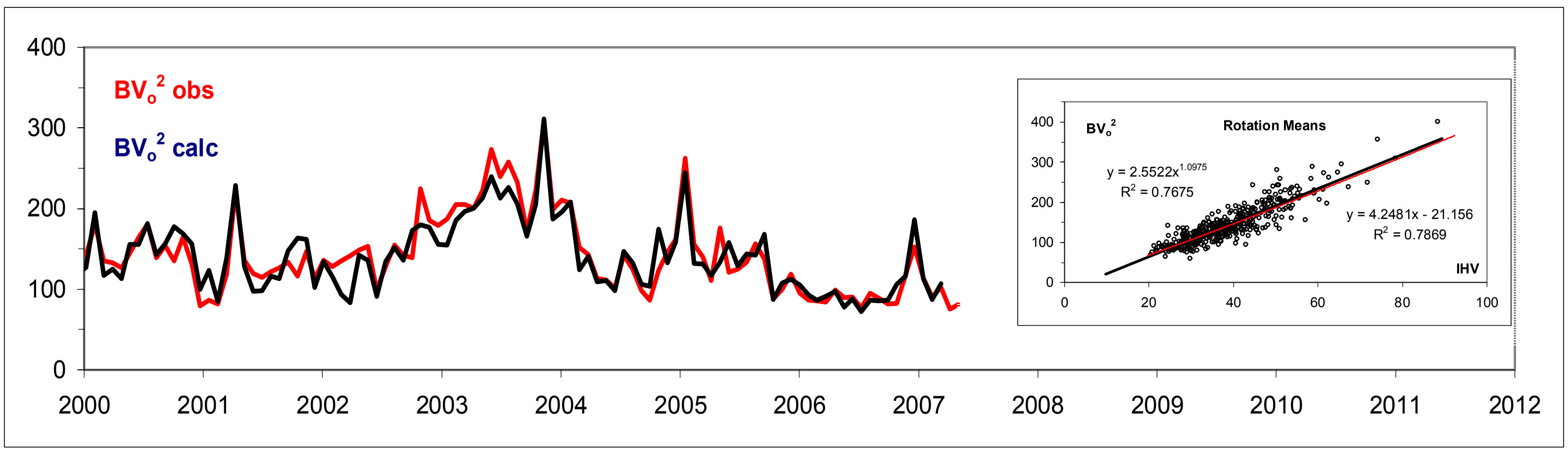
Because these depend on different functions of B and V, we can infer both B and V in the past. Below is the IDV-index and how it can be used to infer IMF B (yearly averages):



