Observations of Polar Magnetic Fields and Cycle 25 Prediction

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Nagoya University, **名古屋大学**, Aichi, Japan
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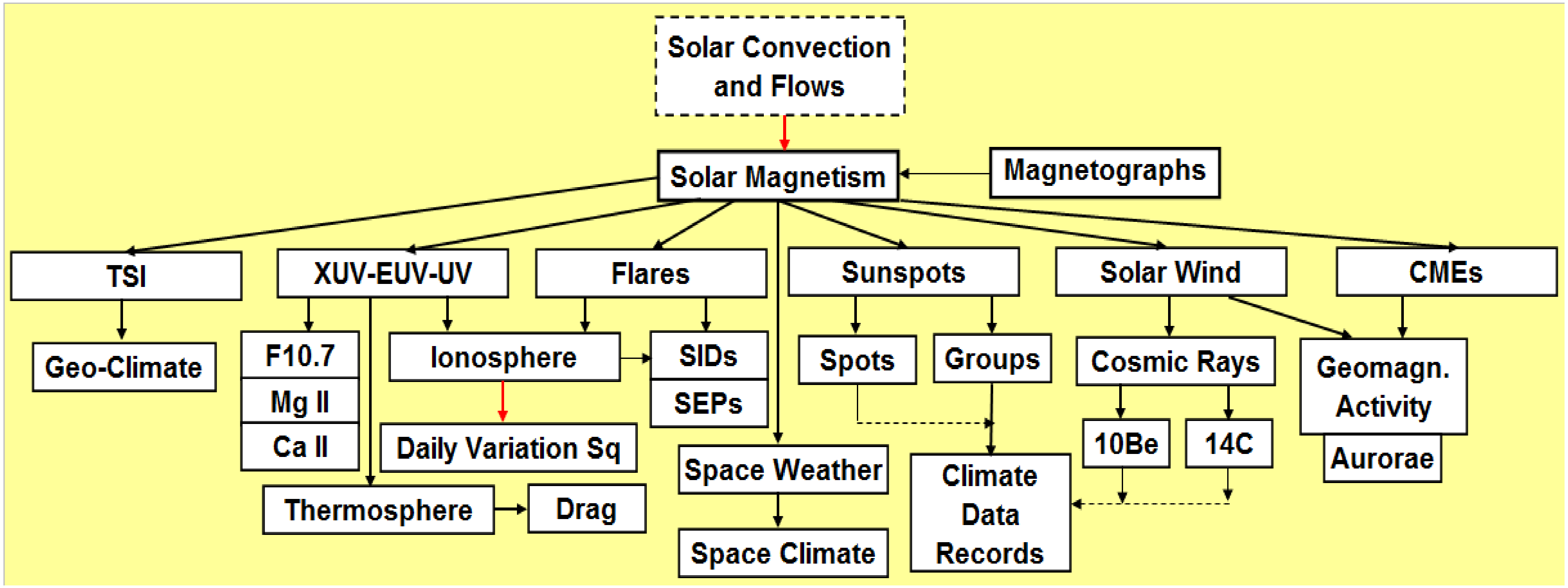
A Systems Approach: Everything Must Fit



Faraday wrote to R. Wolf on 27th August, 1852: “I am greatly obliged and delighted by your kindness in speaking to me of your most remarkable enquiry, regarding the **relation existing between the condition of the Sun and the condition of the Earths magnetism**. The discovery of periods and the observation of their accordance in different parts of **the great system, of which we make a portion**, seem to be one of the most promising methods of touching the great subject of terrestrial magnetism...

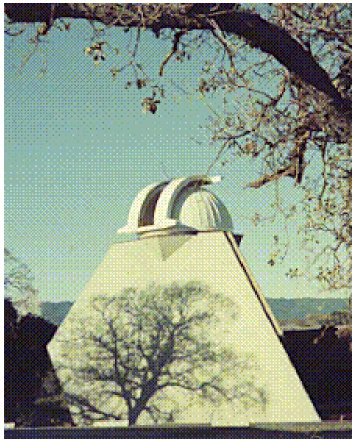
“everything must fit” is a lofty goal and we are not there yet, but it should be a guiding principle

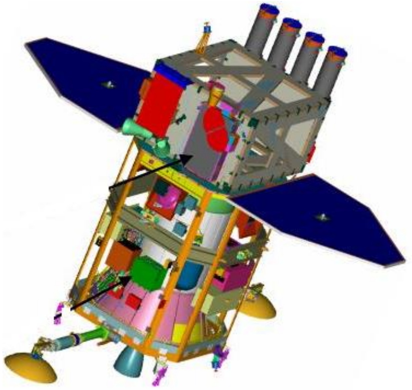
Outline (Where the polar fields are a key parameter)

I have studied this issue for four solar cycles by now and even though we have made *some* progress there are still many mysteries and myths

- Solar Magnetograph Measurement Problems
- The Open Flux Problem and the Polar Fields in Centuries past
- The 3D Heliosphere and Cosmic Rays
- EUV, Microwave Flux, and Magnetic Flux in Time
- The Polar Fields in 17GHz Microwave Flux
- The Polar Field Precursor Hypothesis
- Prediction of Solar Cycle 25 and Beyond
- Caveat Auditor

Solar Magnetograph Measurement Problems





Earliest Measurements of ‘Polar Fields’

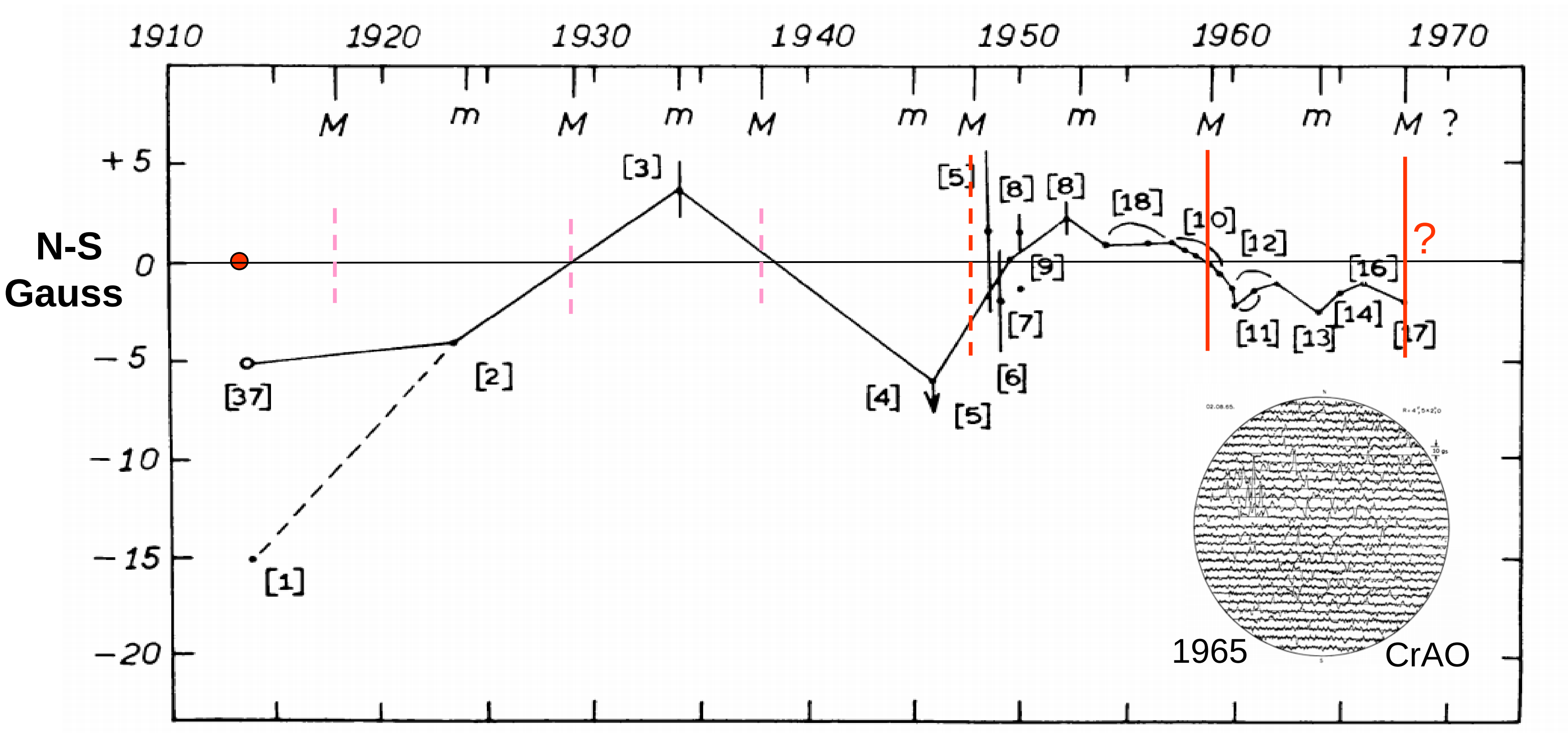


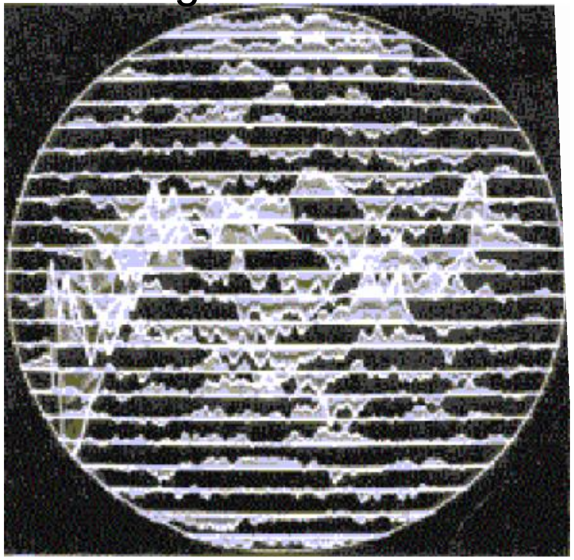
Fig. 1. Representing on a graph the separate determinations of the polarity and magnitude of the general magnetic field of the Sun. [1] = Hale *et al.*, 1918; [2] = Langez, 1936; [3] = Adams, 1934; [4] = Babcock, 1948; [5] = Thiessen, 1946, 1952; [6] = Adams, 1949; [7] = Von Klüber, 1951; [8] = Babcock and Cowling, 1953; [9] = Kiepenheuer, 1953; [10] = Babcock, 1959; [11] = Howard, 1965; [12] = Von Klüber, 1965; [13] = Severny, 1966; [14] = Severny, 1967; [16] = Stenflo, 1968; [17] = Stenflo, 1968; [18] = Babcock and Babcock, 1955; [37] = Stenflo, 1970*. → ●

A.B.Severny, The Polar Fields, etc [Howard, ed. Solar Magnetic Fields, IAU, 1971]
Doubted that the reversals were real…

Early MWO Observations

after Babcock Invented the Magnetograph “by doing everything right”

Strong Polar Fields



MWO Magnetogram 1953

Weak Polar Fields

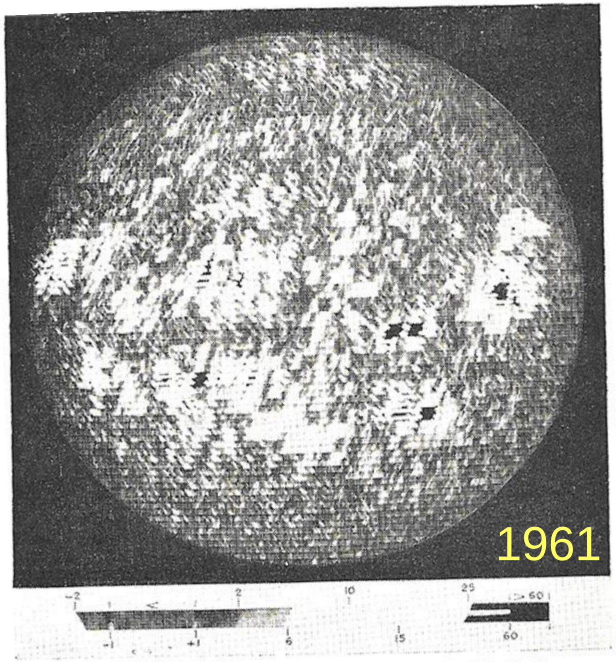
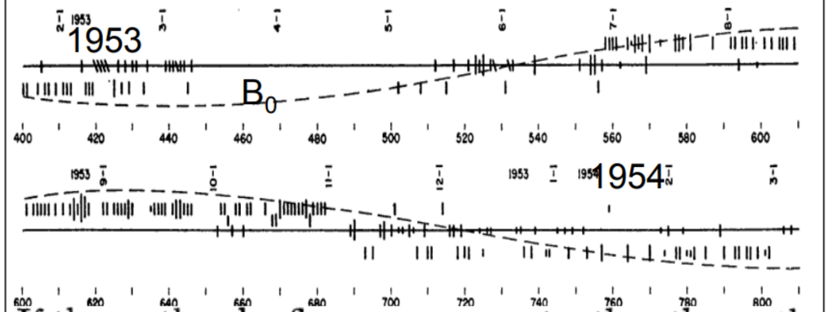
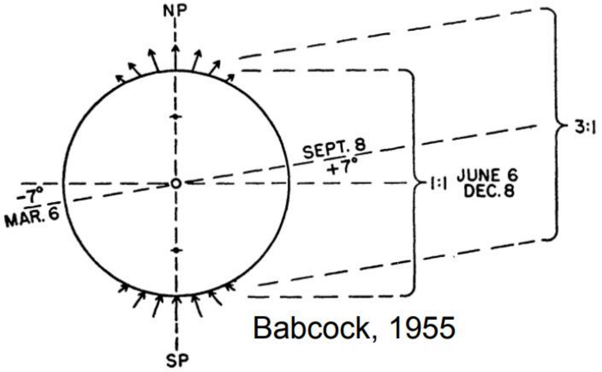


Fig. 1—The Solar Magnetogram for 21 July 1961.

Babcock ApJ 1955



If the north polar flux appears greater than the south, a mark is placed above the horizontal and vice versa.

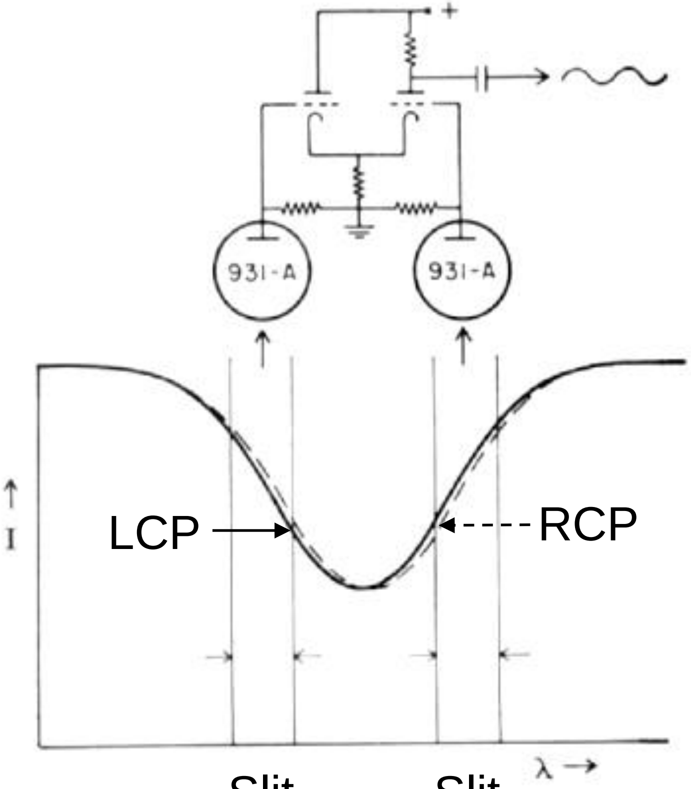


Babcock, 1955

Explanation of the annual variation: concentration at the poles

Magnetograph Principles

Zeeman splitting of spectral lines



LCP

RCP

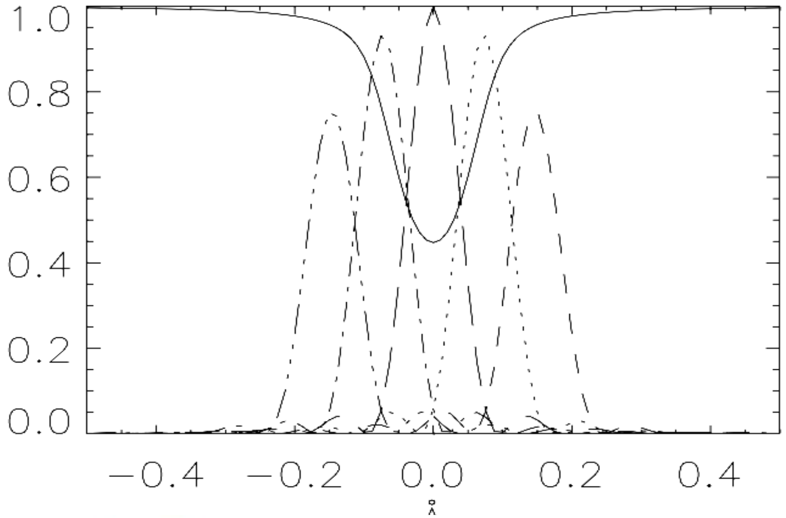
Slit

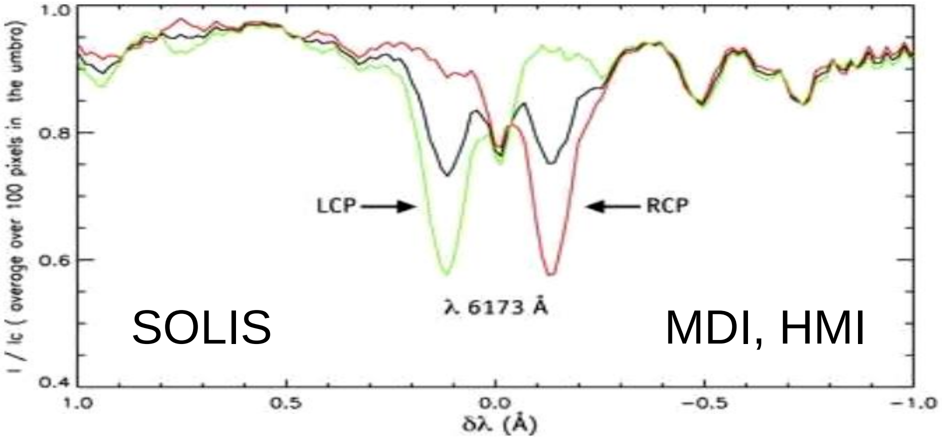
Slit

Babcock-type Magnetograph

MWO, WSO, CrAO

Profile-type Magnetograph

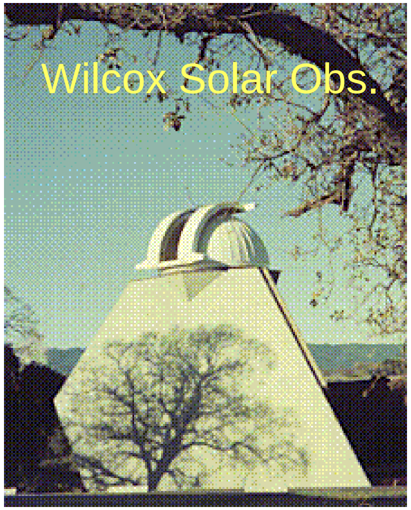


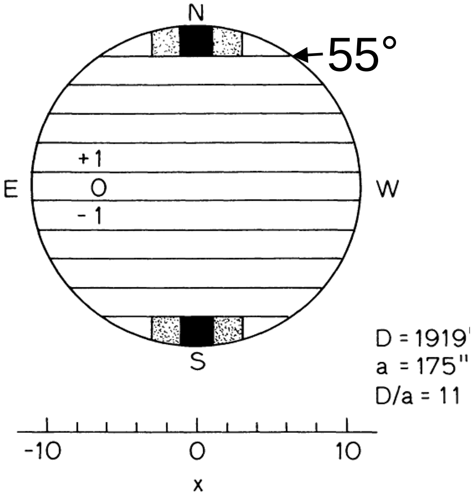


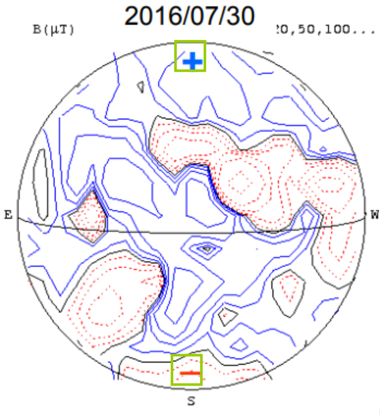
SOLIS

MDI, HMI

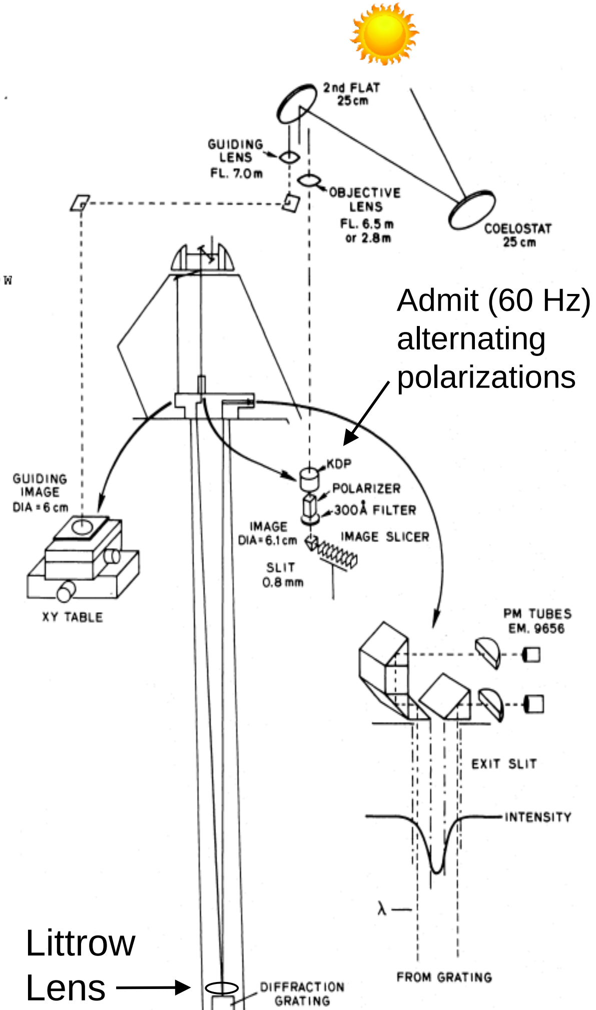
WSO Observations since 1976







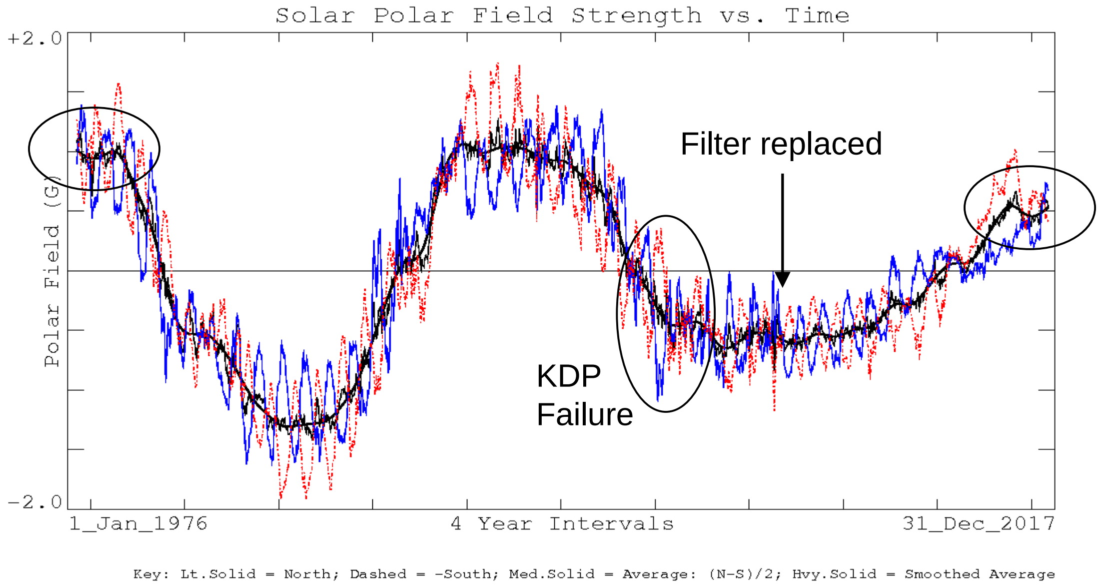
WSO Magnetogram



Admit (60 Hz) alternating polarizations

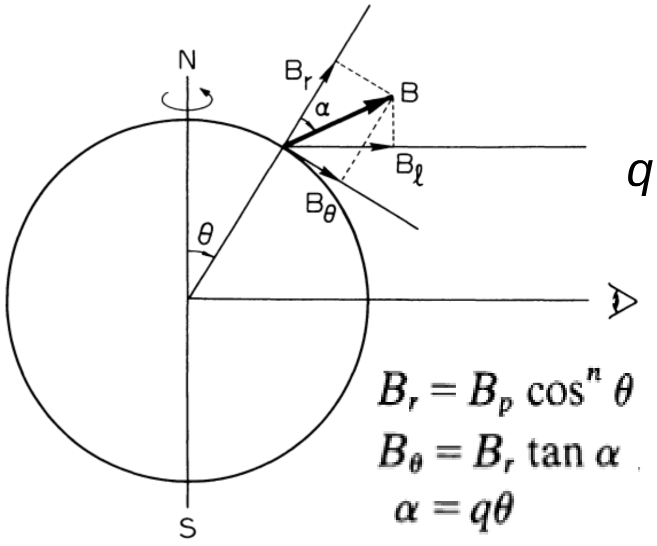
Littrow Lens

Same as MWO's

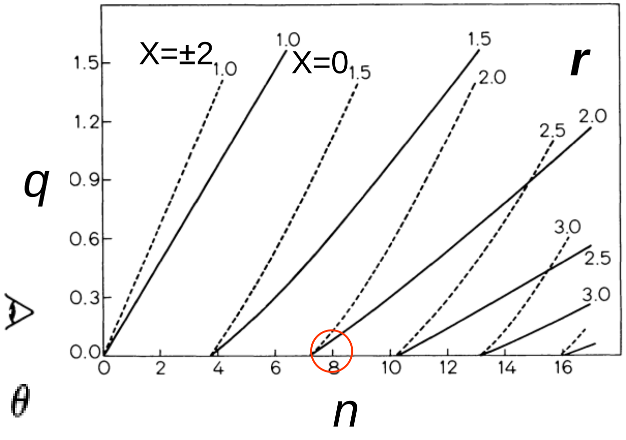


The magnetograph has never been upgraded

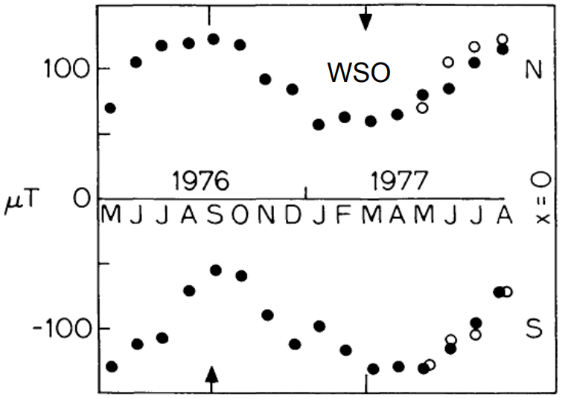
We found the Polar fields to be Radial and strongly Concentrated towards the poles

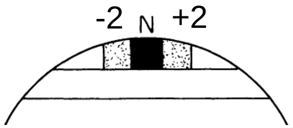


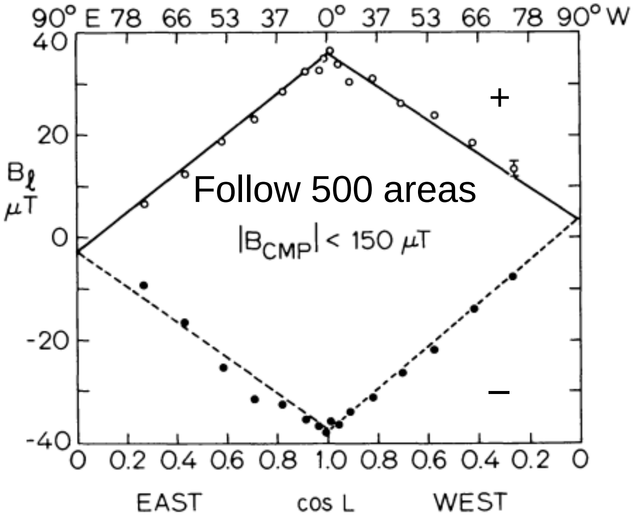
$$B_r = B_p \cos^n \theta$$
$$B_\theta = B_r \tan \alpha$$
$$\alpha = q\theta$$



$$r = \frac{\langle B\rangle_{\rm comp}[\text{toward}]}{\langle B\rangle_{\rm comp}[\text{away}]} = 2.1\pm0.1$$







Follow 500 areas

$|B_{CMP}| < 150$ μT

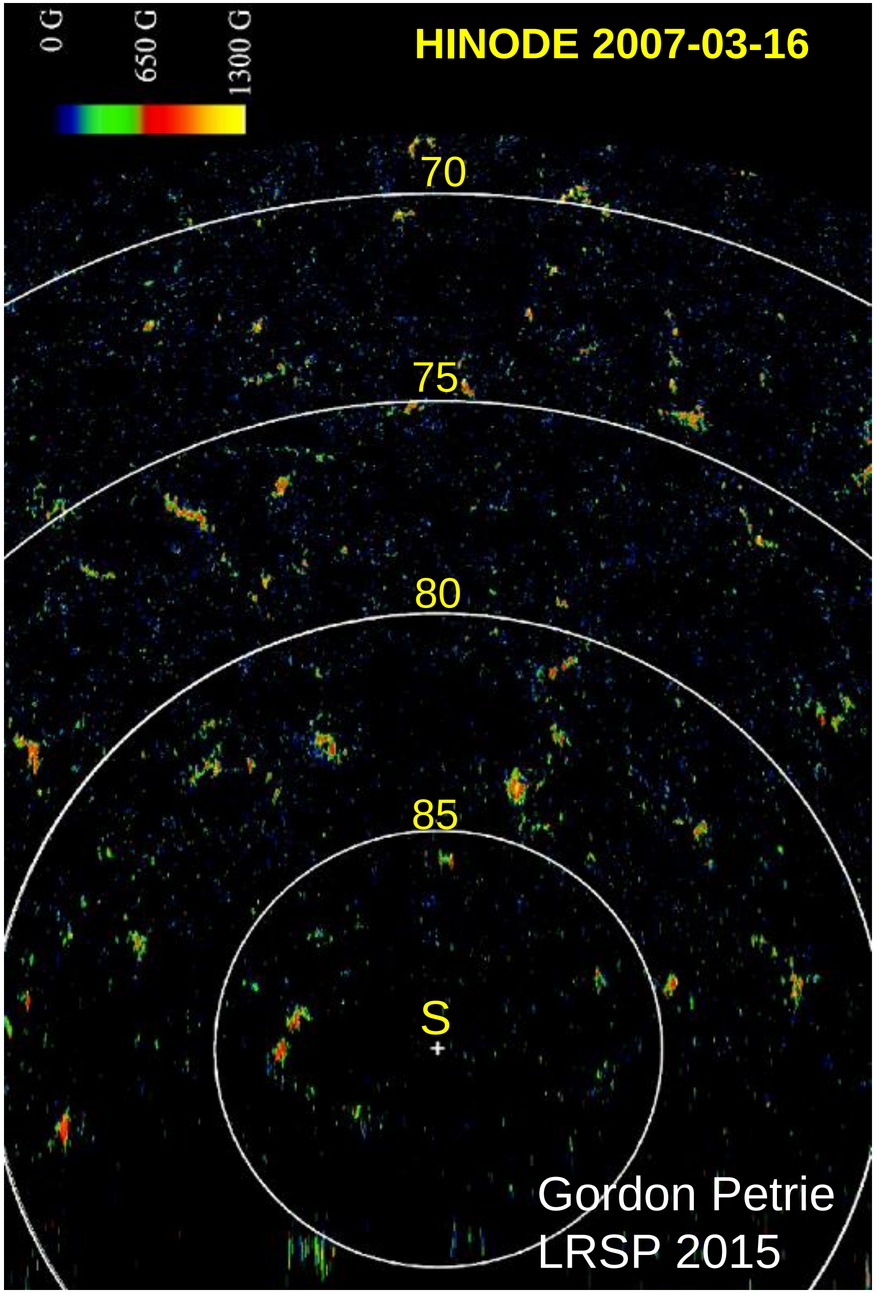
We found $n = 8\pm1$ and $q = 0.0\pm0.1$ and thus:

$$B = B_p \cos^8\theta$$

Other researchers have confirmed this with *n* in the range [7-10]

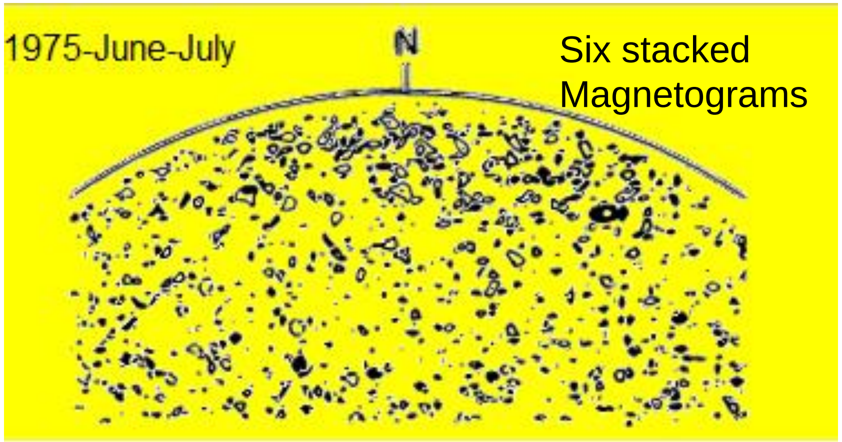
Calculate the average line-of-sight component of the model field weighted by limb darkening within each of our apertures for various tilts, B_0, of the polar axis through the year

Fine Structure of kG Polar Fields



Gordon Petrie
LRSP 2015

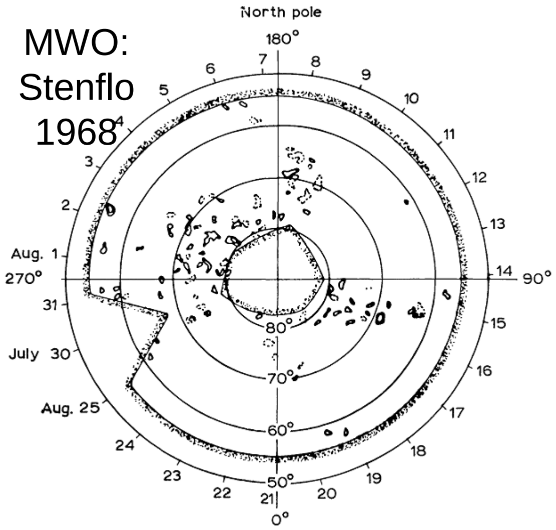
The polar magnetic ‘landscape’



Six stacked Magnetograms

MWO: Howard, R., Solar Physics, 59, 243 (1978)

MWO: Stenflo 1968



This concentration of strong flux elements near the poles has been observed for a long time; a meridional flow seems to be needed for this.

Calibration of WSO Magnetograph

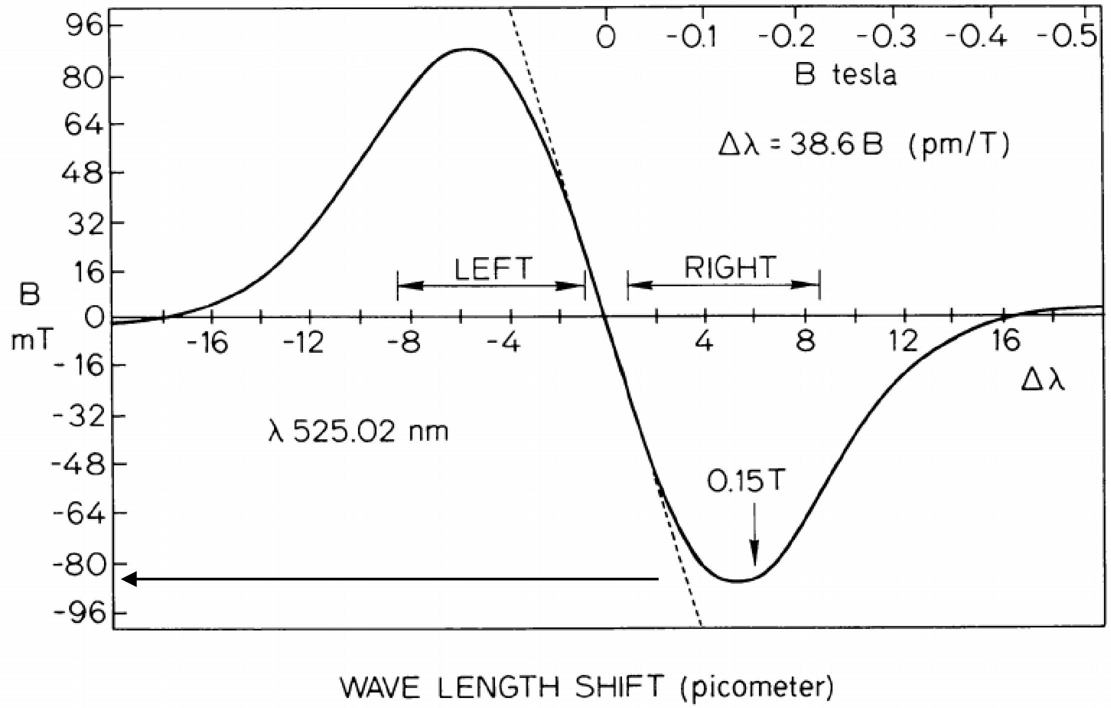
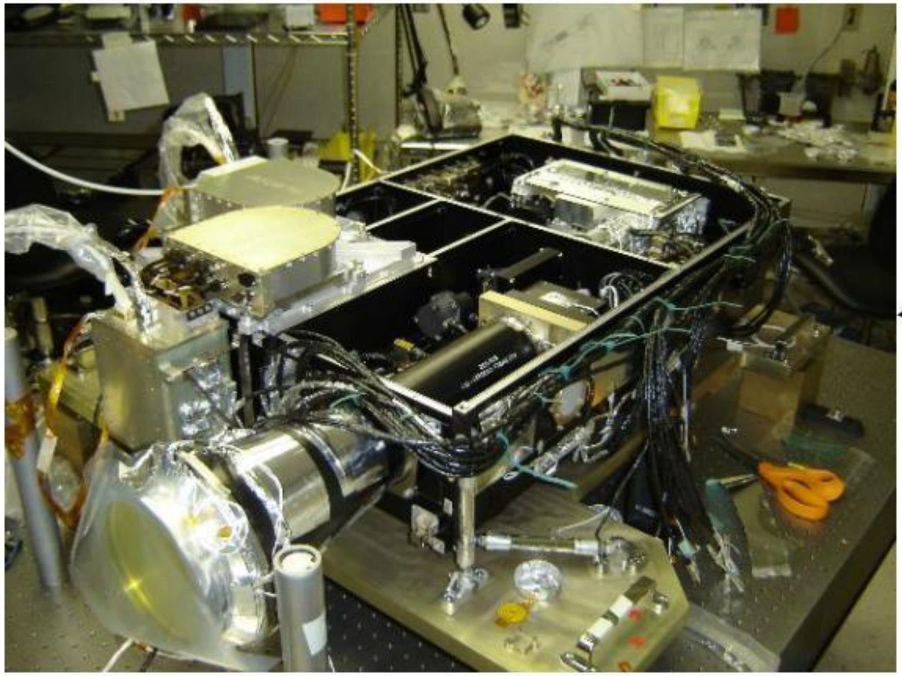


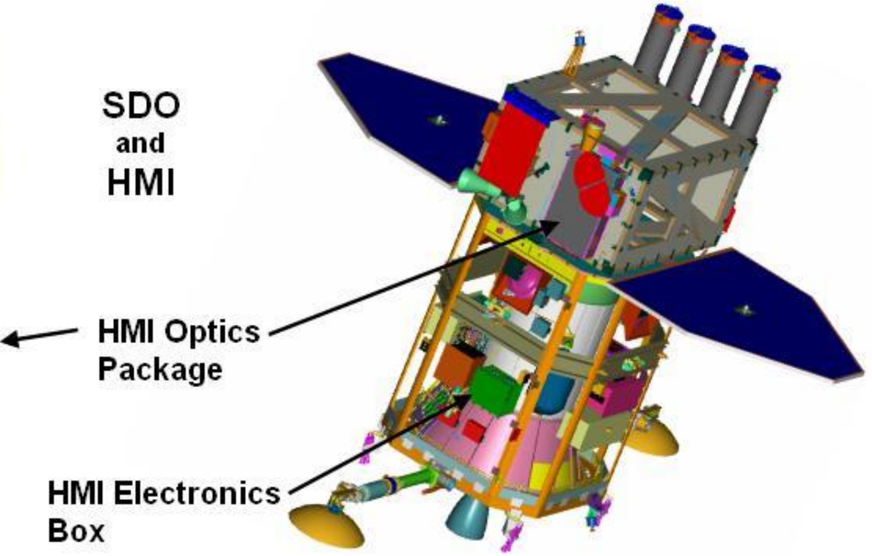
Fig. 7. Calibration curve for the Stanford magnetograph for the Fe I line λ 525.02 nm and for exit slits λ 7.5 pm wide separated by λ 1.8 pm. A magnetic field produces a Zeeman splitting of Δλ = 38.6 pm/T. This relation is shown as the dotted line and is also used to calibrate the scale along the upper right boundary of the figure frame. Slit dimensions are shown in the middle of the figure.

For weak fields (< 50 mT) the magnetic signal is linear with the field strength. As the field increases, the response weakens and at 143 mT, the magnetograph is saturated and any further increase actually decreases the magnetic signal. **If the field strength of the magnetic elements is 150 mT** (1500 G) the reading would be only 83 mT (arrow); hence the effect of magnetograph saturation due to the strong fields in the elements is to reduce the measured flux by a factor 150/83 = **1.8**

We found that the line-of-sight ‘field’ is a simple projection of a radial field and is underestimated by a factor 1.8 for magnetic elements with field strength 150 mT (1500 G) which is independent of the heliocentric angle [if the kG elements are].

Our Shiny New Satellite





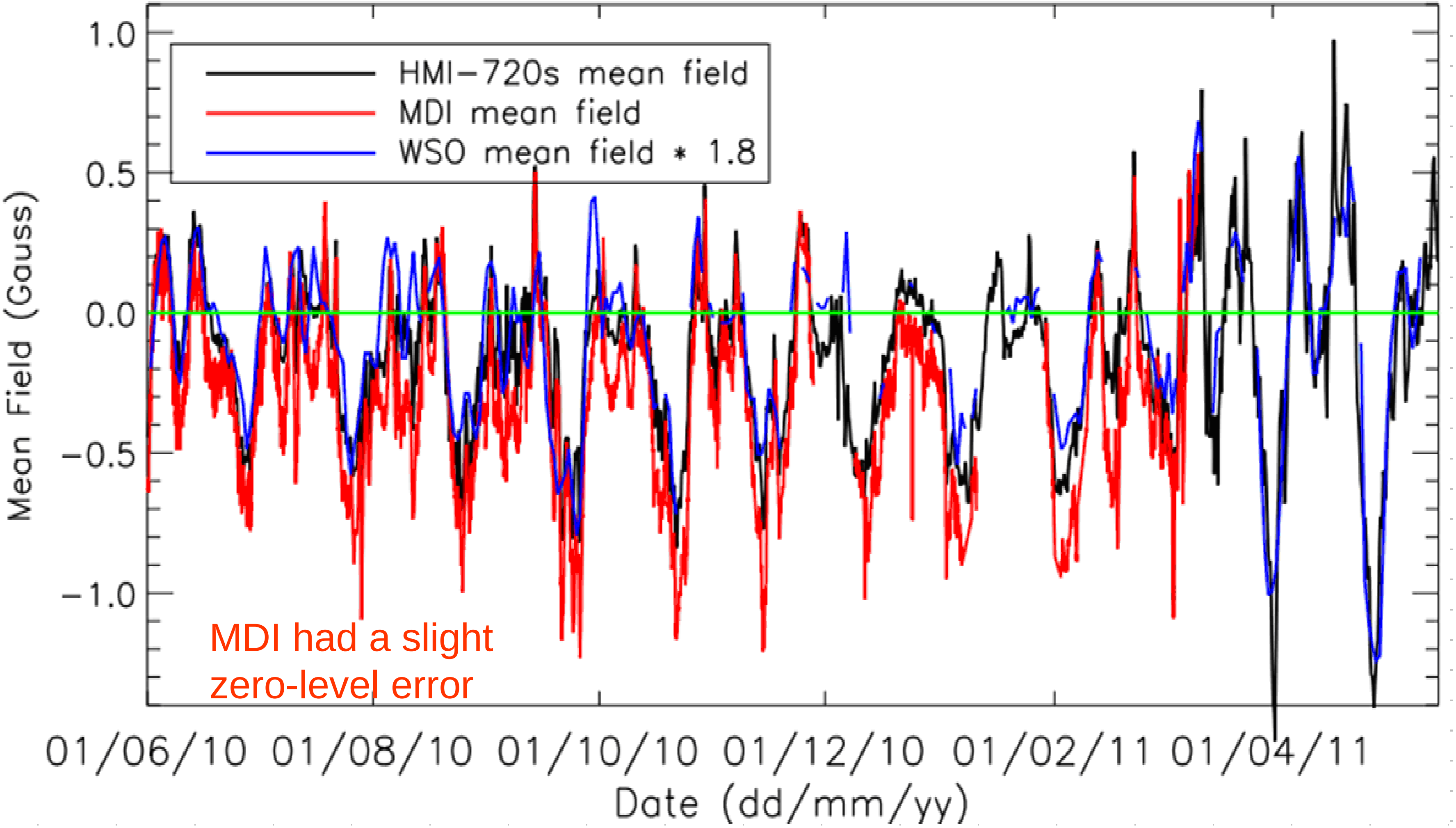
Replacement of the MDI on SOHO that observed in the Ni I line at 676.8 nm.

The Helioseismic and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO) was launched in 2010 and measures the magnetic field [actually ‘flux’] in the Fe I line at 617.3 nm every 45 seconds with 1” resolution.

Instead of just looking at the ‘wings’ of the line, HMI samples the line in six wavelengths spanning the line to reconstruct the profiles of the Zeeman-split circularly polarized components. Thus avoiding most of the saturation of the 525 nm line used at WSO and MWO.