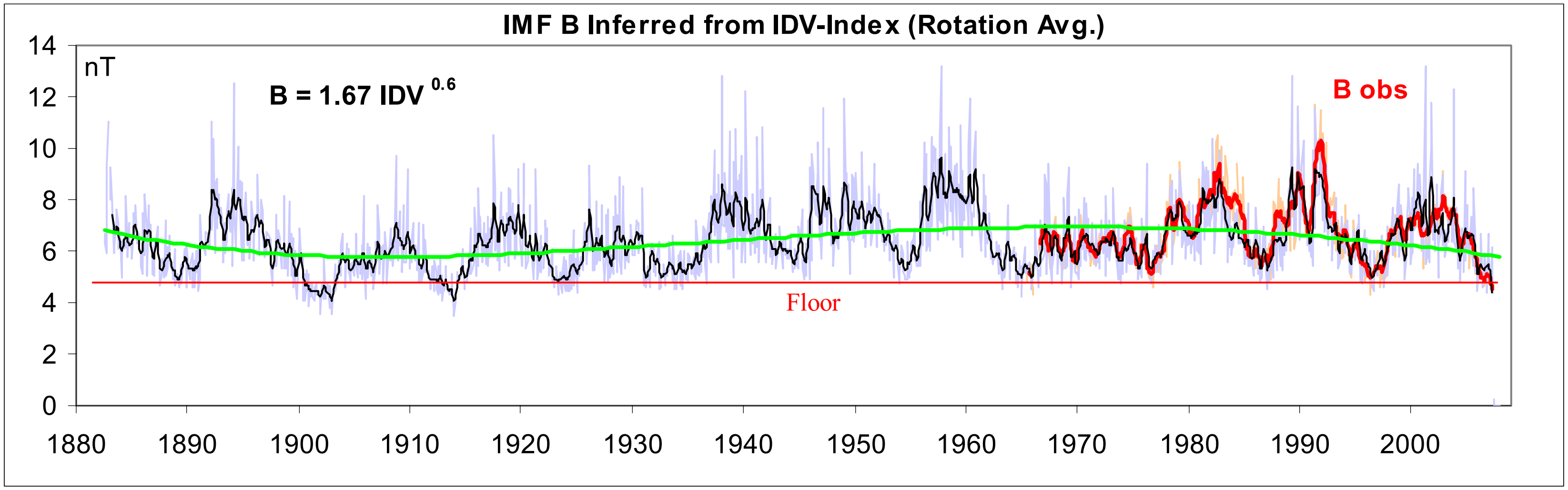


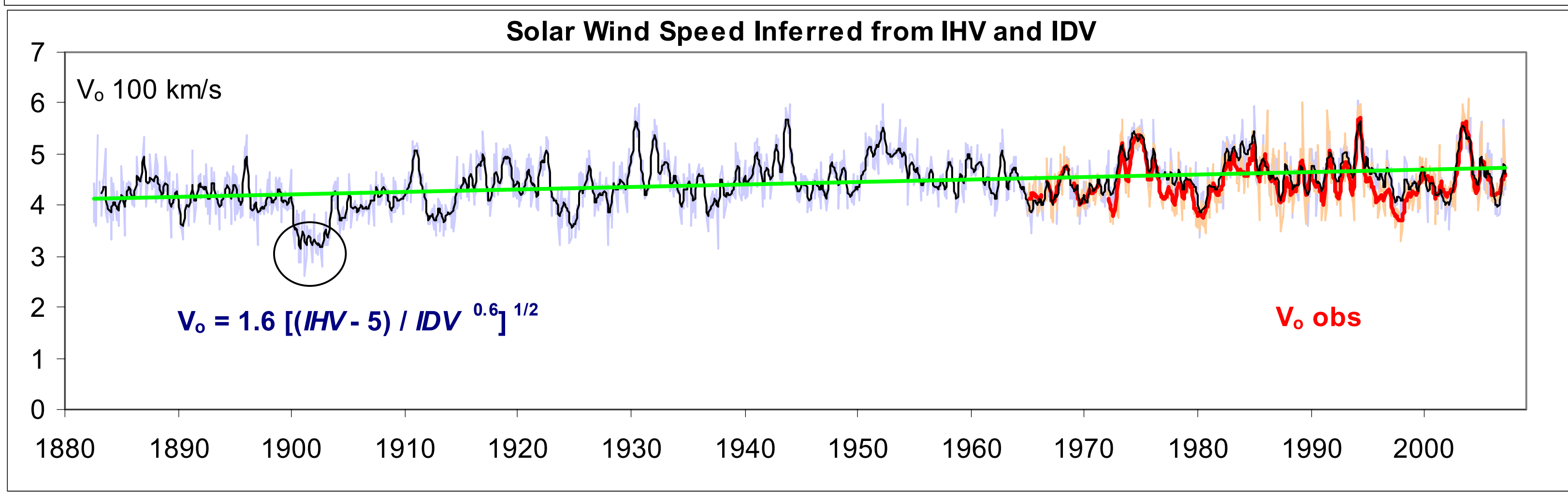
Here is how very well the IHV-index reproduces the product $B\ V^2$:



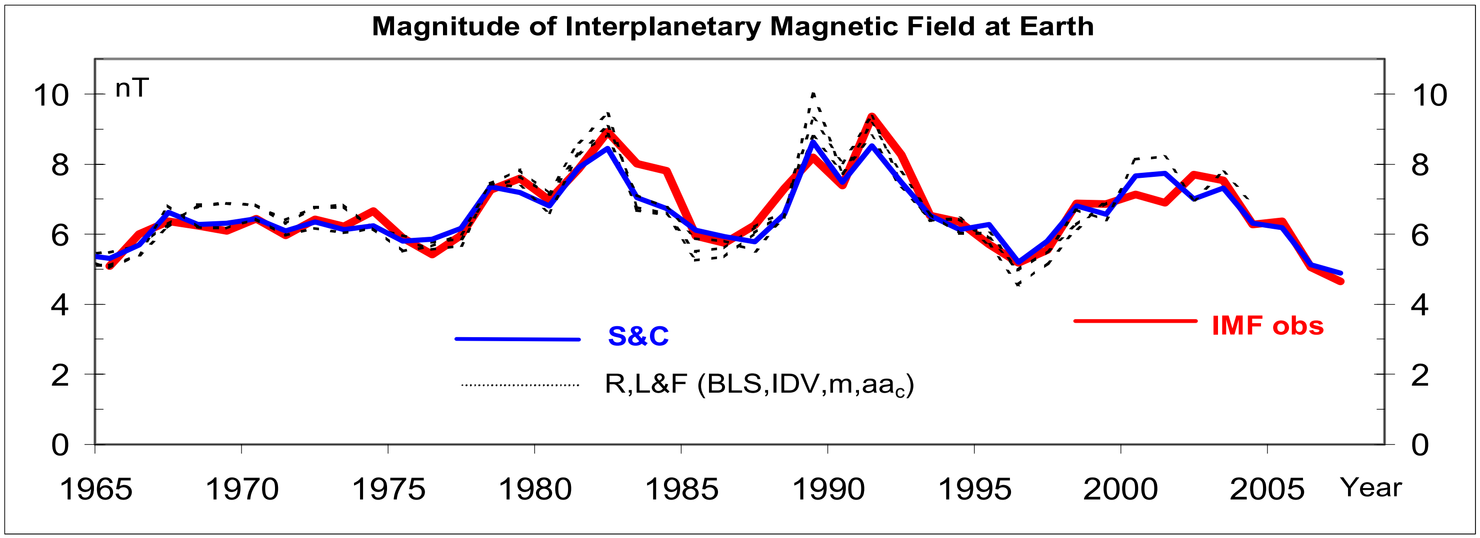


Here are *B* and *V* as inferred from IDV and IHV since 1883:

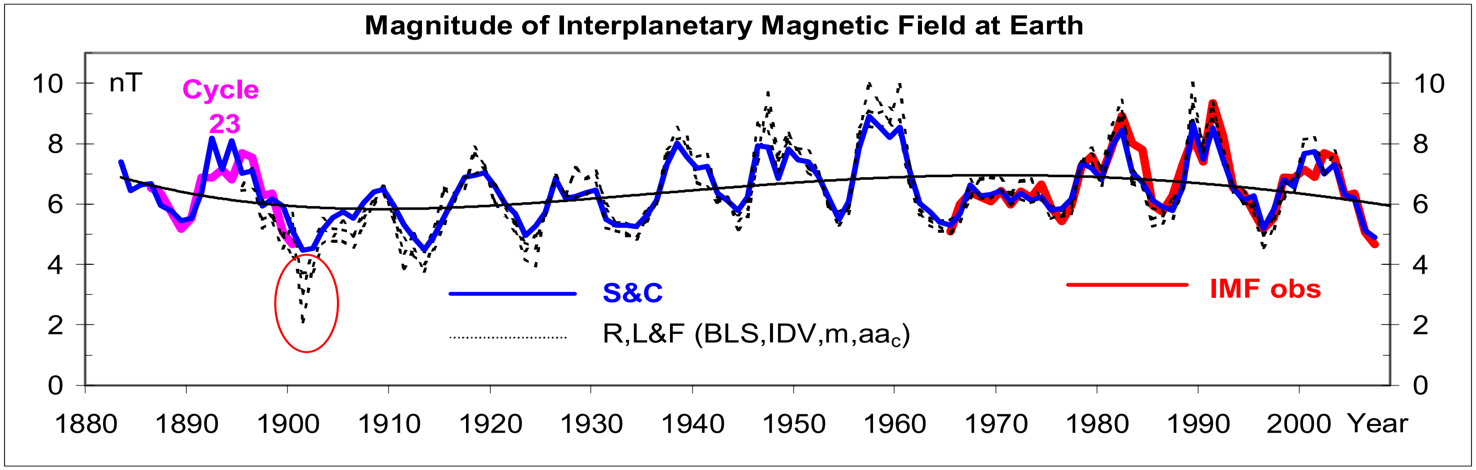




Recently Lockwood *et al*. (Rouillard, Lockwood, & Finch, JGR, **112**, A05103, 2007) have realized that their 1999 (Nature, **399**, 437, 1999) analysis was inaccurate because of reliance on the incorrectly calibrated geomagnetic *aa*-index and breakdown of an *ad hoc* relationship between solar wind speed and the Sargent recurrence index. Combining several indices (including their new *m*-index), their revised calculation of IMF *B* is shown here (dots):