Note: WSO, HMI, and MDI all observe in different lines with different magnetic sensitivity formed at different depths

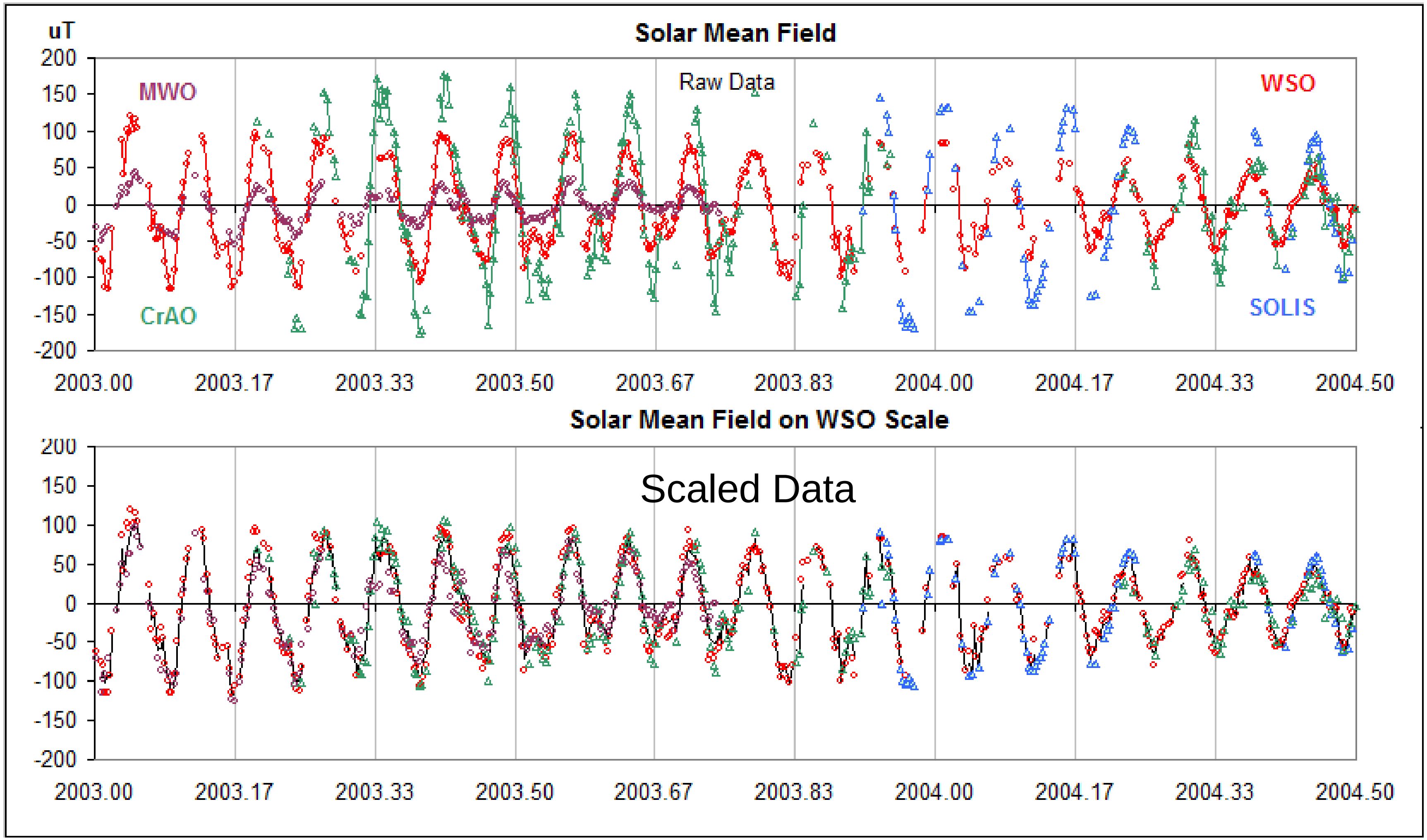
MDI and HMI Confirm the WSO ~1.8 Factor



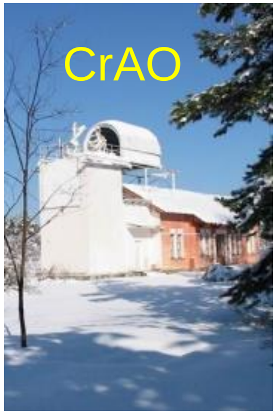
MDI had a slight zero-level error

In spite of the different lines and different observing techniques

All Observatories see the Same Mean Field (Net Flux), but on Different Scales



There exists a set of constant factors that when applied to the raw data puts them all on the same scale. Here we used WSO, but which is the ‘correct’ one?



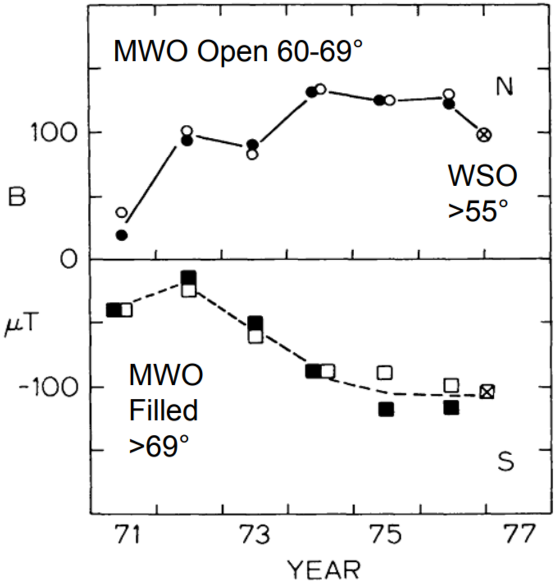
All Observatories see the Same Mean Field, but on Different Scales

Obs.	Line	g	Get HMI	Get WSO
SOLIS	**Fe I 630.2**	**1.67**	**1.06**	**0.62**
CrAO	**Fe I 525.0**	**3.00**	**1.04**	**0.61**
MWO	**Fe I 525.0**	**3.00**	**4.00**	**2.35**
WSO	**Fe I 525.0**	**3.00**	**1.70**	**1.00**
MDI	**Ni I 676.8**	**1.43**	**1.20**	**0.71**
HMI	**Fe I 617.3**	**2.50**	**1.00**	**0.59**
GONG	**Ni I 676.8**	**1.43**	**1.15**	**0.68**

Same line, so differences must be instrumental

Data for the past 20 years

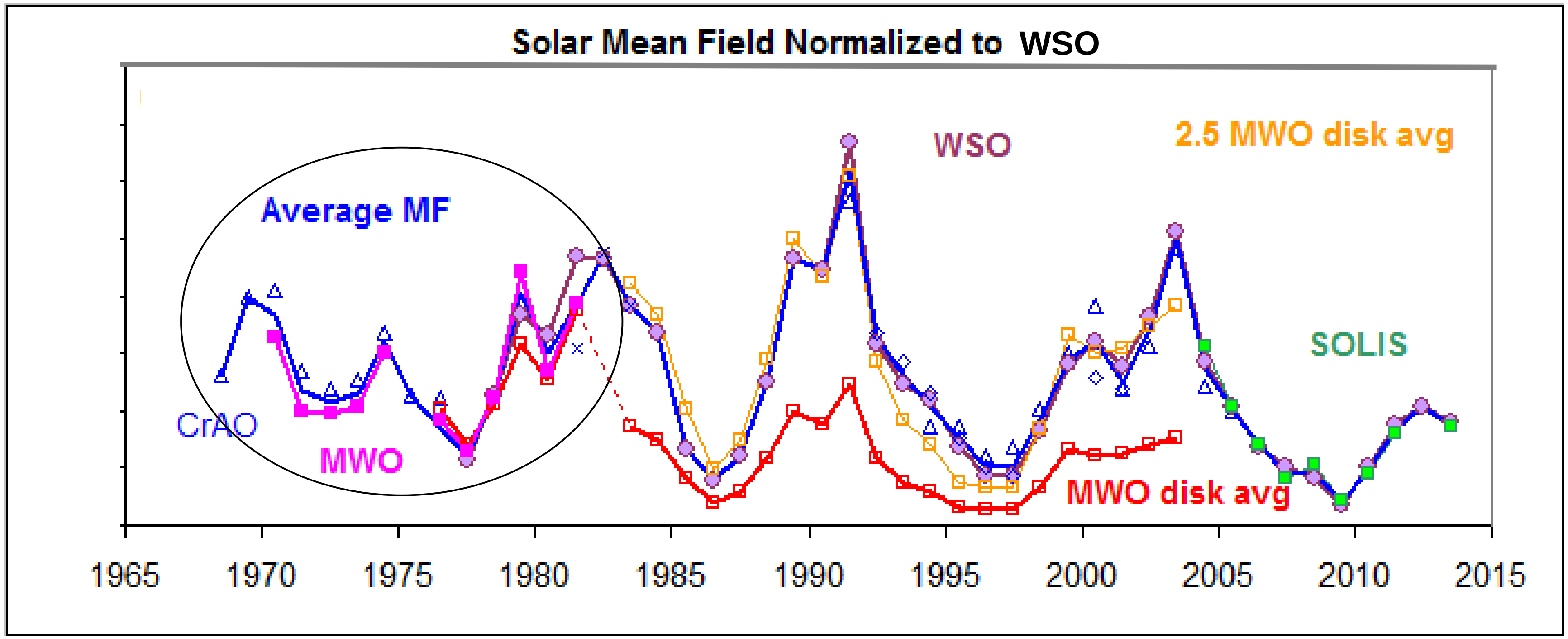
It does not make sense to apply the scale factor for one observatory on the data for another one



We are interested in the polar fields and **back in the 1970s** the polar fields measured at MWO and WSO agreed…

What changed? And When?

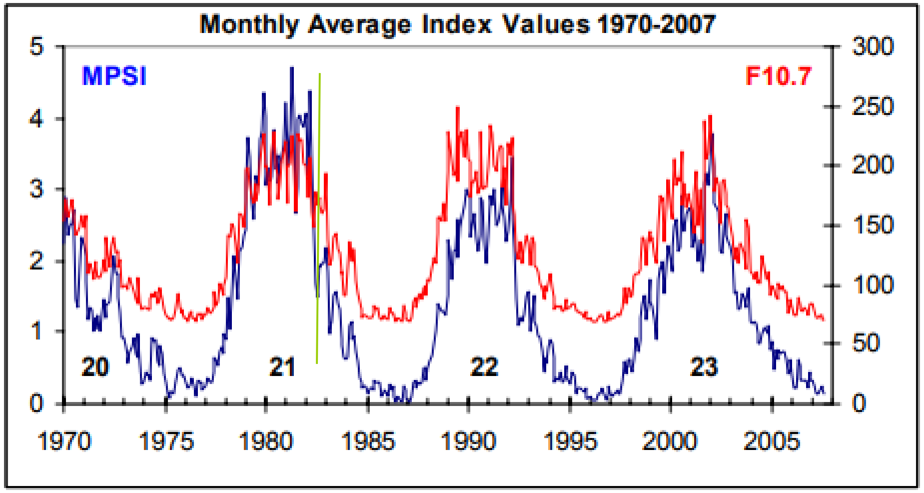
What Happened in 1982?

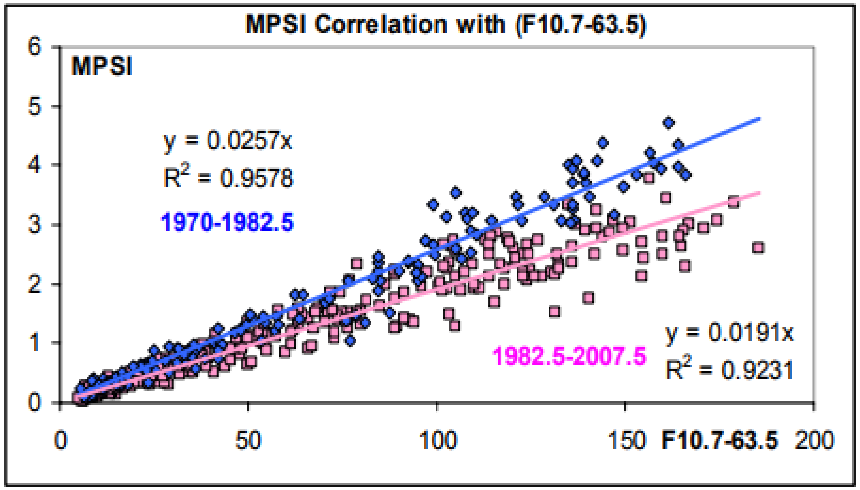


Before 1982, the **Mean Field** [or better: the net flux] *measured* by the MWO magnetograph matched that computed by averaging the field over the disk, and could be scaled to that of the other observatories [CrAO, WSO]. After an ‘**upgrade**’ in 1982 this is no longer the case and the field from MWO has to be scaled up by a factor of ≈2.5.

MWO Magnetic Plage Strength Index

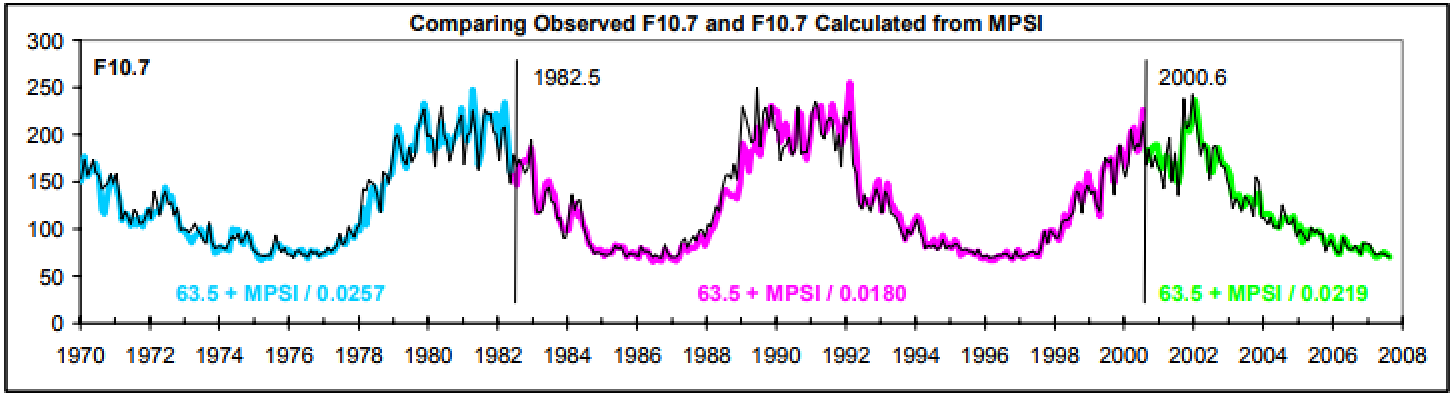
For each magnetogram taken at the 150-Foot Solar Tower at Mount Wilson Observatory (MWO), a Magnetic Plage Strength Index (MPSI) value is calculated: the magnetic field strengths for all pixels where the absolute value of the magnetic field strength is between 10 and 100 gauss are summed. This number is then divided by the total of number of pixels (regardless of magnetic field strength) in the magnetogram. Here are the monthly means of the MPSI and F10.7 radio flux since 1970.





It is clear that highly correlated short time scale variations from month to month are present in both time series, but also that there are significant differences in the long-term behavior, e.g. that cycles 21 and 22 are similar in F10.7, but very different in MPSI. This is an indication that the calibration of the MWO magnetic data is not constant over time.

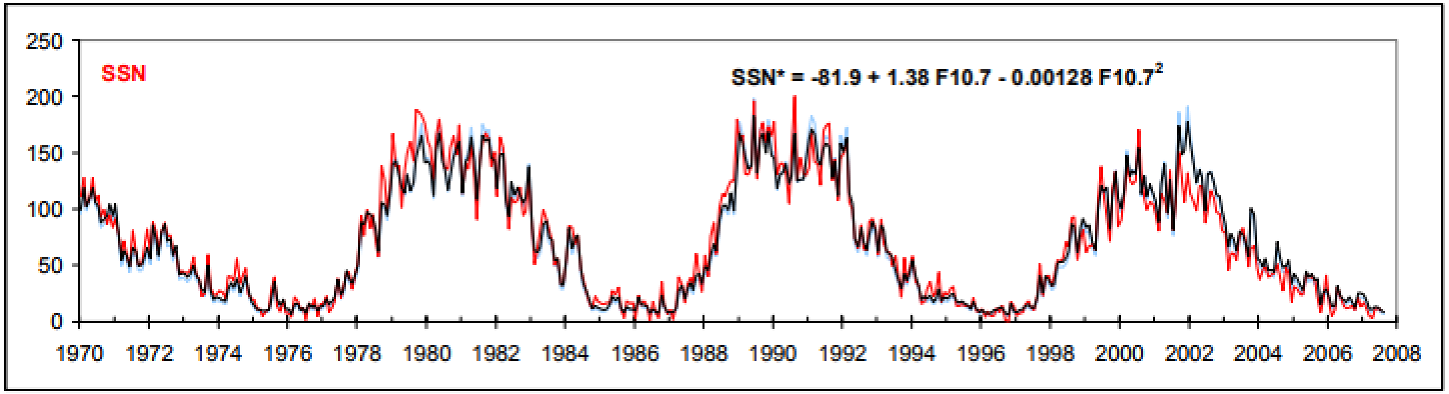
MWO, Further Inhomogeneity



MPSI = 0.0257 (F10.7 – 63.5) before 1982.3

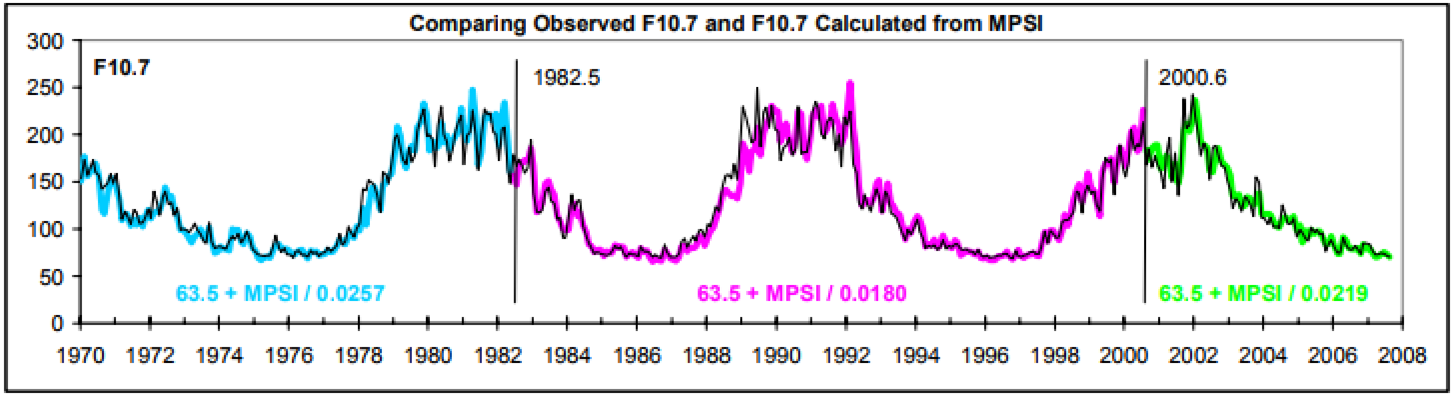
MPSI = 0.0180 (F10.7 – 63.5) between 1982.3-2000.6

MPSI = 0.0219 (F10.7 – 63.5) after 2000.6

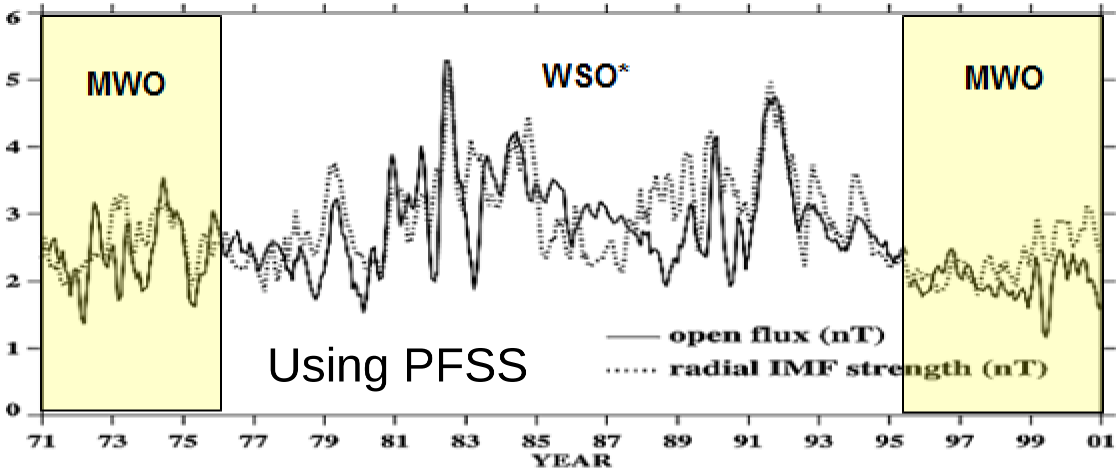


Sunspot number and F10.7 agreed well, so F10.7 is likely not at fault

The Dangers of Cherry Picking in Order to Get a Better Fit…



Corrected MWO MPSI compared to F10.7

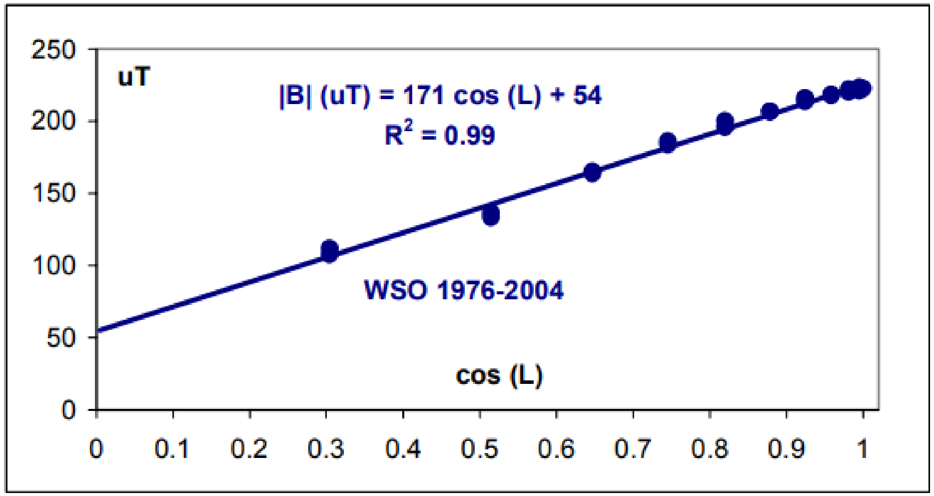


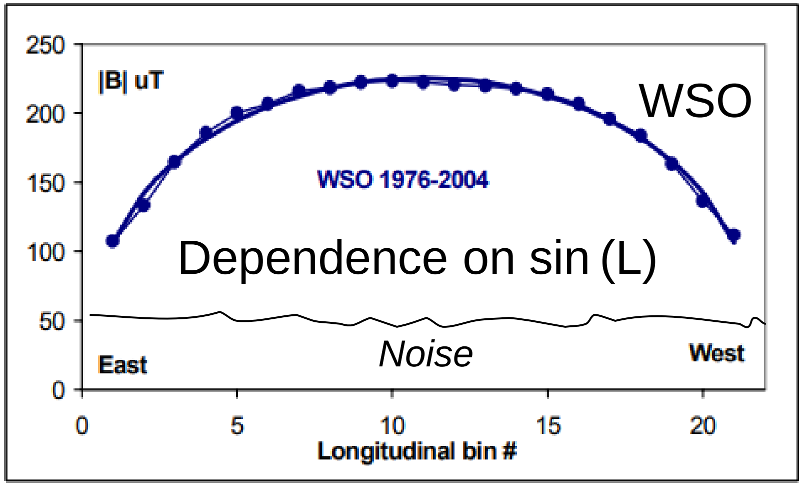
Using PFSS

Wang, Y.-M. and N. R. Sheeley Jr., Sunspot activity and the long-term variation of the **Sun's open magnetic flux**, J. Geophys. Res., 107(A10), 1302, 2002.

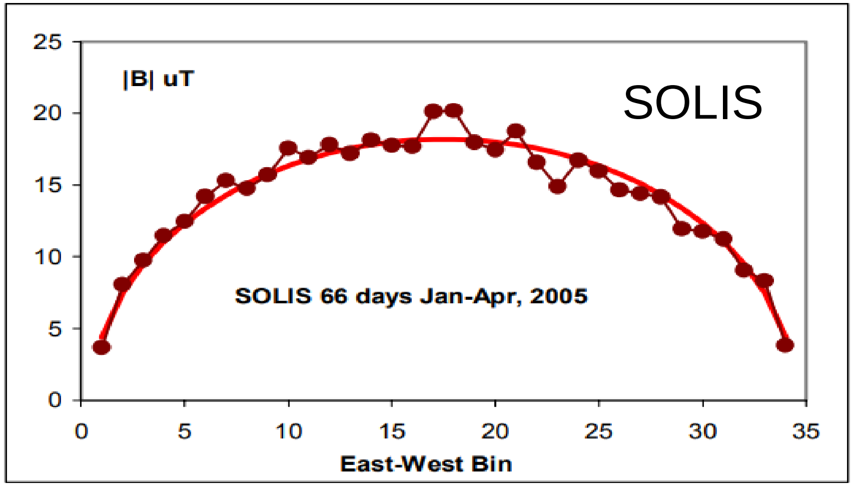
Wang and Sheeley scaled both the MWO and WSO [Carrington Synoptic Maps] data upward by the same factor, which varied from 4.5 at the equator to 2 at the poles. This factor, while appropriate for MWO after 1982, is not applicable for WSO for which a constant factor of 1.8 has been found or for MWO before 1982. Their argument was that that improved the fit…

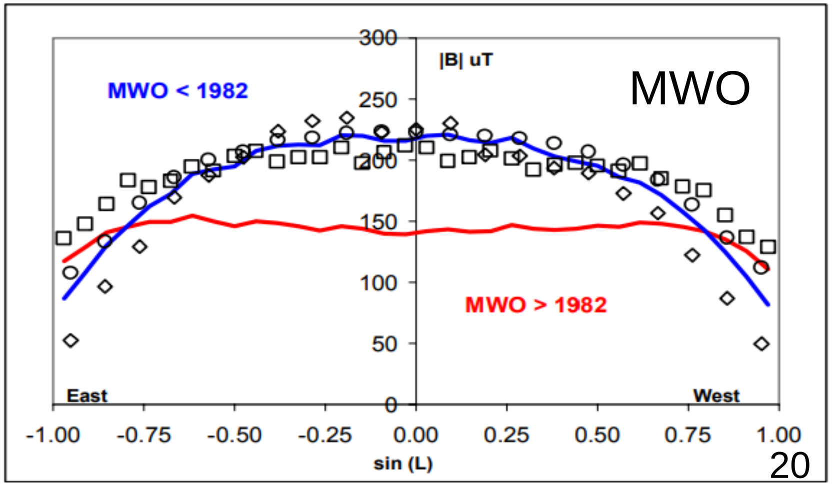
Magnetic Fields Across the Disk



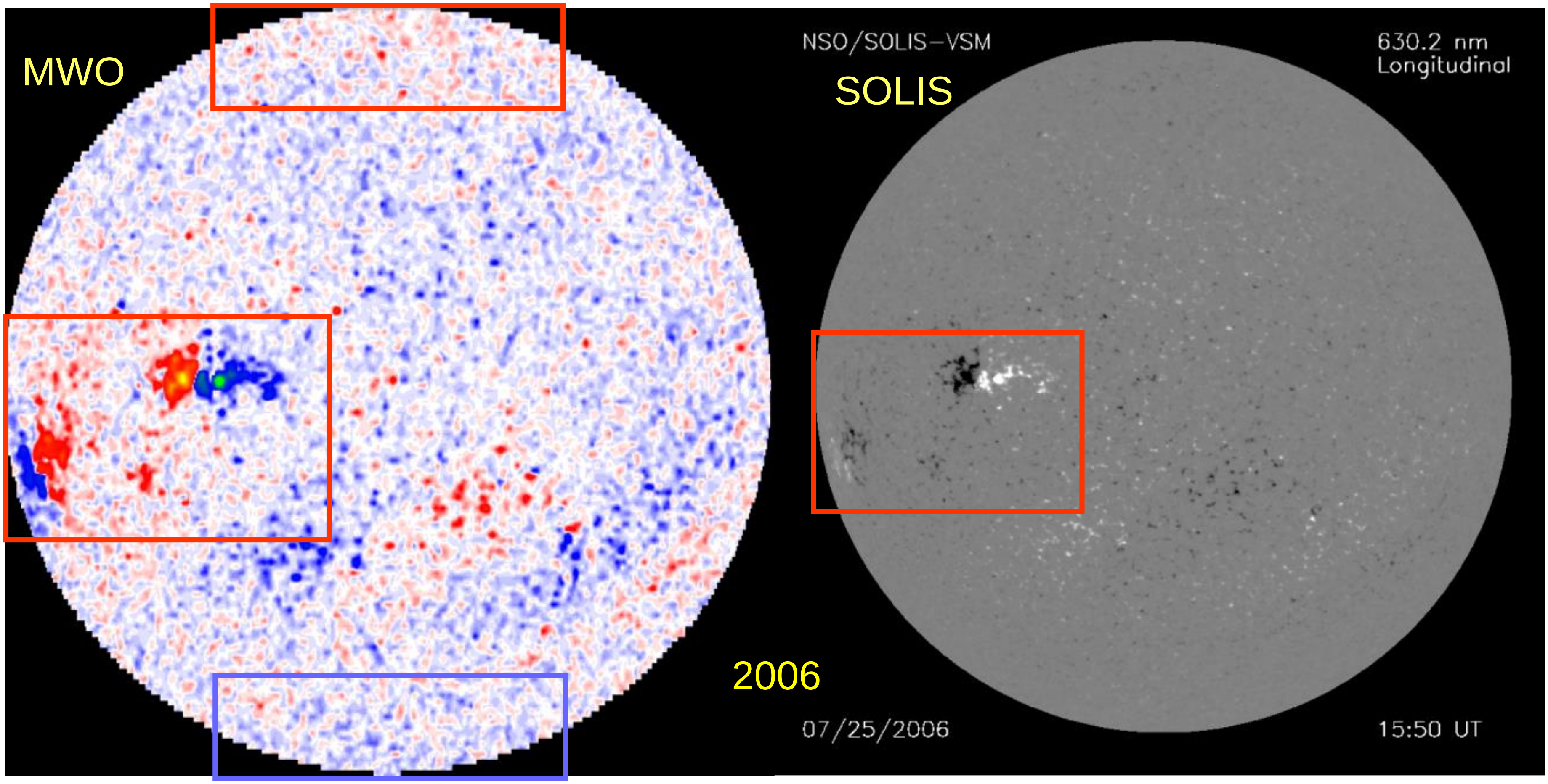


A simpler procedure is just computing the average unsigned field for the equatorial strip. This introduces a noise component, showing up as an offset, but with still a cos (L) dependence above the noise.



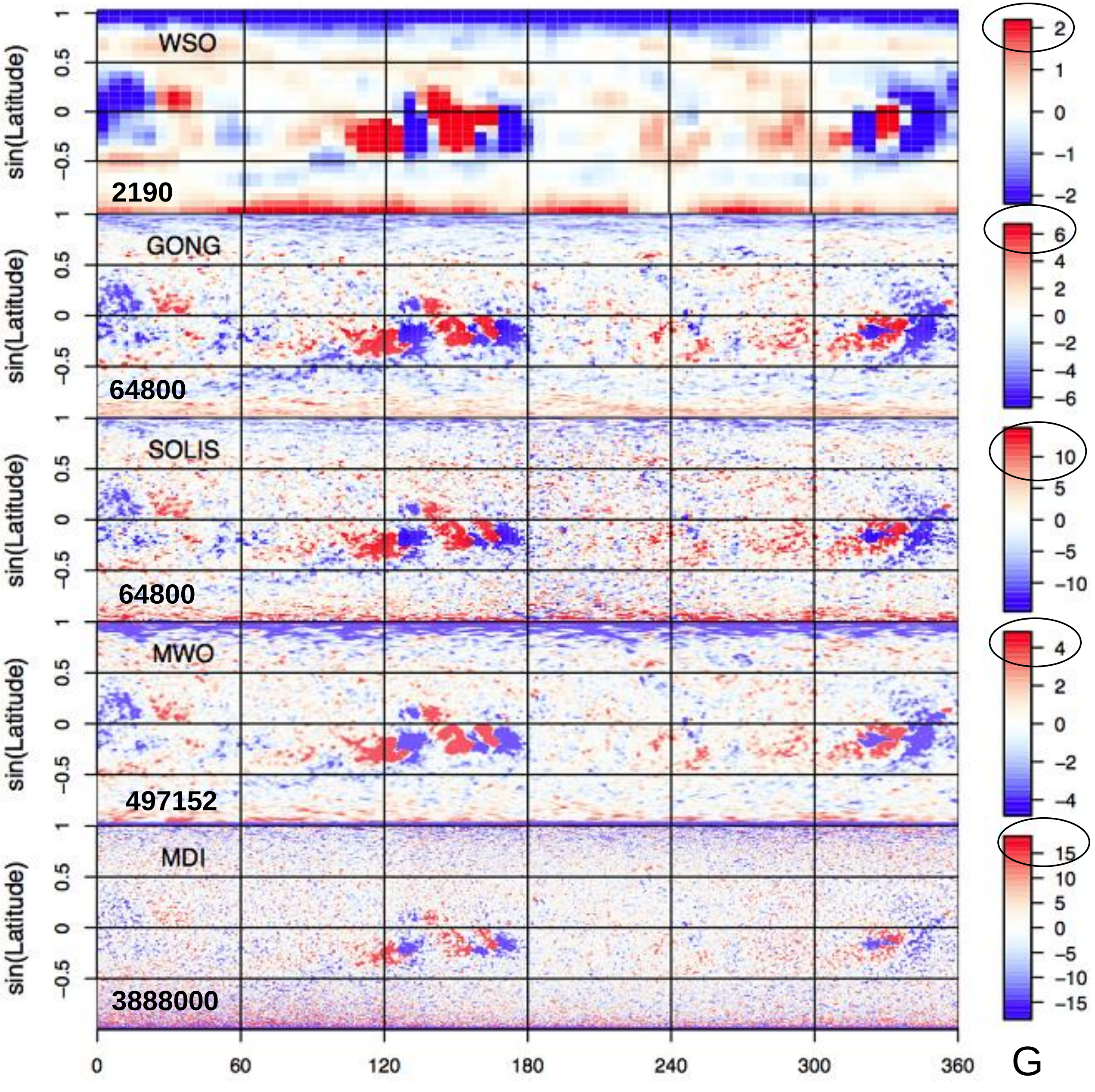


Lack of Center-to-Limb Weakening for MWO



The lack of center-to-limb weakening by projection at MWO can be easily discerned by eye; actually helps in seeing polar fields! MWO left and SOLIS right.

Synoptic Maps



Riley et al. 2014

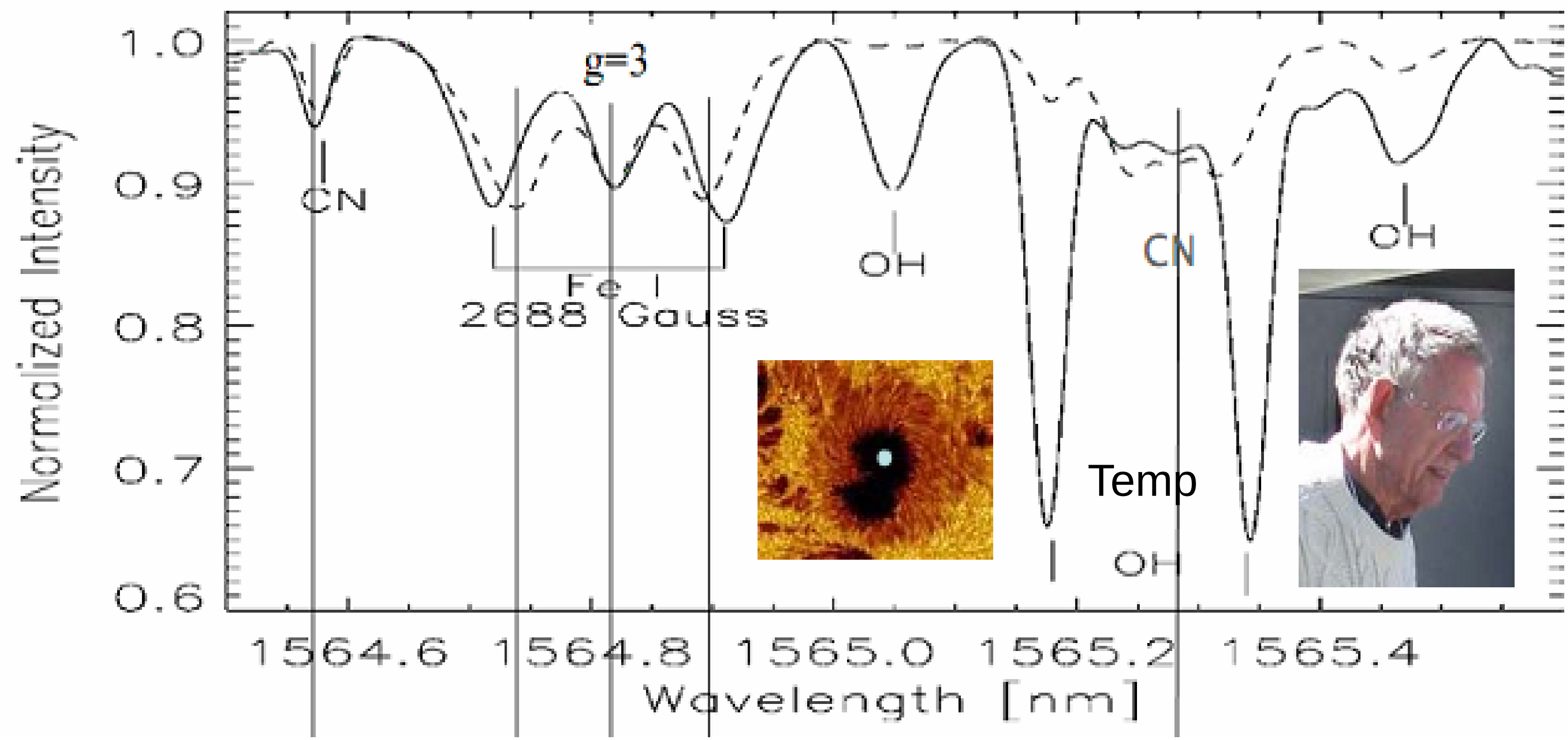
For CRot 2047

Many models use the synoptic maps as input, so it is of interest to know the conversion factors, e.g. for each pixel of the map. The ranges for the color bars were set to ±5×M,where M is the median of the absolute value of each map

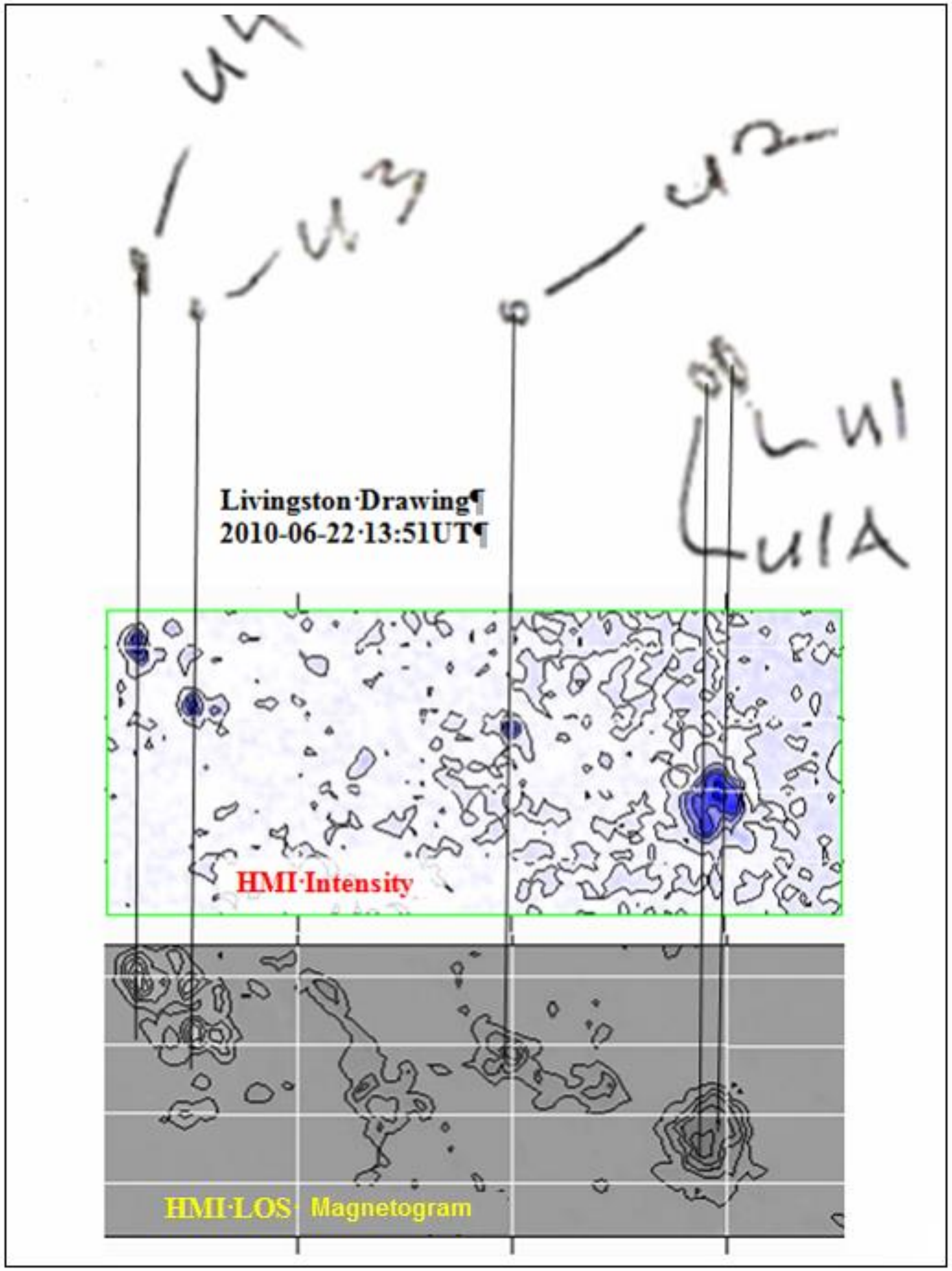
"we find no evidence that the MWO saturation correction factor should be applied to WSO data".

"the models predict [open] field strengths that are substantially (2-3 times) lower than are observed at 1 AU. This is the 'open flux problem'.

What is the True Magnetic Field Strength?



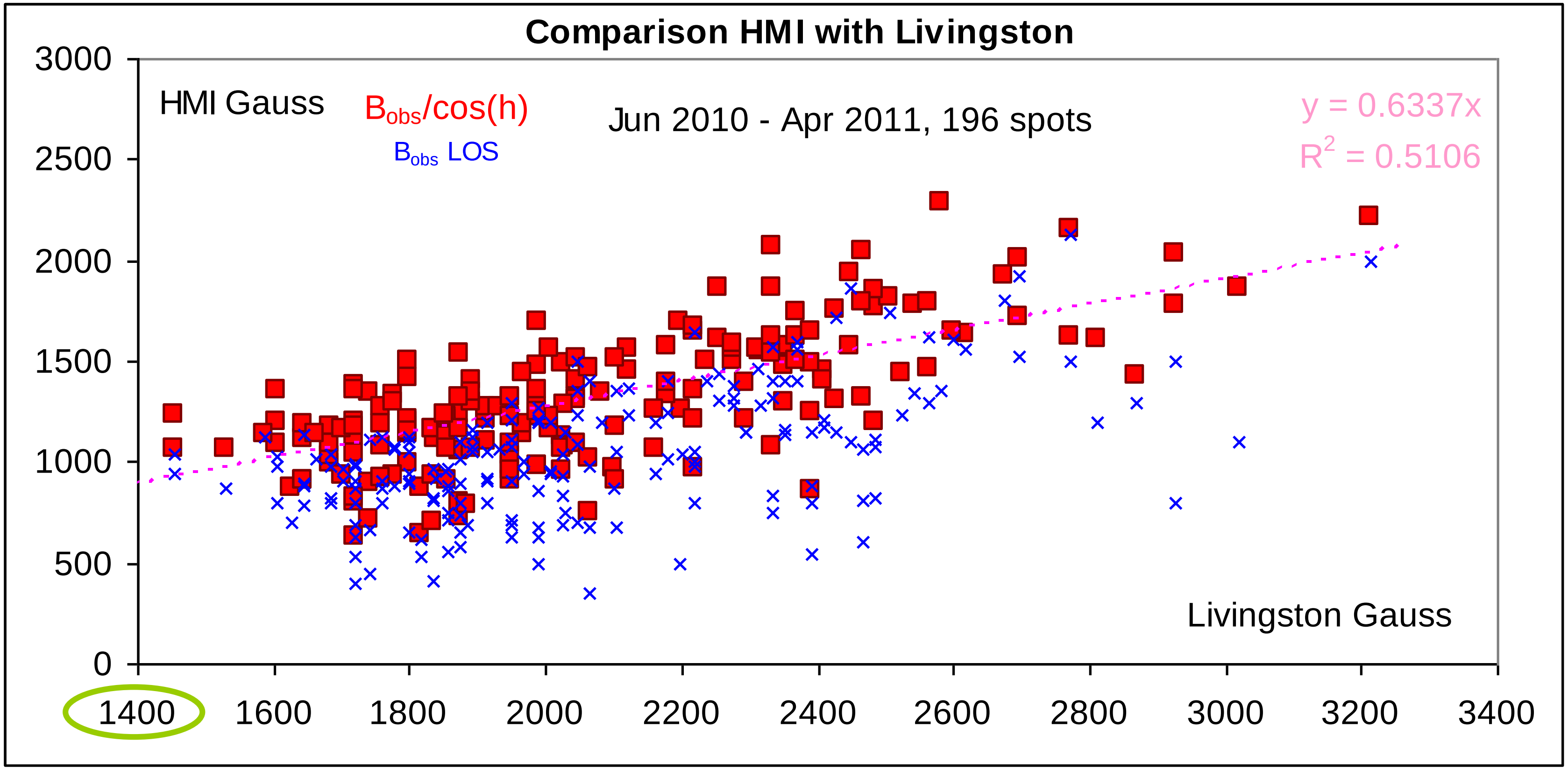
Since 2001 Livingston and Penn have measured field strength and brightness at the darkest position in umbrae of 5800+ spots using the Zeeman splitting of the Fe I 1564.8 nm line. Livingston measured the absolute [**true**] field strength averaged over his [small: 2.5″x2.5″] spectrograph aperture, and not the Line-of-Sight [LOS] field. The true field is independent of the angle of view.



We can find the sunspots on the HMI intensity and Magnetic maps

Using the Livingston provided Finding Chart we can identify the spots and their **darkest** points on HMI (and other) magnetograms and get the Line-of-Sight magnetic field strength recorded by HMI (and MDI as well).

And compare with the measured Line-of-Sight magnetic fields



HMI LOS fields [corrected for simple projection] is only **63%** of Bill Livingston's.