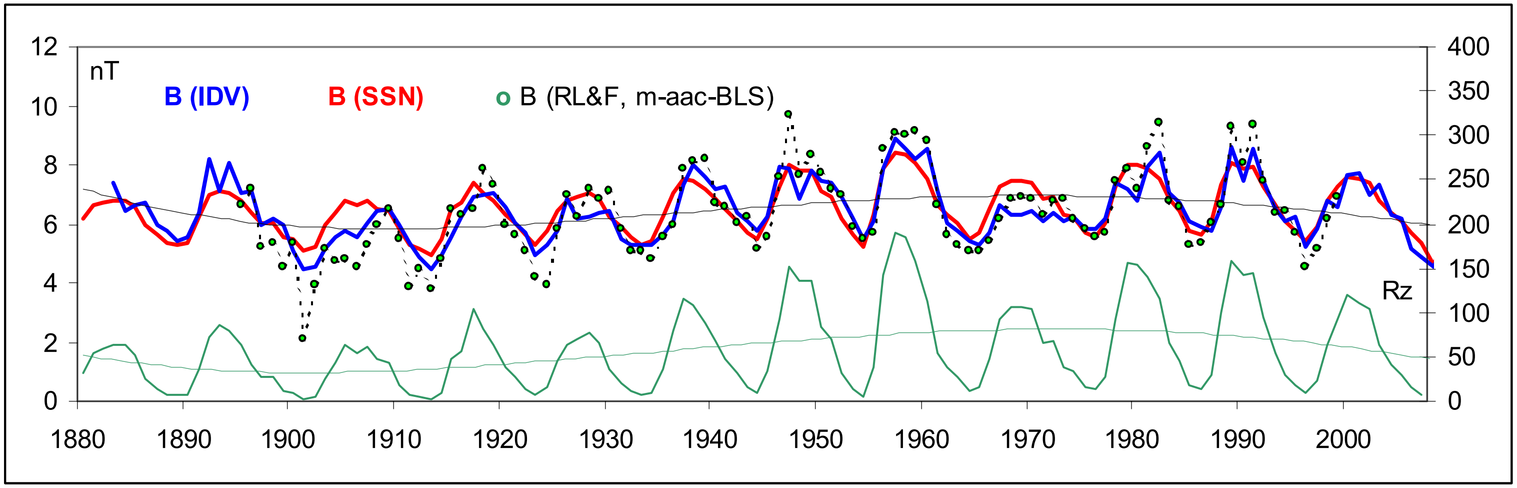


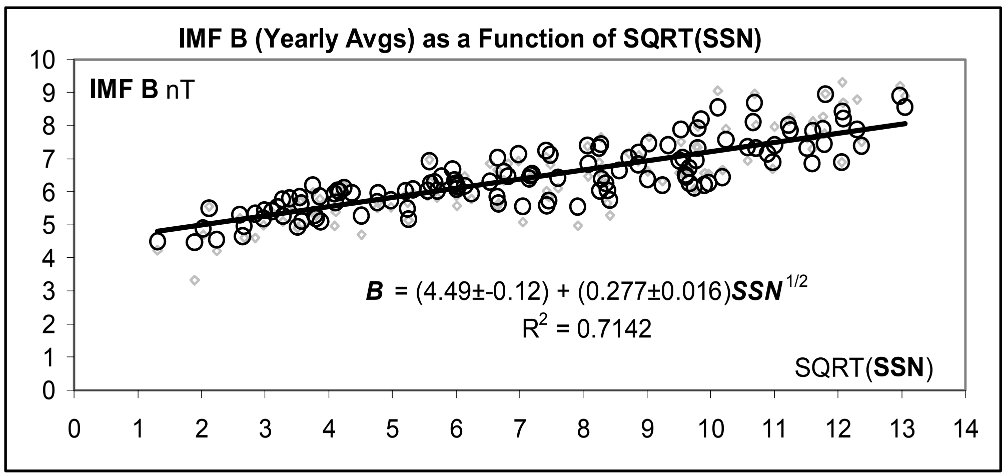
Their revised values (dots) agree reasonably well with the observed IMF and with our inferred *B* from IDV, although their values tend to overshoot (low values too low; high values too high). Here is a comparison back to 1895:



Apart from the overshoots, the long-term trends are in good agreement (4^{th}-order polynomial fit shown). The single year 1901 stands out as an obvious outlier (extreme overshoot: applying a relation outside of the domain on which it was defined). It does not seem reasonable that the IMF should drop by a factor of two in a single solar minimum year and then immediately recover (where did it go? And where did the recovery flux come from?).

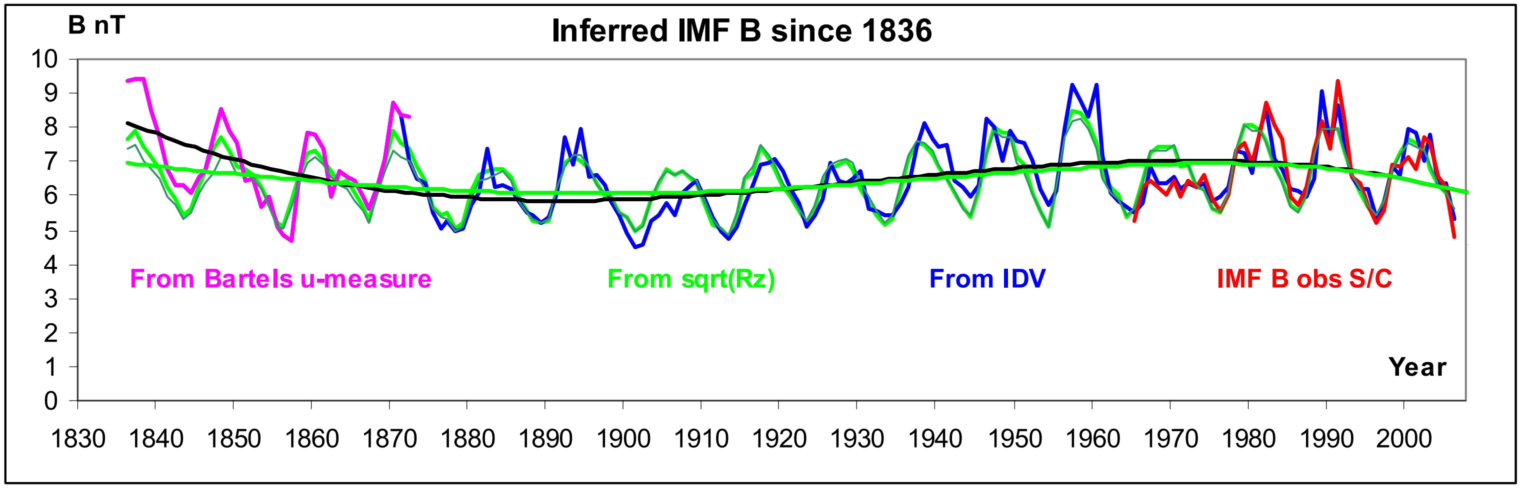
Note that if we shift cycle 23 to 107 years earlier to make it coincide with cycle 13, we see that the IMF was the same then as now. There does not seem to any secular trend over the more than 100 years. There does seem be a “Gleissberg”-type oscillation, just like in the sunspot number:





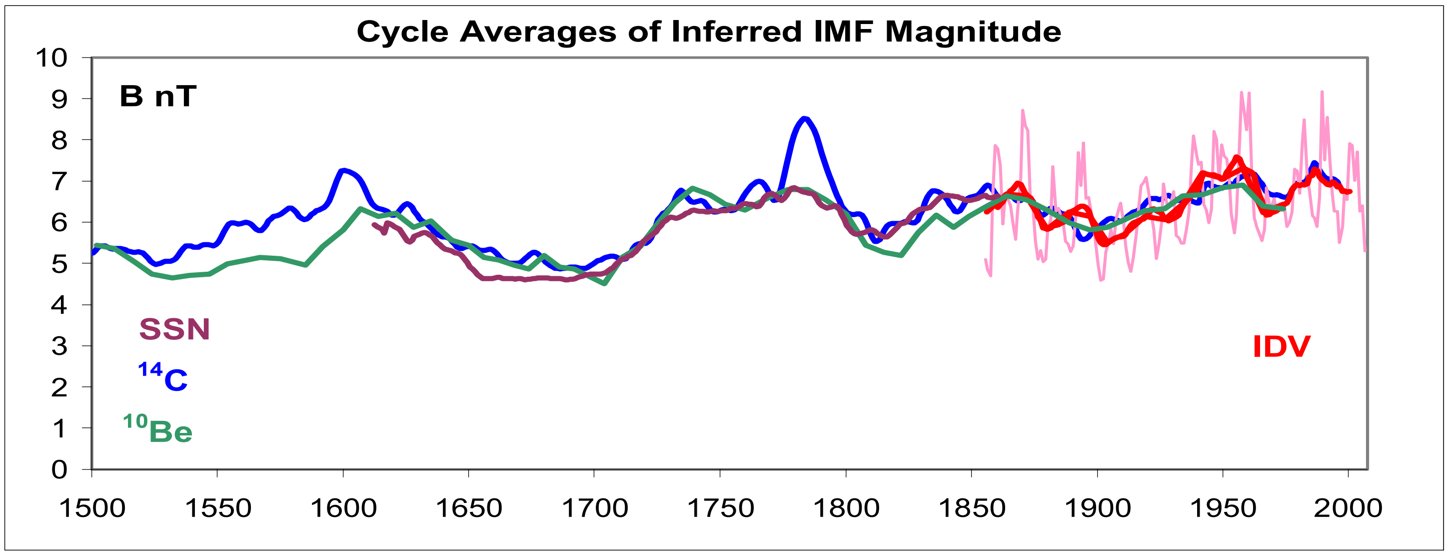
In fact, it seems that most of the variation of the IMF strength can be accounted for (red curve) by a (square root of) sunspot number dependent contribution: riding on a constant "floor" of ~4.5 nT. We interpret this floor as the "open flux", regarding the SSN-related part to be largely "closed" flux. (Svalgaard & Cliver, ApJLetters, **661**, L203, 2007).

There is suitable geomagnetic data back to 1836 allowing estimation of IMF *B* indicating the same basic result: that IMF *B* still that far back can be regarded as a combination of a constant open "floor" and the closed SSN-related part:

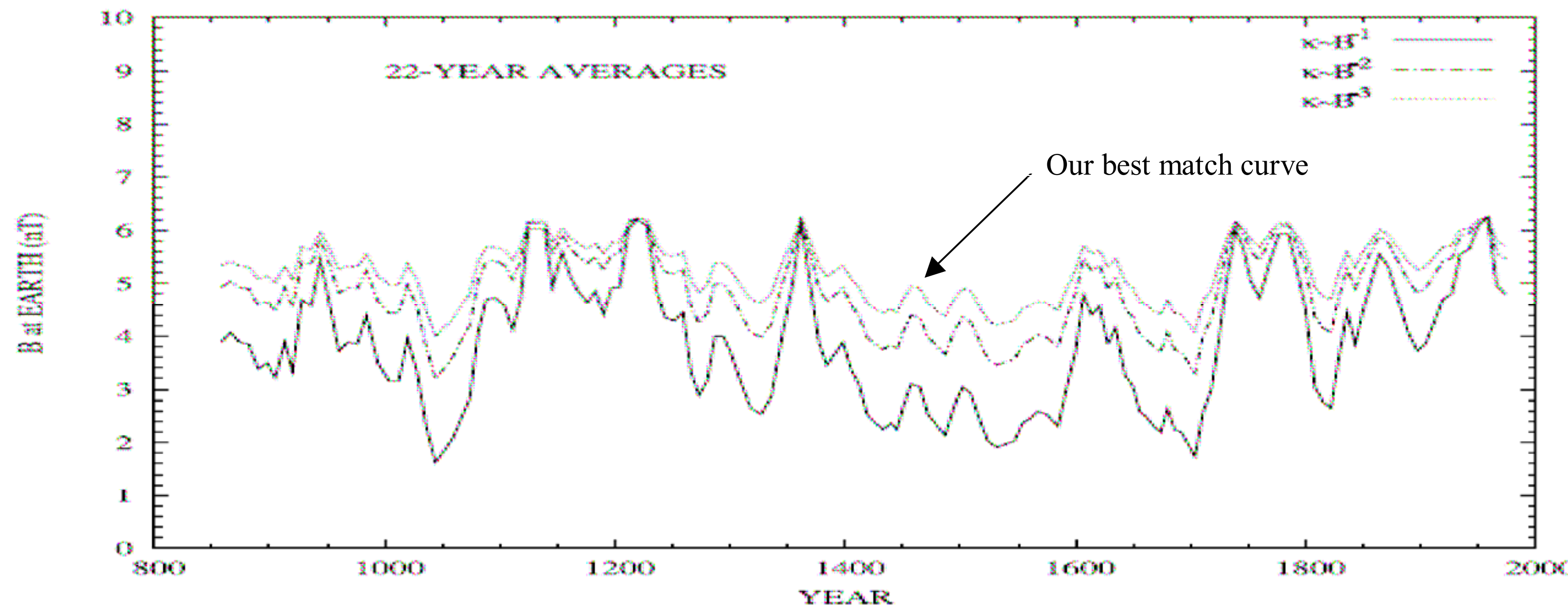


The transport in the Heliosphere of Galactic Cosmic Rays of energy < 10 GeV is governed by the strength, spatial structure, and turbulence of the IMF (or maybe better: the "HMF"), and consequently the intensity of the radiation is strongly modulated by changes in the IMF associated with solar activity. When entering the Earth's atmosphere, the GCR generates secondary particles that then produce the cosmogenic nuclides (*e.g.* ^{10}Be and ^{14}C) that are subsequently deposited in ice cores and tree rings from which the GCR flux in the past may be estimated. Assuming a suitable model (calibrated with modern data) of the influence of *B* on the diffusion and modulation of GCRs, *B* in the past may then be inferred.