SOLIS and HINODE (and HMI) Vector fields agree with Bill. That is: vector fields are considerably larger than LOS fields, even if corrected for projection. **We don't know why.**

Vector Field Larger than LOS Field

Recent paper: Linker et al. https://arxiv.org/pdf/1708.02342.pdf

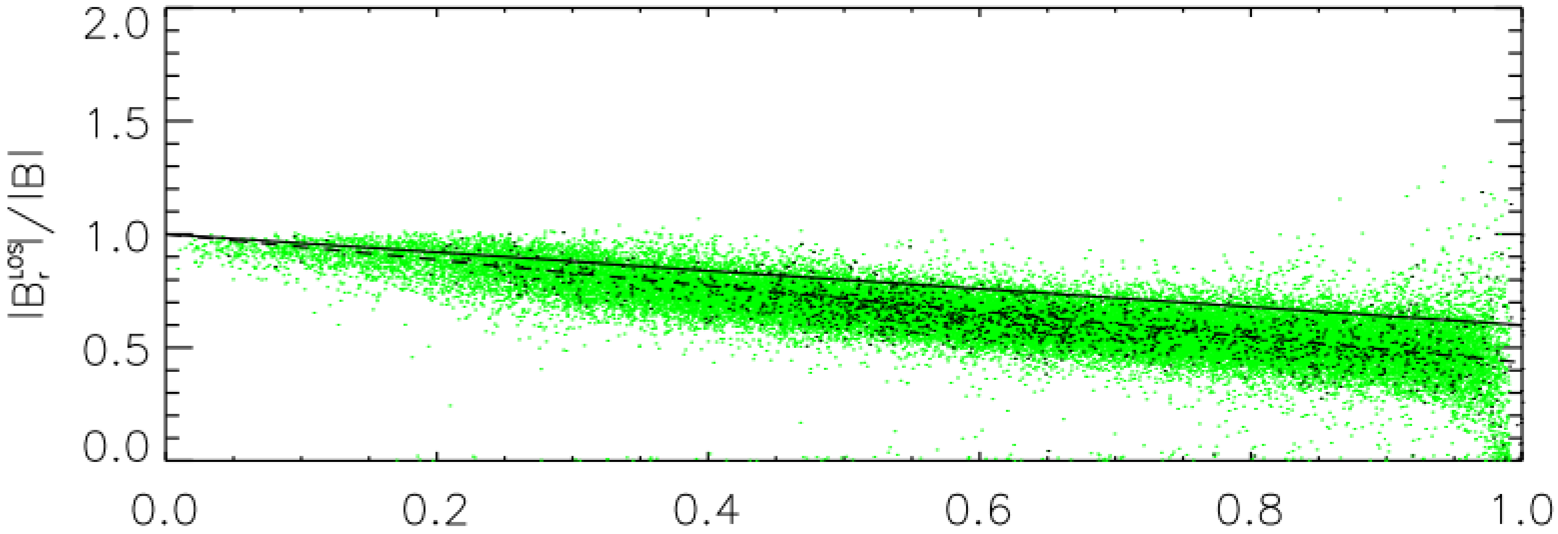
Mode	Instrument	Unsgn Flux 10^{22} Mx	Polar Field N G	Polar Field S G	Dipole N – S Gauss	PFSS R=2.5 Br nT	HMF G Fit Br nT	HMF abs Bx nT	MHD calc. Br nT
LOS	GONG	11.4	-2.40	2.60	-5.00	0.63			
LOS	HMI	13.4	-2.70	2.85	-5.55	0.66			
LOS	average	**12.4**	**-2.55**	**2.73**	**-5.28**	0.65	2.18	2.36	1.34
VECT	SOLIS	16.3	-3.70	3.50	-7.20	0.80			
VECT	HMI	15.1	-3.40	3.25	-6.65	0.79			
VECT	average	**15.7**	**-3.55**	**3.38**	**-6.93**	0.80	2.18	2.36	1.38
Ratio	VECT/LOS	1.27	1.39	1.24	1.31	1.23	3.38 2.74	3.66 2.97	1.69 1.64
	Liv/HMILOS	1.58	Field above latitude 65°				Open Flux Excess		
	Liv/MDILOS	1.26							

Based on Synoptic Maps 2010-05-30 to 2010-08-18 (CRots ~2097-2100).

The Open Flux Problem: the modeled Br [PFSS and MHD] is 2-3 times too small.

Even HMI Vector Fields Seem to Have Systematic Errors

G. V. Rudenko, I.S. Dmitrienko: Examination of artifact in vector magnetic field SDO/HMI measurements, Arxiv 1711.08156, 23 November 2017

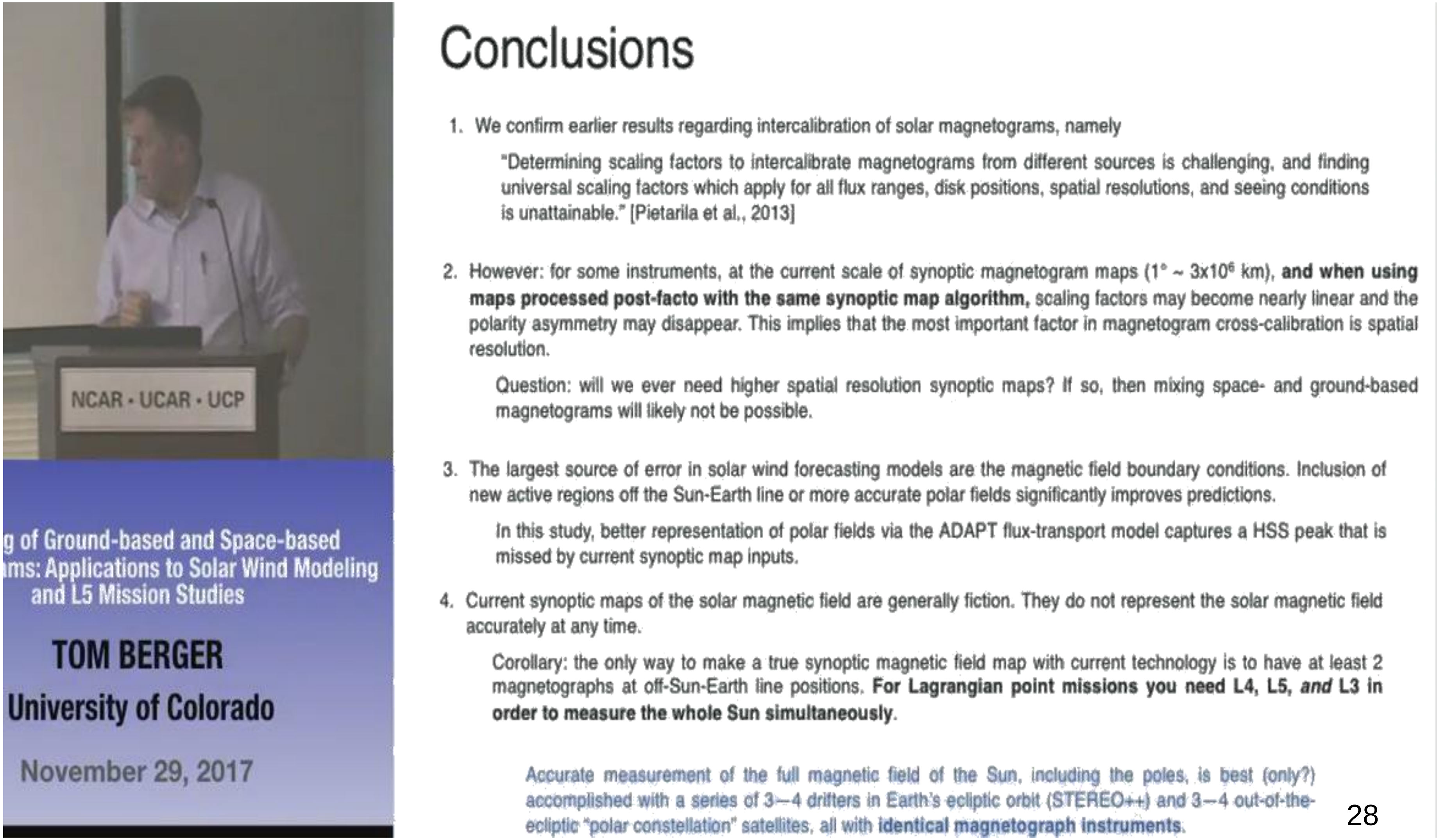


$$B_r^{LOS}/|\mathbf{B}| = \frac{B_{LOS}}{\cos\mu}/|\mathbf{B}|,$$

where $B_{LOS} = B_z$ is projection of vector $\mathbf{B}$ along the line of sight, μ is the angle between the line of sight and the radius-vector of the knot location on the disk ($B_r^{LOS} = |B_r| = |\mathbf{B}|$ when the field is exactly radial);

The vector field of strong magnetic elements (assumed radial) corrected for projection still shows a marked decrease (by a factor of two) with increasing distance from disk center which must be instrumental. This obviously (if corroborated) has implications for the measured polar fields.

Point 4: Current Synoptic Maps of the Solar Magnetic Field are Generally Fiction



g of Ground-based and Space-based
ms: Applications to Solar Wind Modeling
and L5 Mission Studies

TOM BERGER
University of Colorado

November 29, 2017

Conclusions

1. We confirm earlier results regarding intercalibration of solar magnetograms, namely

   "Determining scaling factors to intercalibrate magnetograms from different sources is challenging, and finding universal scaling factors which apply for all flux ranges, disk positions, spatial resolutions, and seeing conditions is unattainable." [Pietarila et al., 2013]

2. However: for some instruments, at the current scale of synoptic magnetogram maps (1° ~ 3×10^6 km), **and when using maps processed post-facto with the same synoptic map algorithm,** scaling factors may become nearly linear and the polarity asymmetry may disappear. This implies that the most important factor in magnetogram cross-calibration is spatial resolution.

   Question: will we ever need higher spatial resolution synoptic maps? If so, then mixing space- and ground-based magnetograms will likely not be possible.

3. The largest source of error in solar wind forecasting models are the magnetic field boundary conditions. Inclusion of new active regions off the Sun-Earth line or more accurate polar fields significantly improves predictions.

   In this study, better representation of polar fields via the ADAPT flux-transport model captures a HSS peak that is missed by current synoptic map inputs.

4. Current synoptic maps of the solar magnetic field are generally fiction. They do not represent the solar magnetic field accurately at any time.

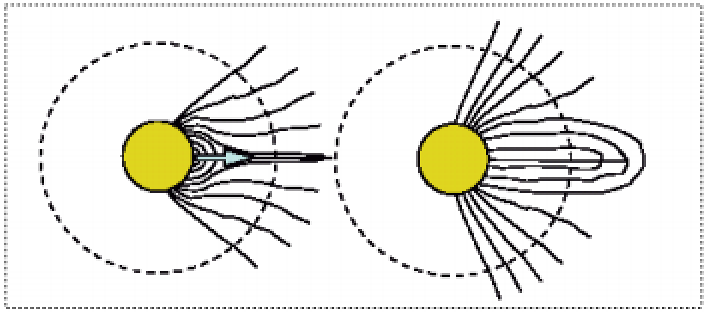
   Corollary: the only way to make a true synoptic magnetic field map with current technology is to have at least 2 magnetographs at off-Sun-Earth line positions. **For Lagrangian point missions you need L4, L5, *and* L3 in order to measure the whole Sun simultaneously.**

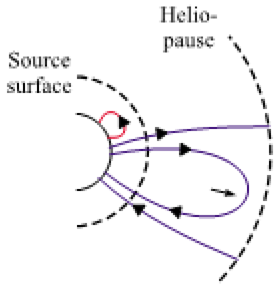
Accurate measurement of the full magnetic field of the Sun, including the poles, is best (only?) accomplished with a series of 3—4 drifters in Earth's ecliptic orbit (STEREO++) and 3—4 out-of-the-ecliptic "polar constellation" satellites, all with **identical magnetograph instruments**.

Summary I (Magnetographs)

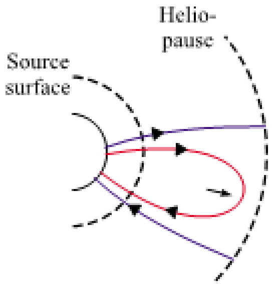
- Different Observatories report differing values for solar magnetic fields. There is as yet no agreed upon ‘Ground Truth’
- Vector data is significantly larger than LOS data corrected for projection, but still may have systematic errors (at least for HMI)
- There is no evidence that the MWO saturation correction factor can be applied to WSO data
- We do not really know what the ‘true’ field strength or even the flux is (except perhaps Livingston’s data).
- This is not important for the PFSS models, but is fatal [?] for MHD models
- “Current Synoptic Maps of the Solar Magnetic Field are Generally Fiction”

The ‘Open Flux’ Problem





Open / closed
solar flux



Open / closed
heliospheric flux

$$F = |B_r|\, 4\pi\, R_F^{\,2} / k$$

The ‘Open Flux’ Problem

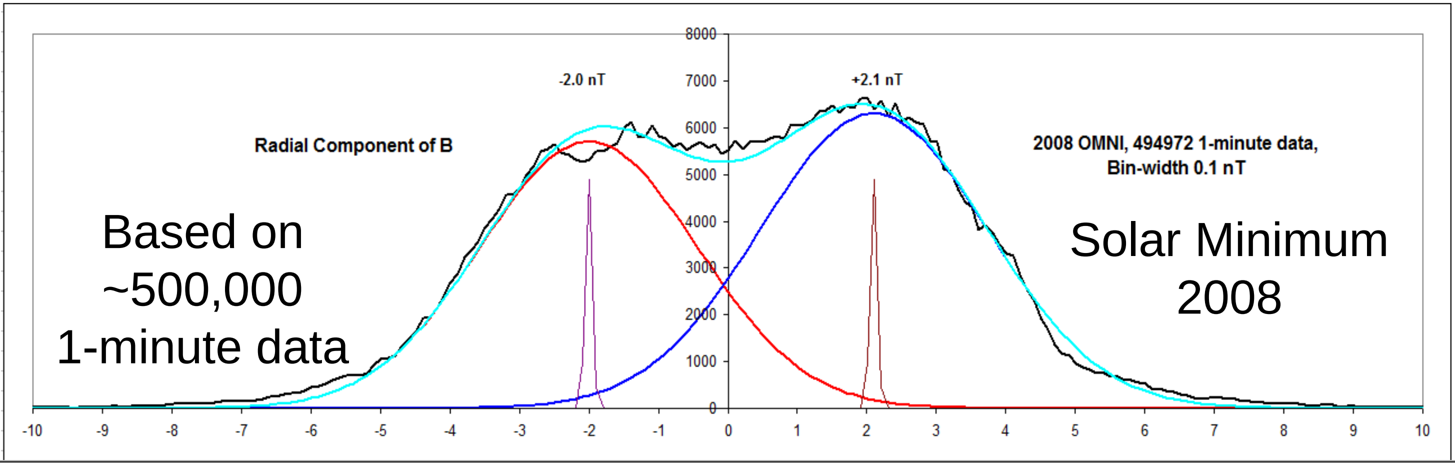
If we understand how the solar wind originates and how it drags the solar magnetic field out into interplanetary space and if our measurements of the magnetic field on the Sun and in space [e.g. at 1 AU] are correct there should not be an Open Flux Problem. But we **do** have a problem [or more than one…]

Our measurements of magnetic fields on the Sun give results that depend strongly on the resolution of the instruments and thus on how the data are binned, and are uncertain [too low?] by about at least a factor of two.

And our measurements of magnetic fields in space also give results that depend on how the data is binned and on the ‘averaging’ window. The longer the window is, the smaller the flux becomes because of cancellation of oppositely directed fields. On the other hand, the magnitude of the scalar field is not degraded much by field cancellation, but is instead dependent on the winding [‘spiral’] angle of the field and thus on the solar wind flow speed. So, determining the ‘open flux’ [basically the radial component of the field] is not trivial and is subject to hard-to-verify assumptions. And some of that flux is not ‘open’ at all [e.g. in CMEs].

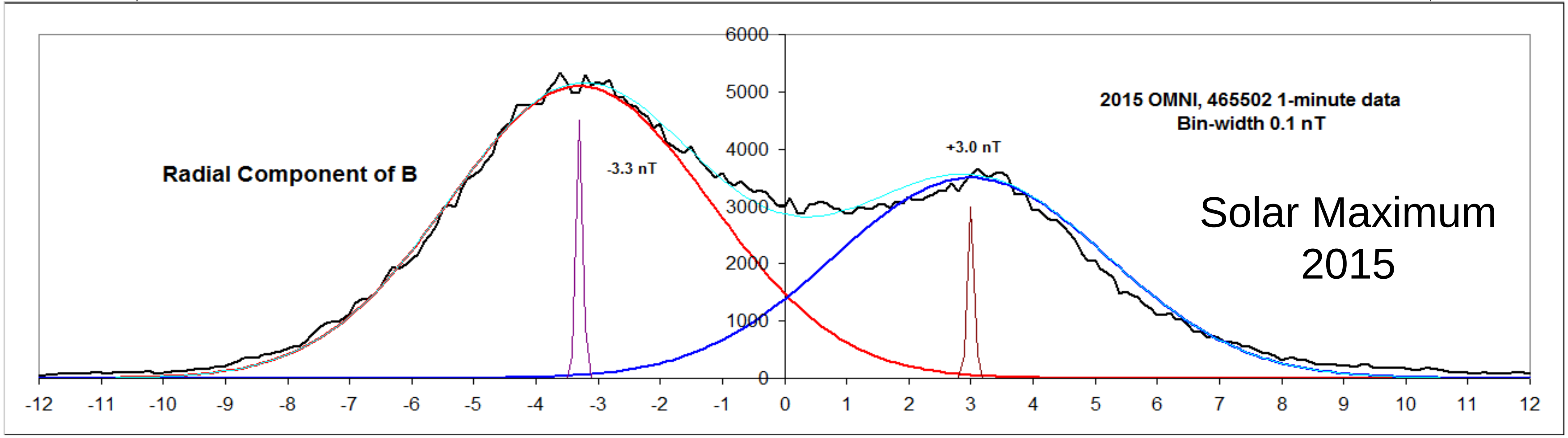
Determining the Radial Component

1 year ≈
526,000
minutes



Based on
~500,000
1-minute data

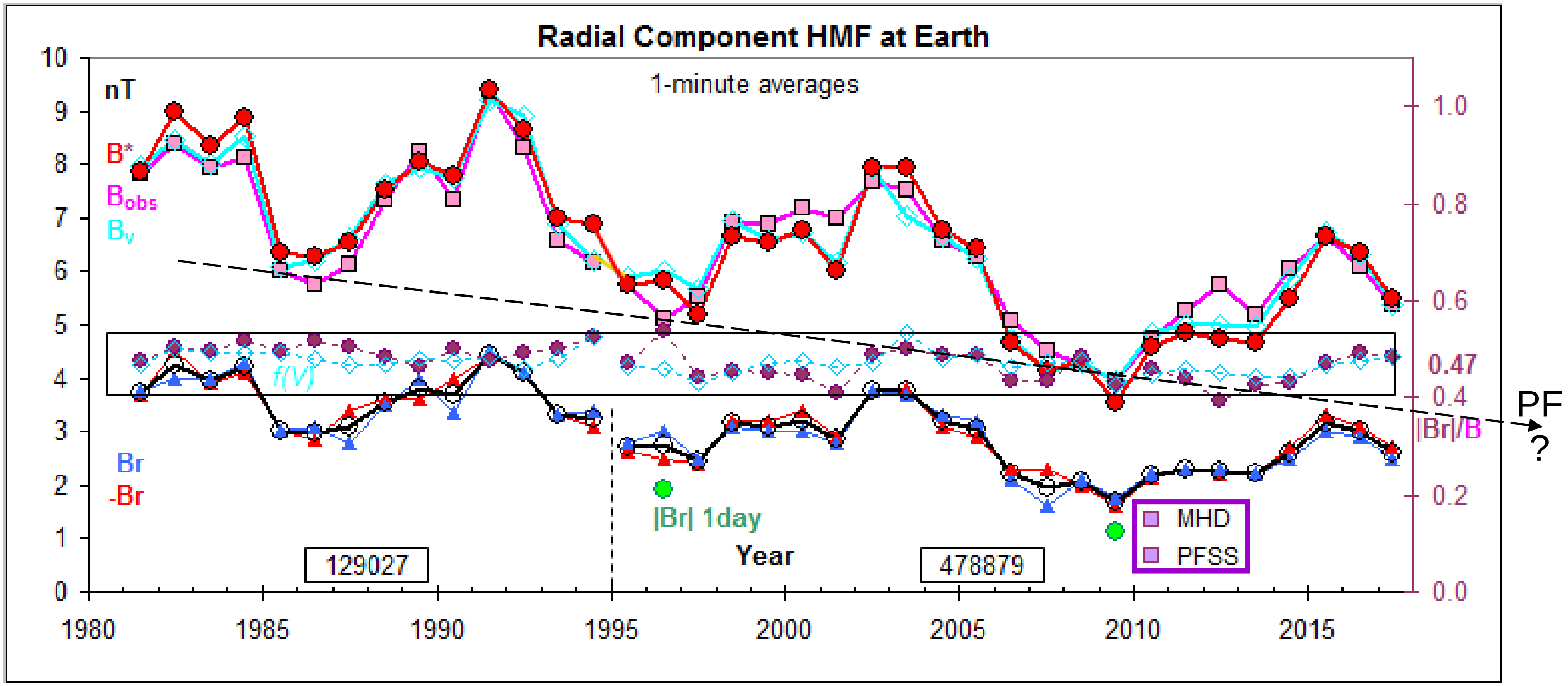
Solar Minimum
2008



Solar Maximum
2015

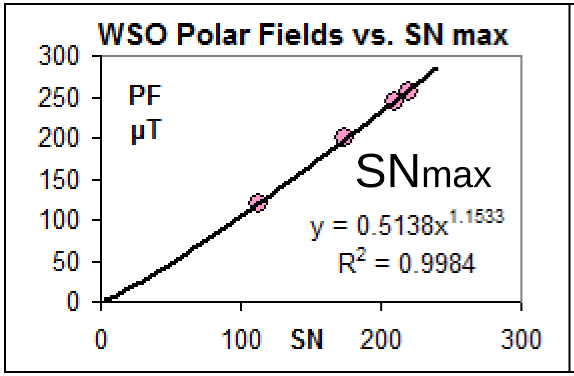
I shall assume there is a slowly varying Large-Scale structure [LSS] in the Heliospheric Magnetic Field [HMF, the Sector structure] organized around the Heliospheric Current Sheet [HCS] with the field rooted in opposite polarity solar [or coronal] fields in opposite sides of the HCS. The LSS is perturbed by turbulence, CMEs, and CIRs so the observed Radial Field, Br, has a noise component that broadens the Br-distribution which can now be described as the sum of two Gaussians (with varying shape parameters) about the peaks for the two polarities, that I take to be the 'true' Br.

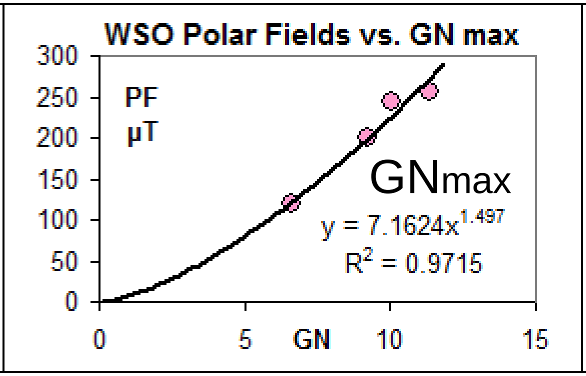
Solar Cycle Variation of Br and B

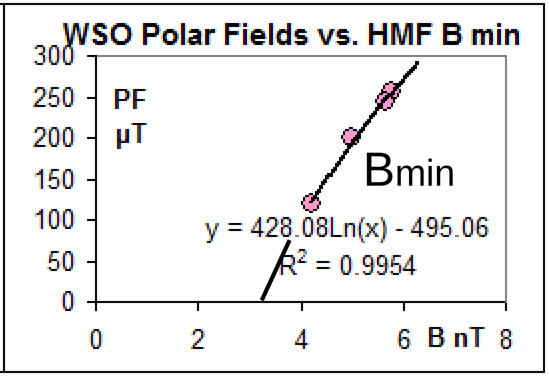


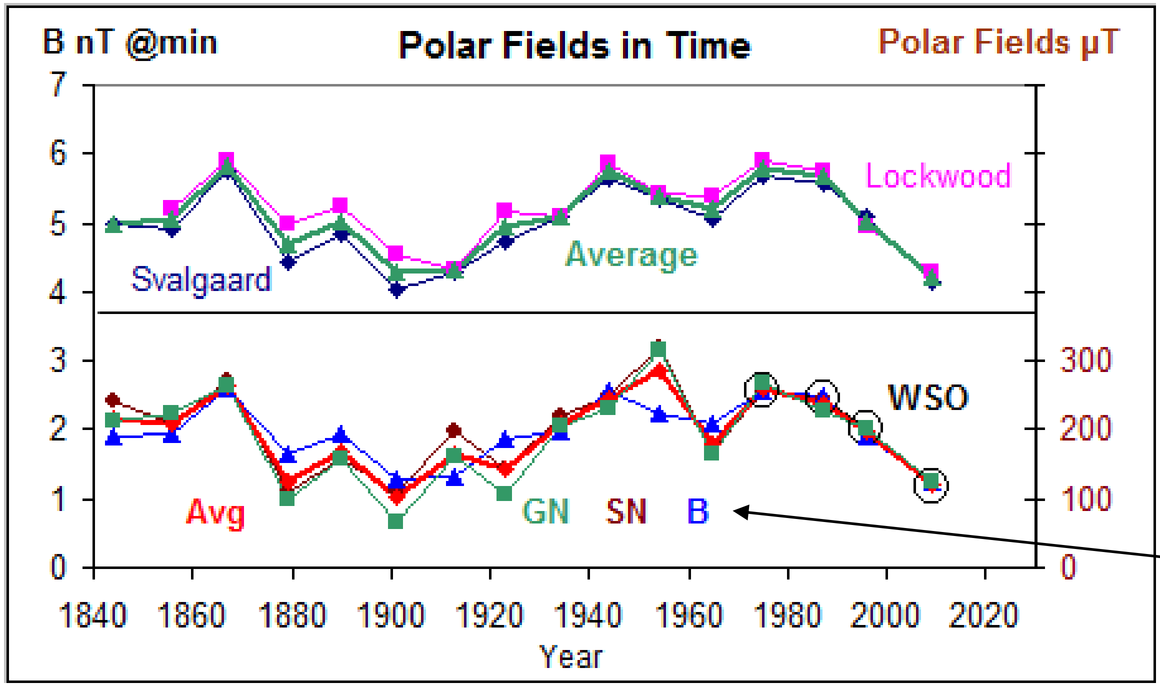
1-minute data is available since 1981, so we can get Br and scalar B since then. The ratio |Br|/B is surprisingly constant [middle box] especially if corrected for flow speed. B is in the range 4-6 nT [Br in range 2-3 nT] at solar minima. Where does that flux come from? The 'traditional' answer is "the polar fields". How does that hold up?

Hindcasting Polar Fields in Time



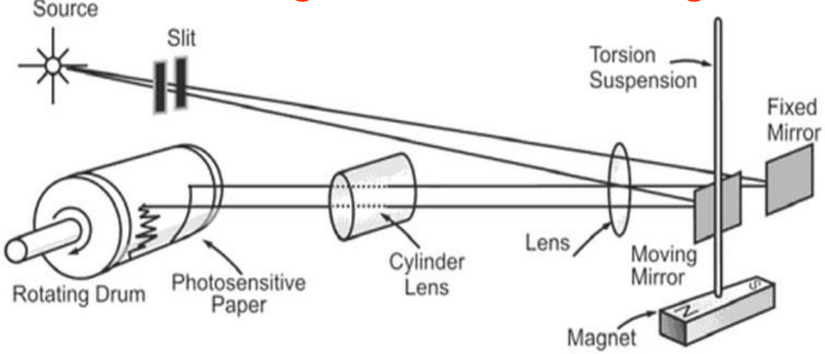




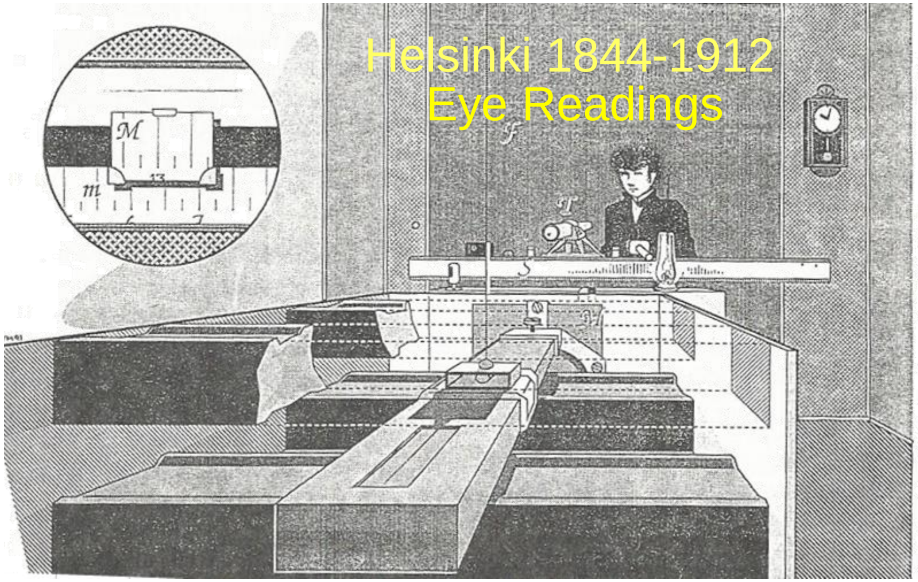


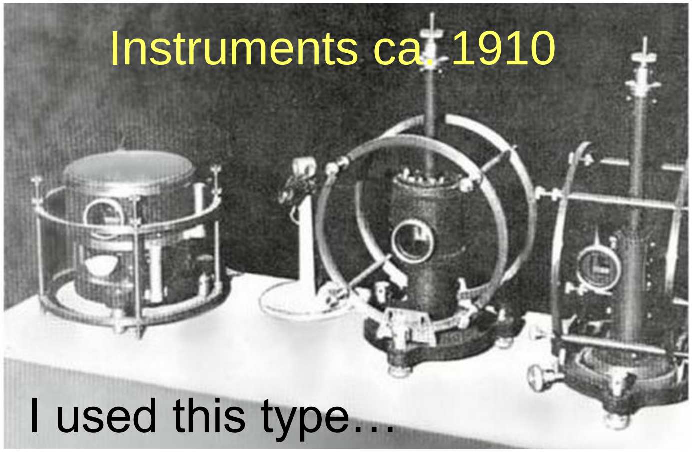
If we can forecast cycle maximum activity from the polar fields, we should be able to hindcast the polar fields from the cycle's maximum activity. If HMF *B* at minimum (proxy for polar fields) forecasts activity maximum, then such maxima hindcast HMF *B*. How do we get *B* for the past?

We get B from Geomagnetic Measurements



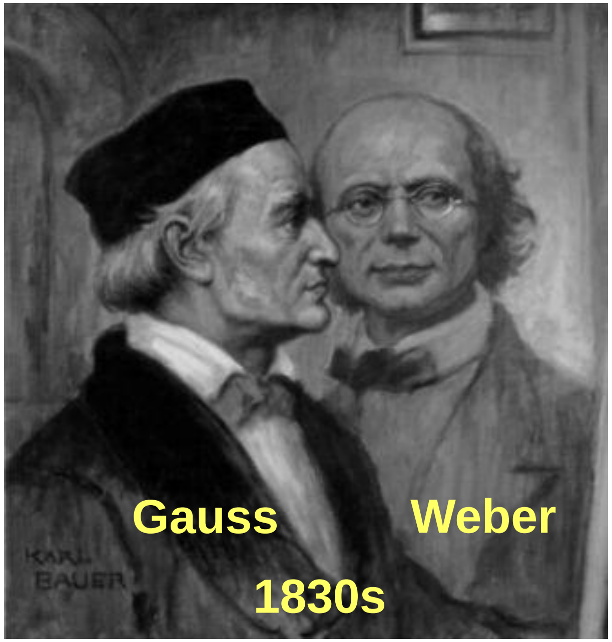
Classic Method since 1846


Helsinki 1844-1912
Eye Readings


Instruments ca. 1910

I used this type…

Modern
Instrument

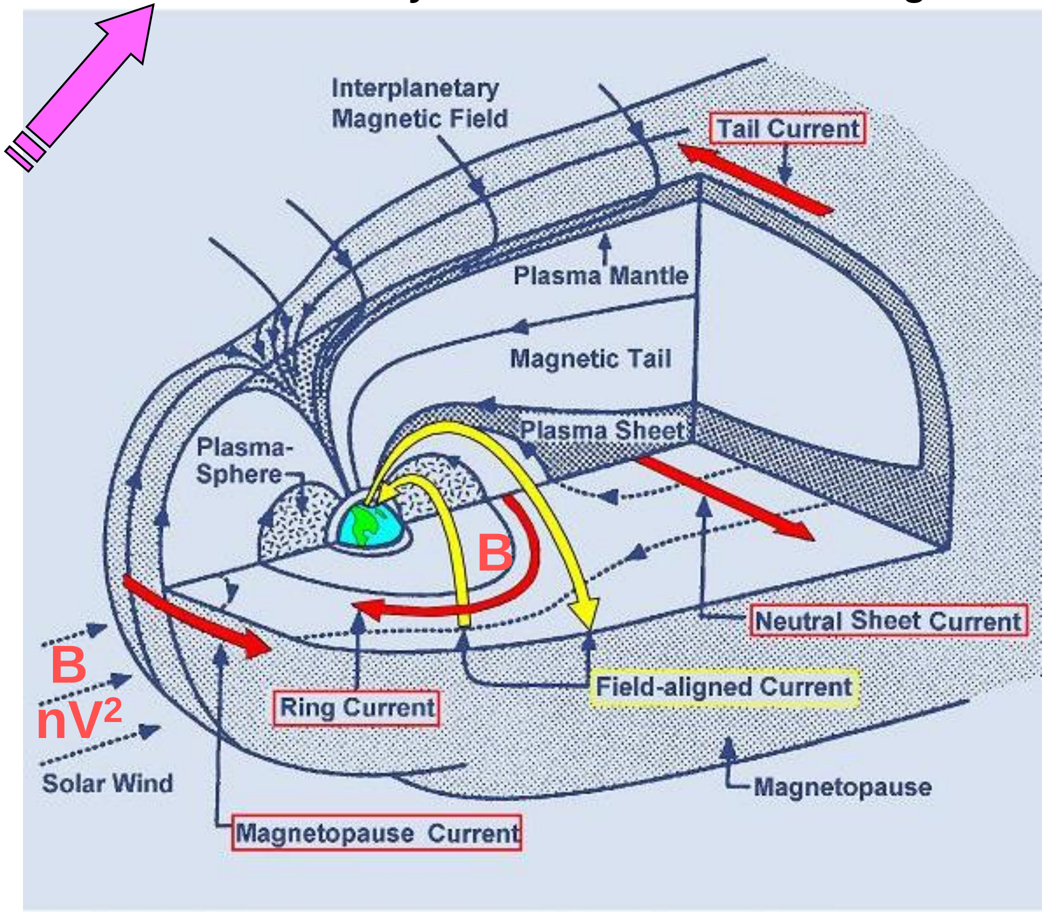

Gauss Weber

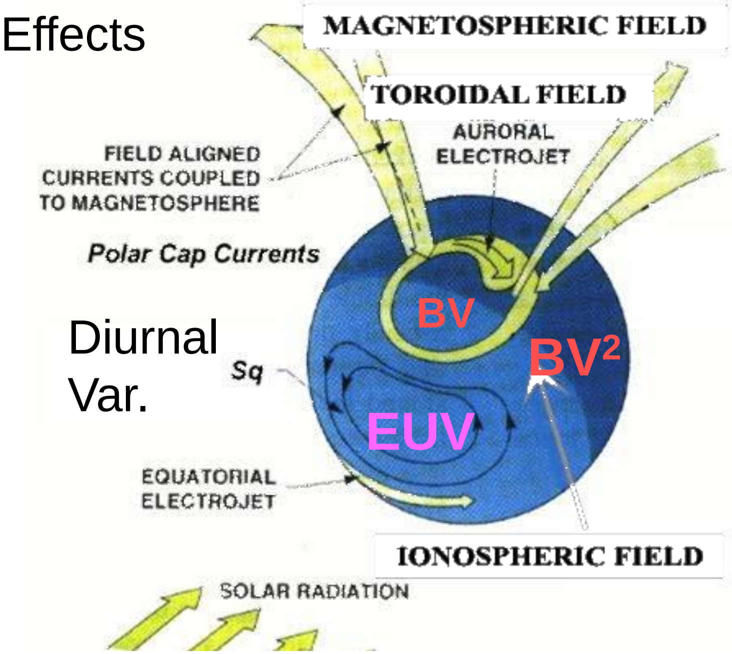
1830s

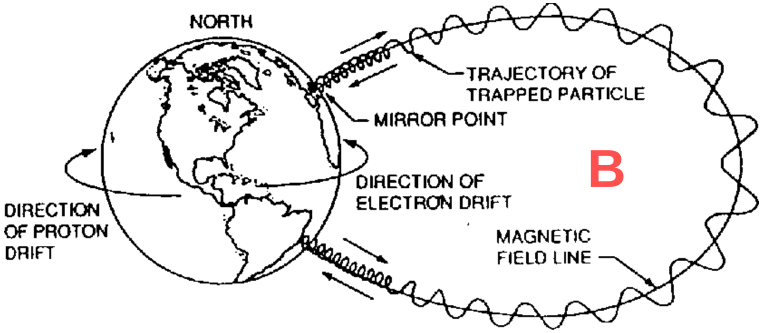
Magnetic Recording over Time

Solar Wind and Solar EUV create Electric Current Systems in Geospace

Different Current Systems → Different Magnetic Effects







We have learned to invert the Solar Wind – Magnetosphere relationships…

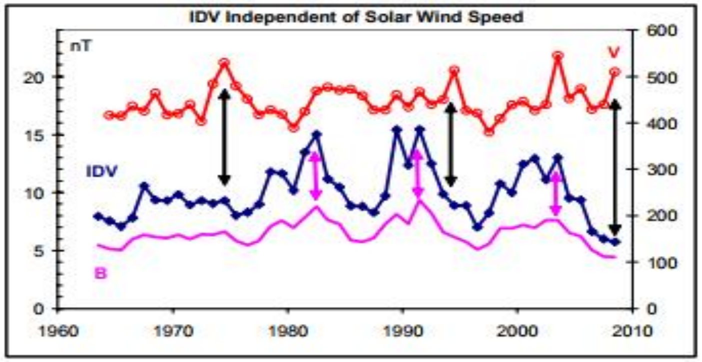
Oppositely charged particles trapped in the Van Allen Belts drift in opposite directions giving rise to a net westward ‘Ring Current’.

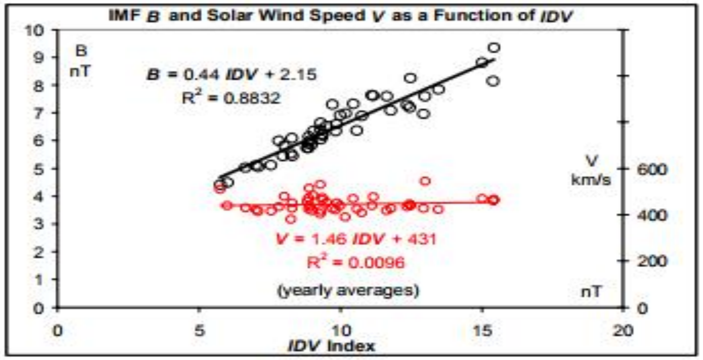
We Deal With all that Complexity by Devising New Geomagnetic Indices

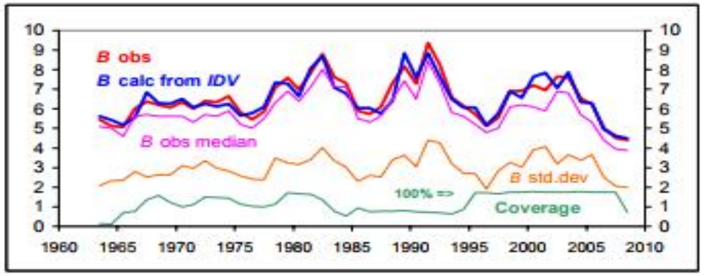
- Day-to-Day Variation, IDV-index, gives us solar wind B
- Hour-to-Hour Variation, IHV-index, gives us solar wind BV^2
- Polar Cap Diurnal Variation, PC-index, gives us solar wind $B \times V \approx BV$
- Mid-latitude Diurnal Variation, rY, gives us EUV [and indirectly solar magnetic flux]

Over-determined system allows us to separate B and V and to verify the result

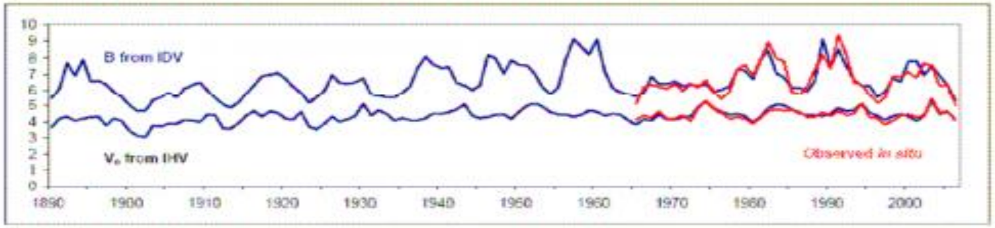
Getting and Verifying B and V

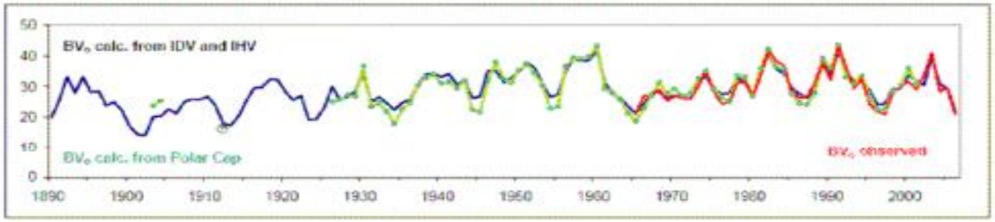






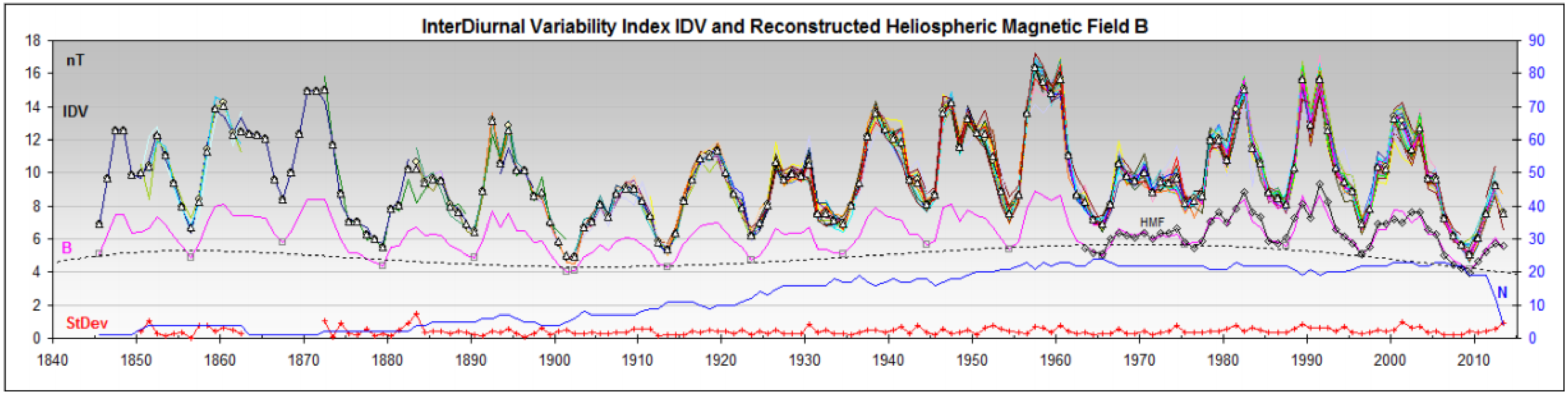
The IDV index has the useful property of being essentially 'blind' to the solar wind speed, but robustly correlated with IMF *B*. So, from IHV we get product BV^2; dividing by *B* from IDV we can now get *V*:

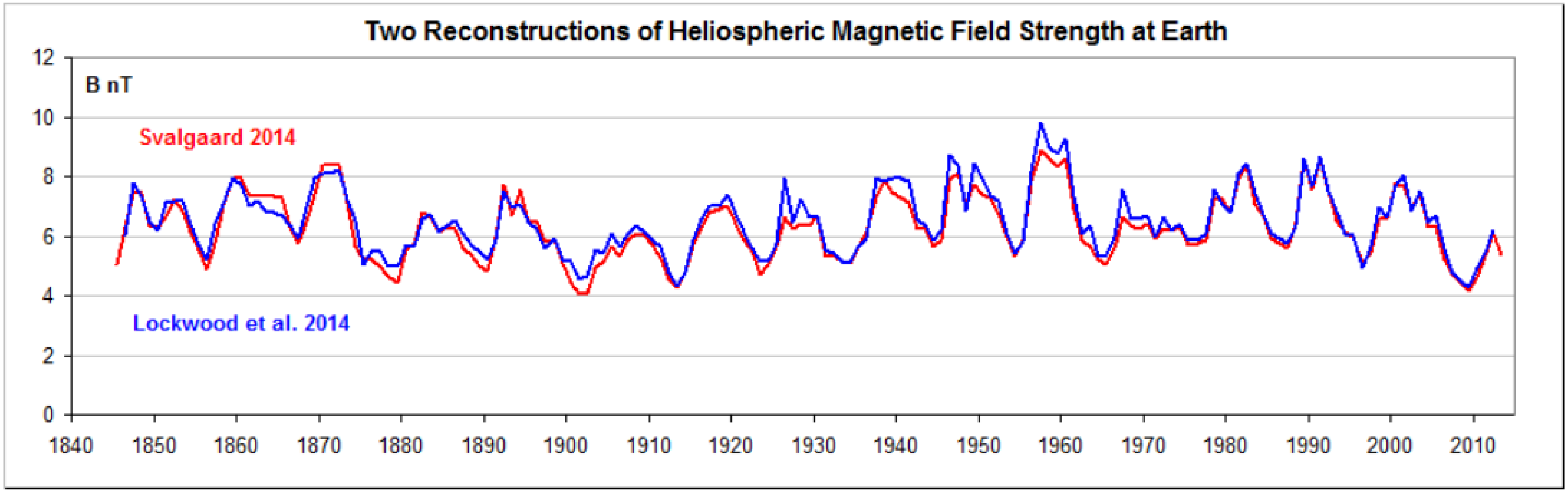




From the amplitude of daily variation of the polar cap current sheet we can get the product *BV* [LeSager&Svalgaard, 2004] and can use that as independent confirmation.

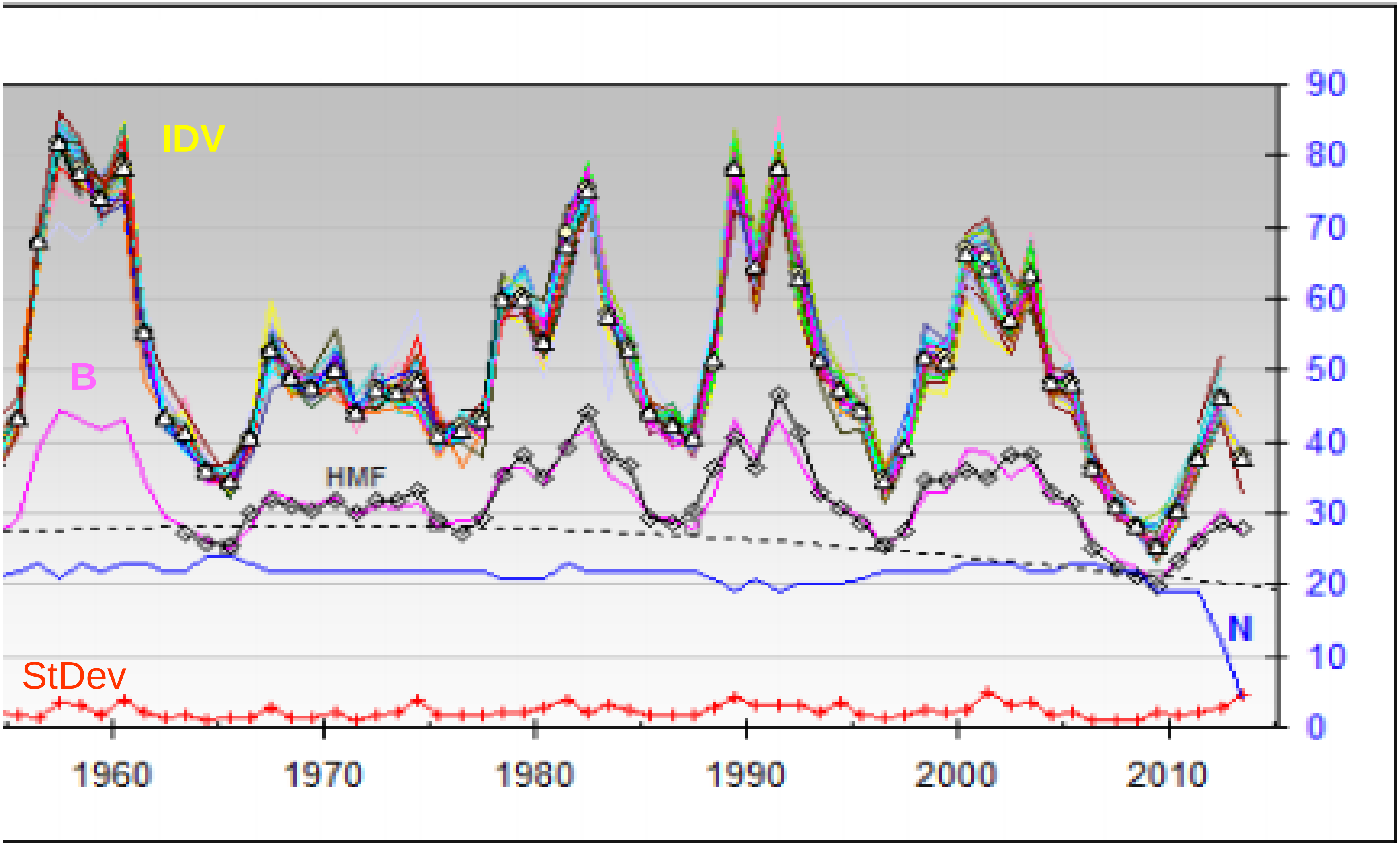
Applying these relations we can reconstruct HMF magnetic field B with Confidence:





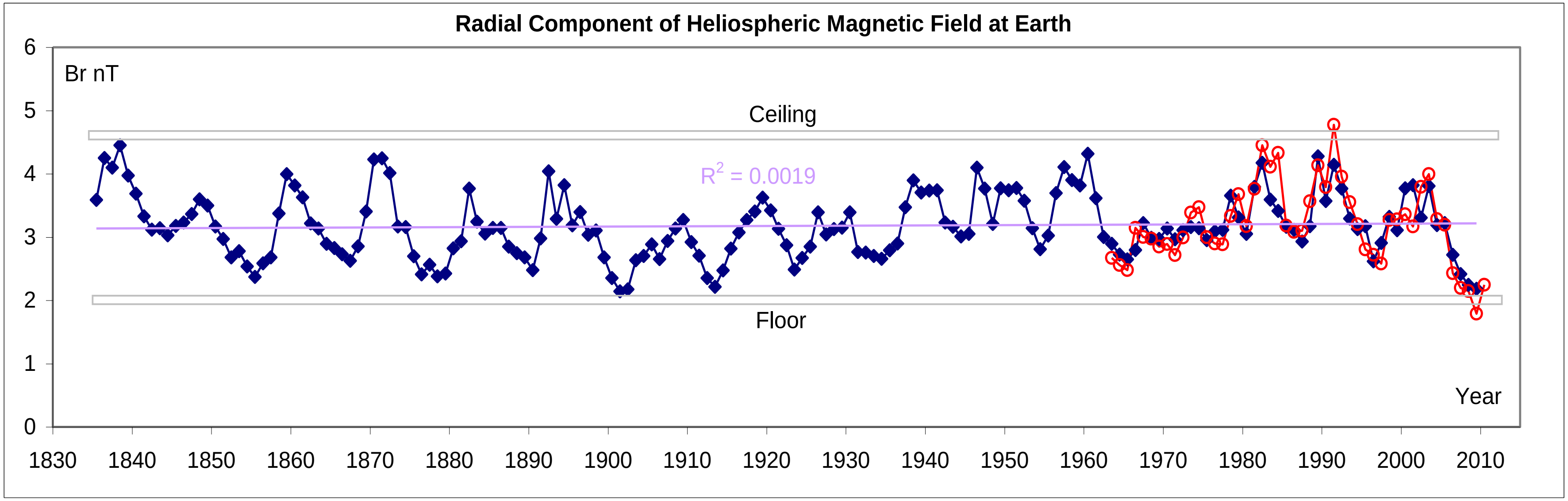
After a decade of struggle Lockwood et al. finally agree with our reconstruction

Blowup of Previous Slide to Show How Well IDV-derived *B* (pink curve) matches Observed HMF *B*



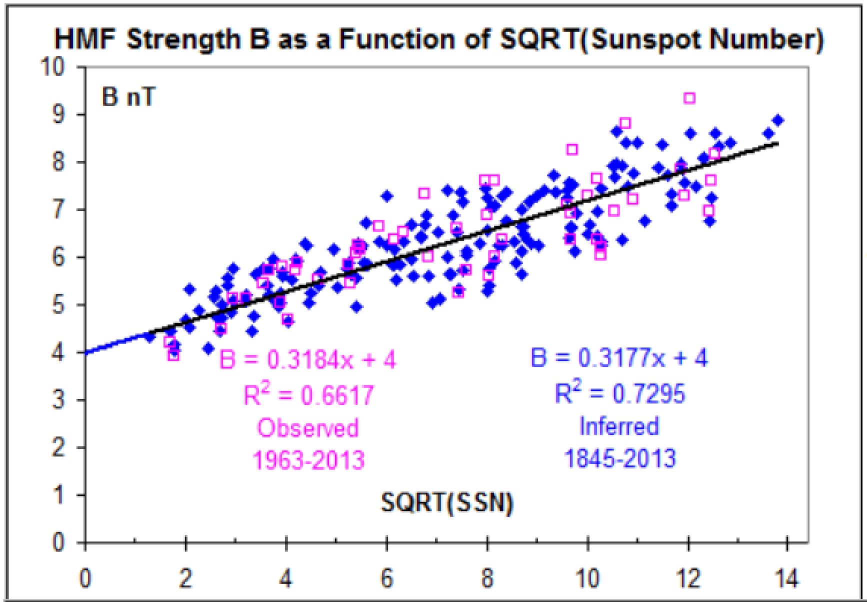
Radial Magnetic Field (‘Open Flux’)

Since we can also estimate solar wind speed from geomagnetic indices [IHV, Svalgaard & Cliver, JGR 2007] we can calculate the radial magnetic flux from the total *B* [from IDV] using the Parker Spiral formula:

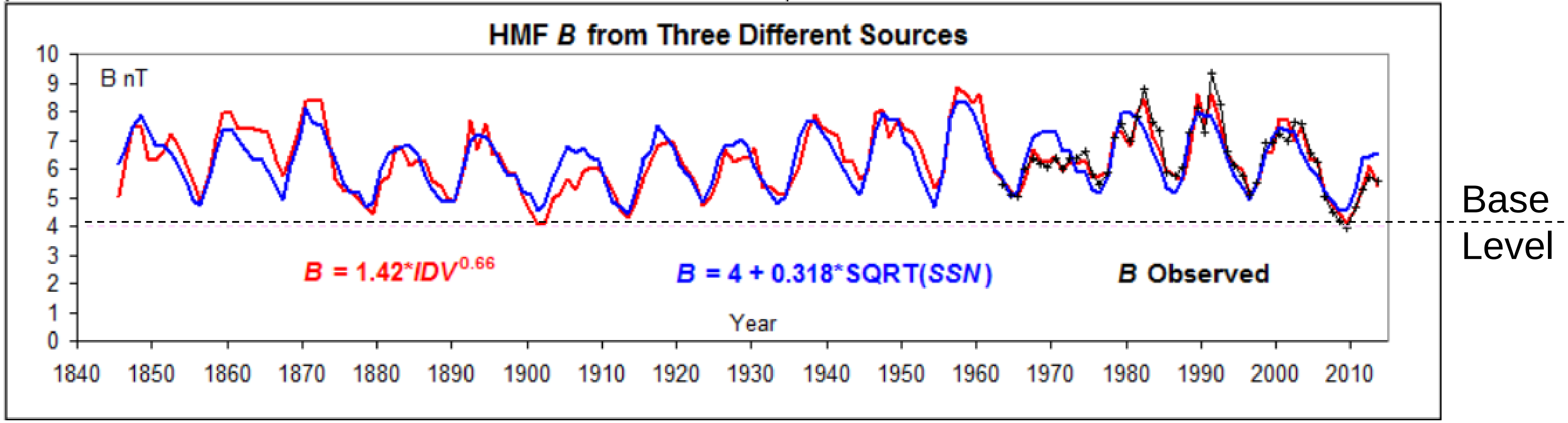


There seems to be both a Floor and a Ceiling and most importantly no long-term trend since the 1830s. Thus no Modern **Grand** Maximum (claimed by some to be the largest in the last 12,000 years).

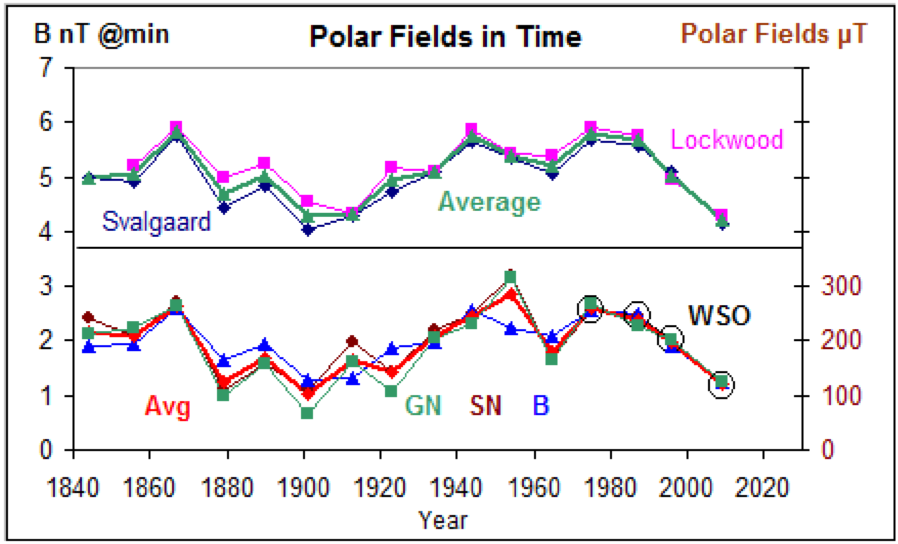
HMF B Dependence on Sunspot Number



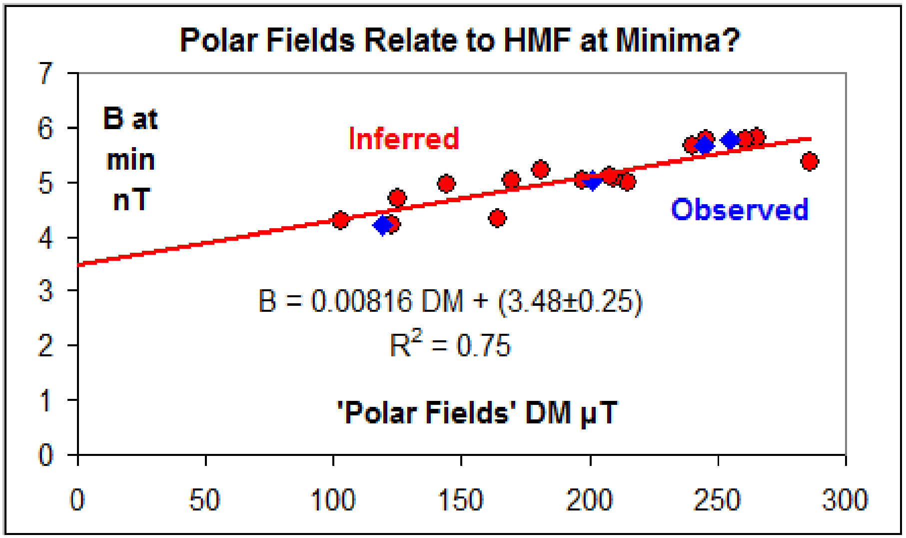
The main sources of the equatorial components of the Sun’s large-scale magnetic field are large active regions. If these emerge at random longitudes, their net equatorial dipole moment will scale as the square root of their number. Thus their contribution to the average HMF strength will tend to increase as $SSN^{1/2}$ (see: Wang and Sheeley [2003]; Wang et al. [2005]).



A Relation Between Polar Fields and HMF Strength at Minimum



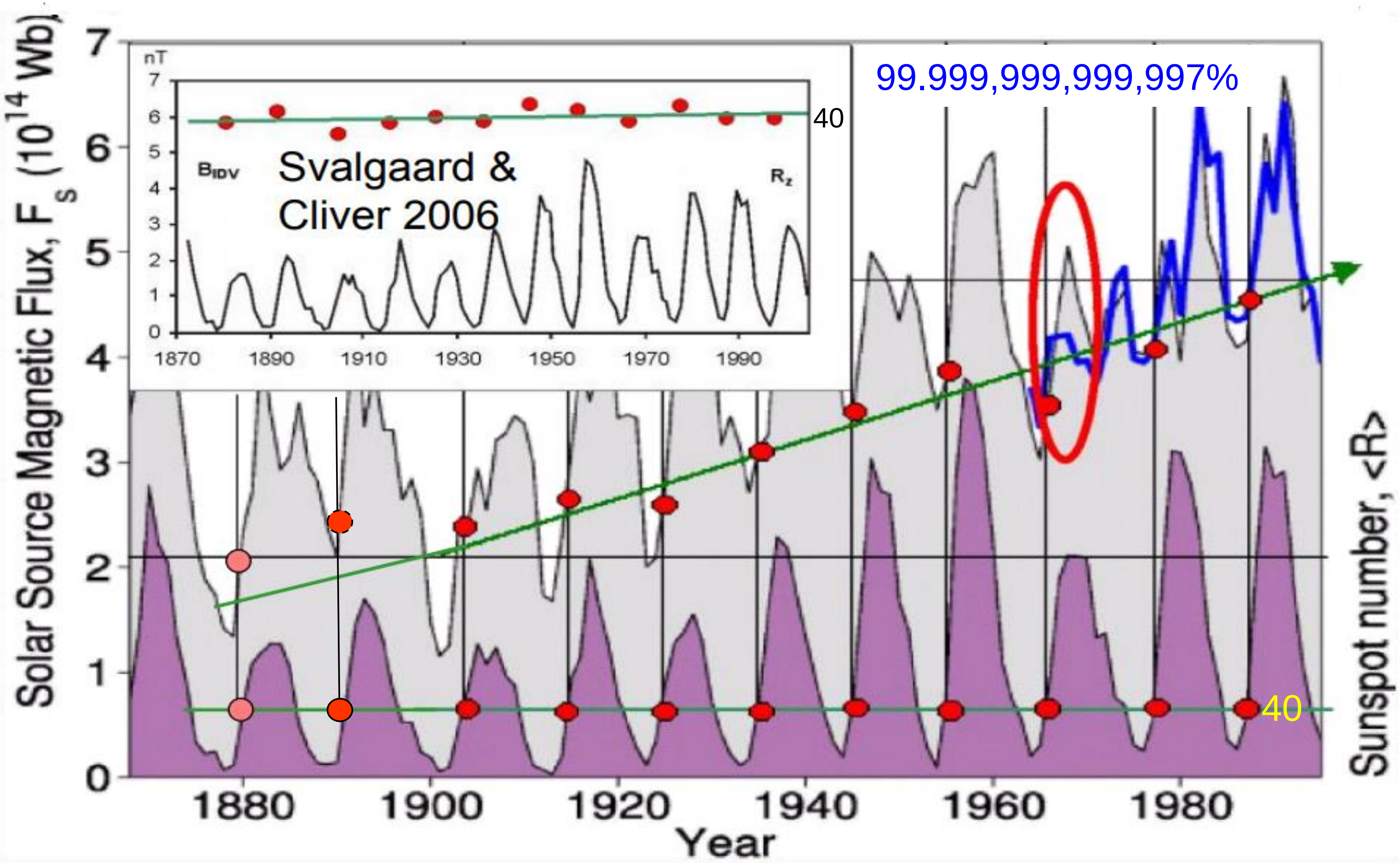
From geomagnetic IDV-index we get HMF B. From GN and SN we get the polar field DM



We can thus establish a relationship between B and DM and estimate the value of the ‘floor’

There is enough room for speculation about the cause of the floor, but eventually it all has to fit

The Claimed More than Doubling of the Coronal Open Flux Did Not Happen



Lockwood, M., R. Stamper, and M. N. Wild (1999), A **doubling of the Sun's coronal magnetic field** during the past 100 years, Nature, 399(6735), 437, doi:10.1038/20867

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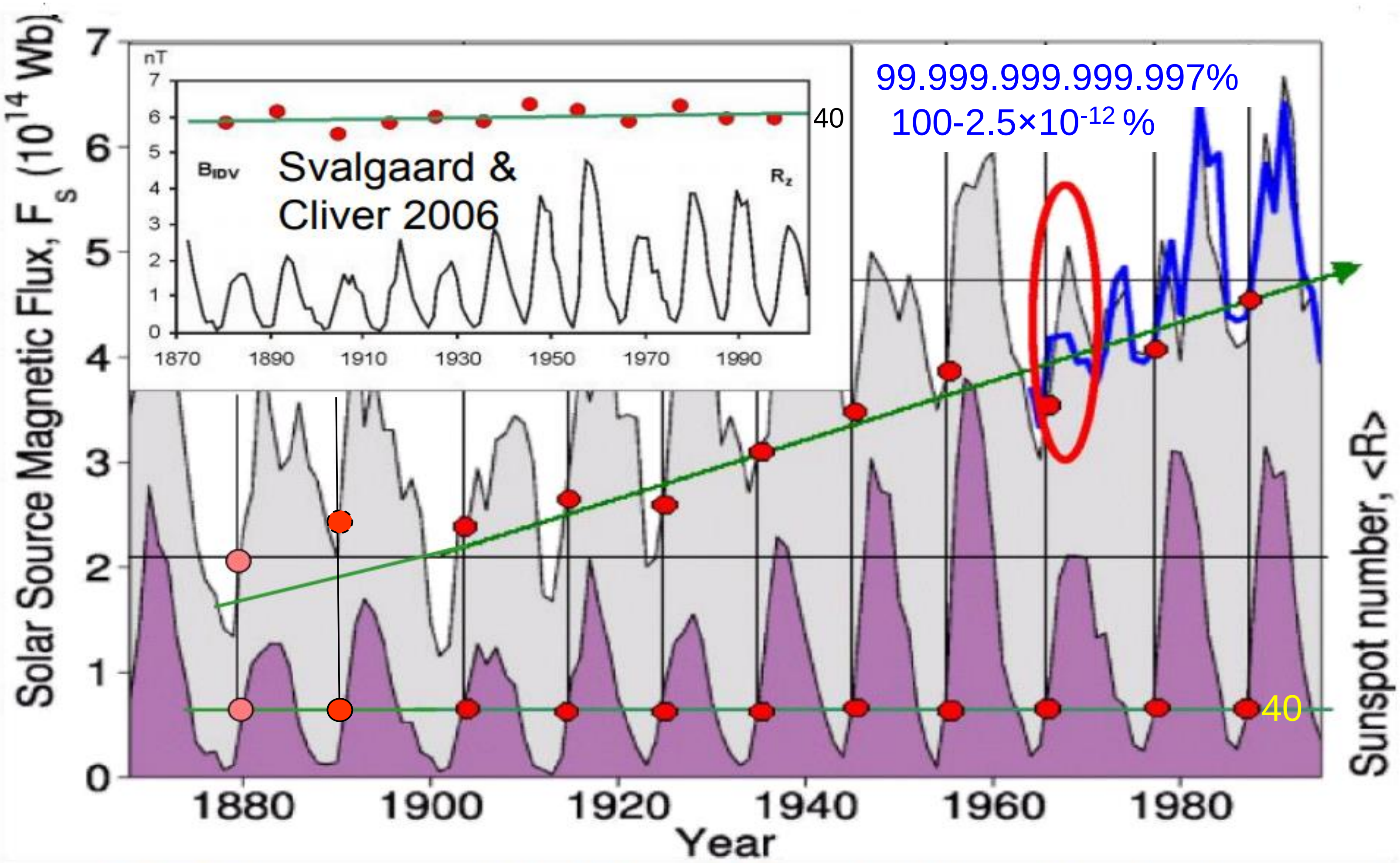
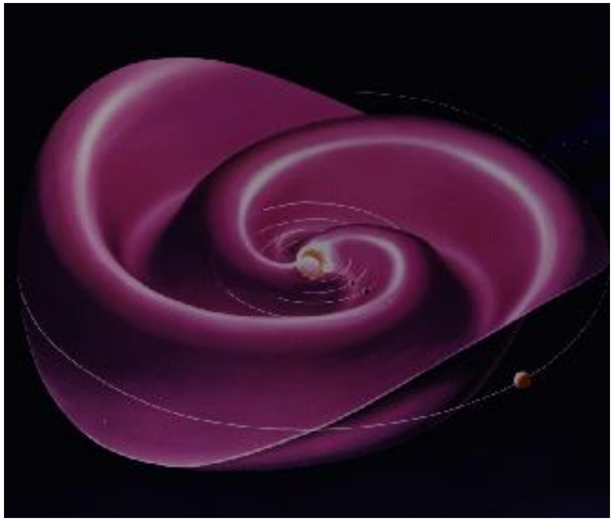


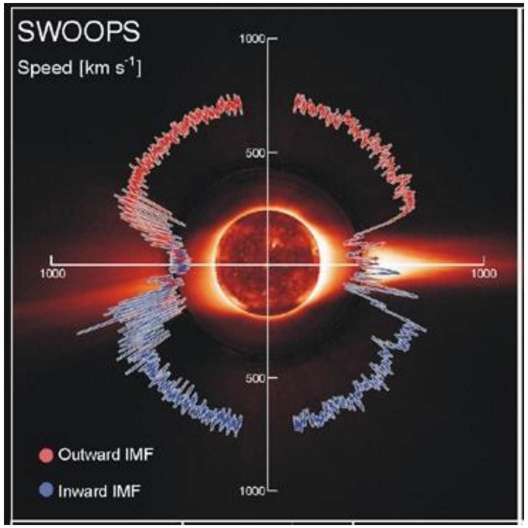
Lockwood, M., R. Stamper, and M. N. Wild (1999), A **doubling of the Sun's coronal magnetic field** during the past 100 years, Nature, 399(6735), 437, doi:10.1038/20867

Summary II (The Open Flux and HMF in time)

- We have learned how to infer and reconstruct the Heliospheric Magnetic Field with confidence back to the 1830s
- HMF B at minima seems to be related to the Polar Fields
- The is no long-term trend in HMF since the 1830s
- Thus no Modern Grand Maximum
- There seems to be both a ceiling and a floor in the open flux
- which is still too ‘large’ by a factor of two or more

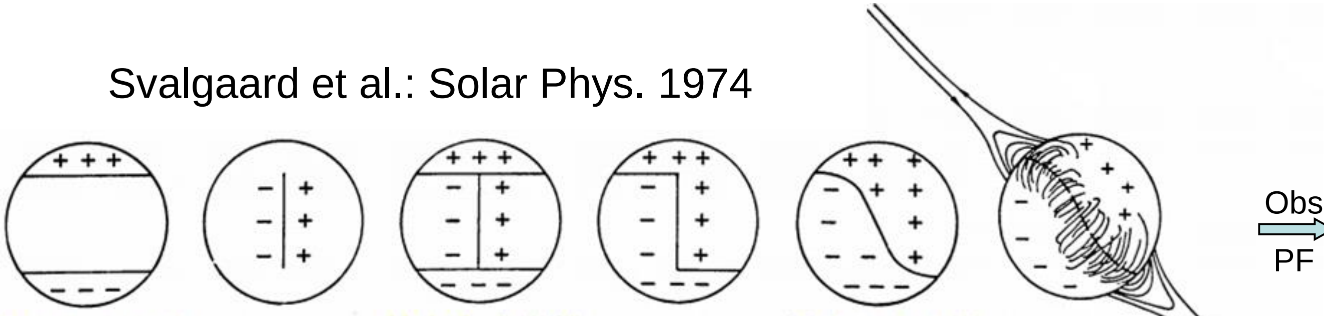
The 3D Heliosphere Sculpted by the Polar Fields

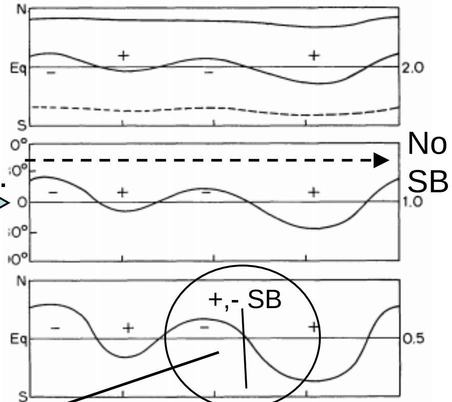




The 3D-Sun Into the Heliosphere

Svalgaard et al.: Solar Phys. 1974





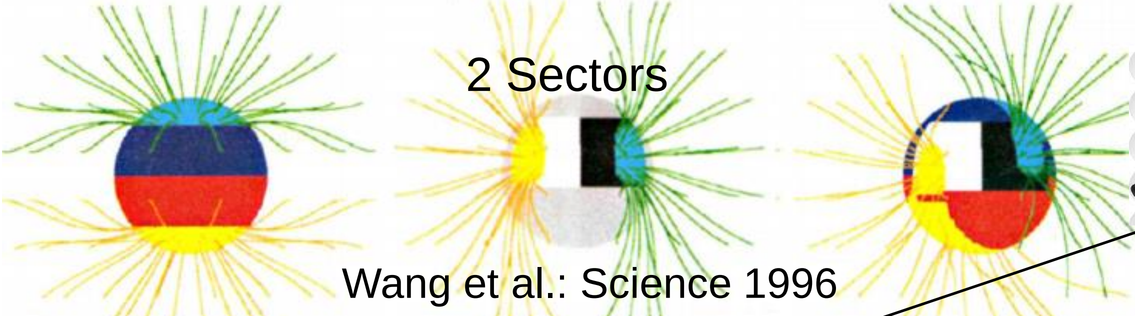
No SB

Obs.

PF

+,- SB

4-Sector Structure

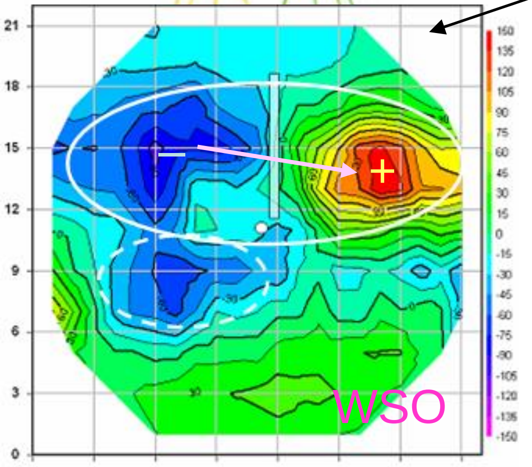


2 Sectors

Wang et al.: Science 1996

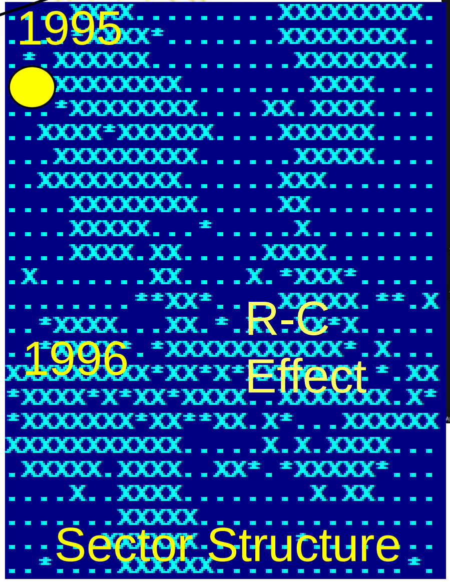
For (-,+) SB Red and Blue are reversed.

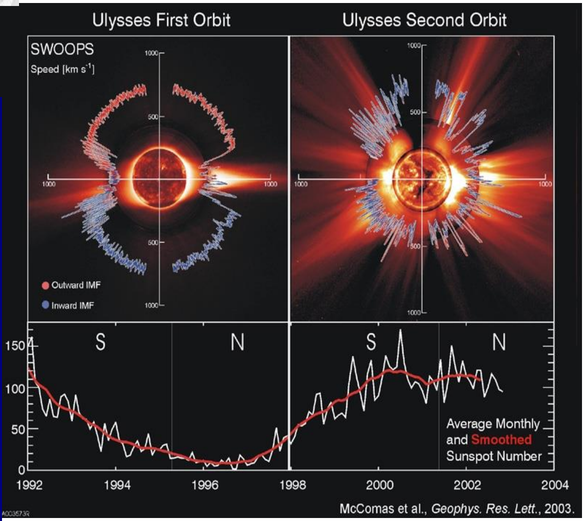
For Even cycles North and South are reversed



Superposed WSO Magnetograms

(+,-) Sector Boundaries. Odd cycles

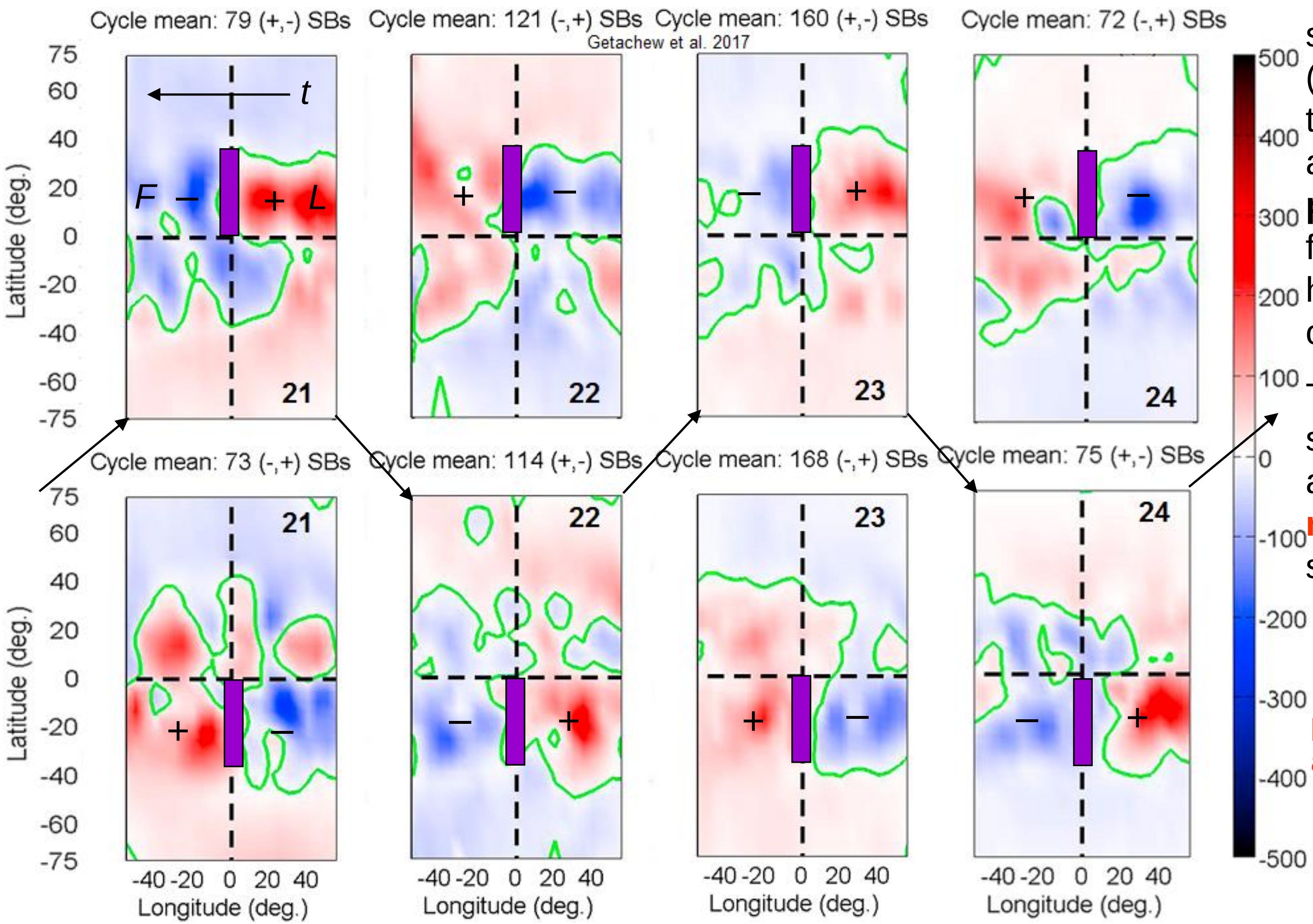




McComas et al., *Geophys. Res. Lett.*, 2003.

Ulysses out-of-ecliptic polar passes

The Structured Hale Boundaries

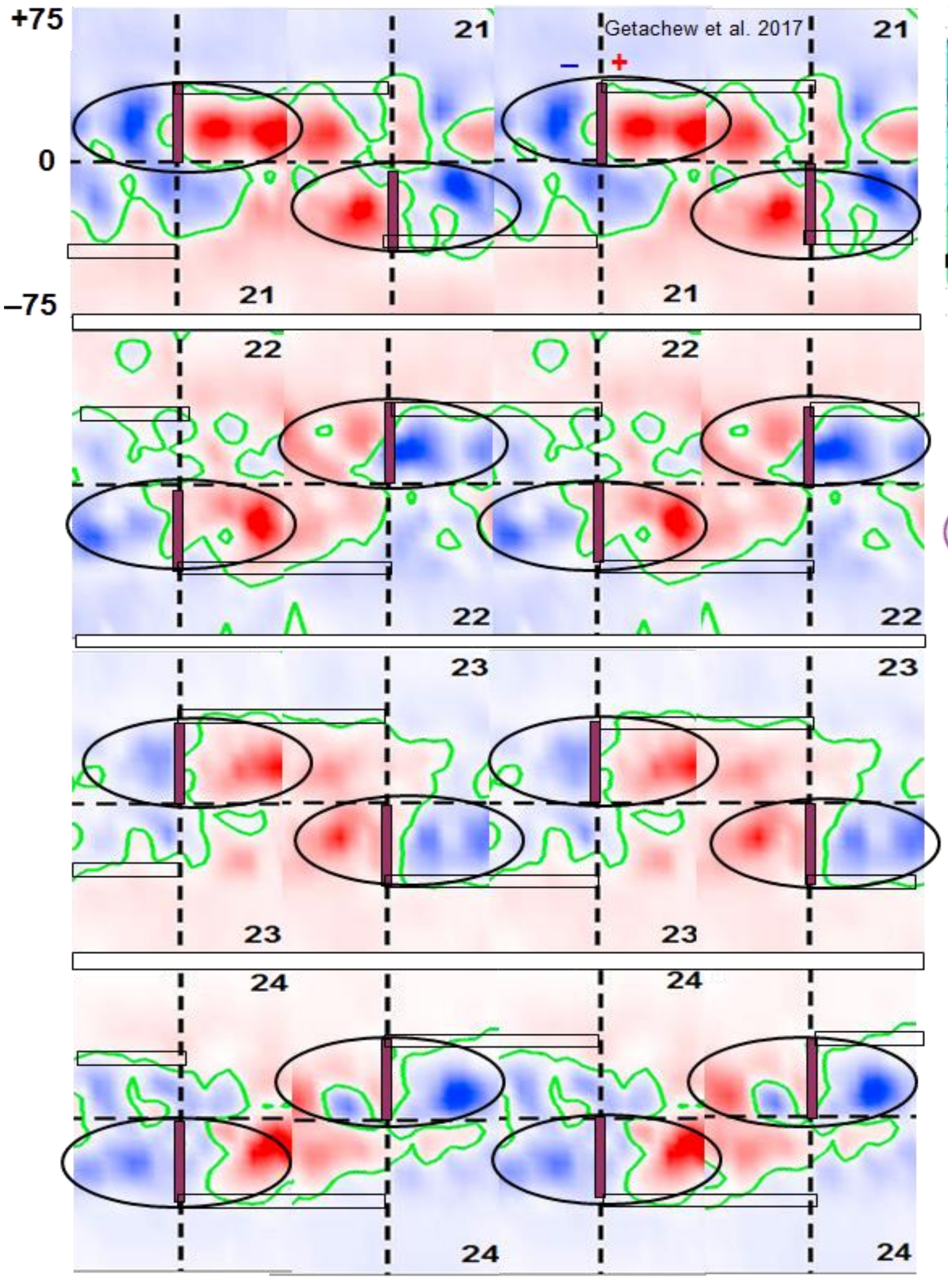


Getachew et al. 2017

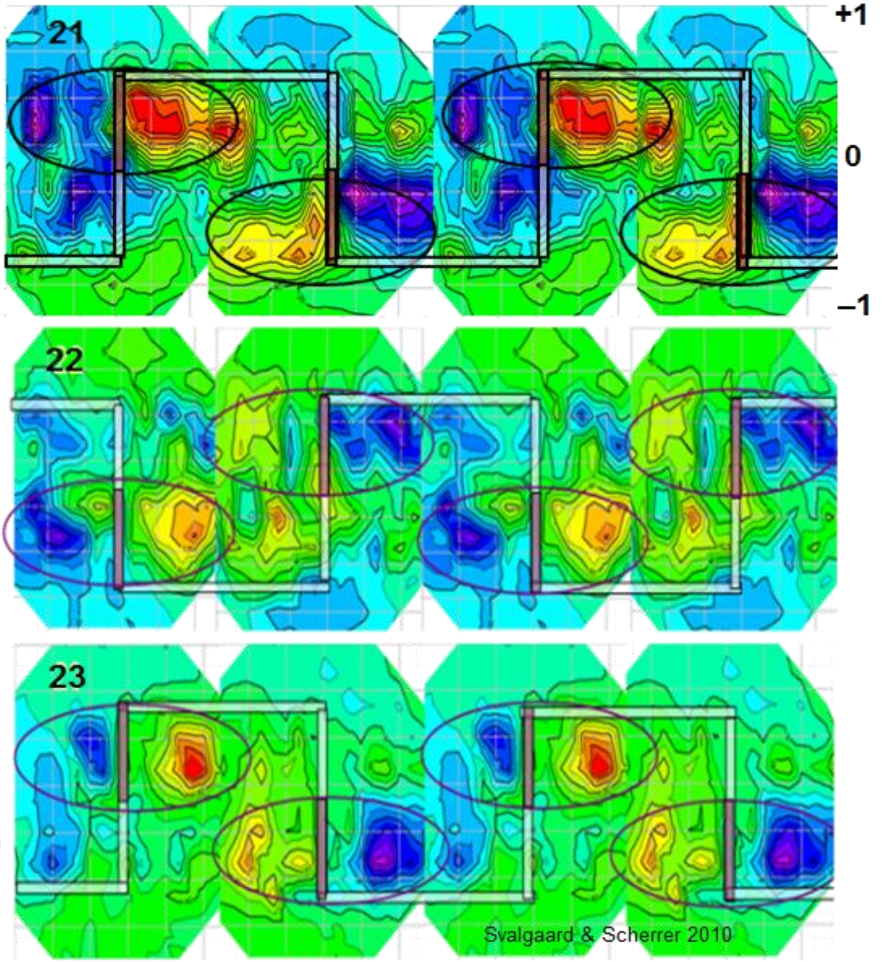
The sector structure (warps in the HCS) arises **primarily** from one hemisphere only.

This hints at some deep and **un-modeled** structure.

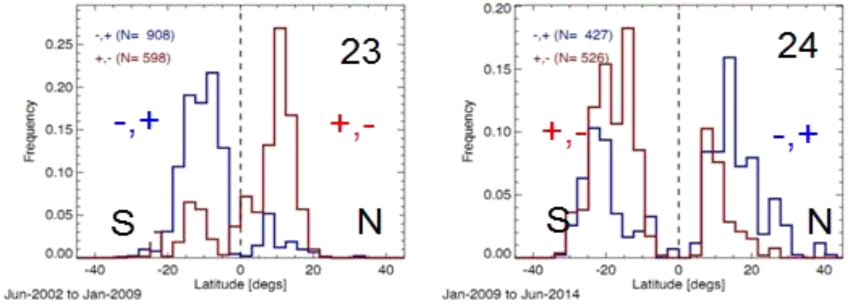
Flares occur predominantly at Hale Sector Boundaries ▮



Getachew et al. 2017



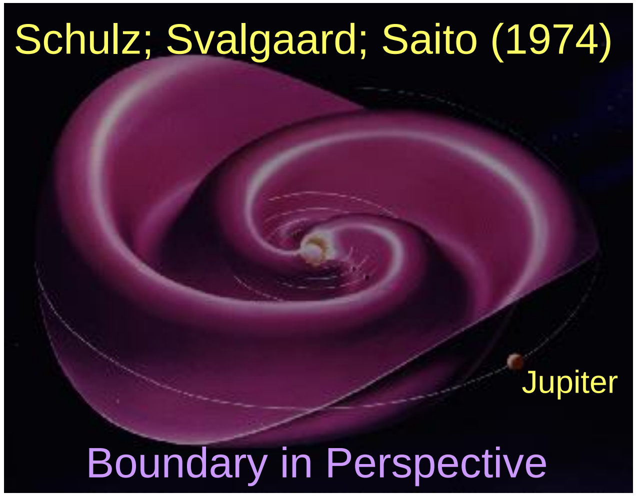
Svalgaard & Scherrer 2010



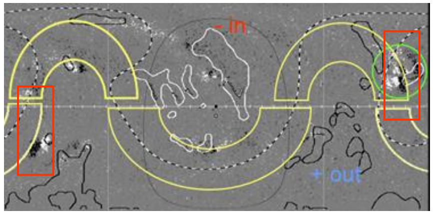
Rhessi Flares, Hannah et al. 2015

Nominal 4-Sector Structure in Photosphere

The Un-tilted Heliospheric Current Sheet


Schulz; Svalgaard; Saito (1974)

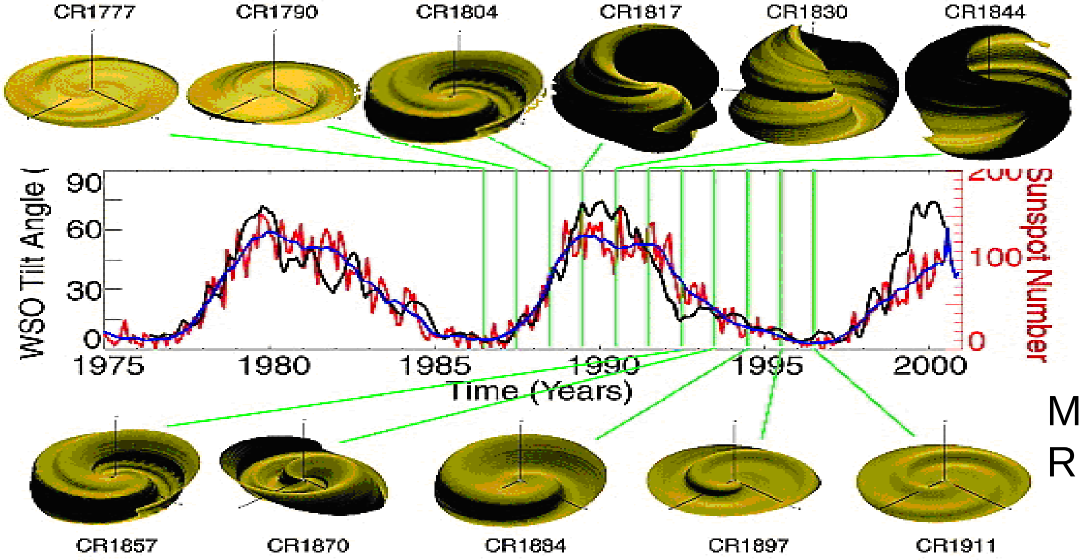
Boundary in Perspective



Sector boundary

The Boundary through the Cycle

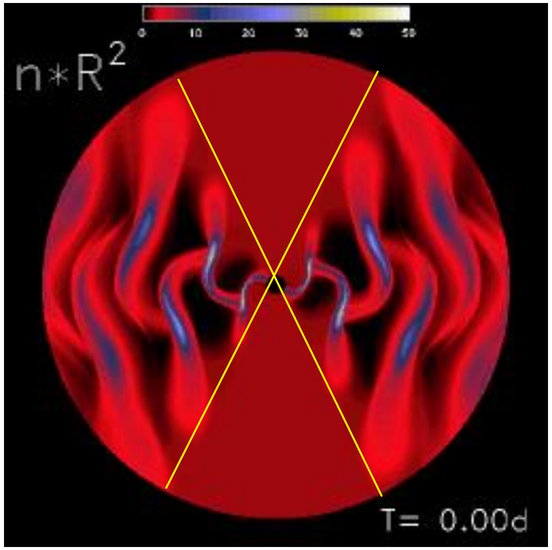
Near the sector boundary the solar wind is denser and slower. As the Sun rotates this builds up spiraling layers of denser plasma wrapping around the Sun many times:

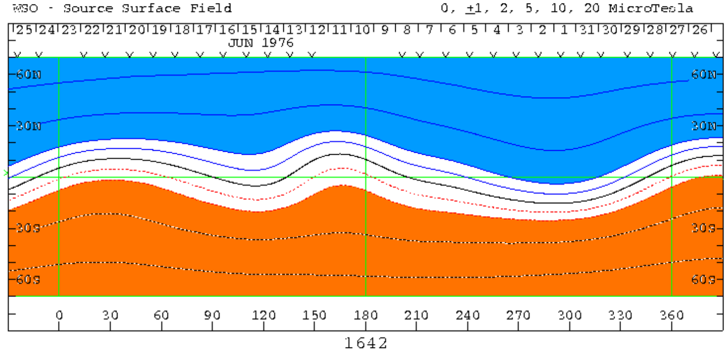


MHD
Riley

‘Vertical’ cut through the sweeping boundary:

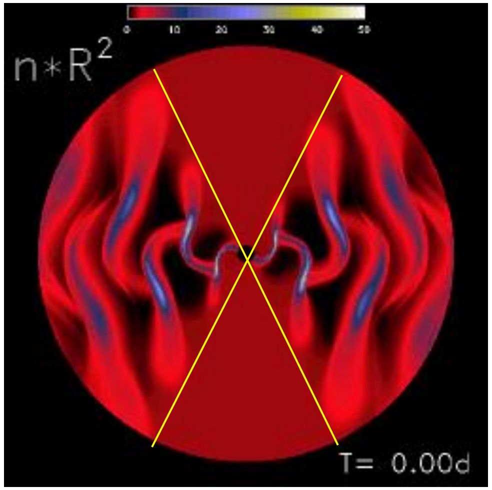
← 50 AU →

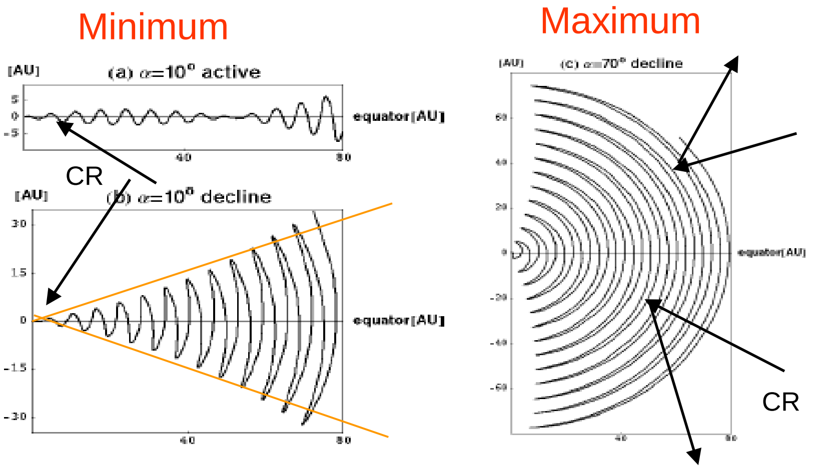




The ‘flapping’ sector boundary in time. Note the changing extent

Cosmic Rays from the Milky Way Galaxy

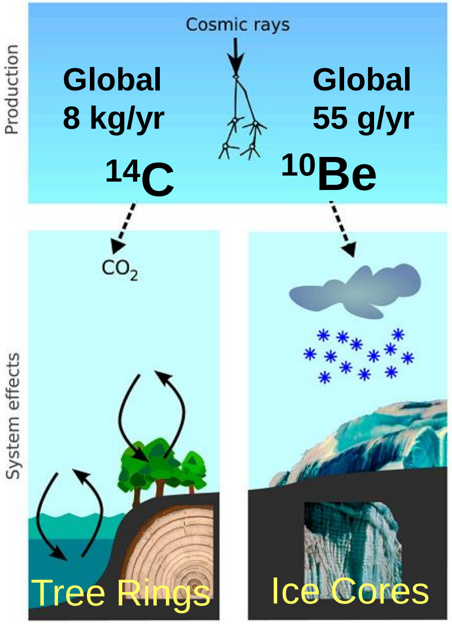




Cosmic Ray Modulation caused by solar cycle variation of current sheet extent and of solar storms