A major unknown is how the diffusion coefficient, κ depends on *B*. Caballero-Lopez *et al.* (JGR, **109**, A12102, 2004) consider three cases of dependence of κ on correlation length and field variance variation with solar activity: low ($\kappa \sim B^{-1}$), moderate ($\kappa \sim B^{-2}$) or strong ($\kappa \sim B^{-3}$). The latter case would occur if large-scale, transient structures, such as ICMEs play an important role during periods of high solar activity. We can compare the result of the Caballero-Lopez *et al.* inversion under the assumption that $\kappa \sim B^{-3}$ with *B* inferred from IDV and SSN and note good agreement [also with the "middle" ^{14}C inversion by Müscheler *et al.* (Nature, **436**, 3, 2005)]:

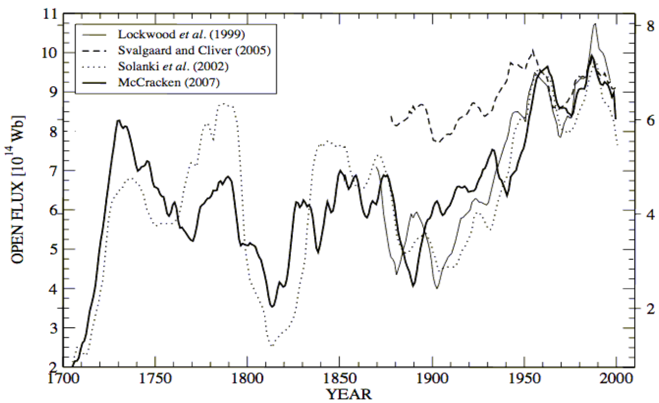


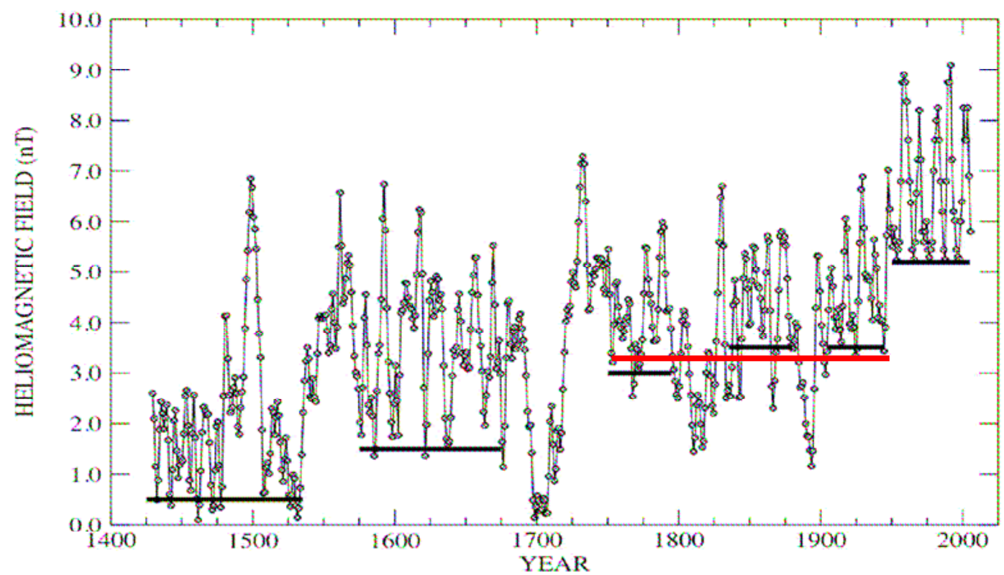
The IMF inferred from GCRs is very sensitive to the dependence of the diffusion coefficient on B, as can be seen in the following Figure from Caballero-Lopez *et al.*:

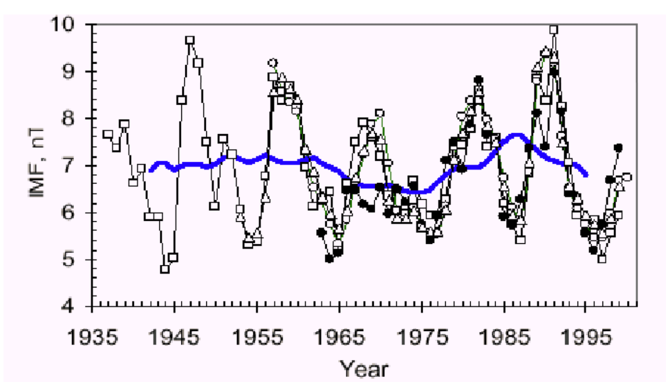


McCracken (*e.g.* Space Weather, **5**, S07004, 2007) argues that there has been very large changes (of an order of magnitude) in the open flux commensurate with $\kappa \sim B^{-1}$ or weaker. Evidence for this are Lockwood's original claim (the "doubling") and a re-calibration of old "ionization-chamber" cosmic ray records:

McCracken postulates ~4 “floors” of IMF strength in the last 600 years, the lowest (and earliest) being only one-tenth of the “modern” floor. The last “jump” (from 3.5 nT to 5.2 nT) in floor value took place around 1949. That year is well within the range of the high-quality geomagnetic record that does not support such a jump.