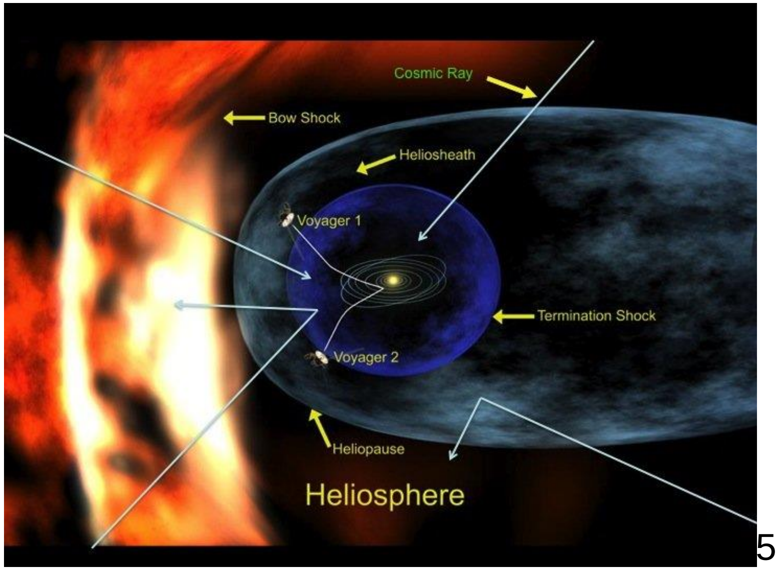
Svalgaard & Wilcox, 1976

At maximum, more Cosmic Rays are deflected out of the solar system and do not reach the Earth:

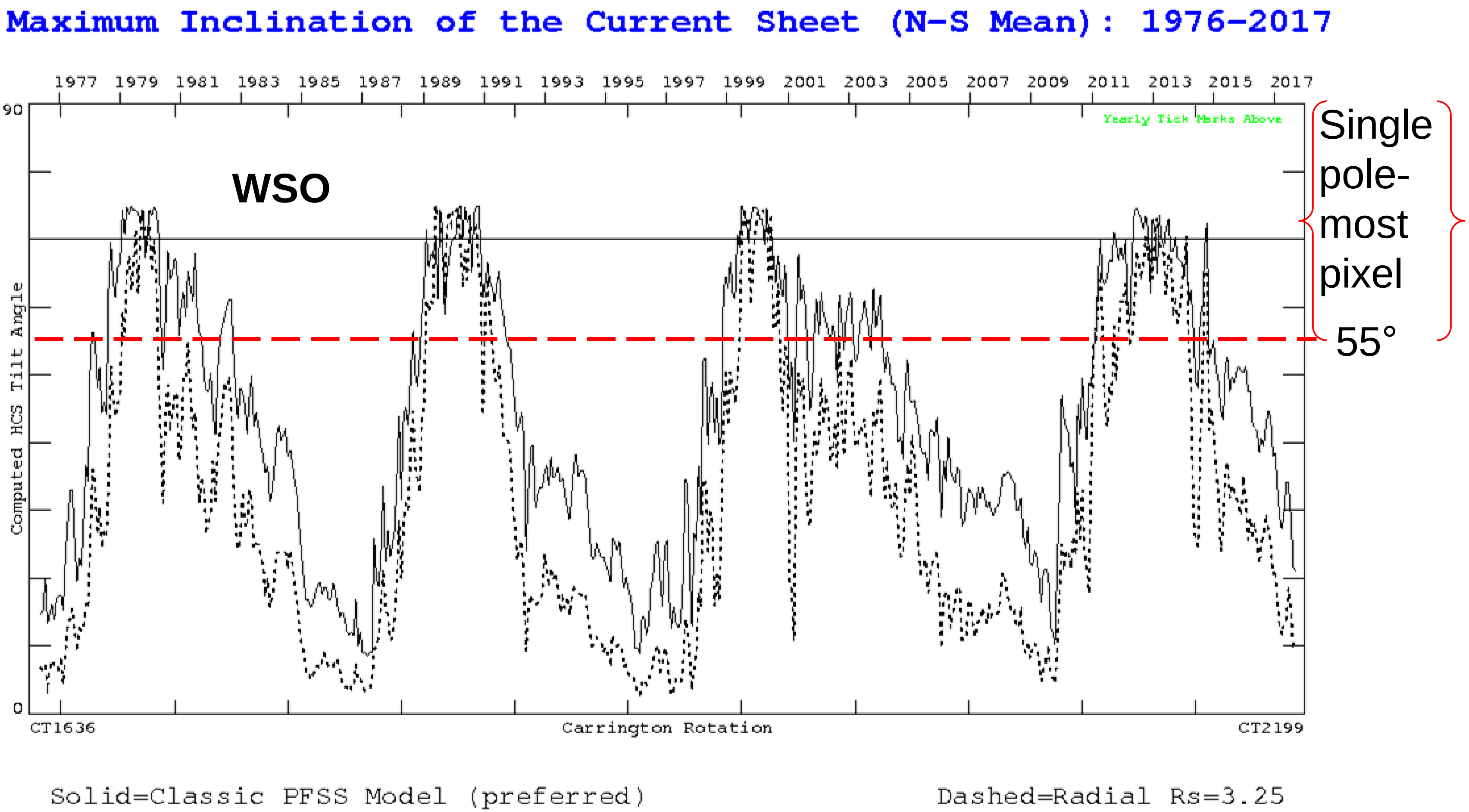


About 30 [secondary] cosmic rays fly through your body every second

When hitting the atmosphere Cosmic Rays produce radioactive Carbon14 and Beryllium10 isotopes

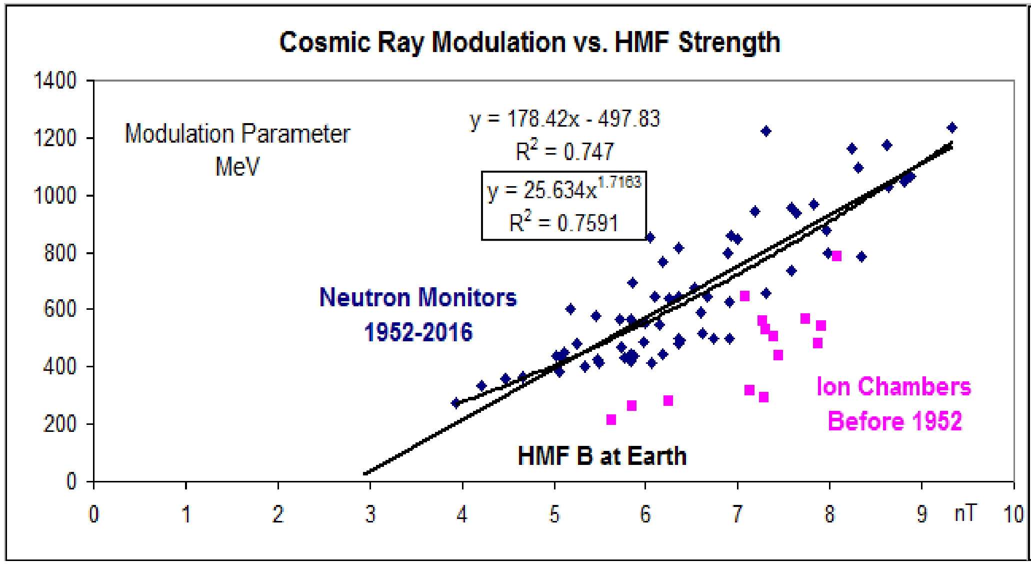


The Misnamed ‘Tilt’ of the HCS

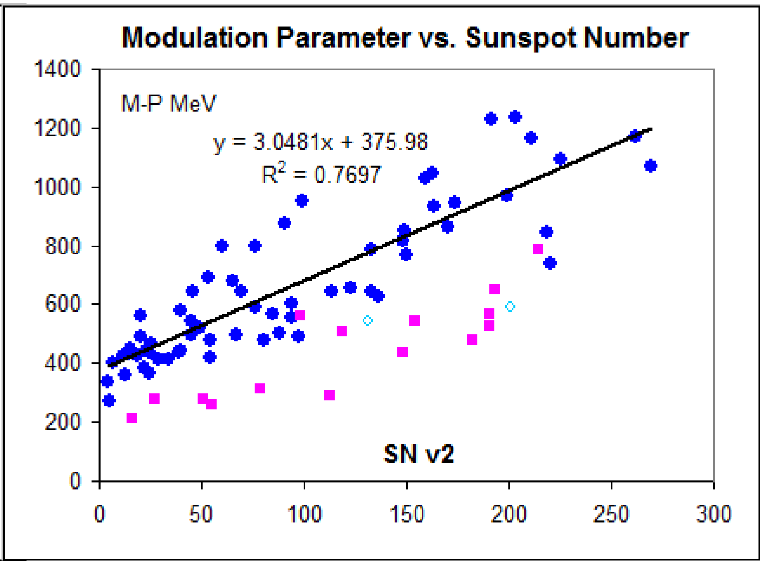


The HCS is not ‘tilted’ but warped and what is computed is the latitudinal extent of the fictitious ‘dipole’ warping. At polar field reversal the warping should be 90° by definition

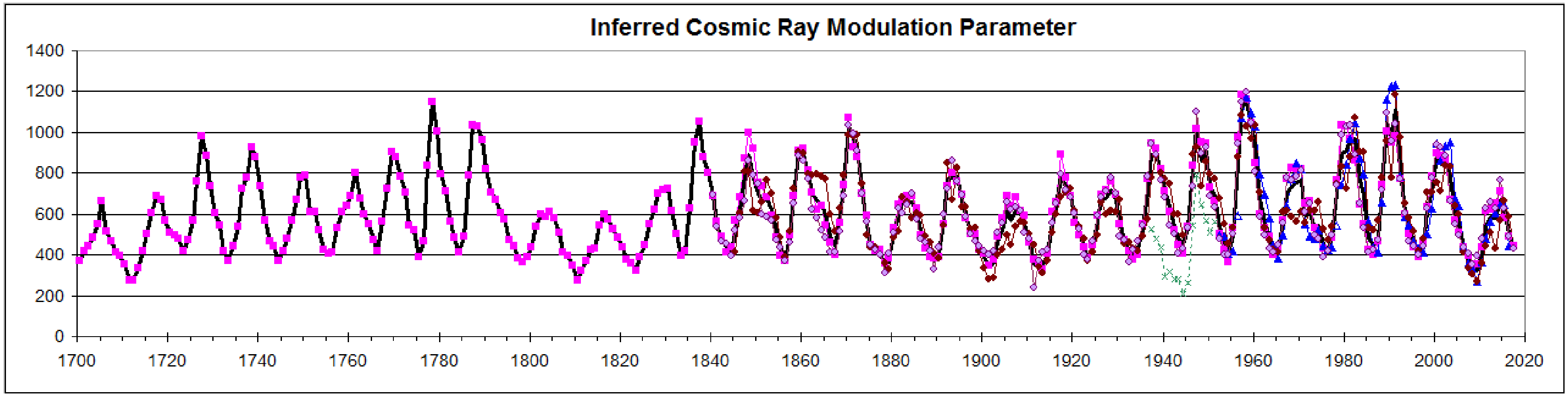
Cosmic Ray Modulation in Time



Cosmic Ray Modulation vs. HMF Strength

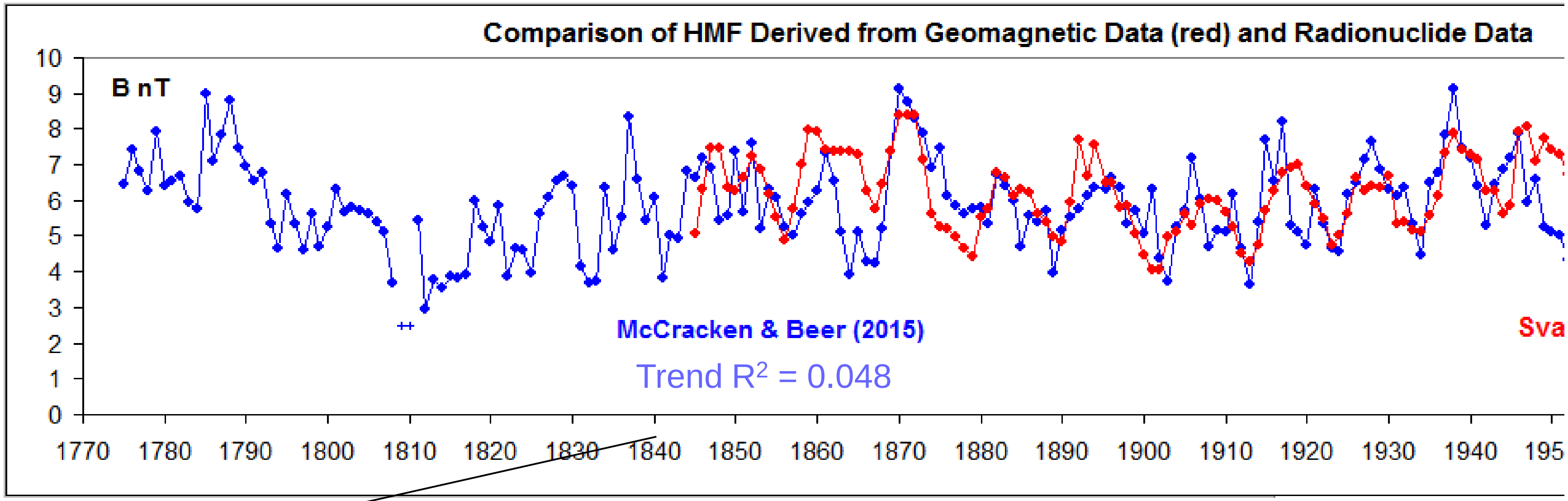


Modulation Parameter vs. Sunspot Number



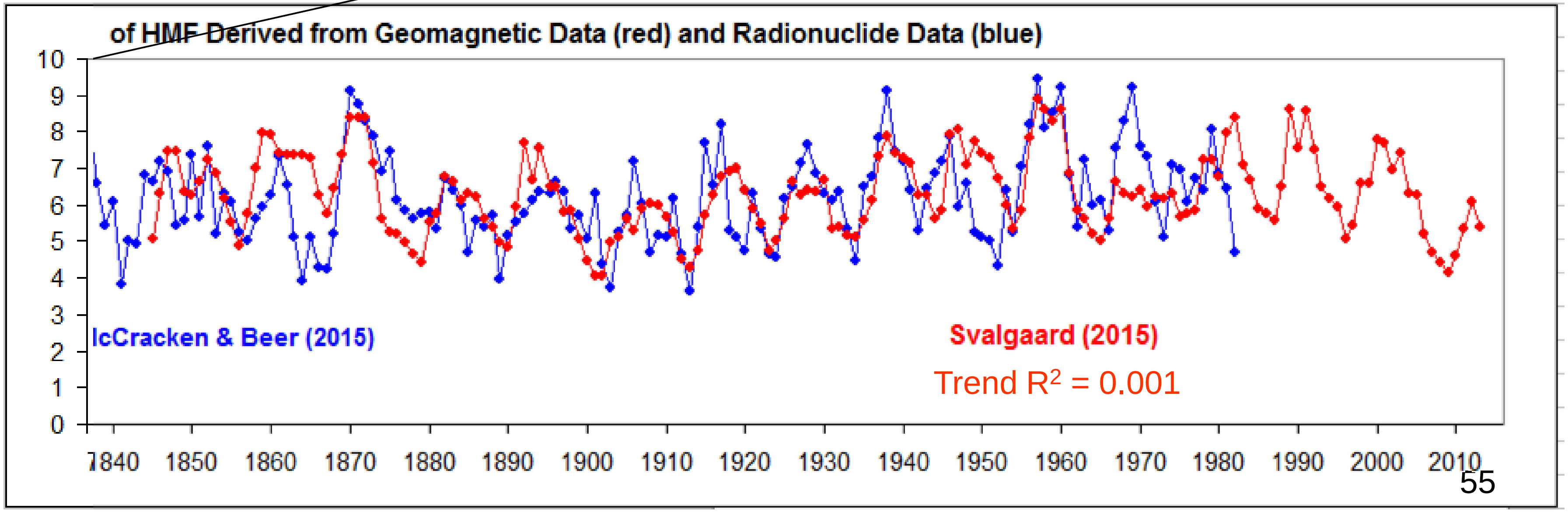
Inferred Cosmic Ray Modulation Parameter

Heliospheric Magnetic Field from ^{10}Be



Comparison of HMF Derived from Geomagnetic Data (red) and Radionuclide Data

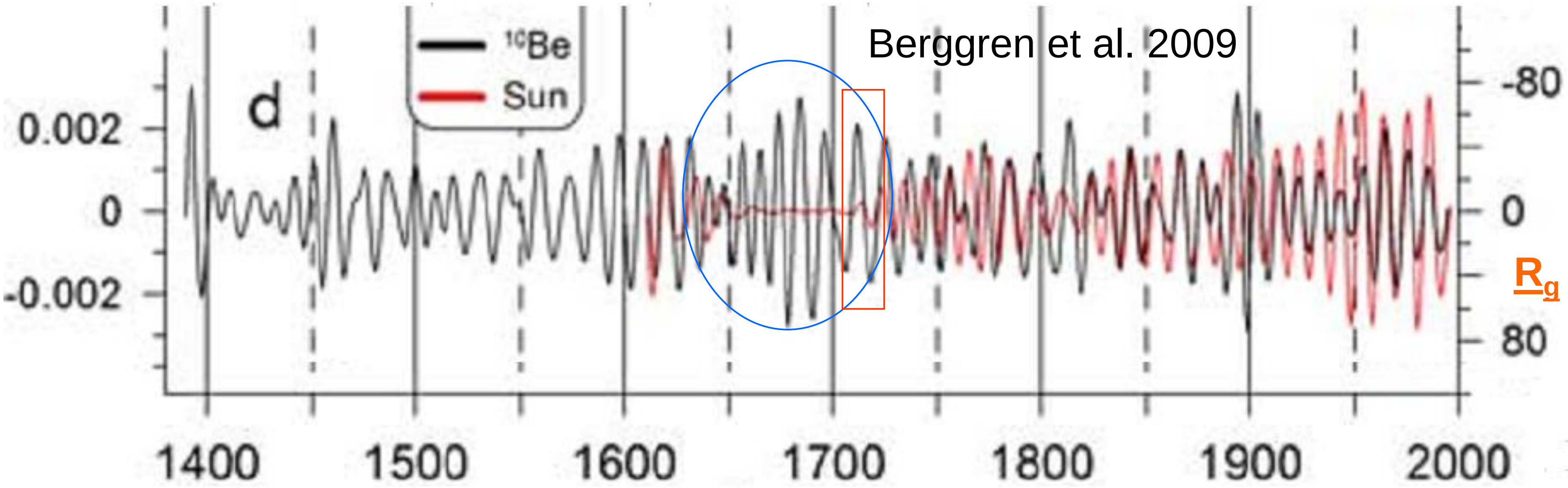
Trend $R^2 = 0.048$



of HMF Derived from Geomagnetic Data (red) and Radionuclide Data (blue)

Trend $R^2 = 0.001$

Cosmic Ray Modulation During the Maunder Minimum



Berggren et al. 2009

Band pass (8-16 yrs) filtering of sunspot and 10Be data around the length of the Schwabe cycle. (d) NGRIP 10Be flux and H&S Group Sunspot Number. The large variation during the M.M. is helped by non-linear response of modulation.

The solar dynamo was apparently working producing magnetic fields and a solar wind (causing long and straight comet ion tails), but few *visible* sunspots.

Red Flash => ‘Burning Prairie’ => Network Magnetism

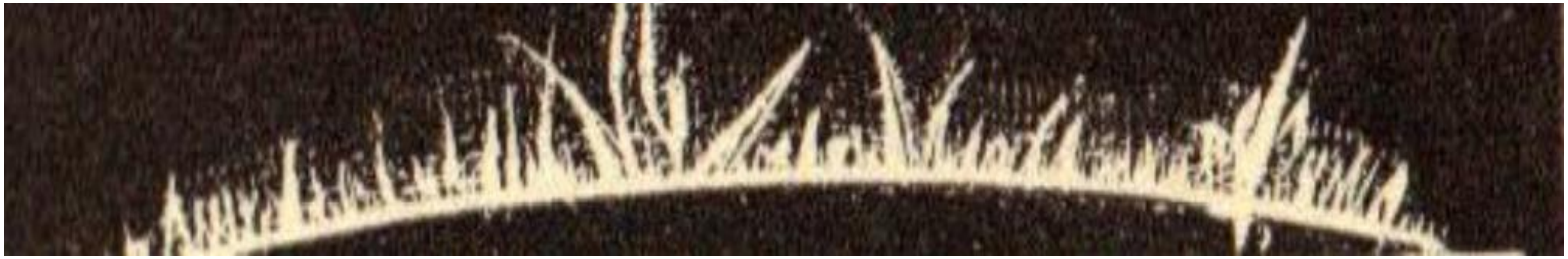
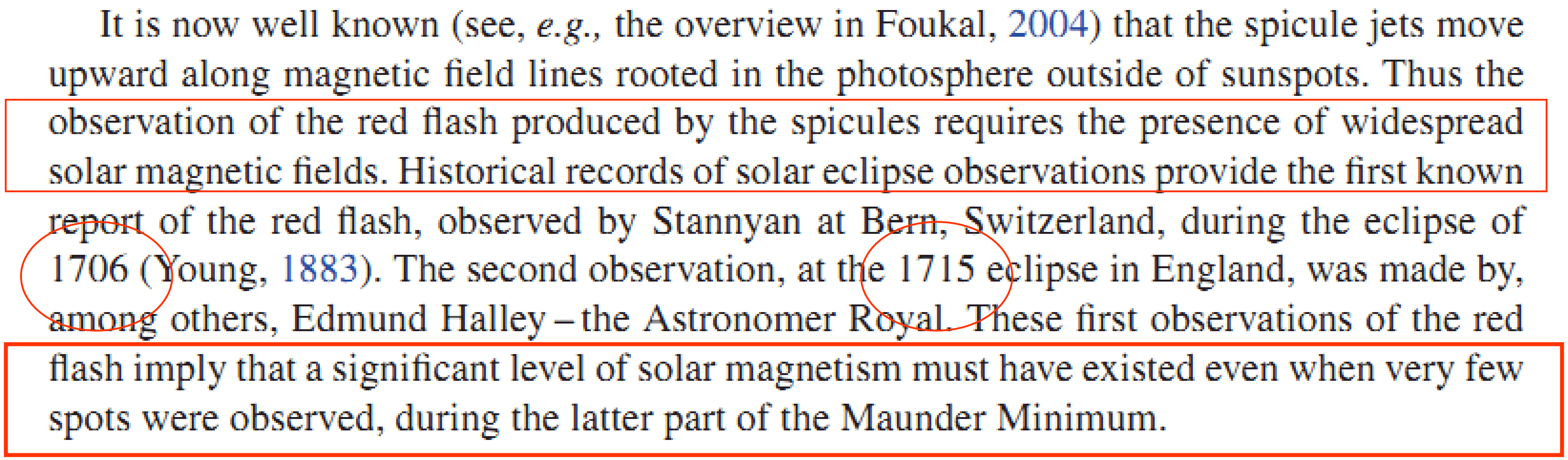


Figure 1 An early drawing of the “burning prairie” appearance of the Sun’s limb made by C.A. Young, on 25 July 1872. All but the few longest individual radial structures are spicules.

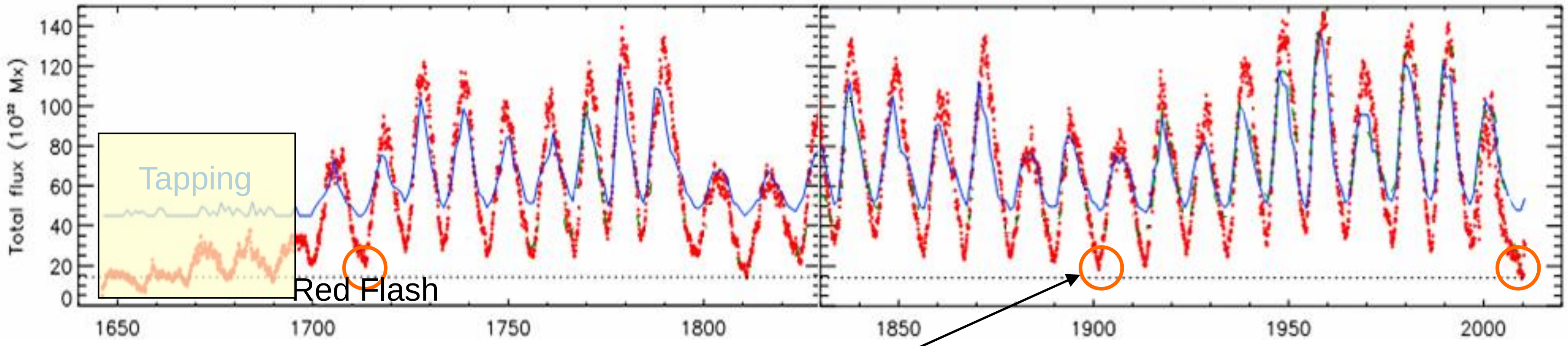


It is now well known (see, *e.g.*, the overview in Foukal, 2004) that the spicule jets move upward along magnetic field lines rooted in the photosphere outside of sunspots. Thus the observation of the red flash produced by the spicules requires the presence of widespread solar magnetic fields. Historical records of solar eclipse observations provide the first known report of the red flash, observed by Stannyan at Bern, Switzerland, during the eclipse of 1706 (Young, 1883). The second observation, at the 1715 eclipse in England, was made by, among others, Edmund Halley – the Astronomer Royal. These first observations of the red flash imply that a significant level of solar magnetism must have existed even when very few spots were observed, during the latter part of the Maunder Minimum.

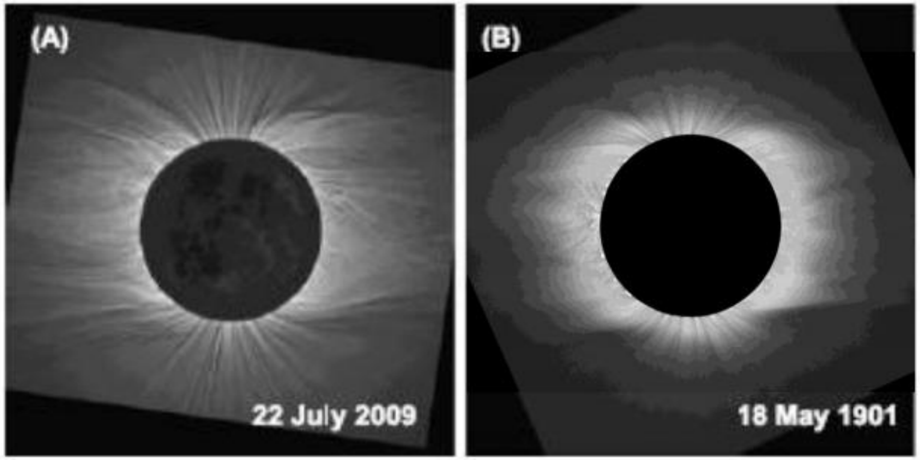
Foukal & Eddy, Solar Phys. 2007, *245*, 247-249

Perhaps There was a Base-level Solar Magnetic Field Even During the M. M.

Total Magnetic Flux on Sun (Schrijver, Livingston, Woods, Mewalt, GRL 2011)



Back to the Future

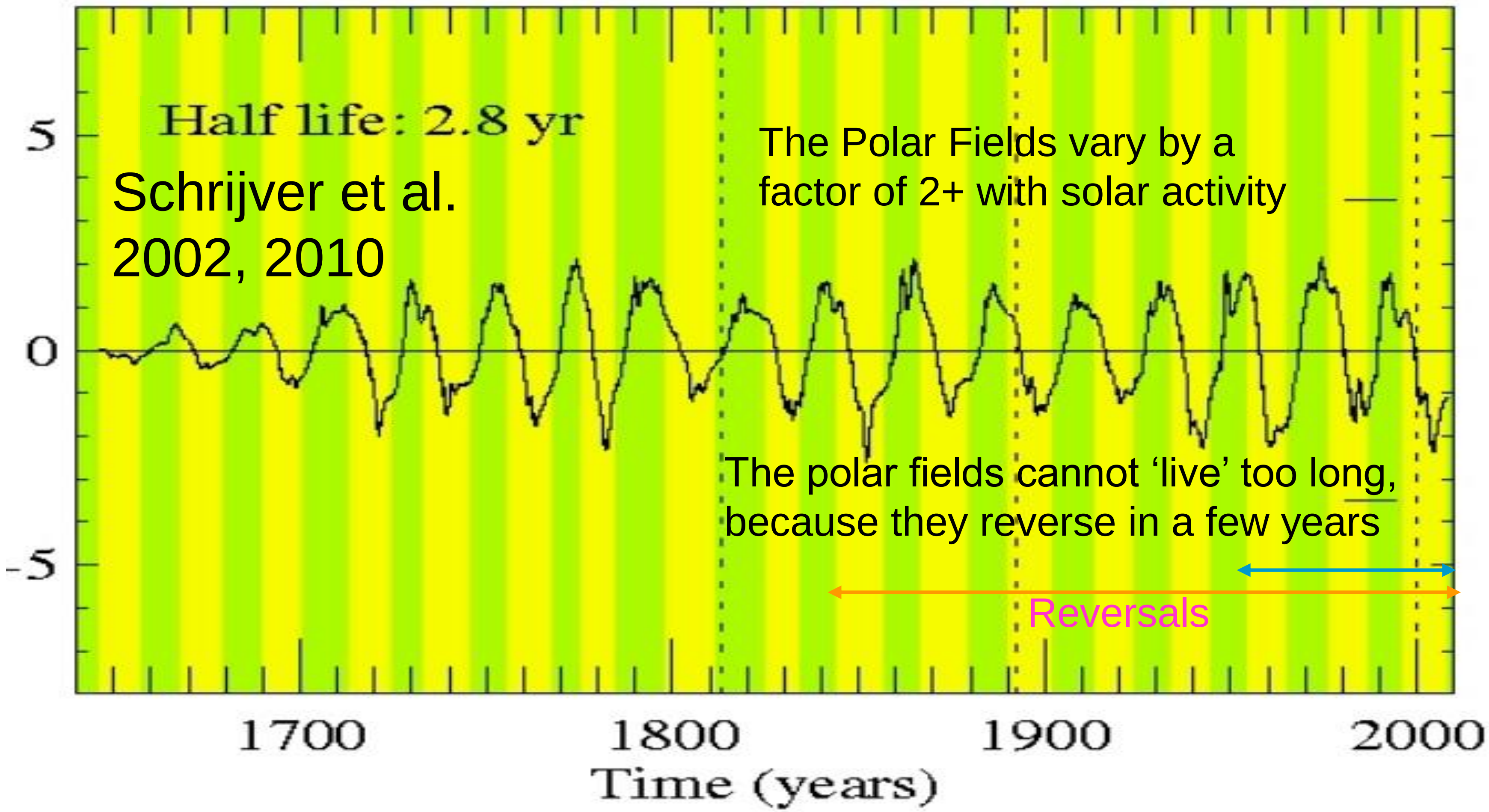


2008-2009 HMF B = 4.14
Sunspot Number, Ri = 3

1901-1902 HMF B = 4.10 nT
Sunspot Number, Rz = 4

"Estimate of the unsigned surface magnetic flux based on a surface flux-transport model that uses the sunspot number records to determine flux emergence with 2D surface dispersal based on observed properties of the solar field. This model has no free parameters, assuming only that the frequency of active-region emergence changes over time in direct proportion to the yearly-averaged sunspot number."

“Polar Cap Flux Key Driver of Heliospheric Magnetic Field”



Schrijver et al. 2002, 2010

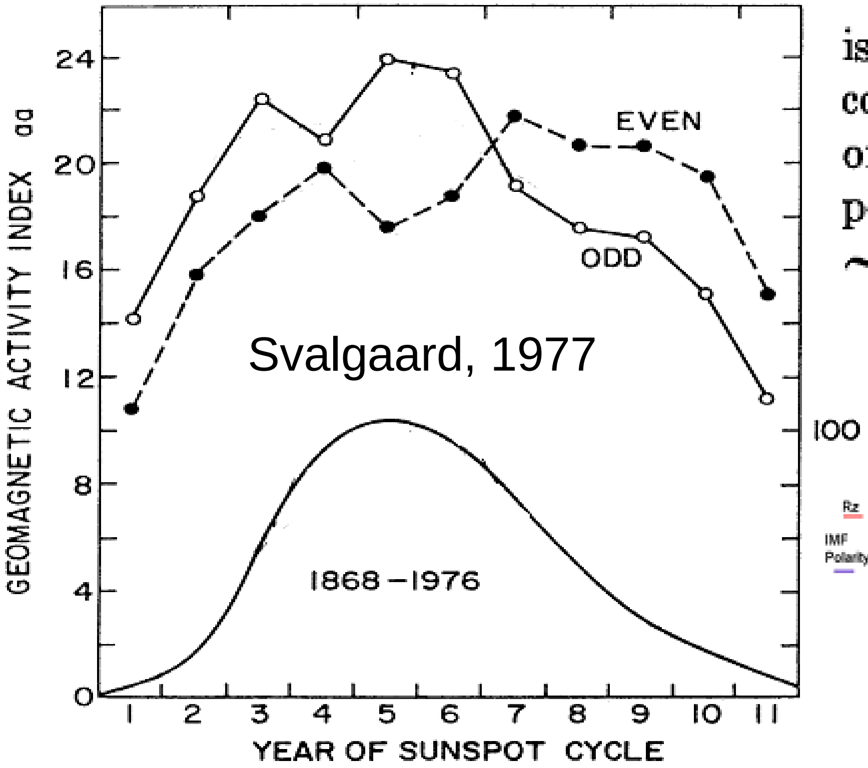
The Polar Fields vary by a factor of 2+ with solar activity

The polar fields cannot ‘live’ too long, because they reverse in a few years

Reversals

Polar Cap (above 65° North) Magnetic Flux [10^{22} Mx] for half-life of 2.8 years are just about 1% of the total measured flux that itself is probably much smaller than the real flux

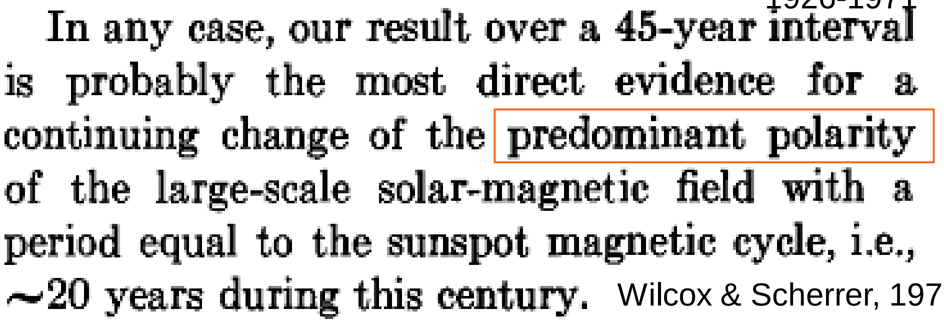
How do we Know that the Poles Reversed Regularly before 1957?



Svalgaard, 1977

“Seasonal variations of the ratio of positive and negative sectors give clear evidence of solar magnetic field reversals starting from the second half of the nineteenth century”. Vokhmyanin & Ponyavin, JGR 2013

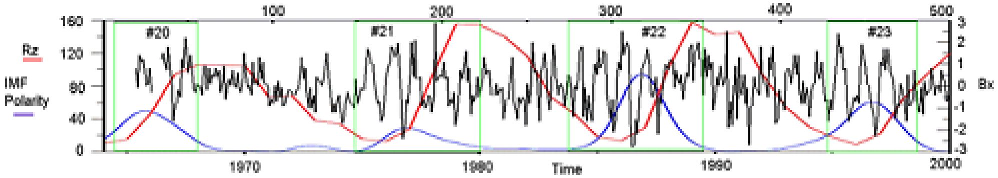
1926-1971



In any case, our result over a 45-year interval is probably the most direct evidence for a continuing change of the predominant polarity of the large-scale solar-magnetic field with a period equal to the sunspot magnetic cycle, i.e., ~20 years during this century.

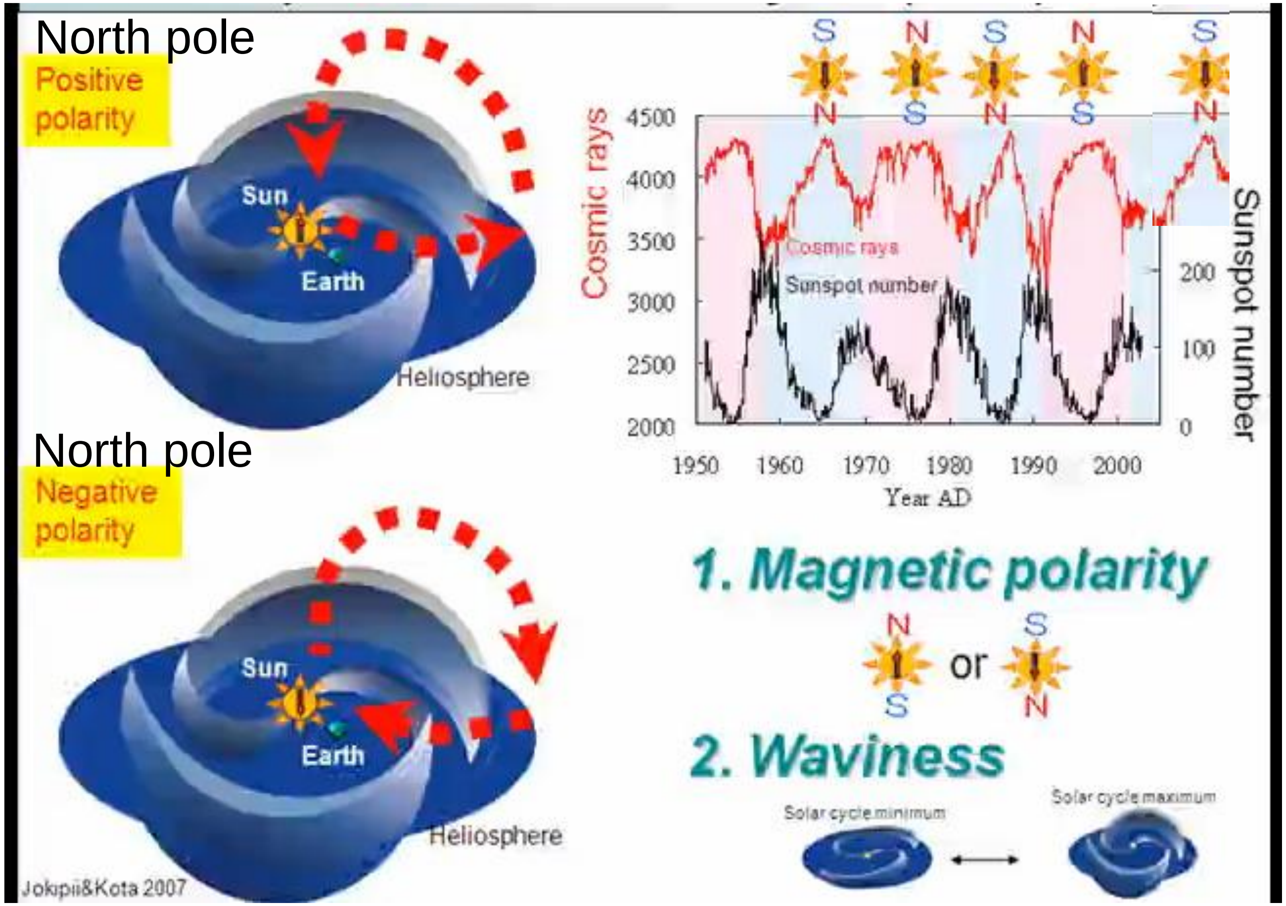
Wilcox & Scherrer, 1972

The predominant polarity ≈ polar field polarity (Rosenberg-Coleman effect) annually modulated by the B-angle.



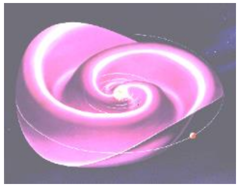
This effect combined with the Russell-McPherron effect [geomagnetic activity enhanced by the Southward Component of the HMF] predicts a 22-year cycle in geomagnetic activity synchronized with polar field reversals, as observed (now for 1840s-Present).

Cosmic Ray Modulation Depends on the Sign of Solar Pole Polarities



Miyahara, 2011

Ion-chamber data do not show the peaks and flat tops…

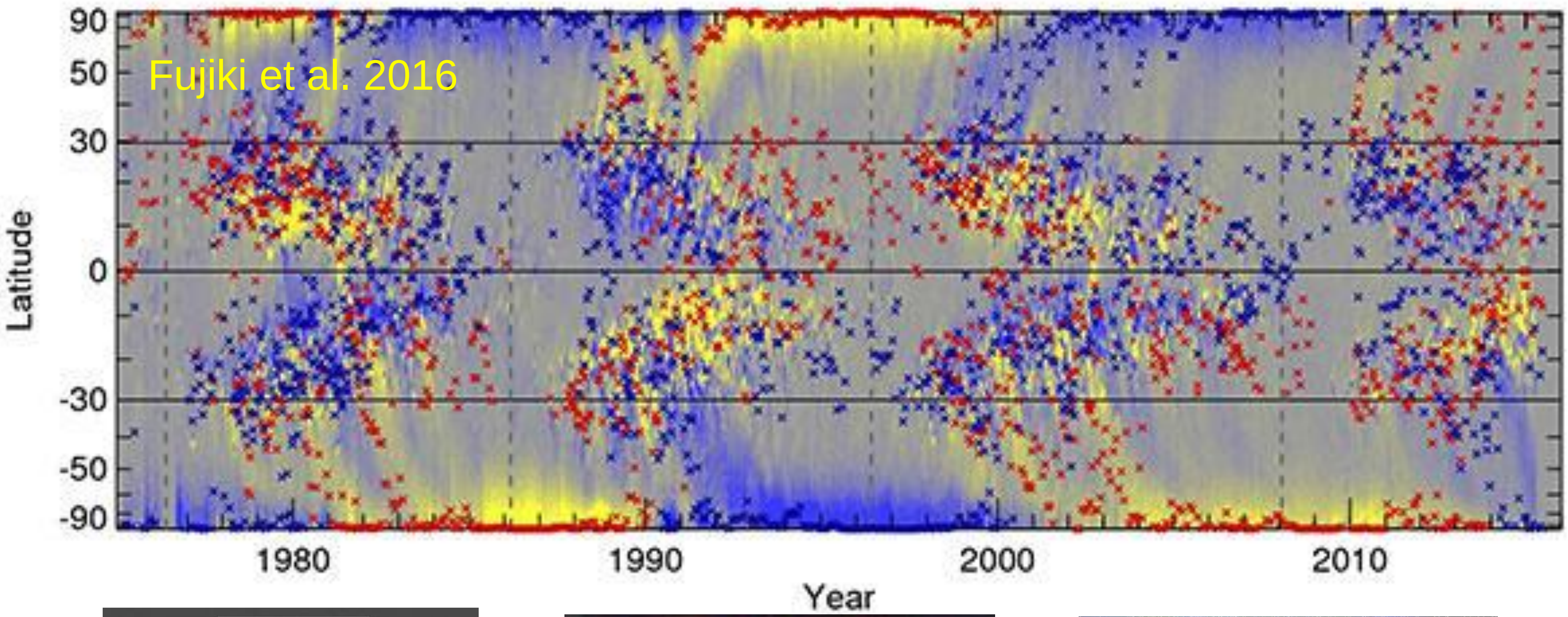


Wilcox & Svalgaard, 1976

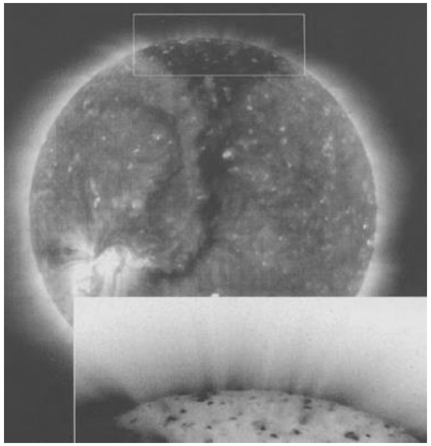
The shape of the modulation curve [alternating ‘peaks’ and ‘flat tops’] shows the polar field sign.

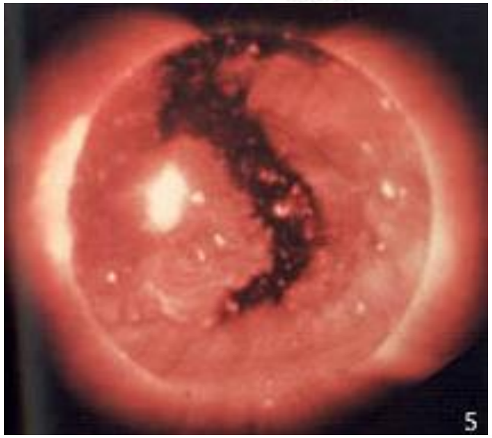
Ice cores contain a long record of 10Be atoms produced by cosmic rays. The record can be inverted to yield the cosmic ray intensity. The technique is not *yet* good enough to show peaks and flats, but might with time be refined to allow this.

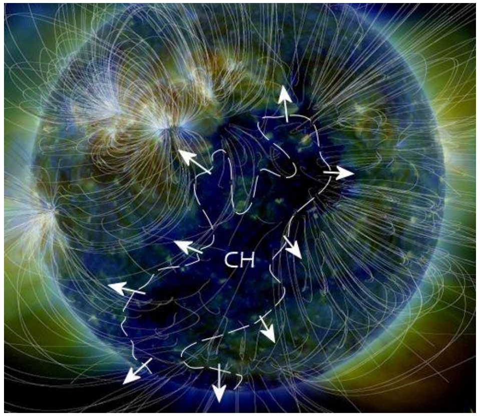
Coronal Holes are Not Polar Cap ‘Extensions’ but Flux on its Way to the Poles



Fujiki et al. 2016

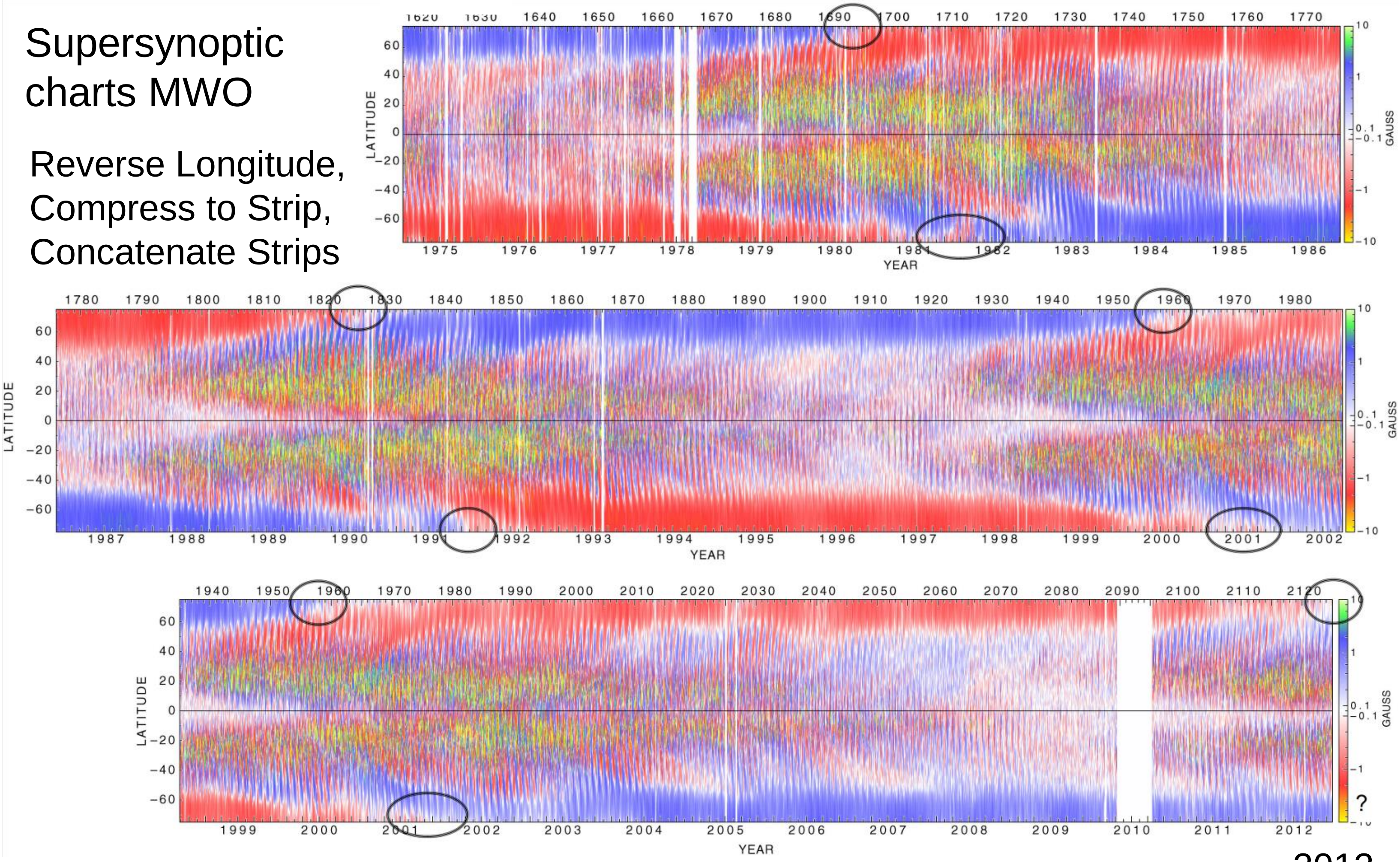






Fine-Structured Polar Field Reversals

1975



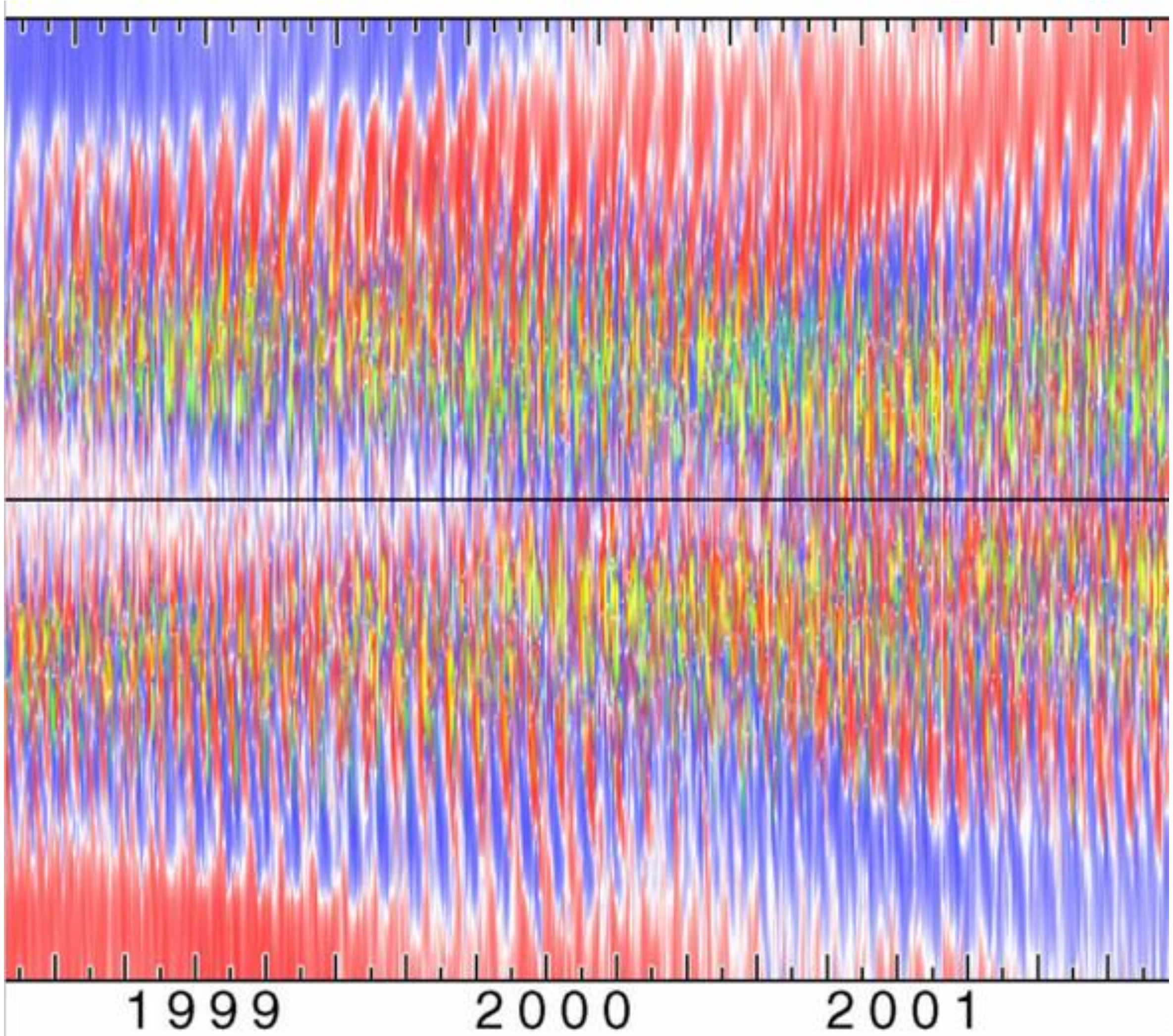
Supersynoptic charts MWO

Reverse Longitude,
Compress to Strip,
Concatenate Strips

2012

MWO: Roger Ulrich, 2012

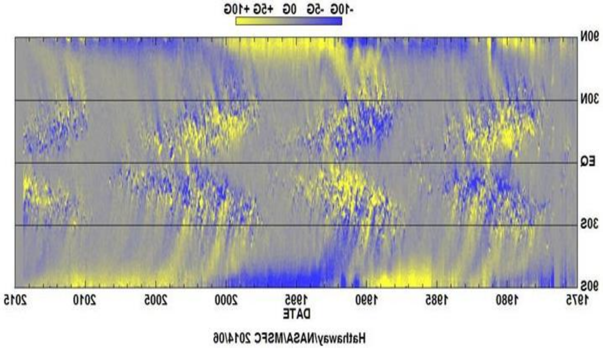
Poleward Migration of Flux



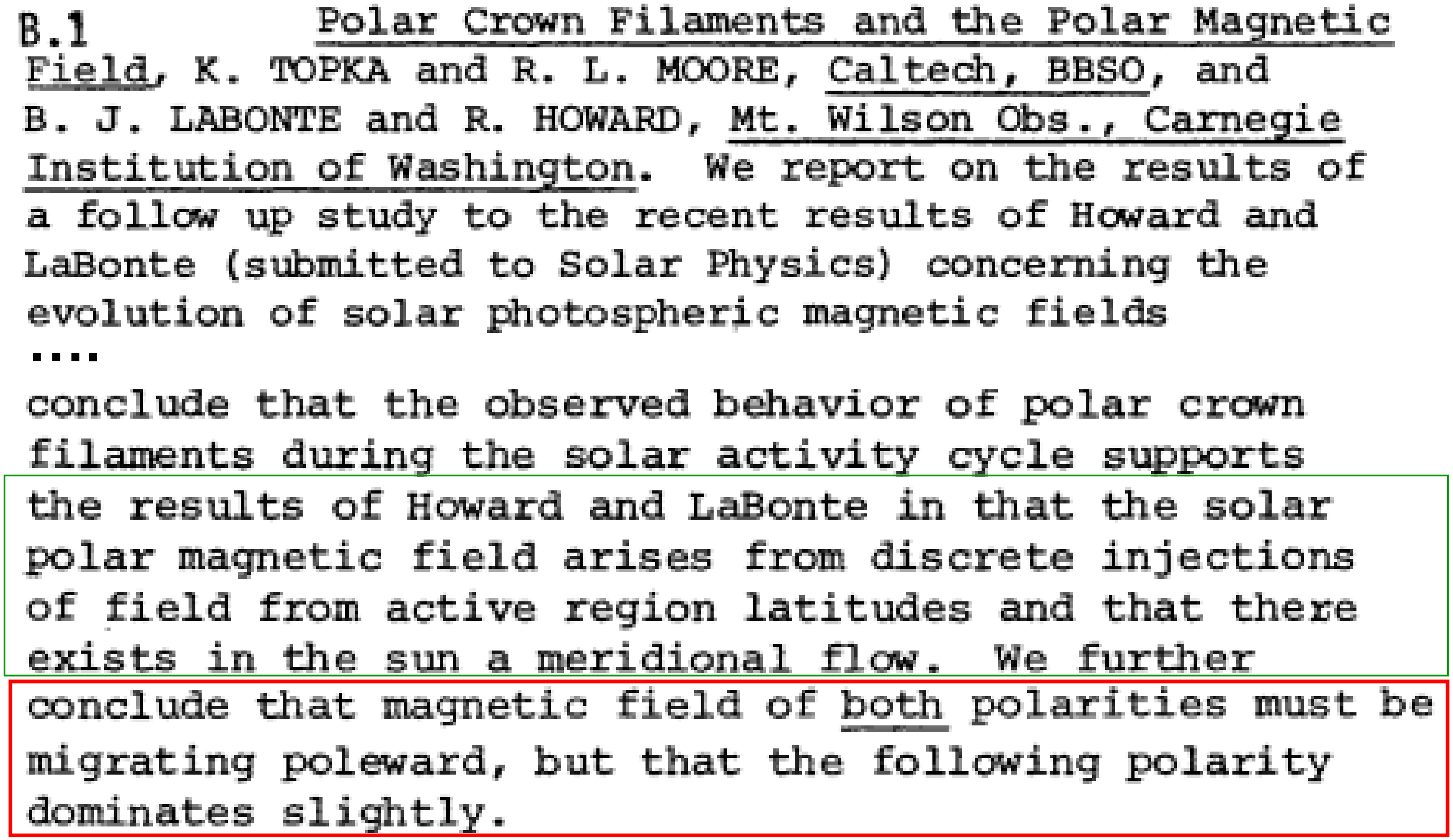
Neutral lines are North-South, not East-West

Flux of **both** polarities move towards the pole. There is no evidence for significant amount of flux crossing the equator

Zonal averaging over a rotation (as is often done) obscures the actual, real magnetic flux migration:



This is No News, of Course



B.1 Polar Crown Filaments and the Polar Magnetic Field, K. TOPKA and R. L. MOORE, Caltech, BBSO, and B. J. LABONTE and R. HOWARD, Mt. Wilson Obs., Carnegie Institution of Washington. We report on the results of a follow up study to the recent results of Howard and LaBonte (submitted to Solar Physics) concerning the evolution of solar photospheric magnetic fields

....

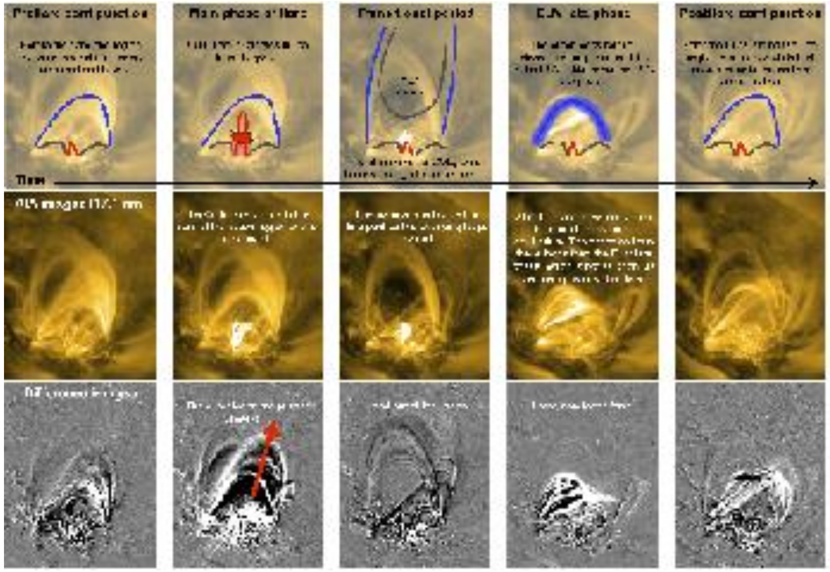
conclude that the observed behavior of polar crown filaments during the solar activity cycle supports the results of Howard and LaBonte in that the solar polar magnetic field arises from discrete injections of field from active region latitudes and that there exists in the sun a meridional flow. We further conclude that magnetic field of both polarities must be migrating poleward, but that the following polarity dominates slightly.

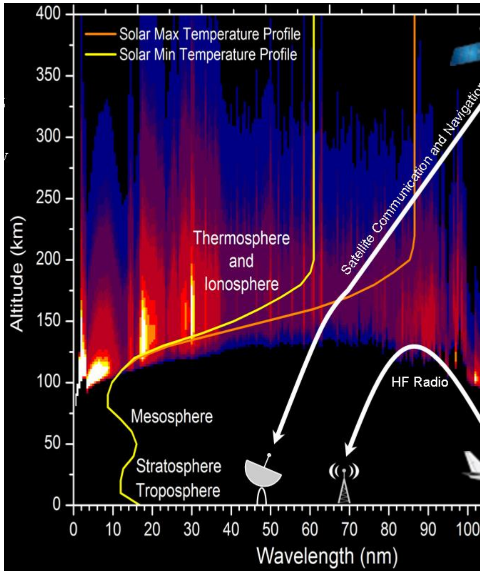
SPD Meeting, 1980, BAAS, 12, 893, B1

Summary III (The 3D Heliosphere)

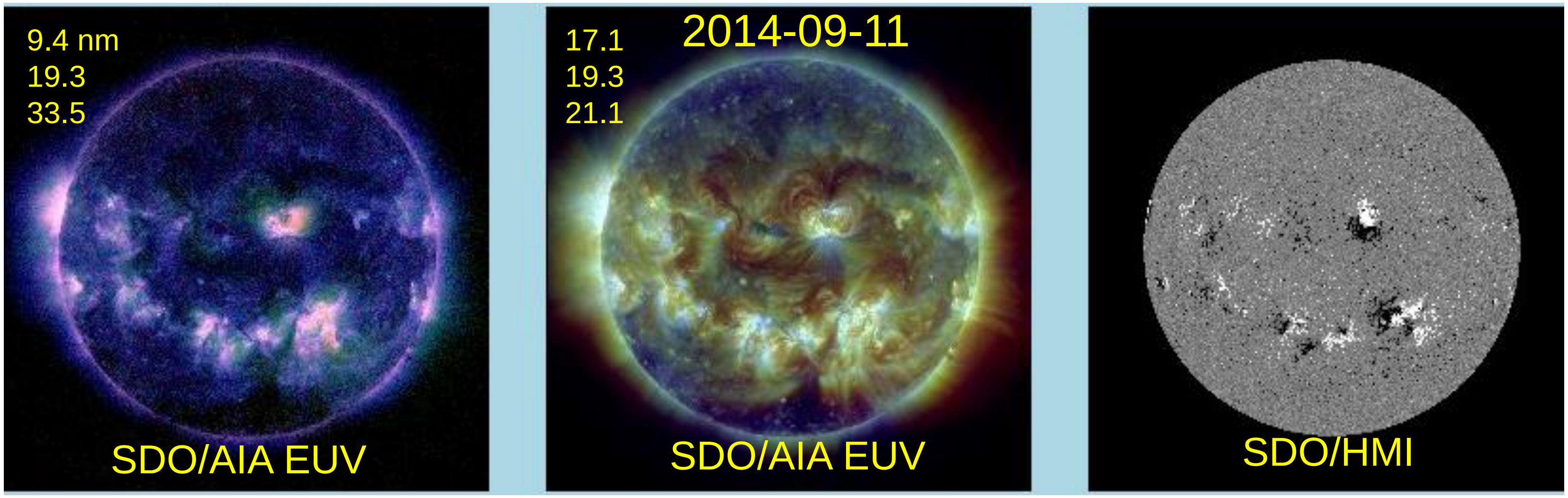
- The large-scale Heliospheric structure is 3D and varies through the Solar Cycle. “Polar Cap Flux Key Driver of Heliospheric Magnetic Field”
- The Structure is the result of an interplay between the Polar Fields and Low-Latitude Unipolar Regions located in opposite hemispheres organized along Hale Boundaries
- The Heliospheric Current Sheet is warped and not ‘tilted’.
- The Latitudinal Extent of the Warping controls the access and variation of Galactic Cosmic Rays [GCR]
- There was strong modulation of GCR and wide-spread solar magnetic fields even during the Maunder Minimum
- We can reconstruct the GCR modulation potential since 1700
- We know that the Polar Fields have reversed regularly at least since the 1840s
- Both polarities move towards the poles (obscured when taking zonal averages). Neutral Lines are N-S, not E-W

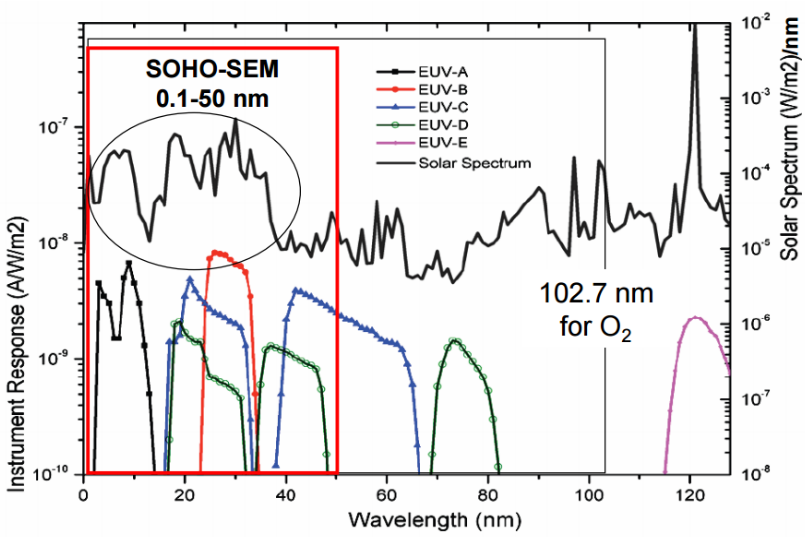
Microwaves, EUV, and Magnetic Flux in Time





We get Solar EUV from the Million-degree Corona fed by the Surface Magnetic Flux



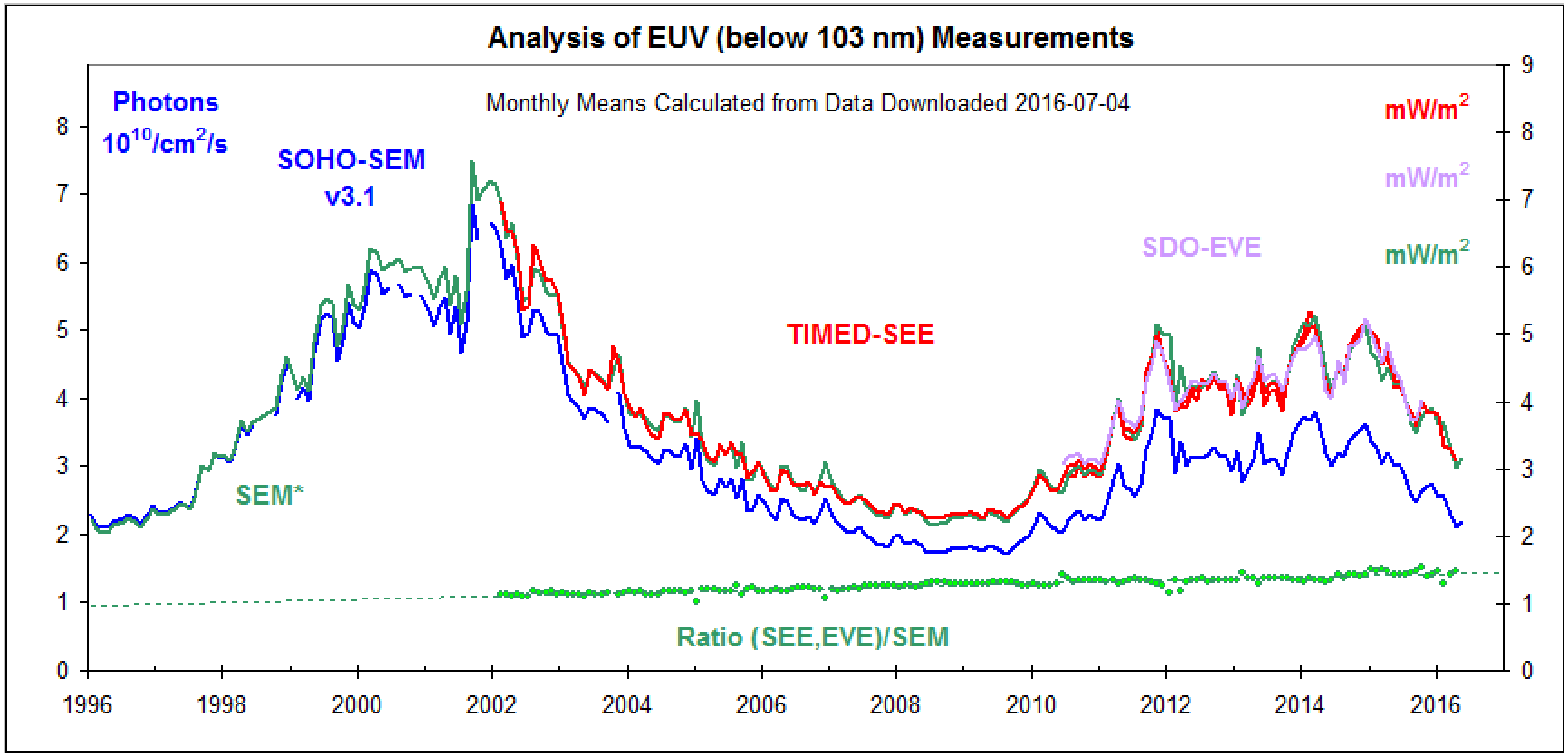


λ<102.7 nm to ionize molecular Oxygen

$$O_2 + h\nu \rightarrow O_2^+ + e^-$$

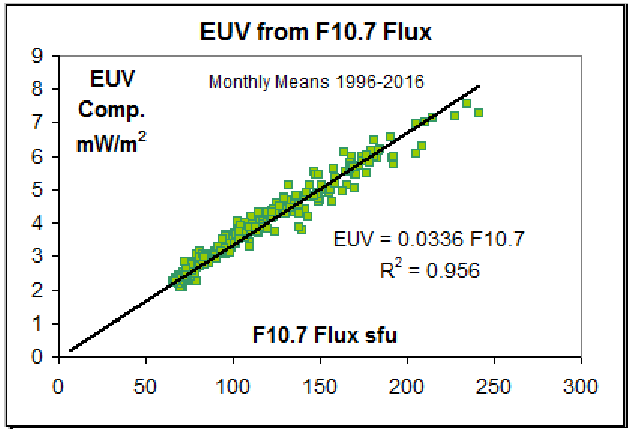
This reaction creates and maintains the conducting E-region of the Earth's Ionosphere (at ~105 km altitude)

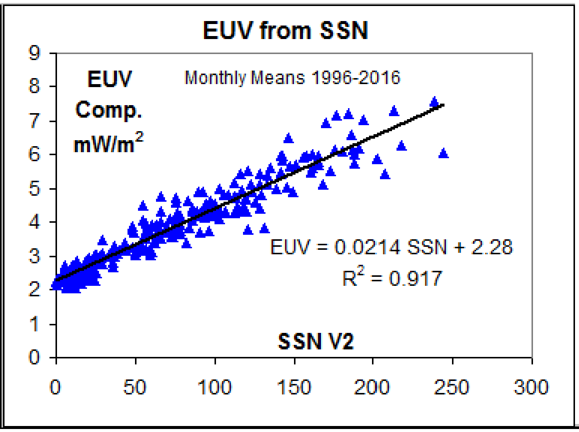
Creating an EUV (<103 nm) Composite



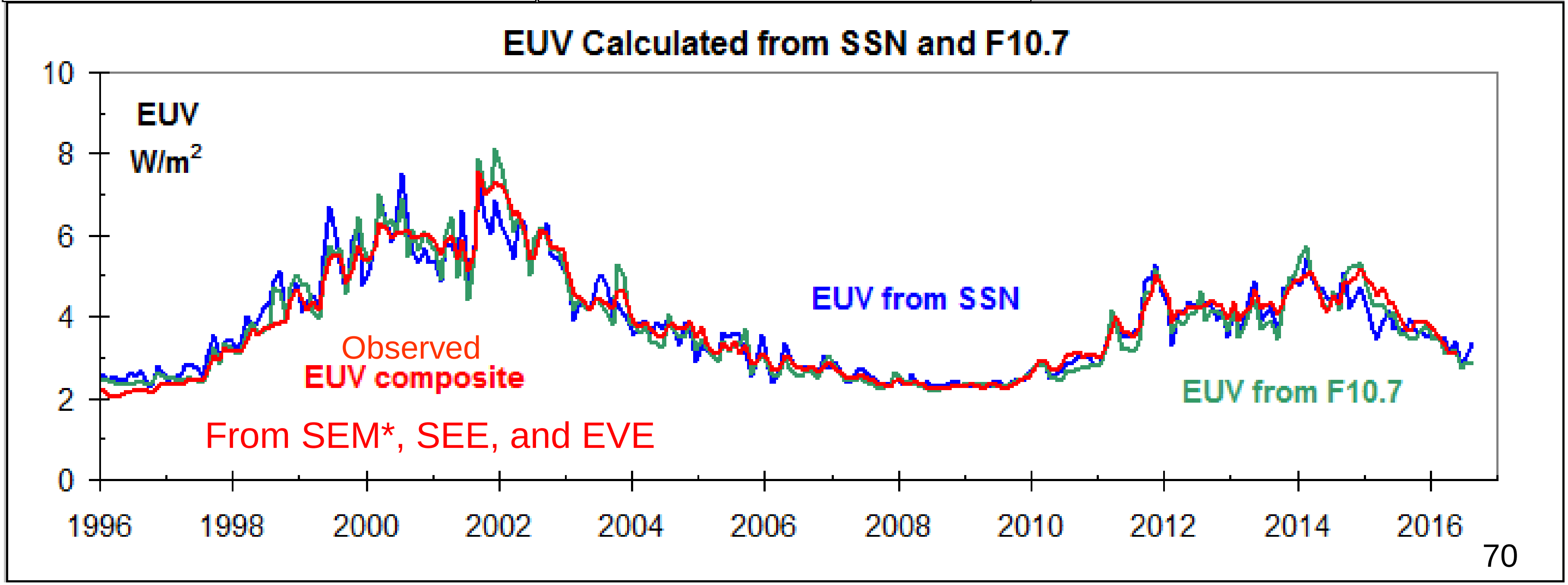
SEE and EVE agree nicely and we can form a composite (SEE,EVE) of them. SEM is on a different scale, but we can convert that scale to the scale of (SEE,EVE). The scale factor [green line] shows what to scale SEM with to match (SEE,EVE) [SEM*. upper green curve], to get a composite of all three (SEM*,SEE,EVE) covering 1996-2016, in particular the two minima in 1996 and 2008.

EUV Composite Matches F10.7 Flux and Sunspot Numbers

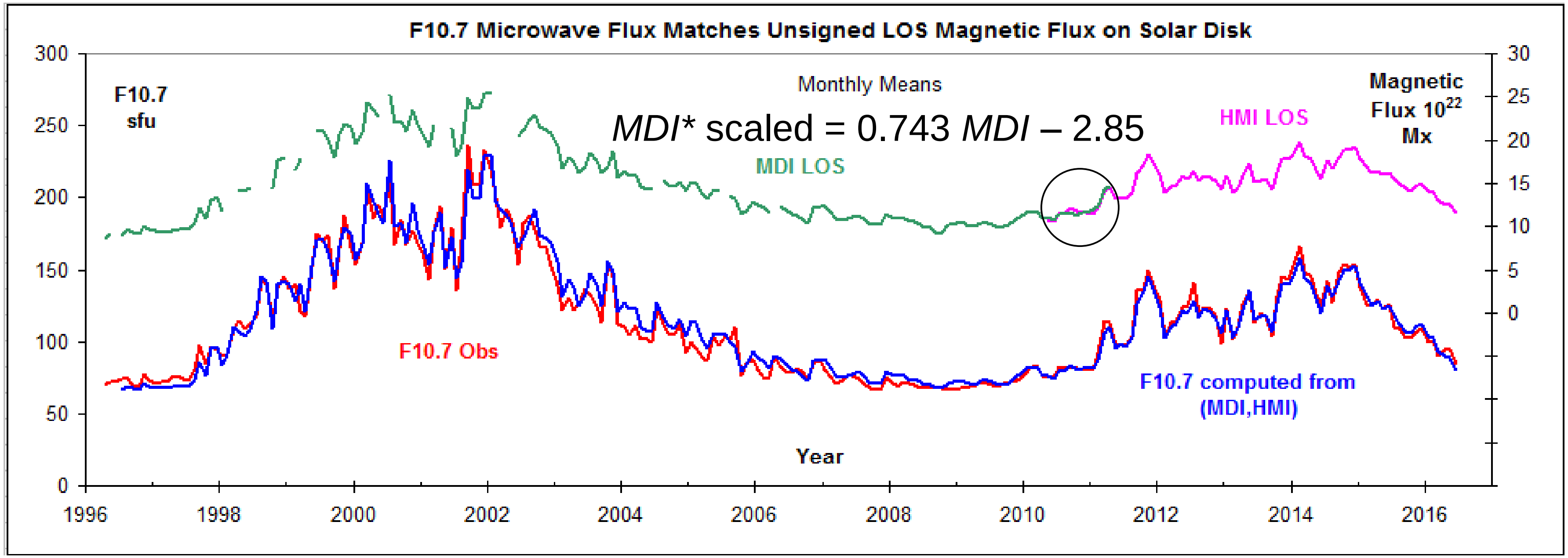


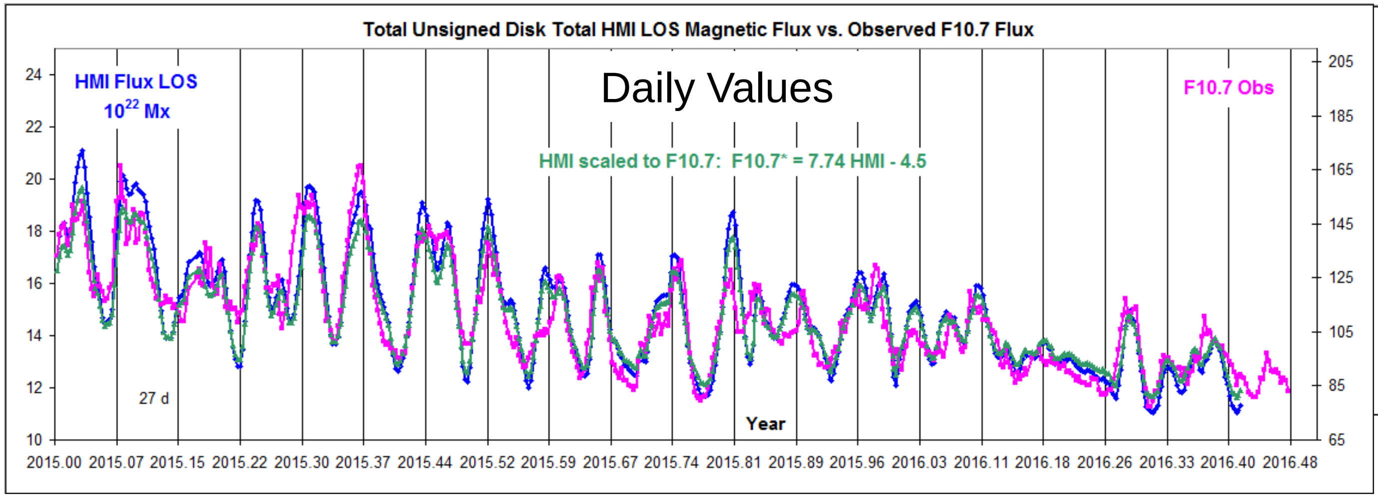


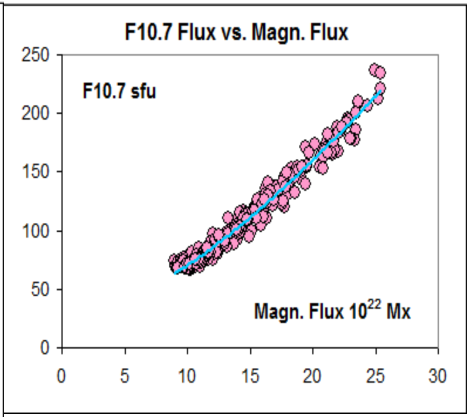
So, we can calculate the EUV flux both from the Sunspot Number and from the F10.7 flux which then is a good proxy for EUV [as is well-known].



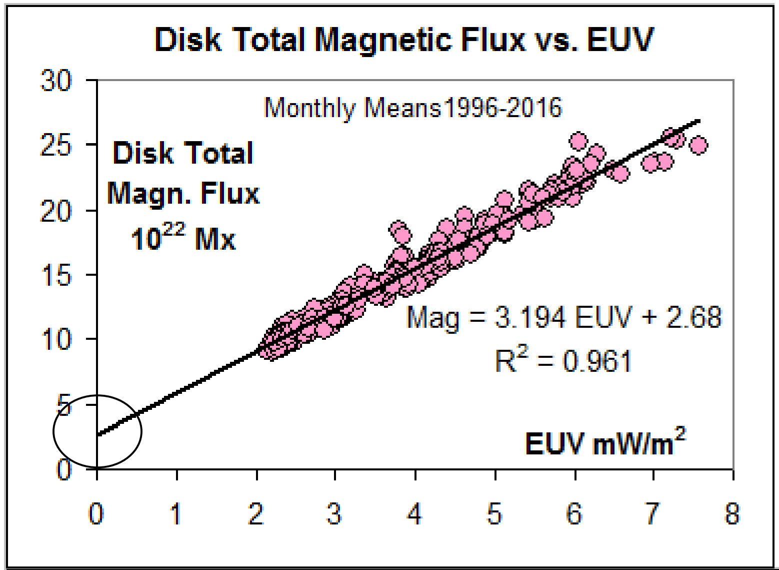
Magnetic LOS Flux from MDI and HMI Match F10.7 Microwave Flux

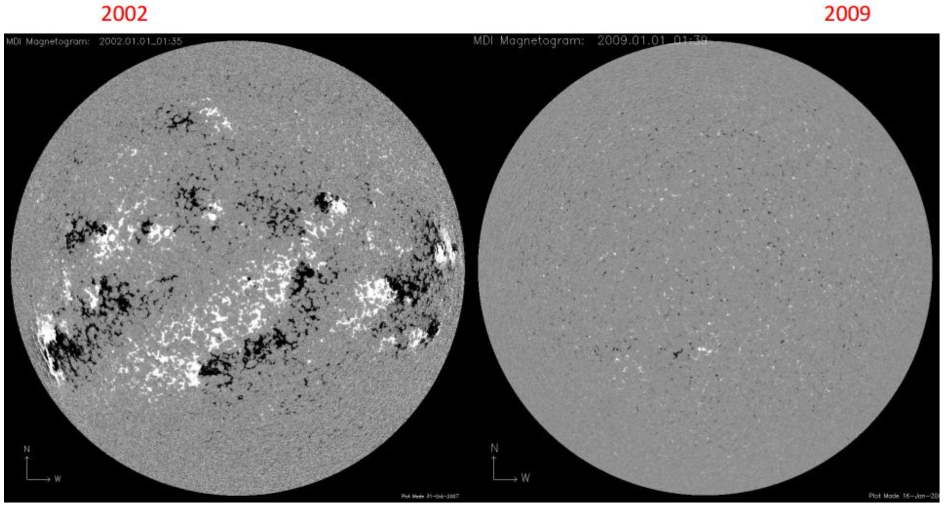

F10.7 Microwave Flux Matches Unsigned LOS Magnetic Flux on Solar Disk


Total Unsigned Disk Total HMI LOS Magnetic Flux vs. Observed F10.7 Flux

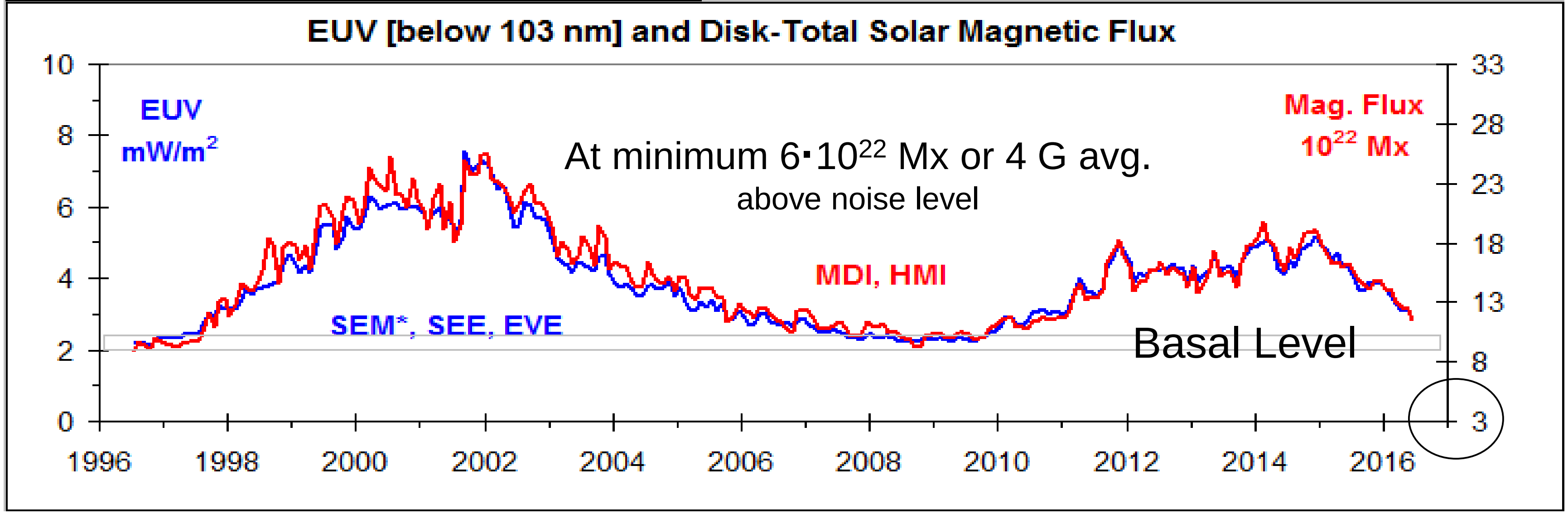

F10.7 Flux vs. Magn. Flux

EUV Follows Total Unsigned Magnetic Flux





Offset interpreted as Noise Level ≈ $3 \cdot 10^{22}$ Mx



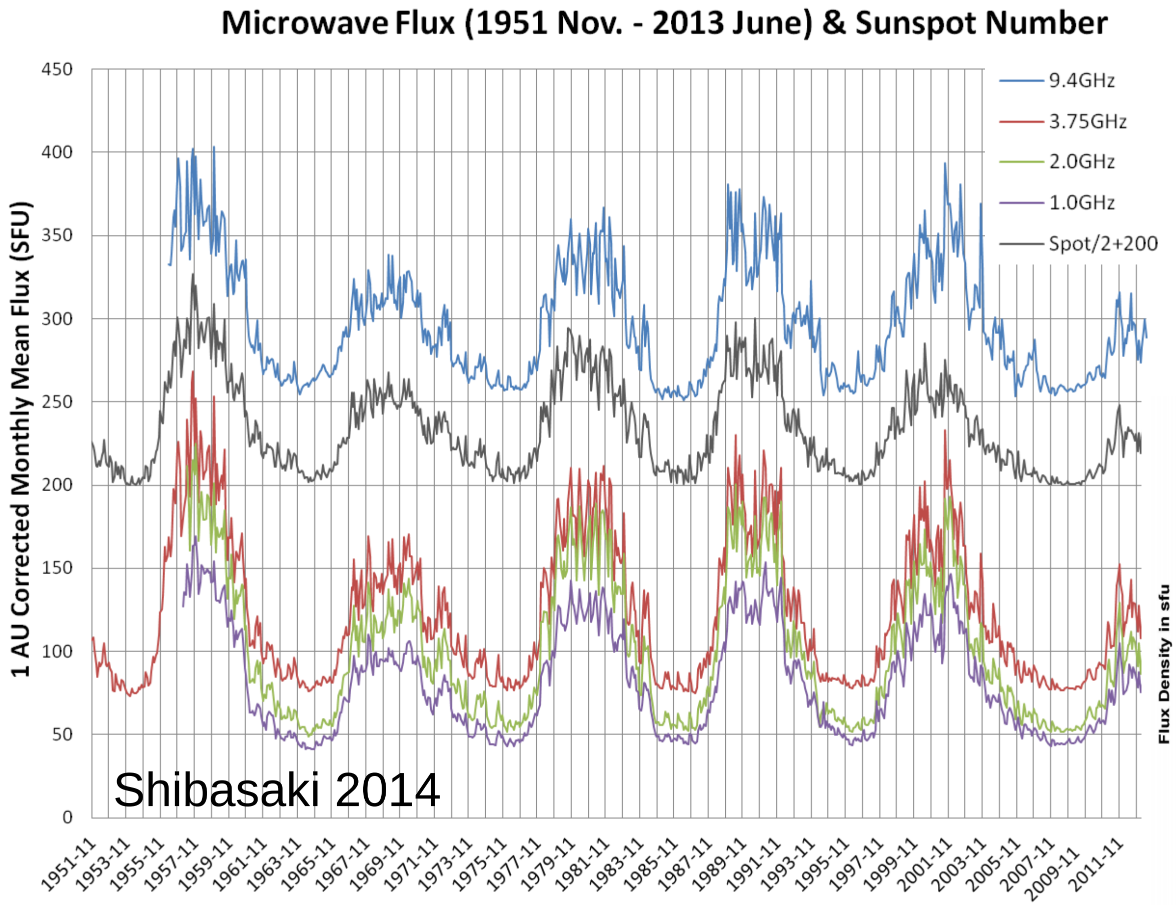
At minimum $6 \cdot 10^{22}$ Mx or 4 G avg.

above noise level

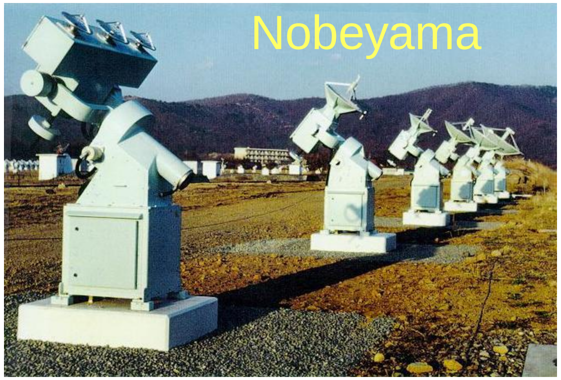
Basal Level

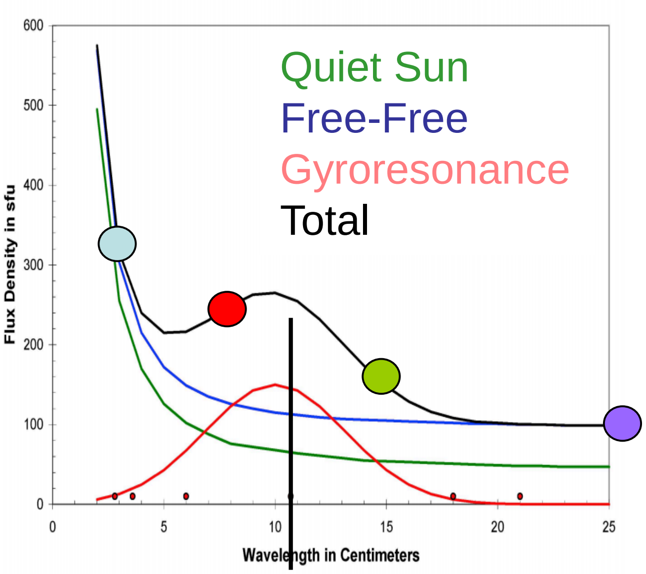
There is a ‘basal’ level at solar minima. Is this the case at every minimum?