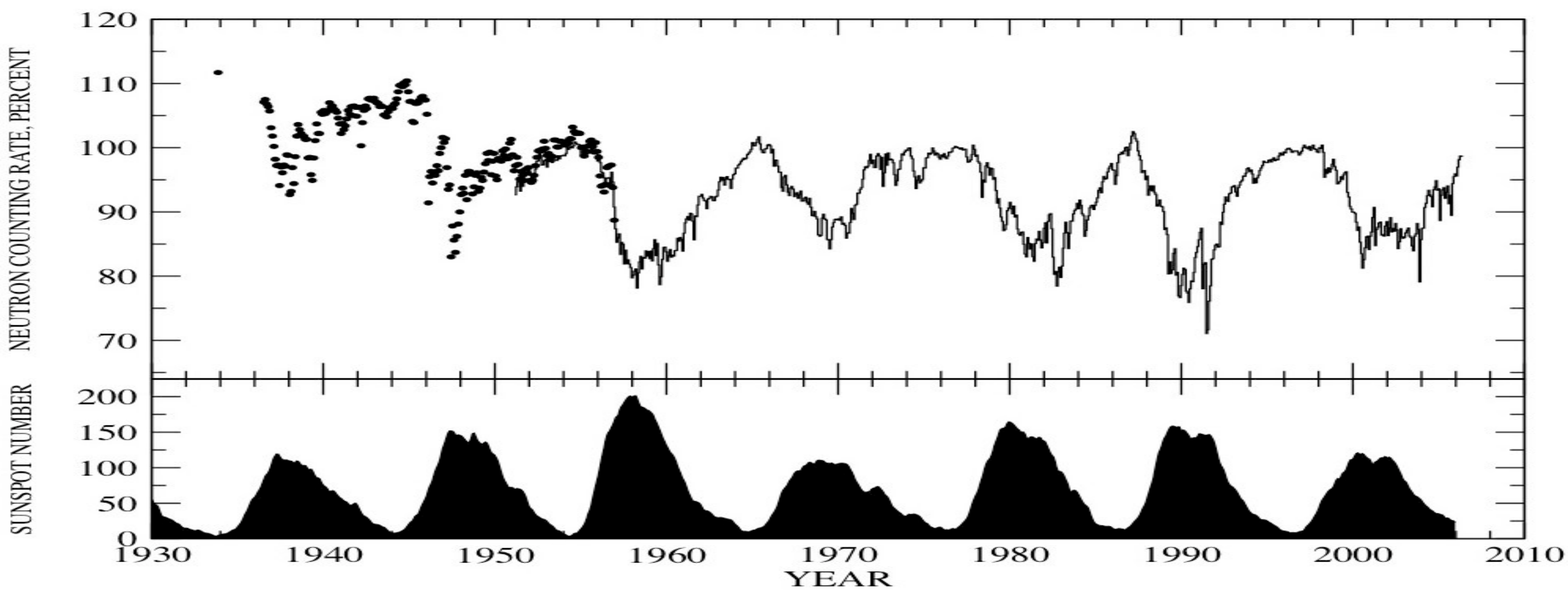






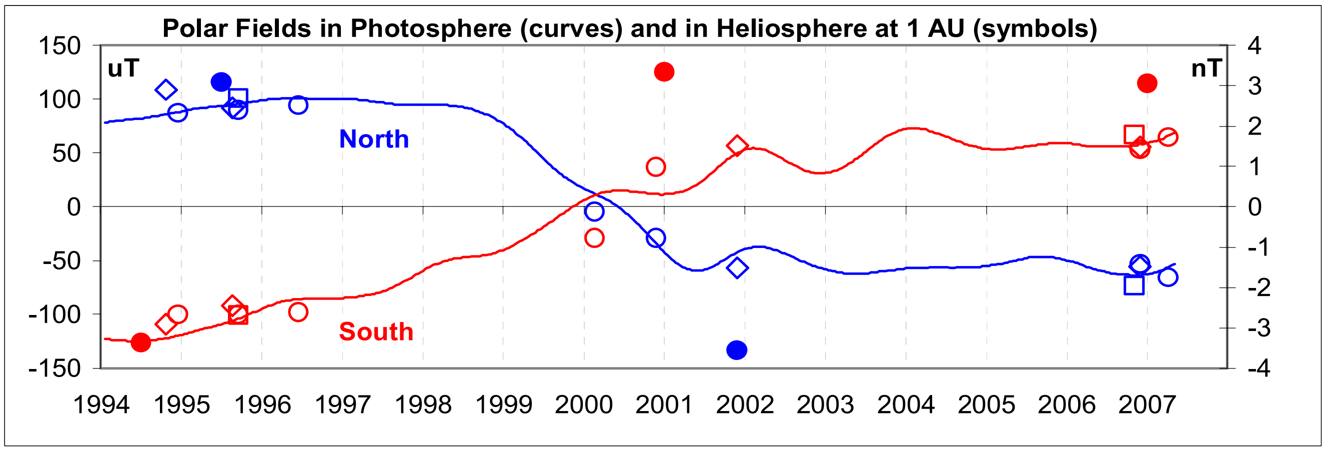
Another reconstruction incorporating the old ionization-chamber data (left) by Stozhkov *et al.* [Proc. ICRC, p.3883, 2001] does not show any “jump” around 1950.