The Microwave Flux (Proxy for EUV) Record Extends 70 years in the Past


Microwave Flux (1951 Nov. - 2013 June) & Sunspot Number

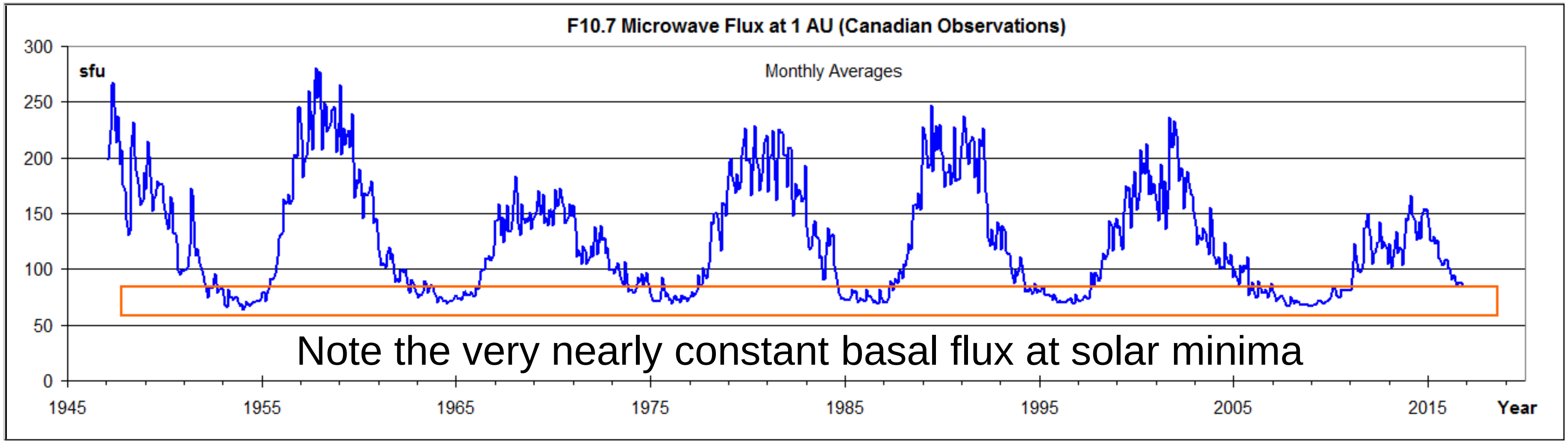
Shibasaki 2014



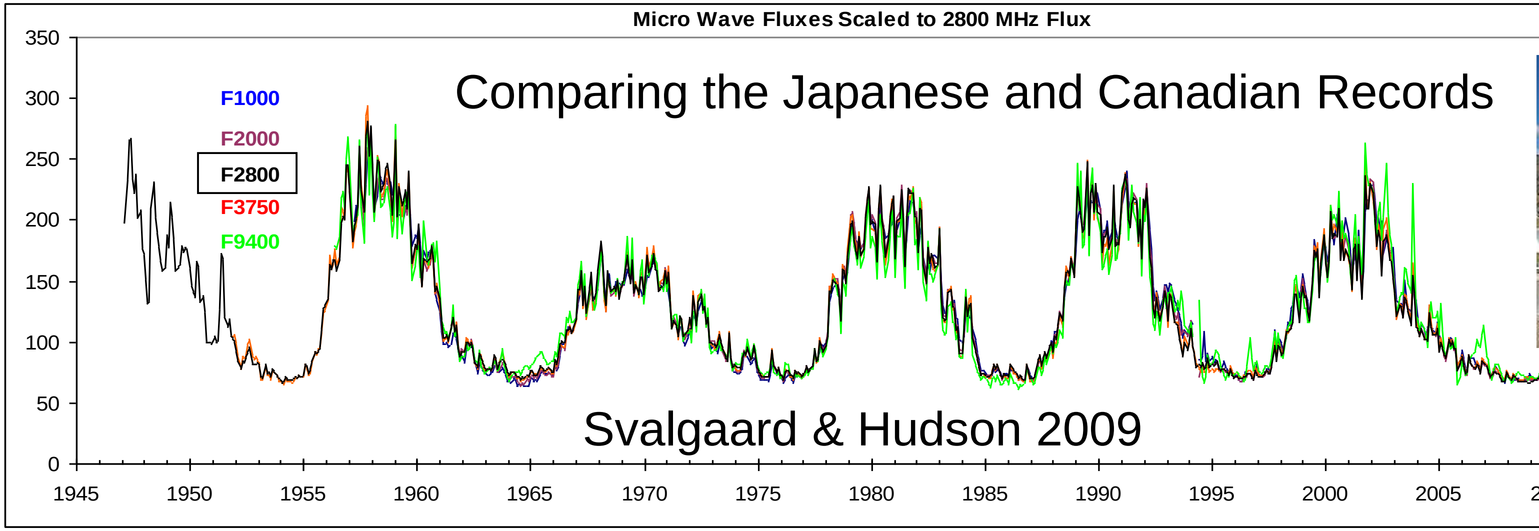


The microwave flux comes from the Transition Region which is threaded by the magnetic field

The Japanese and Canadian Microwave Records agree



Note the very nearly constant basal flux at solar minima

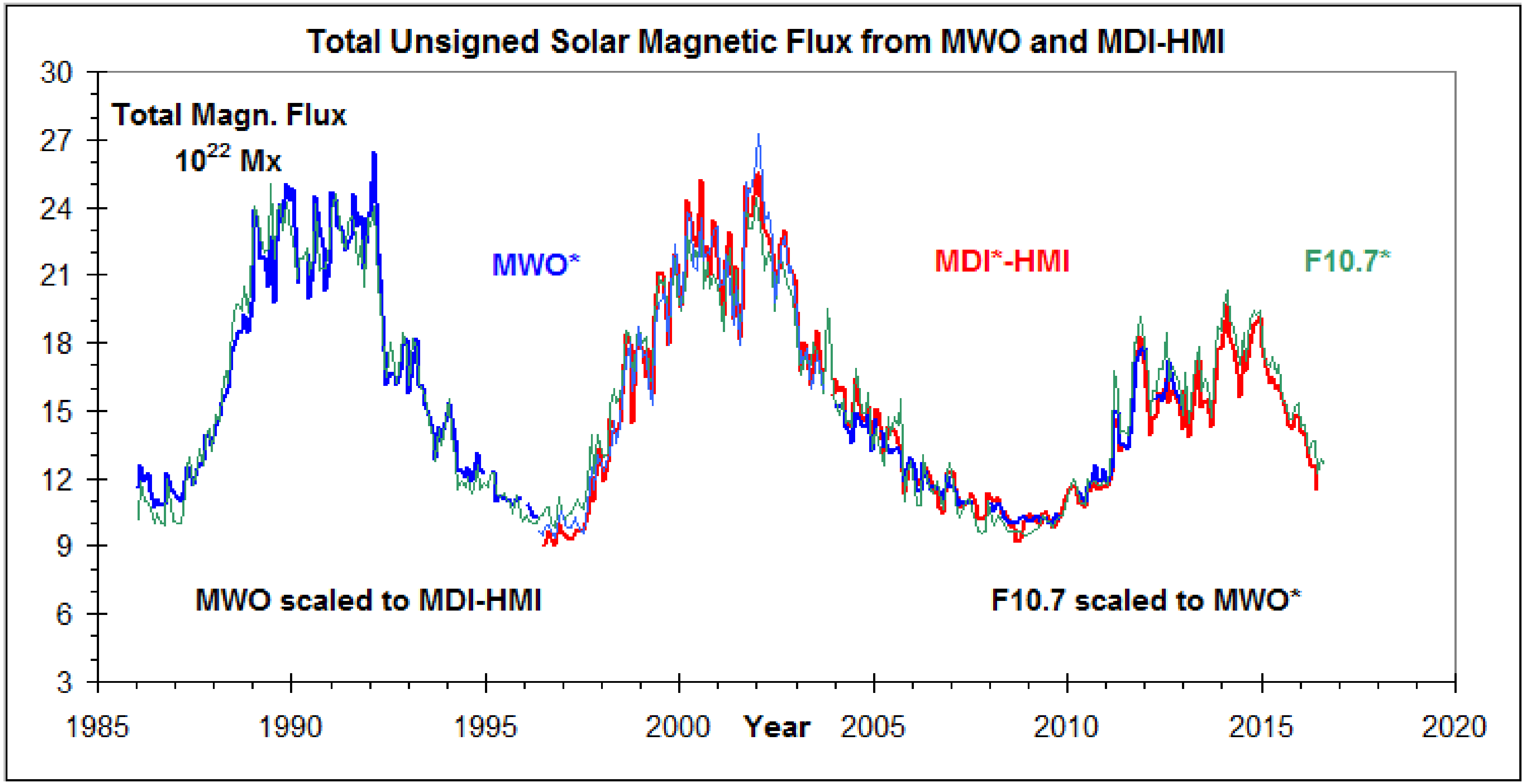


Comparing the Japanese and Canadian Records

Svalgaard & Hudson 2009

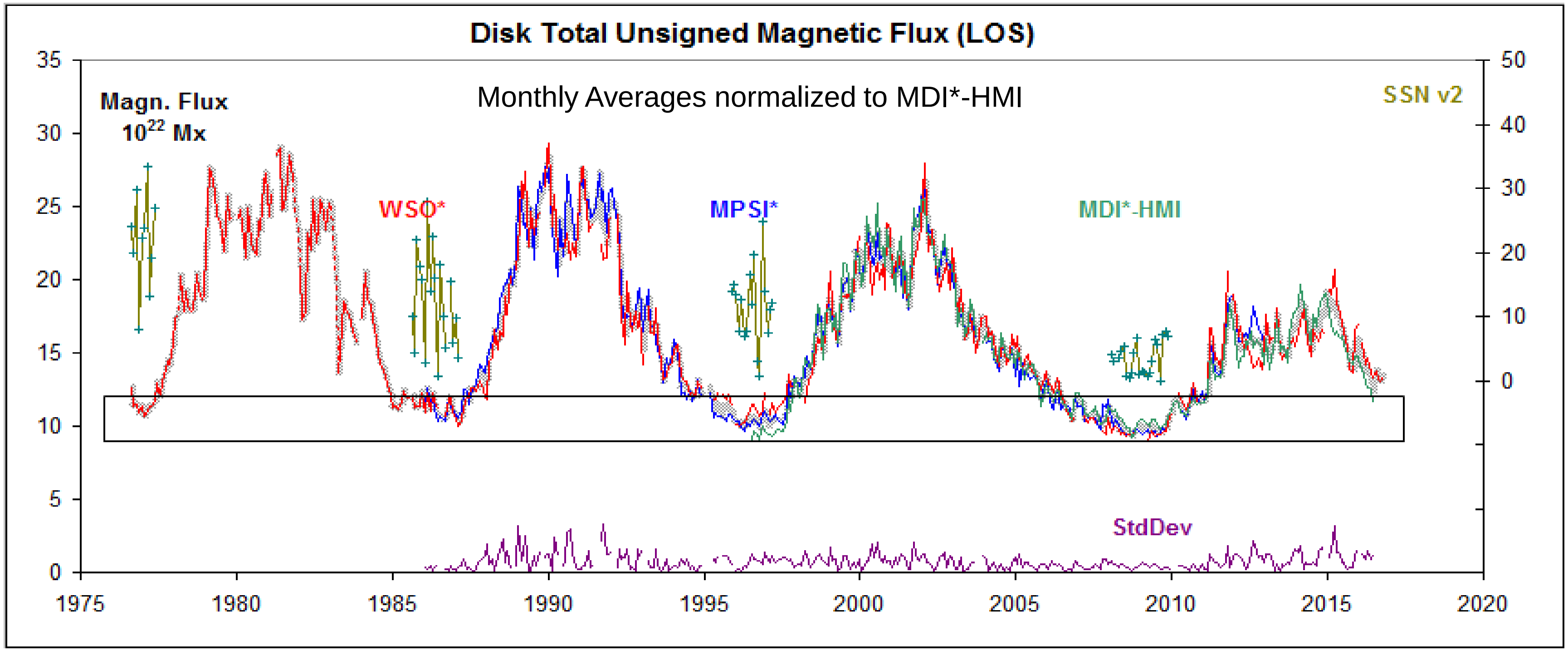
Penticton, BC

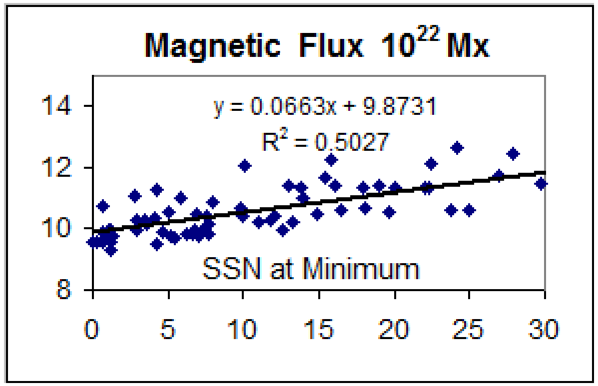
Magnetic Flux from MWO Tracks MDI-HMI and the F10.7 Flux



MWO magnetic flux from digital magnetograms can be put on the MDI-HMI scale and, just as MDI-HMI, tracks the F10.7 flux very well.

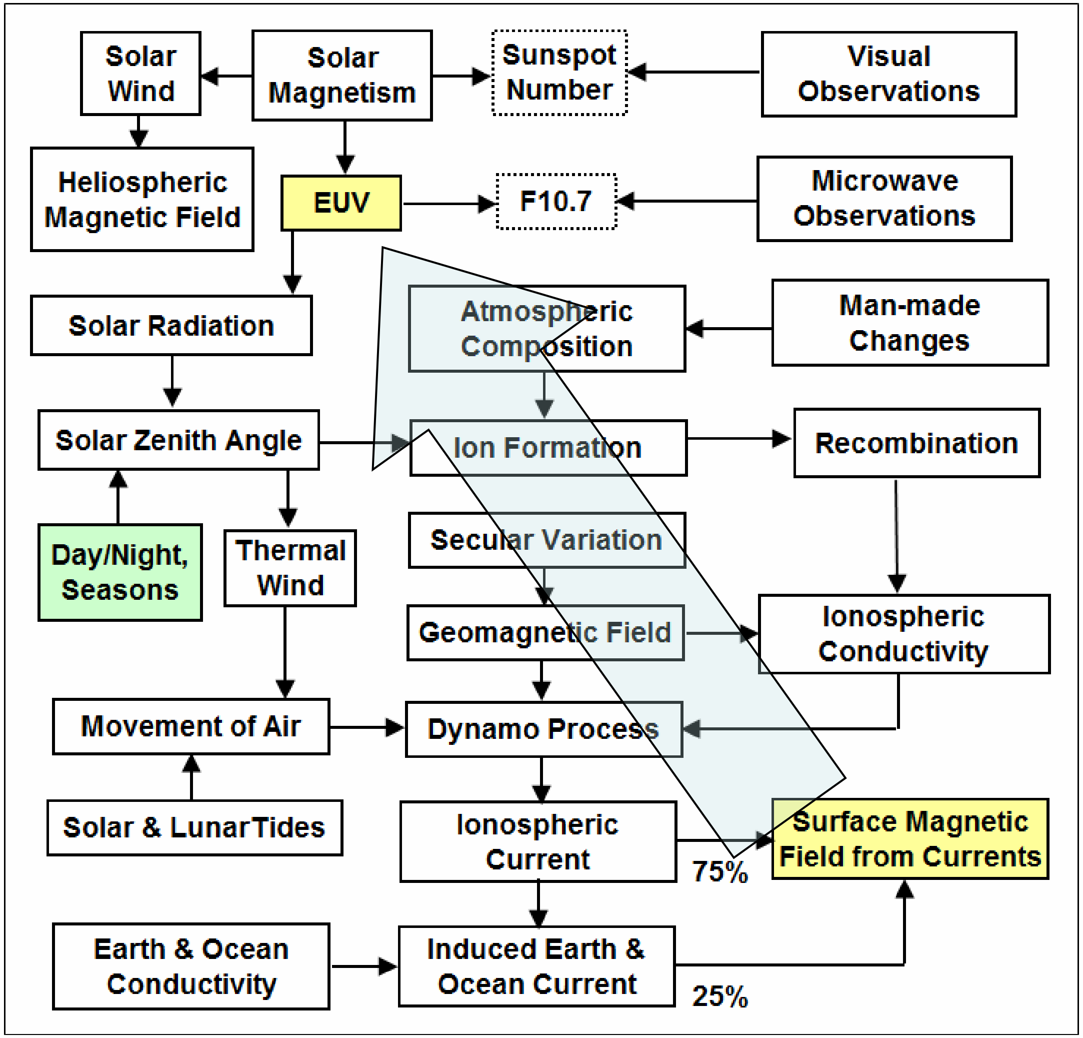
Magnetic Flux back to 1976





The Wilcox Solar Observatory and the Mount Wilson Observatory give us a longer baseline. A very slight decrease with time of the flux at solar minimum is probably due to the effect of decreasing residual sunspot number [if not instrumental]

Determining EUV Flux from Geomagnetism (Graham, 1722)



Solar Wind

Solar Magnetism

Sunspot Number

Visual Observations

Heliospheric Magnetic Field

EUV

F10.7

Microwave Observations

Solar Radiation

Atmospheric Composition

Man-made Changes

Solar Zenith Angle

Ion Formation

Recombination

Day/Night, Seasons

Thermal Wind

Secular Variation

Geomagnetic Field

Ionospheric Conductivity

Movement of Air

Dynamo Process

Solar & LunarTides

Ionospheric Current

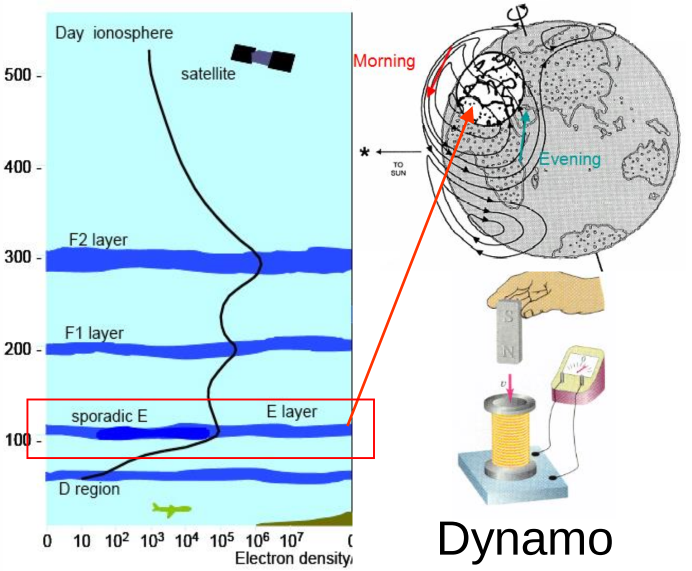
75%

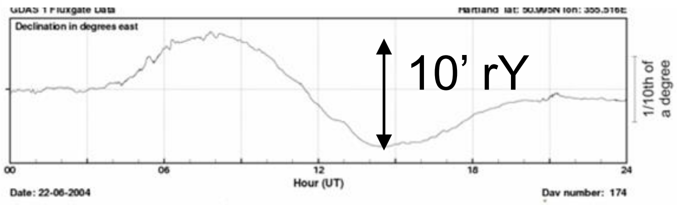
Surface Magnetic Field from Currents

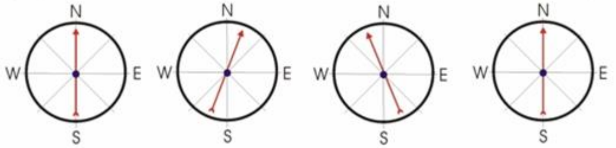
Earth & Ocean Conductivity

Induced Earth & Ocean Current

25%







The effect is in the East [the Y] Component: rY

Electron Density due to EUV

< 102.7 nm

$$O_2 + h\nu \xrightarrow{J} O_2^+ + e^-$$

$$O_2^+ + e^- \xrightarrow{\alpha} O + O$$

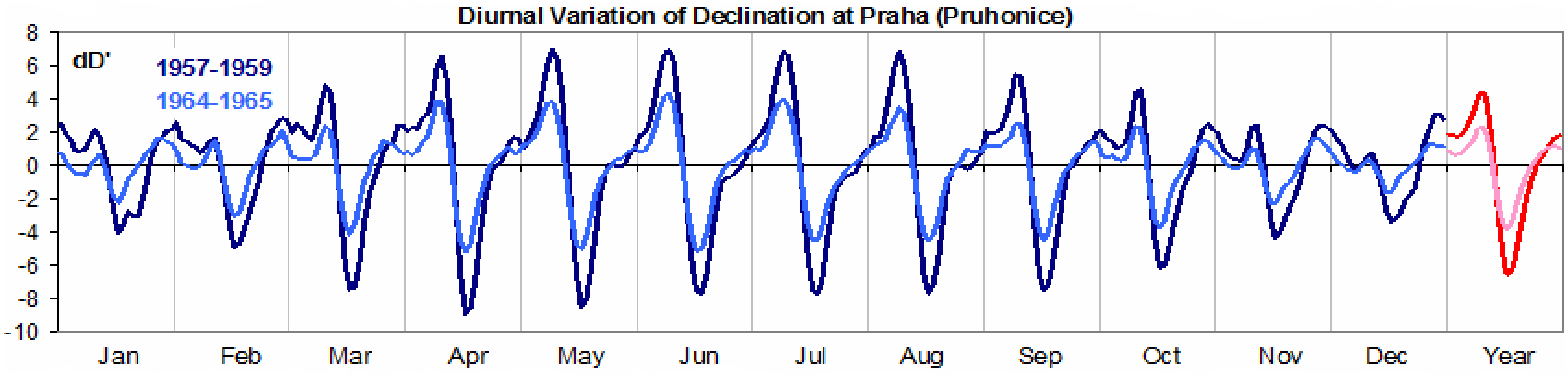
The conductivity at a given height is proportional to the electron number density N_e. In the dynamo region the ionospheric plasma is largely in photochemical equilibrium. The dominant plasma species is O^+_2, which is produced by photo ionization at a rate J (s^{-1}) and lost through recombination with electrons at a rate α (s^{-1}), producing the Airglow.

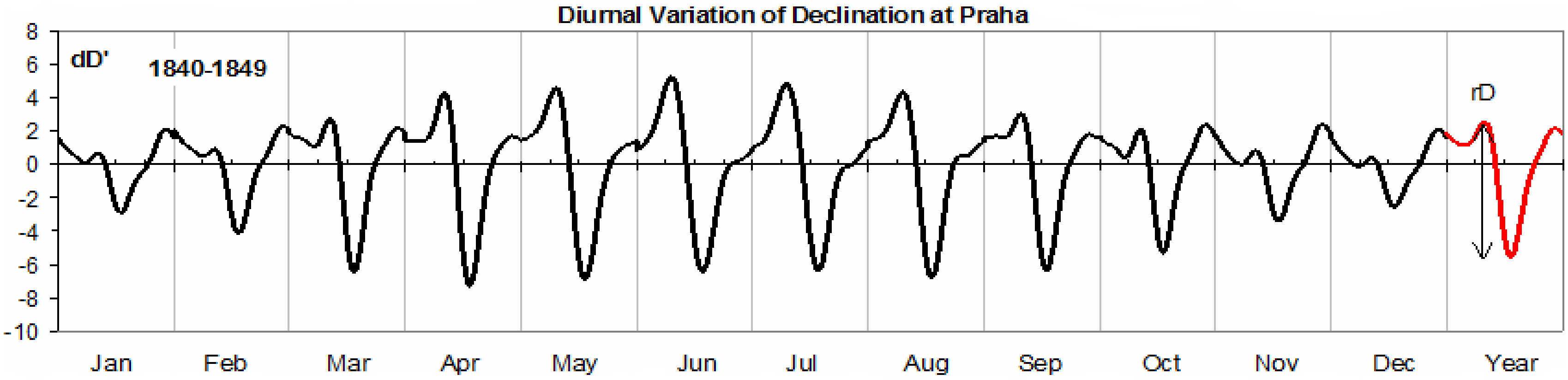
The rate of change of the number of ions N_i, dN_i/dt and in the number of electrons N_e, dN_e/dt are given by $dN_i/dt = J \cos(\chi) - \alpha\, N_i\, N_e$ and $dN_e/dt = J \cos(\chi) - \alpha\, N_e\, N_i$. Because the Zenith angle χ changes slowly we have a quasi steady-state, in which there is no net electric charge, so $N_i = N_e = N$. In a steady-state $dN/dt = 0$, so the equations can be written $0 = J \cos(\chi) - \alpha\, N^2$, and so finally

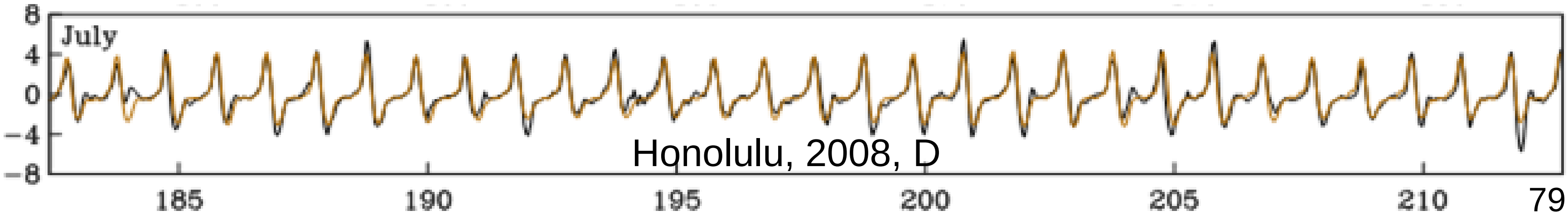
$$N = \sqrt{(J\, \alpha^{-1} \cos(\chi))}$$

Since the conductivity, Σ, depends on the number of electrons N, we expect that Σ scales with the square root $\sqrt{(\boldsymbol{J})}$ of the overhead EUV flux with λ < 102.7 nm.

The Diurnal Variation [rY=H cos(D) rD]


Diurnal Variation of Declination at Praha (Pruhonice)

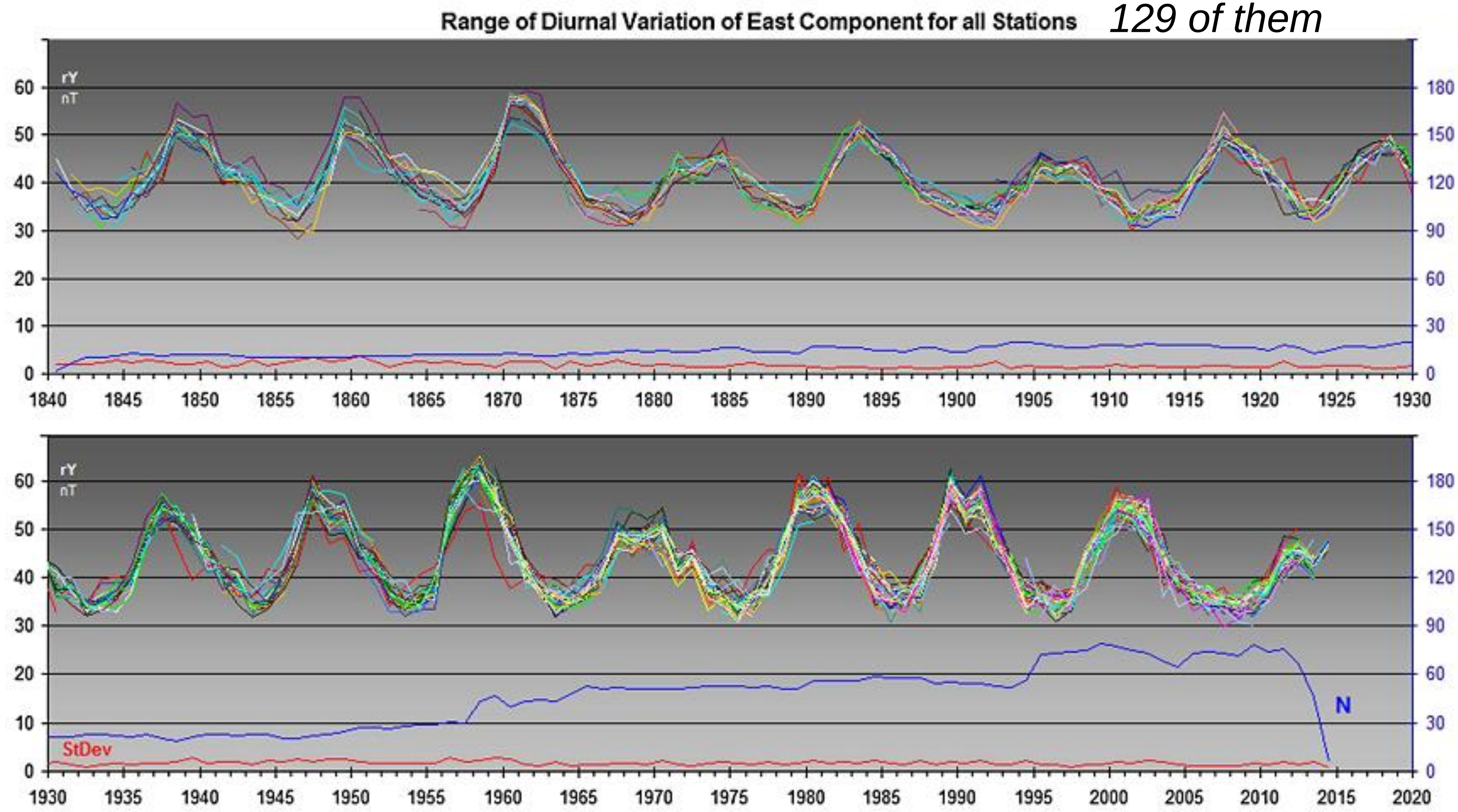

Diurnal Variation of Declination at Praha



Honolulu, 2008, D

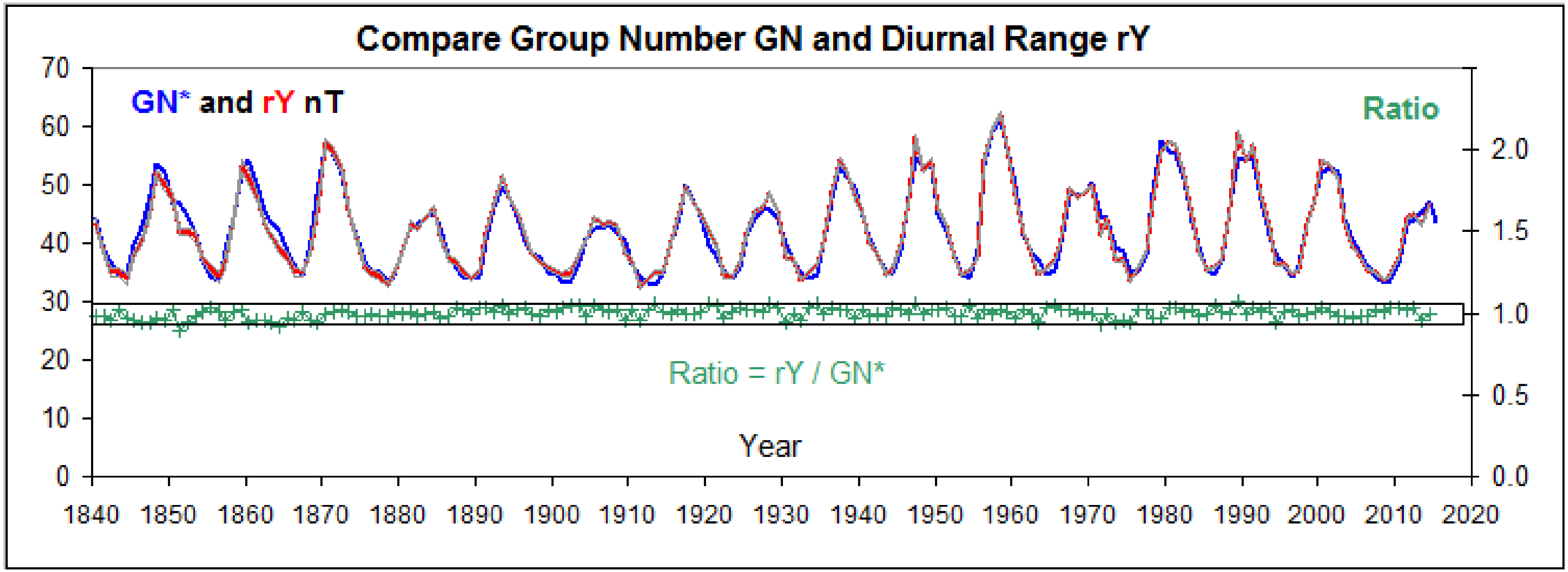
Observed Diurnal Ranges of the Geomagnetic East Component since 1840

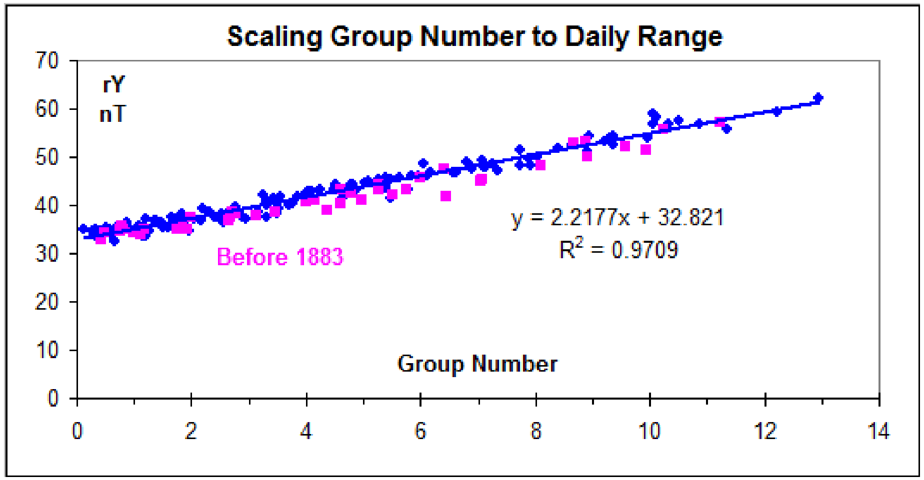
129 of them



We plot the yearly average range to remove the effect of changing solar zenith angle through the seasons. A slight normalization for latitude and underground conductivity has been performed. The blue curve shows the number of stations

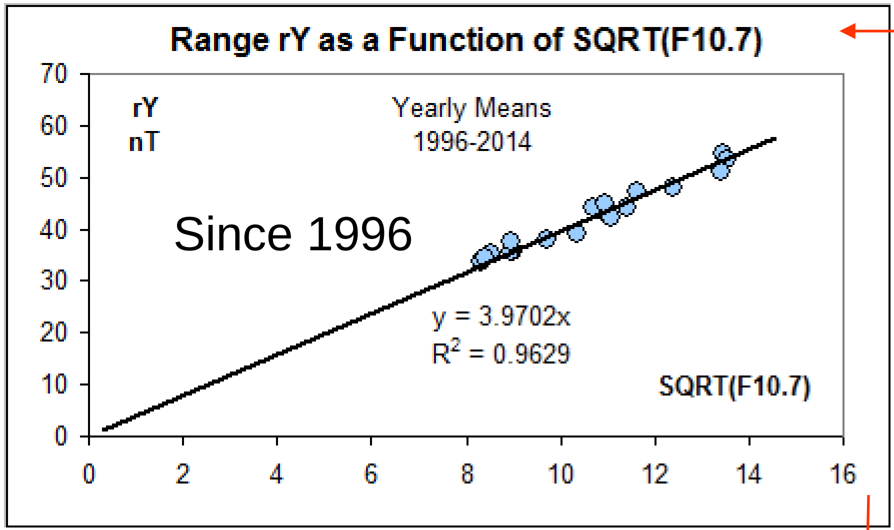
The Range (Amplitude) of the Daily Variation Matches that of the Scaled Group Numbers



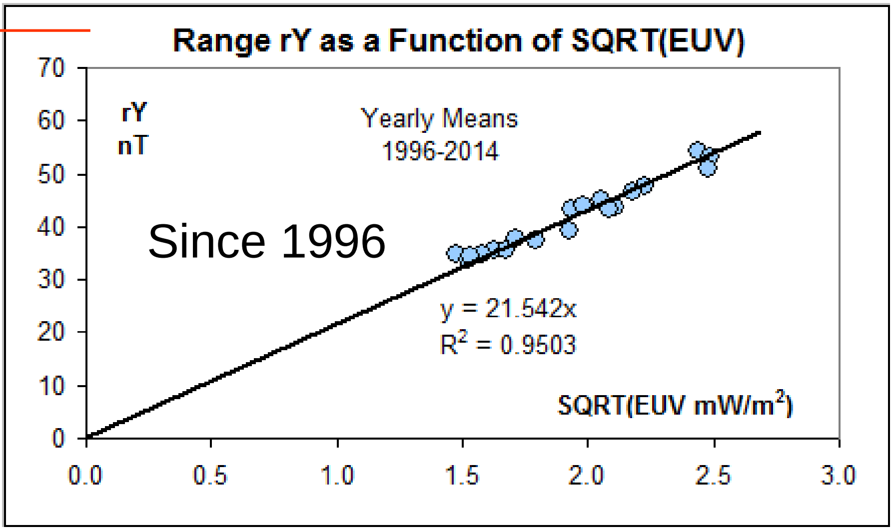


There is a good **linear** relationship between the Daily Range, rY, and the Group Number, GN, allowing us the scale GN to rY. The relationship is not different before [pink squares] and after 1883 [blue dots]. The ratio rY/GN* [green] is unity throughout.

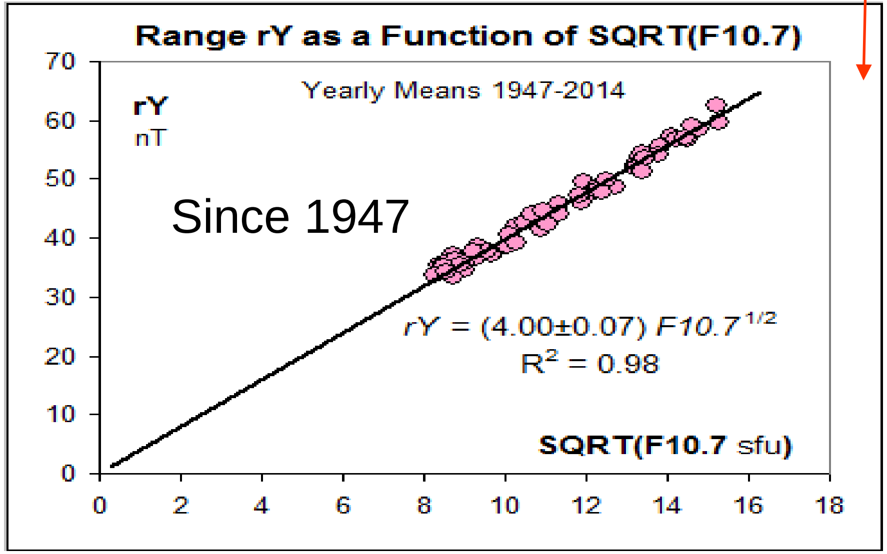
Theory tells us that the conductivity [and thus rY] should vary as the square root of the EUV [and F10.7] flux, and so it does:


Range rY as a Function of SQRT(F10.7)

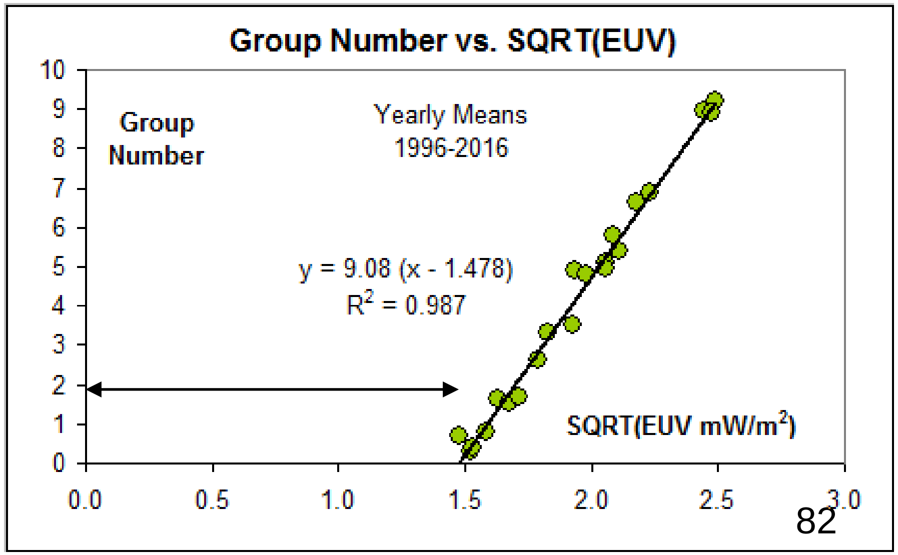
Since 1996


Range rY as a Function of SQRT(EUV)

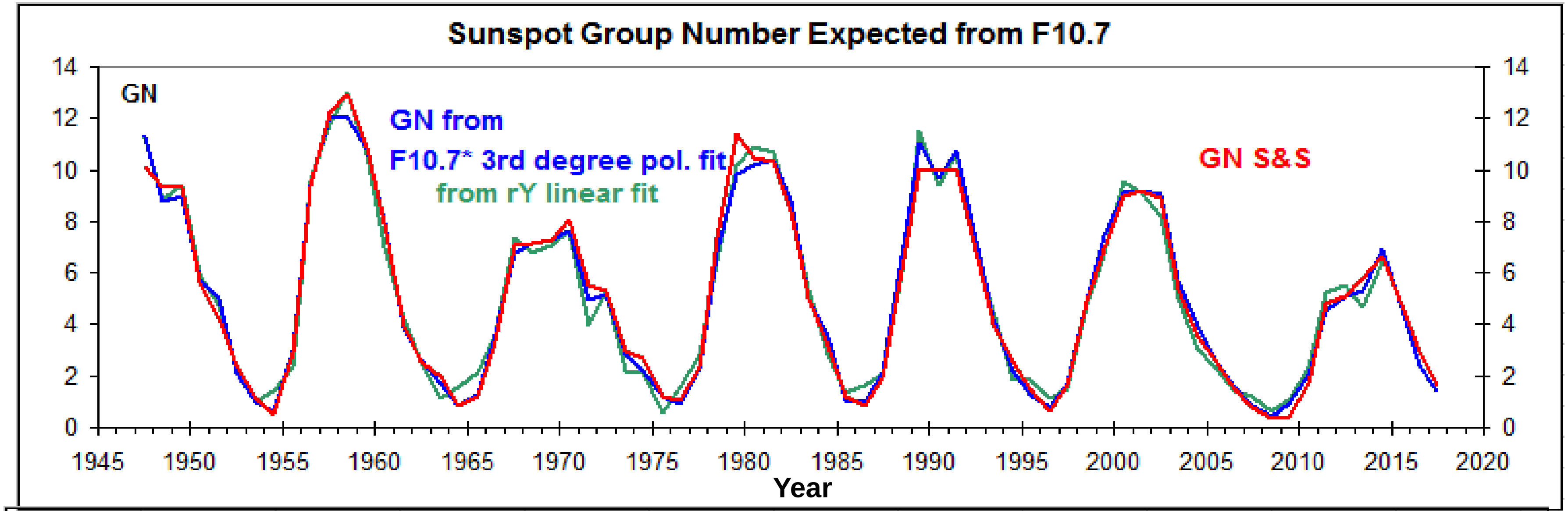
Since 1996

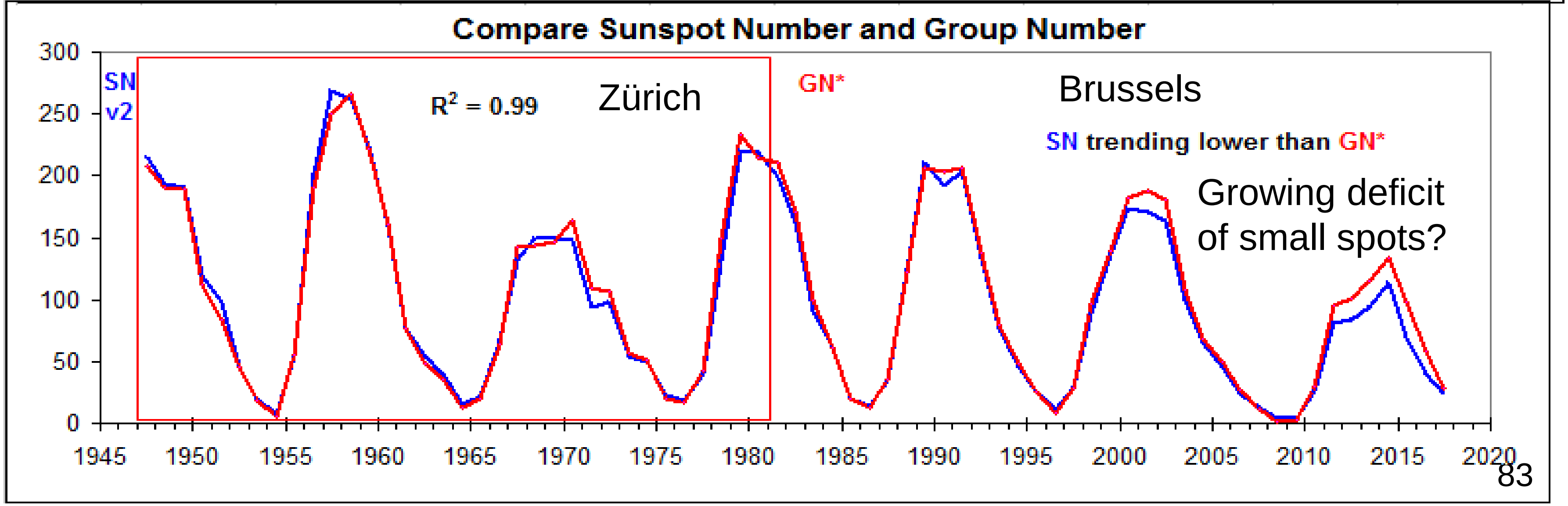

Range rY as a Function of SQRT(F10.7)

Since 1947


Group Number vs. SQRT(EUV)

The Group Number is a Better Fit to F10.7 and rY than the Relative Sunspot Number


Sunspot Group Number Expected from F10.7


Compare Sunspot Number and Group Number

R² = 0.99

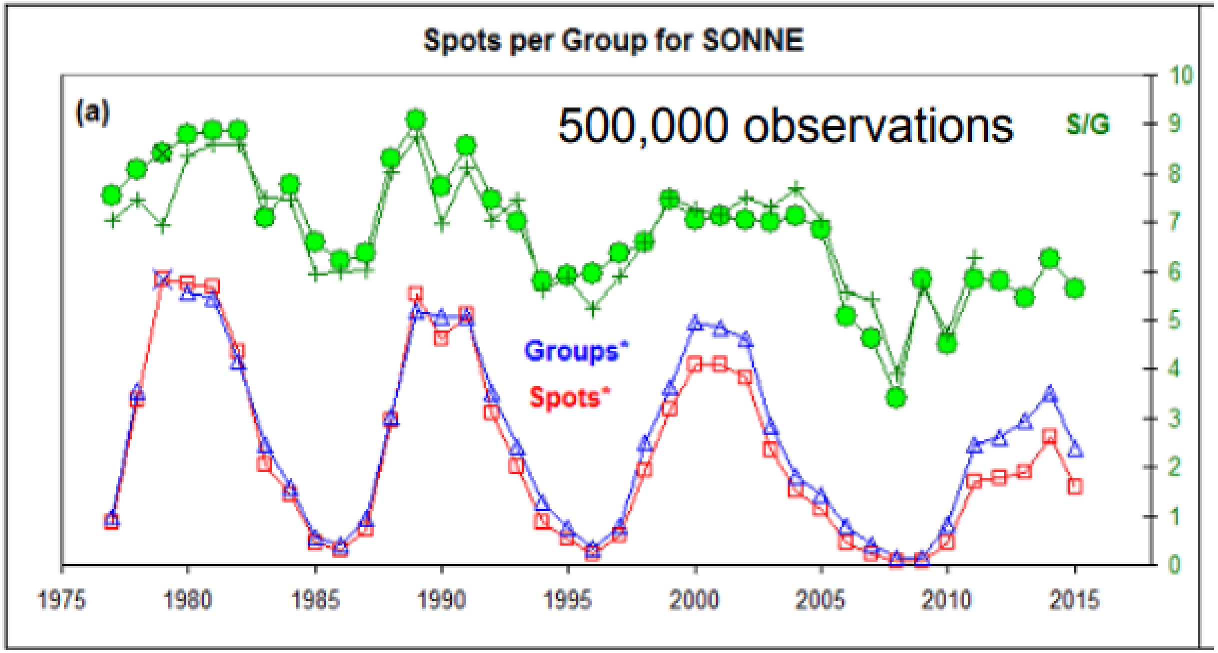
Zürich

Brussels

SN trending lower than GN*

Growing deficit of small spots?