Here is McCracken's re-calibrated GCR-record (dots = ionization-chambers; line = neutron monitors). Just like with the *aa*-index (and the sunspot number) we are faced with the problem of ensuring the long-term stability of the calibration of our primary data. This is a thankless (but important) job.



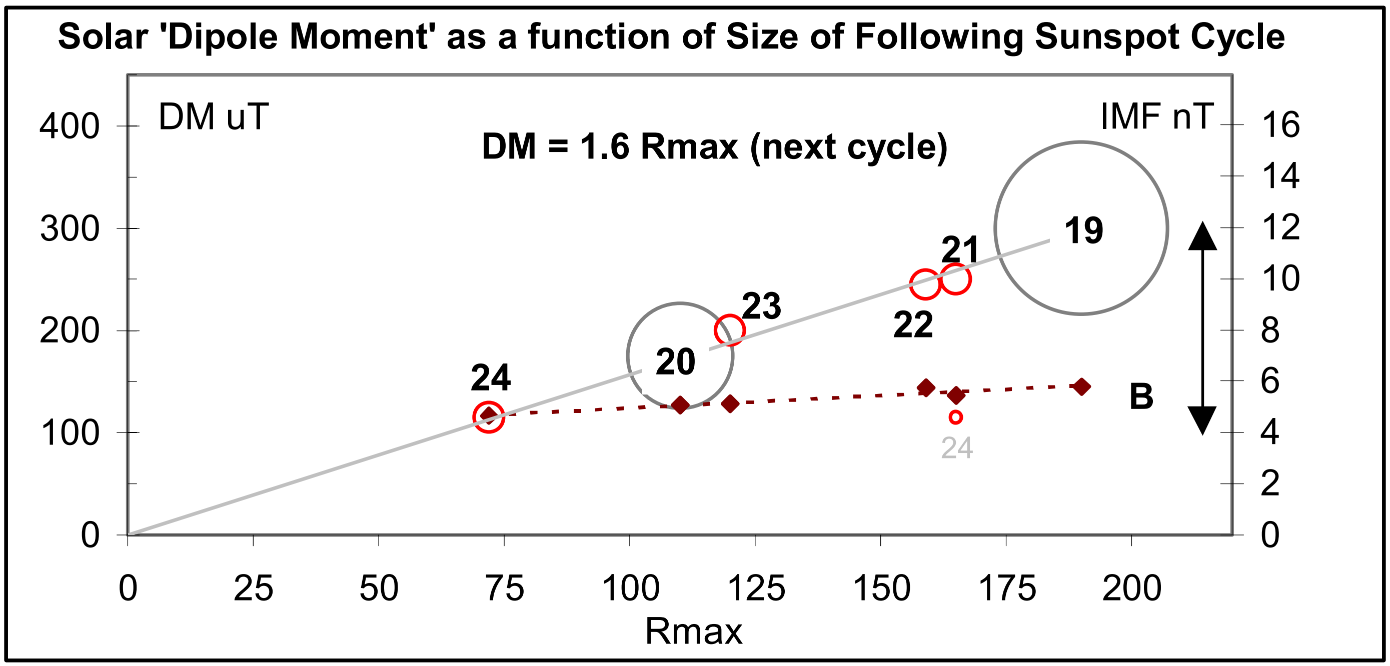
The solar cycle modulation in the ionization-chamber GCR data seems distorted compared with the neutron monitor data and seems to lack to characteristic "sharp-flat" alternation of the peaks. I'm not qualified to comment much further on the GCR measurements, except to note that the GCR inversions are very model-dependent.

The existence of a Floor in the IMF (one throughout or several [McCracken]) presents a puzzle: Our understanding, codified in our models, of the origin of the IMF dictates that the IMF at solar minimum is very sensitive to the solar polar fields. “As the polar fields go, so goes the calculated IMF” (open symbols = modeled B_r per WSA & MAS; filled symbols = Ulysses B_r per the team):



The polar fields at different minima are observed to vary by a factor of two or more; either predicting the size of the next solar cycle (Svalgaard *et al.*) or, as the remnants of the previous cycle, reflecting the size of that cycle (Dikpati *et al.*). We would thus expect the IMF to vary by the same factor; the puzzle is that it does not:

For the two minima before cycles 20 and 19, respectively, the polar fields can only be roughly estimated. As a measure of the Sun's dipole moment, *DM*, we take the absolute value of the difference between the North and South polar fields. *DM* varies as 1.6 R_{max}, so for R_{max} varying from 64 (cycle 14) to 190 (cycle 19), *DM* should vary from 100 uT to 300 uT, and IMF *B* at minimum should vary from 4 nT to 12 nT which it clearly does not. **What is missing in our models (and understanding)?**



Conclusions

1. The geomagnetic record back to ~1840 supports the notion that the IMF is the sum of a constant “floor” at 4.5 nT (open flux) and a variable contribution (mostly closed flux) from CMEs and other sunspot-related flux.

2. This is consistent with the IMF strength derived from cosmogenic nuclides under the assumption that large-scale, transient structures, such as ICMEs play an important role in the modulation of GCRs during periods of high solar activity, although there is (unresolved) disagreement with a recent re-calibration of GCR flux derived from ionization-chamber data before about 1949.

3. The IMF B at solar minimum does not seem to vary in concert with the solar polar fields as our models suggest it should.