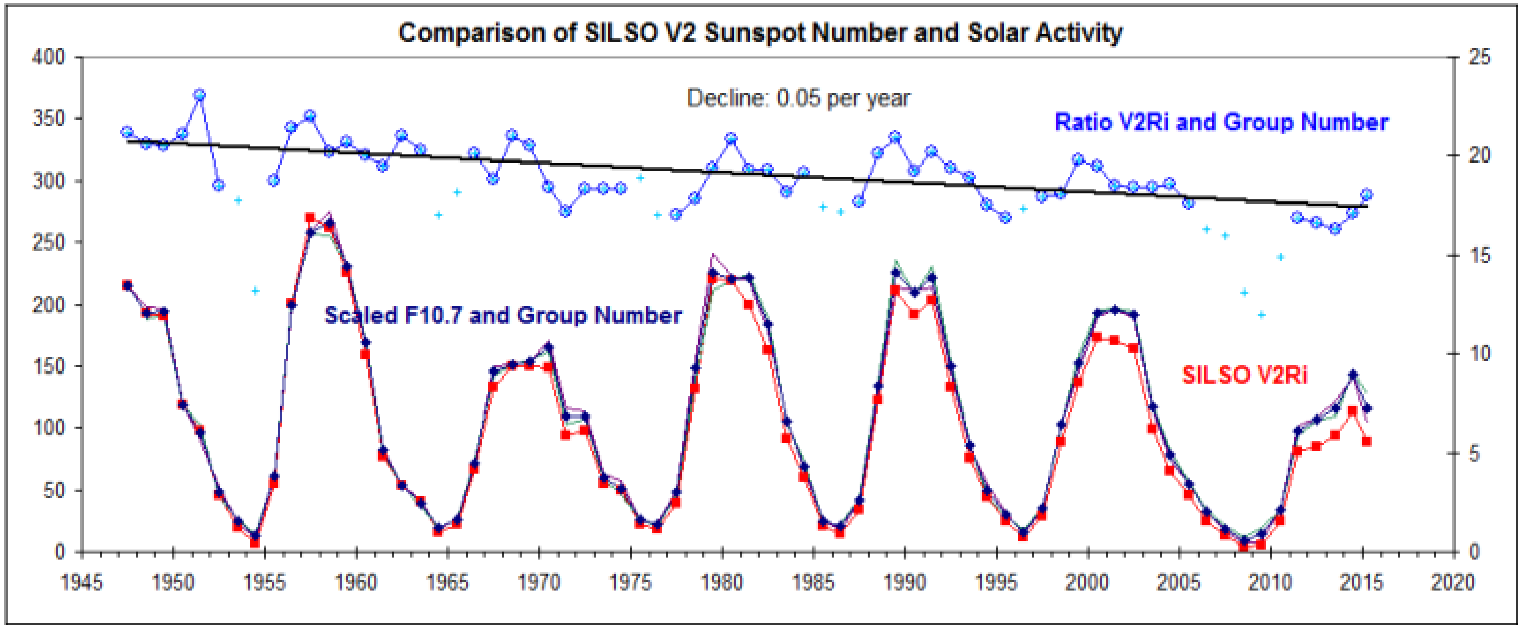
Perhaps we should predict F10.7 or the GN, not the SN…



The Number of Spots per Group is Decreasing

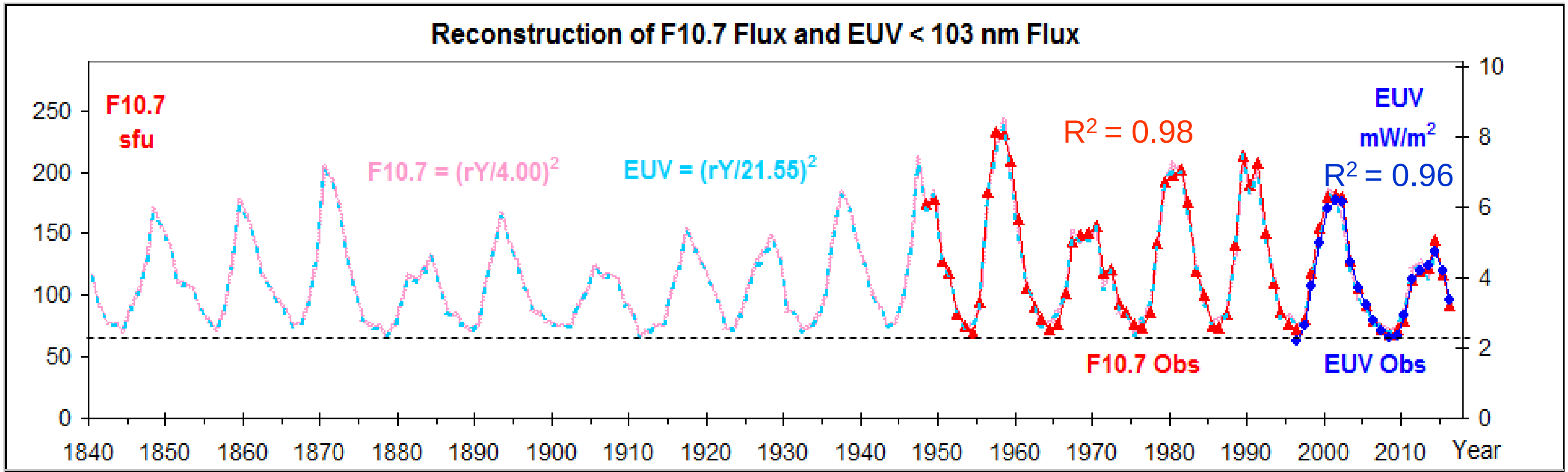
So using a constant (i.e. 10) weight for groups in Wolf's definition of the Relative Sunspot Number SN = k (10 G + S) is now problematic.

Good reason to prefer F10.7 as a measure of solar activity.

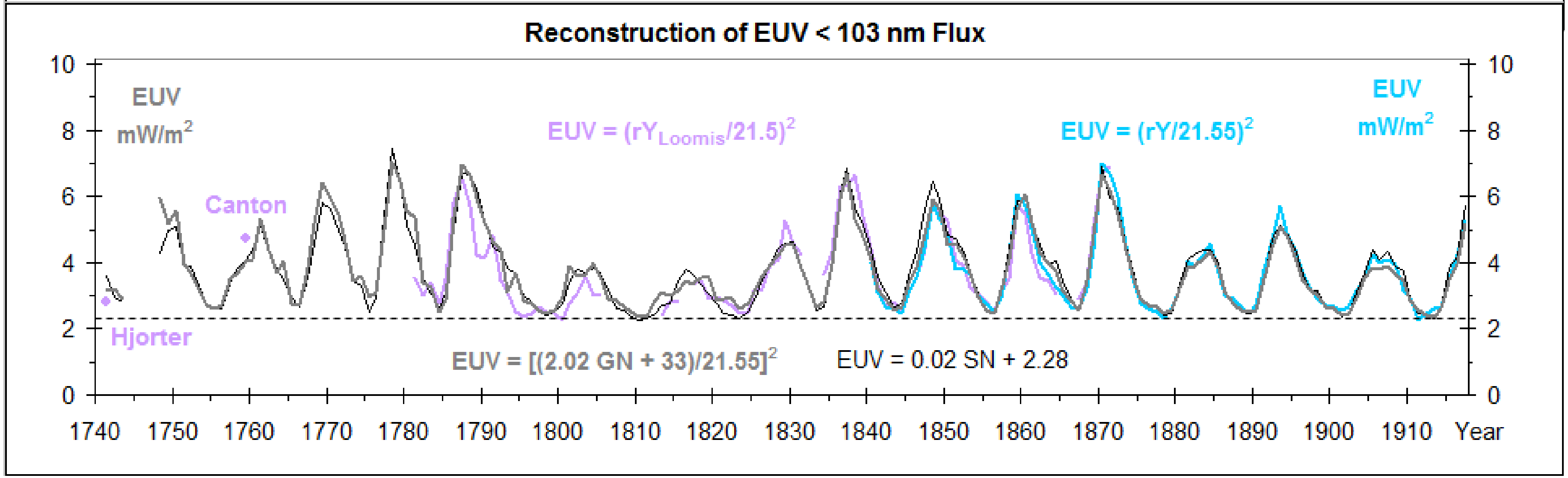


We should not stop counting sunspots. In future we should keep track of the Groups, G, and Spots, S, separately.

Reconstructions of EUV and F10.7



Reconstruction of F10.7 Flux and EUV < 103 nm Flux



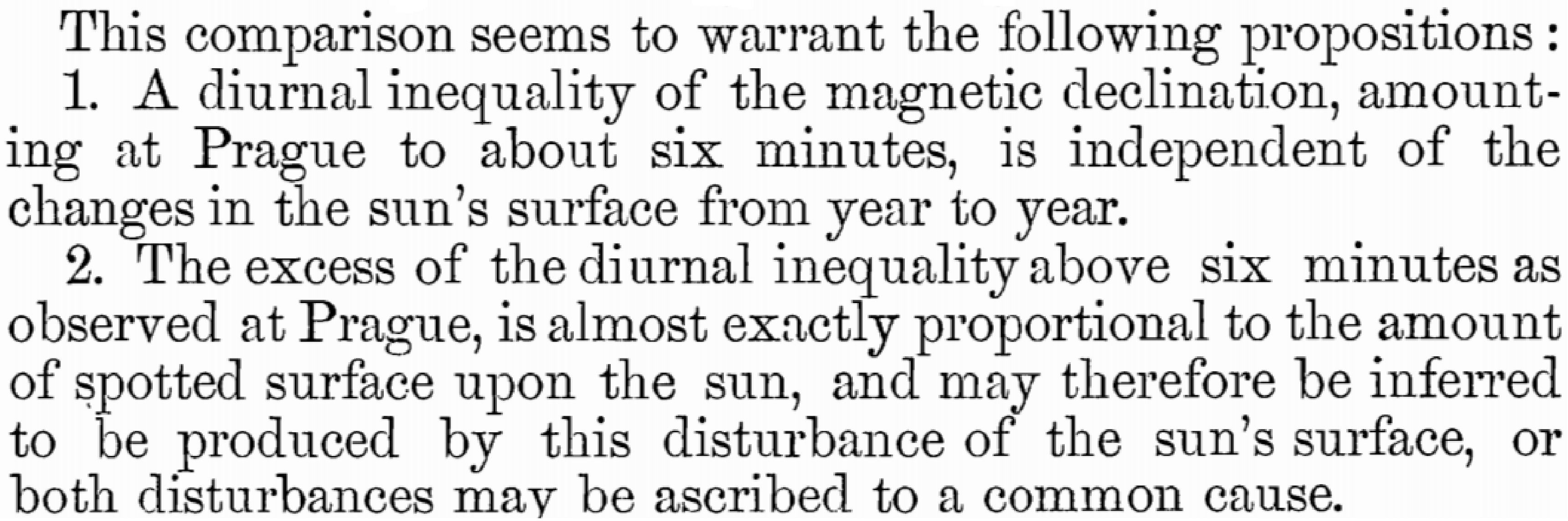
Reconstruction of EUV < 103 nm Flux

Note the constant basal level at *every* solar minimum

This Observational **Fact** is Not New

THE AMERICAN JOURNAL OF SCIENCE AND ARTS. Second Series

ART. XVI.-Comparison of the mean daily range of the Magnetic Declination, with the number of Auroras observed each year, and the extent of the black Spots on the surface of the Sun, by ELIAS LOOMIS, Professor of Natural Philosophy in Yale College. Vol. L, No.149. Sept.1870, pg 160.



This comparison seems to warrant the following propositions:

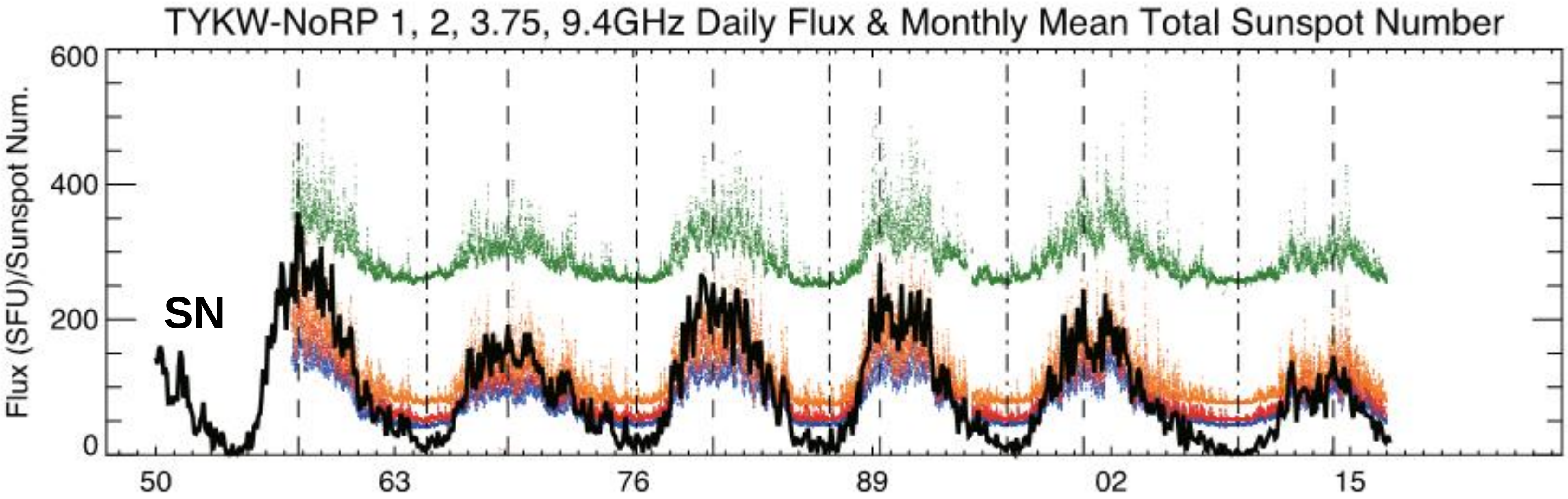
1. A diurnal inequality of the magnetic declination, amounting at Prague to about six minutes, is independent of the changes in the sun's surface from year to year.

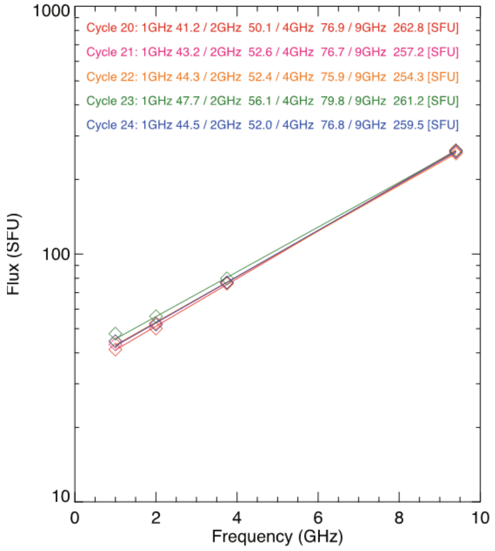
2. The excess of the diurnal inequality above six minutes as observed at Prague, is almost exactly proportional to the amount of spotted surface upon the sun, and may therefore be inferred to be produced by this disturbance of the sun's surface, or both disturbances may be ascribed to a common cause.

19th century 'Inequality' = deviation from [i.e. 'not equal to'] the mean

And is Re-discovered From Time to Time

e.g. Shimojo et al., ApJ 848:62 Oct. 2017, doi.org/10.3847/1538-4357/aa8c75





20

...

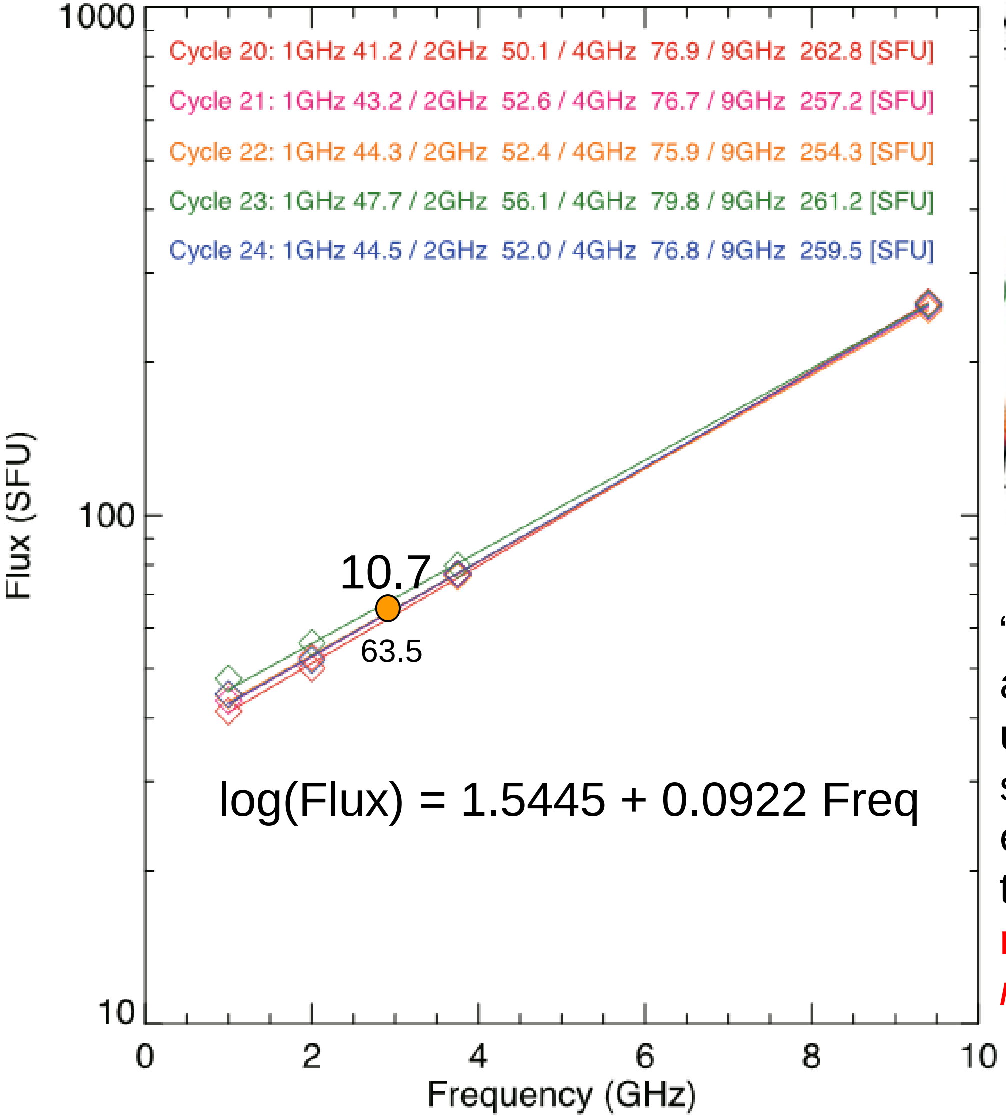
24

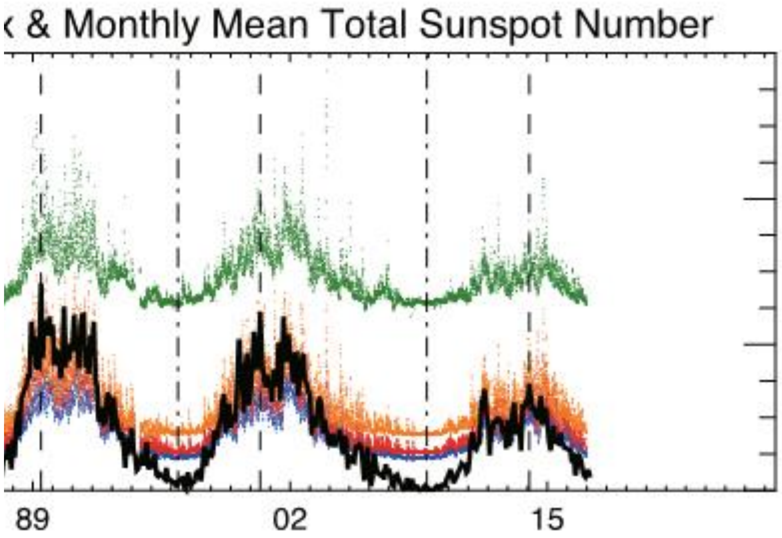
Microwave spectra at solar minima: No variation with time

"Therefore, the results indicate that the average atmospheric structure above the upper chromosphere in the quiet-Sun at solar minima, which may be related to the energy input for atmospheric heating from the sub-photosphere to the corona, has not varied for half a century".

And is Re-discovered From Time to Time

e.g. Shimojo et al., ApJ 848:62 Oct. 2017, doi.org/10.3847/1538-4357/aa8c75

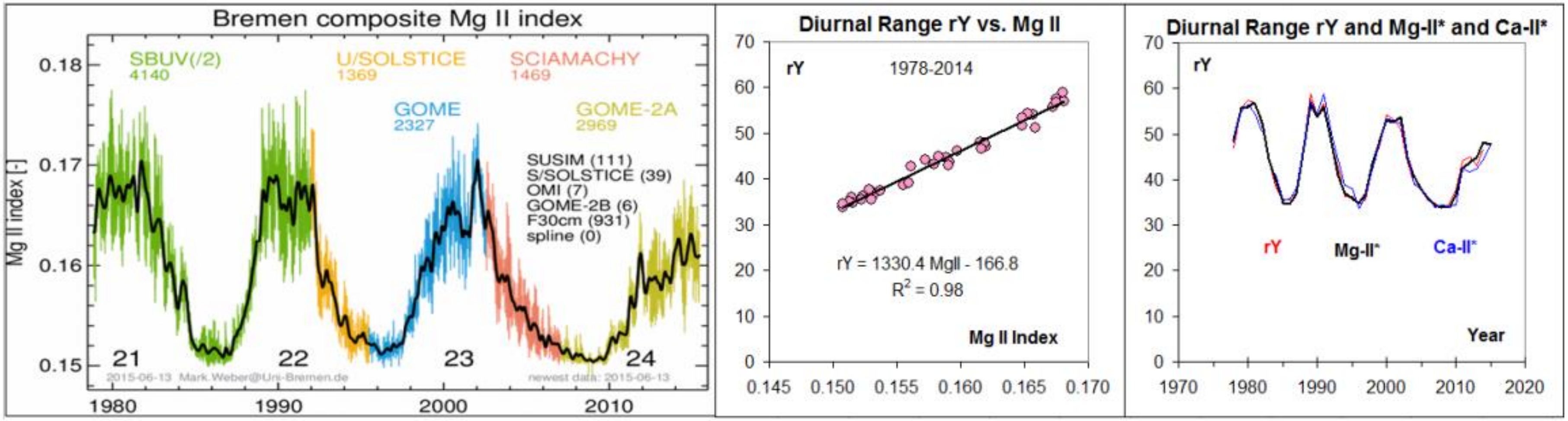




“Therefore, the results indicate that the average atmospheric structure above the upper chromosphere in the quiet-Sun at solar minima, which may be related to the energy input for atmospheric heating from the sub-photosphere to the corona, has not varied for half a century”. *And as we now know not for at least ~280 years*.

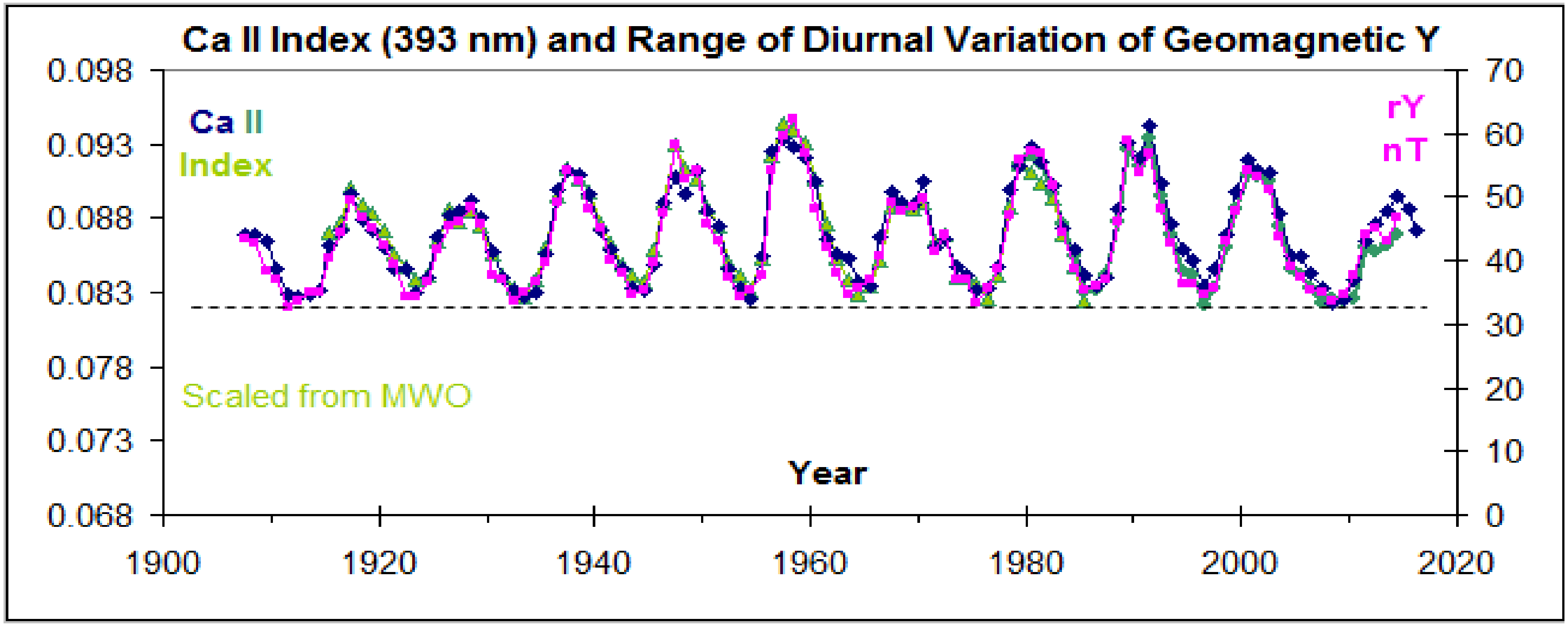
Local dynamo? Probably not…

Solar Irradiance in the UV is Also Reflected in the rY Diurnal Range



The emission core of the Magnesium II doublet (λ = 280 nm) exhibits the largest natural solar irradiance variability above 240 nm. The Mg II doublet is a broad absorption feature with narrow emission peaks in the core. Radiation in the line wings originates in the photosphere and shows much less variability. Therefore, the ratio of line core intensity to wing intensity provides a good estimate of solar variability because the use of an intensity ratio cancels degradation effects. The core-to-wing ratio is frequently used as a proxy for spectral solar irradiance variability from the UV to EUV. The so-called 'Bremen' composite series covering 1978-2015 (Snow et al., 2014) utilizes all available satellite data

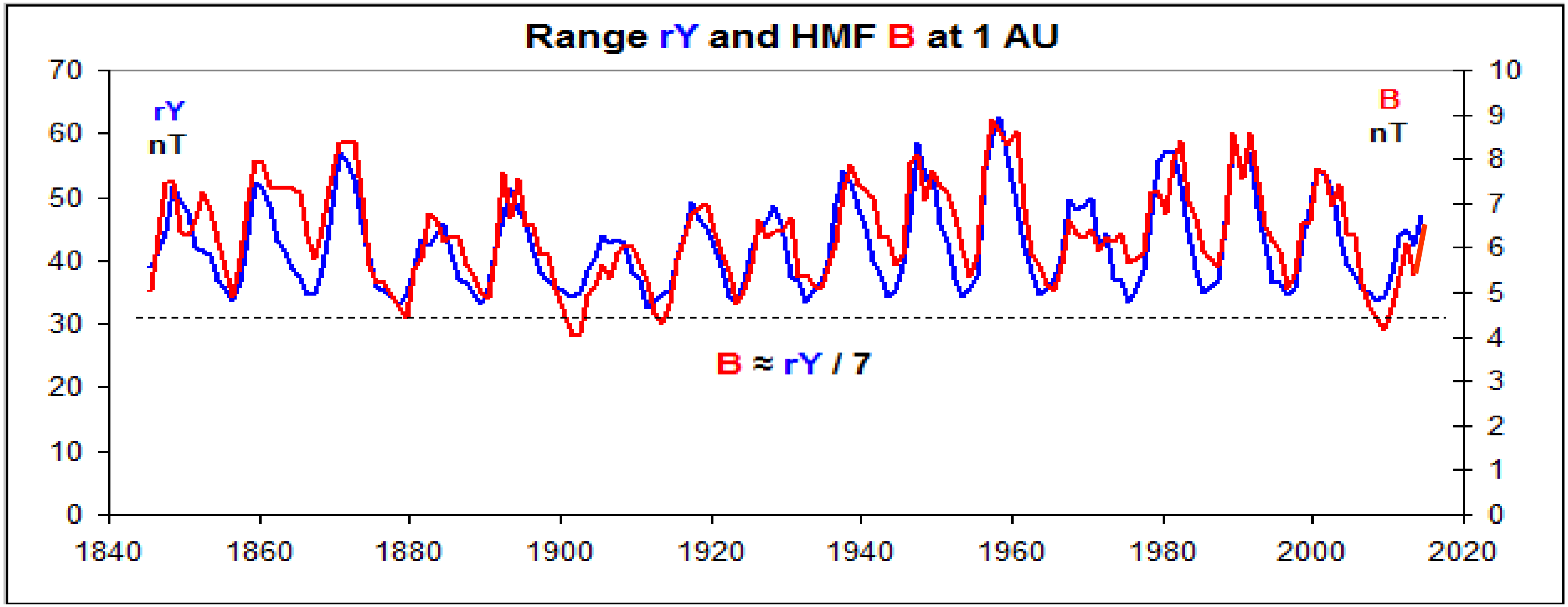
The Ca II Index Shows the Same Basal Floor at Minima as rY and EUV



The long-term **Ca** II Index is constructed from Kodaikanal, Sacramento Peak, and SOLIS/ISS data [Luca Bertello, NSO]. Data from Mount Wilson [**Green**] has been scaled to the Kodaikanal series. Calibration of the old spectroheliograms is a difficult and on-going task.

Bottom Line: All our solar indices show that solar activity [magnetic field] is constant at every solar minimum. [except for *tiny* SSN residual variation]

Solar Field and Solar Wind Field



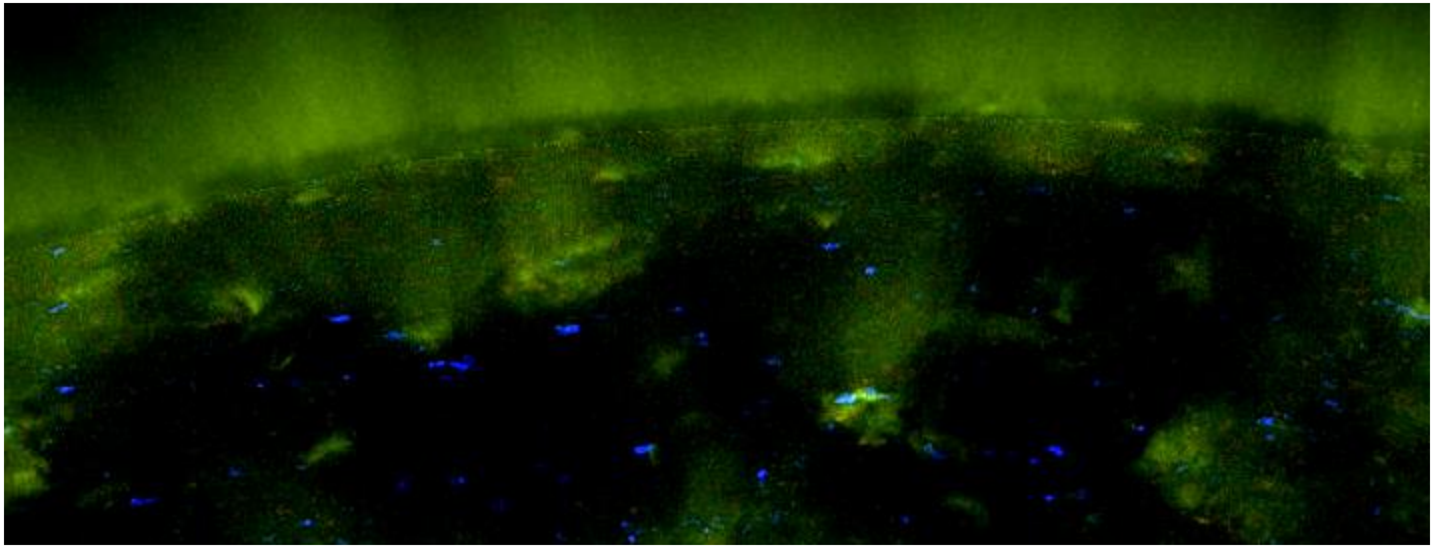
The magnetic field in the solar wind (the Heliosphere) ultimately arises from the magnetic field on the solar surface filtered through the corona, and one would expect an **approximate** relationship between the solar field (EUV and rY) and the Heliospheric field, as observed.

For both proxies we see that there is a constant ‘floor’ upon which the magnetic flux ‘rides’. I see no good reason that the same floor should not be present at all times, even during a Grand Minimum.

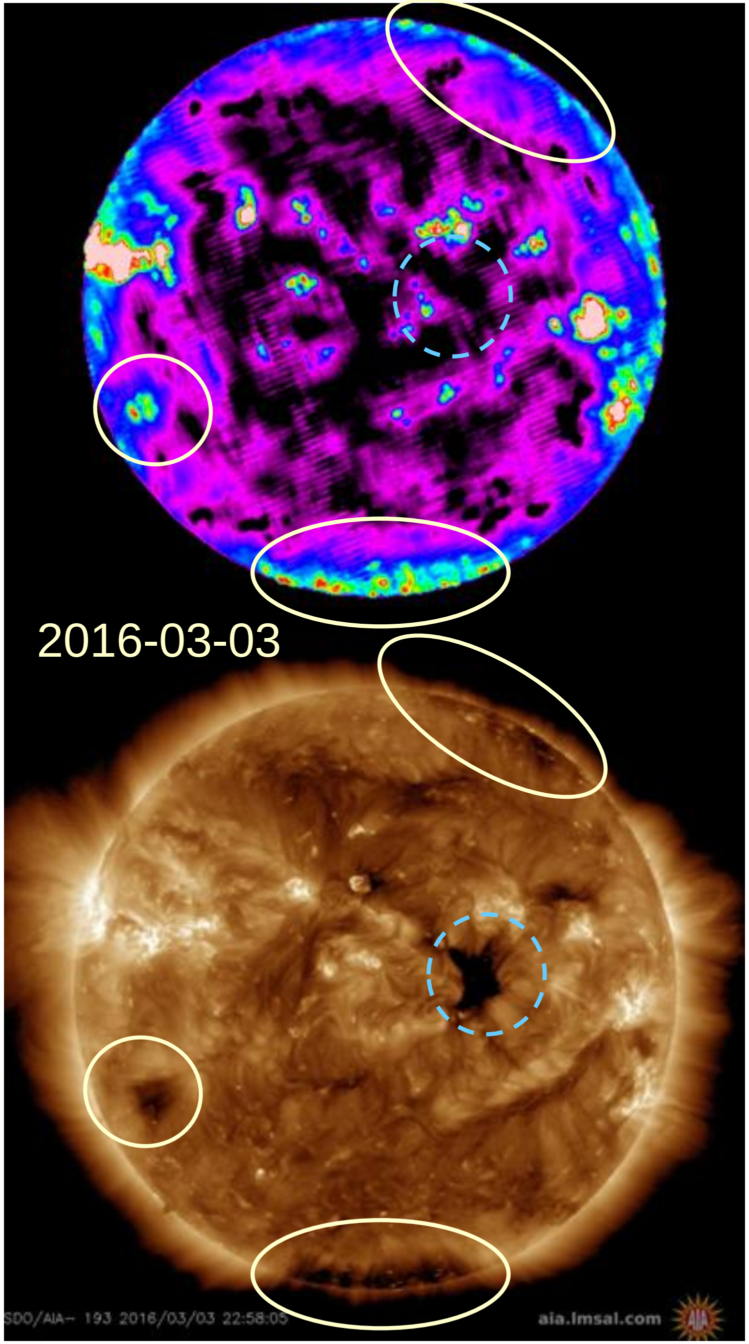
Summary IV (F10.7, EUV, and Magnetic Flux in Time)

- Magnetic LOS Flux from MDI and HMI Match F10.7 Microwave Flux and EUV
- EUV and F10.7 are strictly proportional to the Total Unsigned Magnetic Flux over the Solar Disk
- The Range rY of the Geomagnetic Diurnal Variation follows the Square Root of the F10.7 and EUV fluxes
- UV, EUV, F10.7, and rY [and thus Magnetic Flux] are constant at all solar minima at least back to the 1740s; some 280 years

Fine Structure of the Polar Fields



17 GHz Microwave Chromospheric Emission

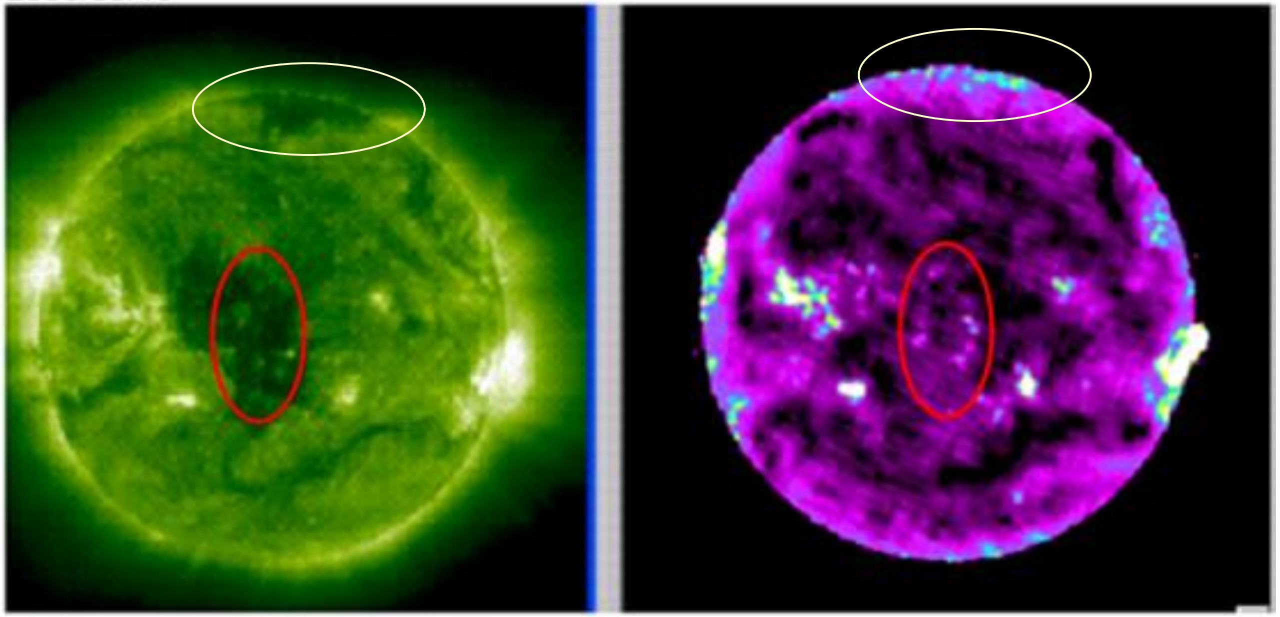


Coronal Holes at the limbs are bright in 17GHz emission mapping out magnetic field elements but are optically thin away from the limb

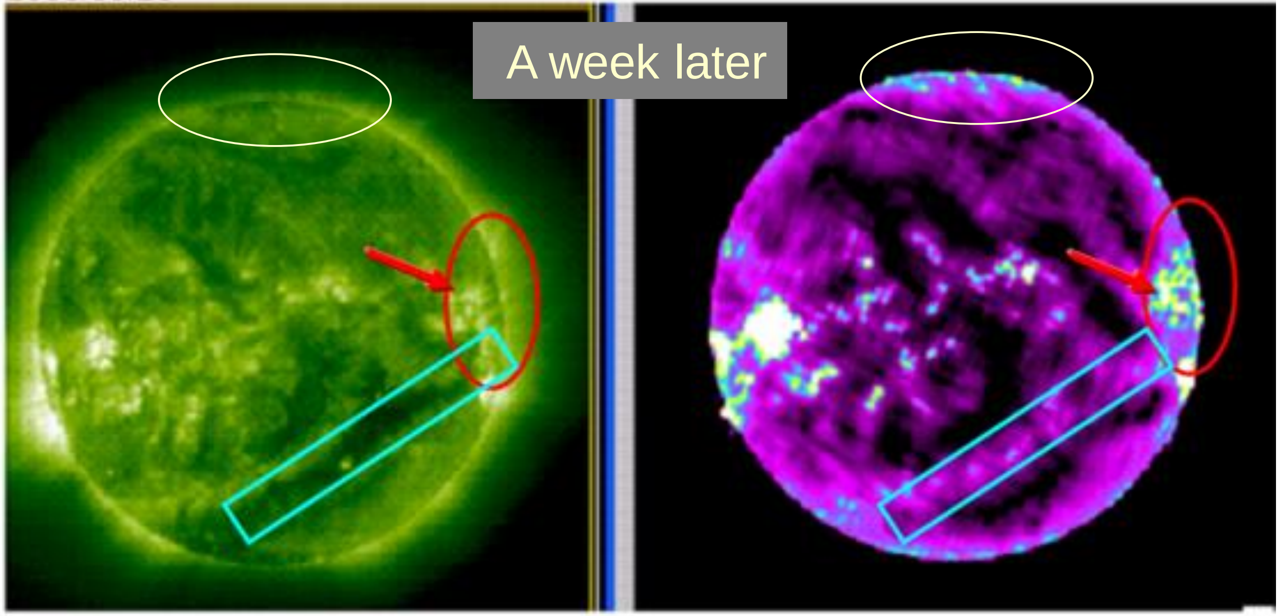
Some More Examples

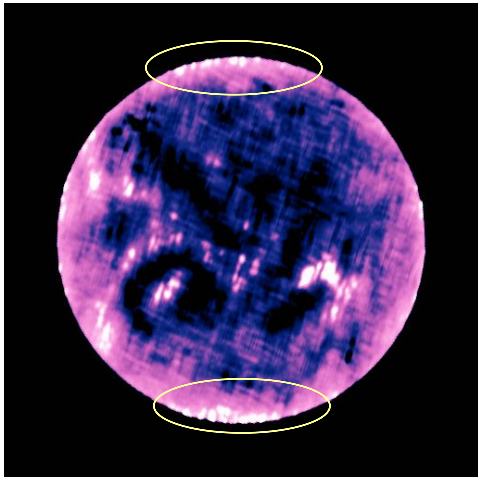
The emission is from optically thin layers (temperature ~10,000K) so on the disk we just see through them. At the limb we integrate along the line of sight and pick up the emission.

2003/09/16



2003/09/23

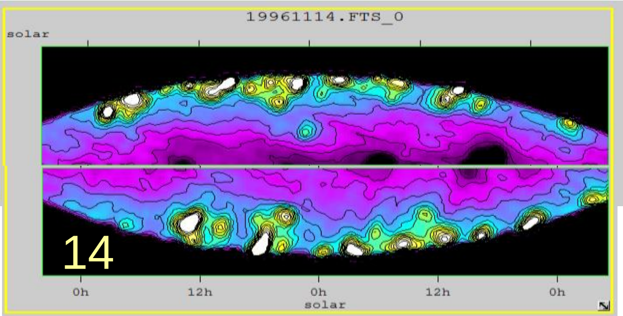


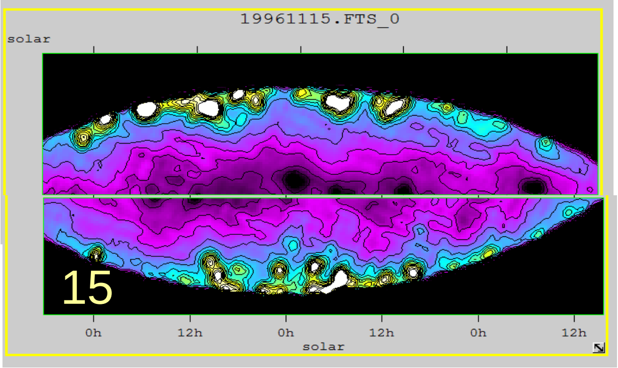


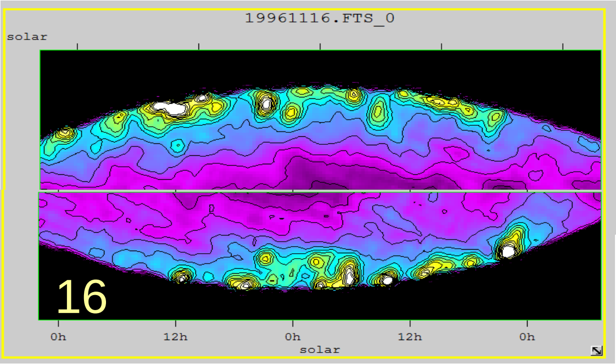
2017-11-22

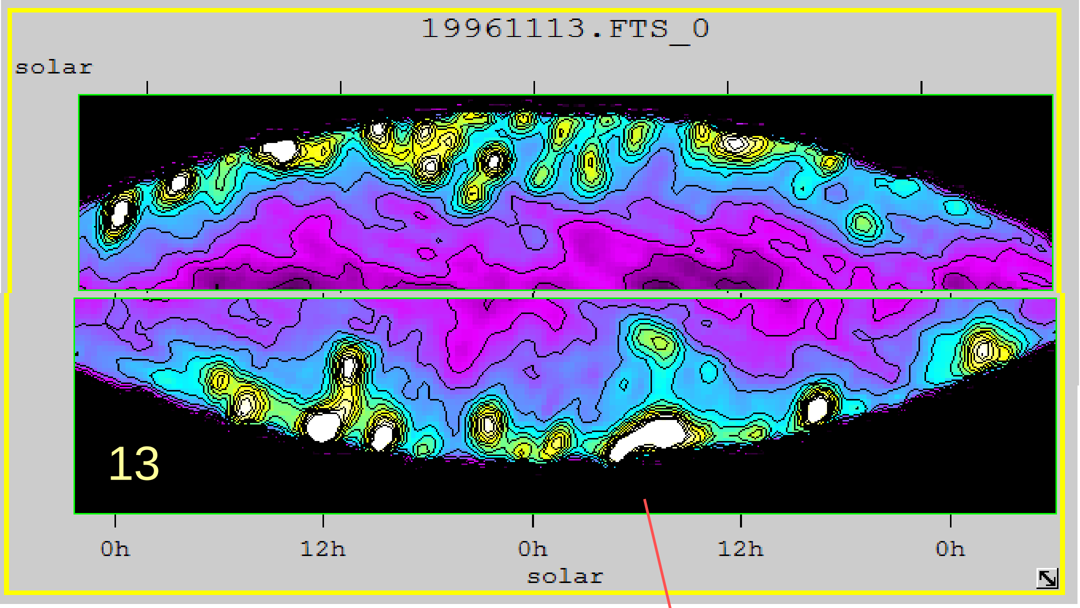
Strong at Solar Minimum

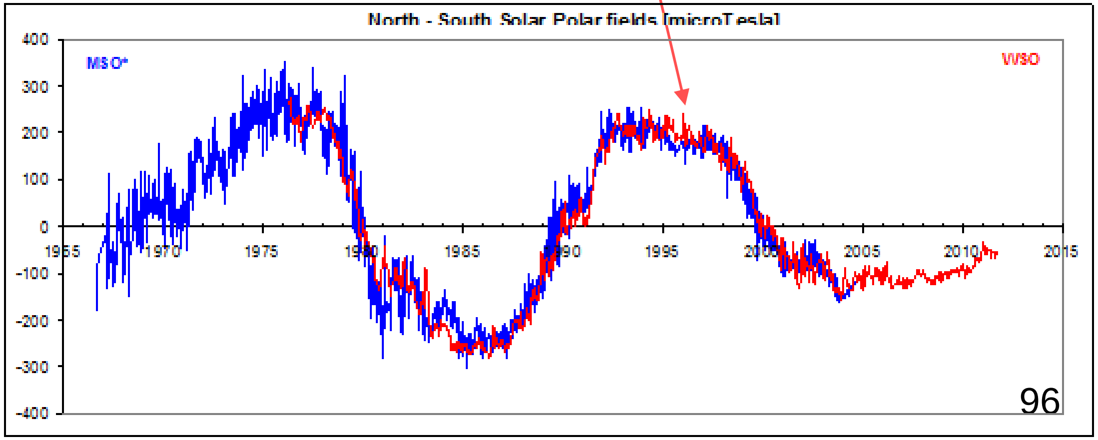
Rotate and long-lived



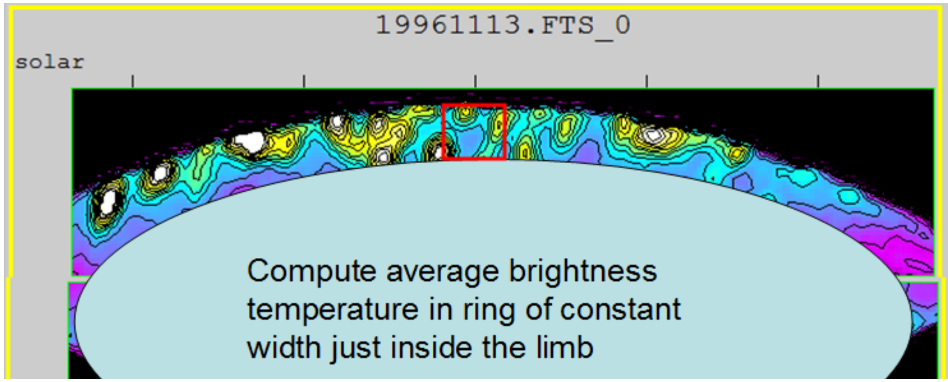




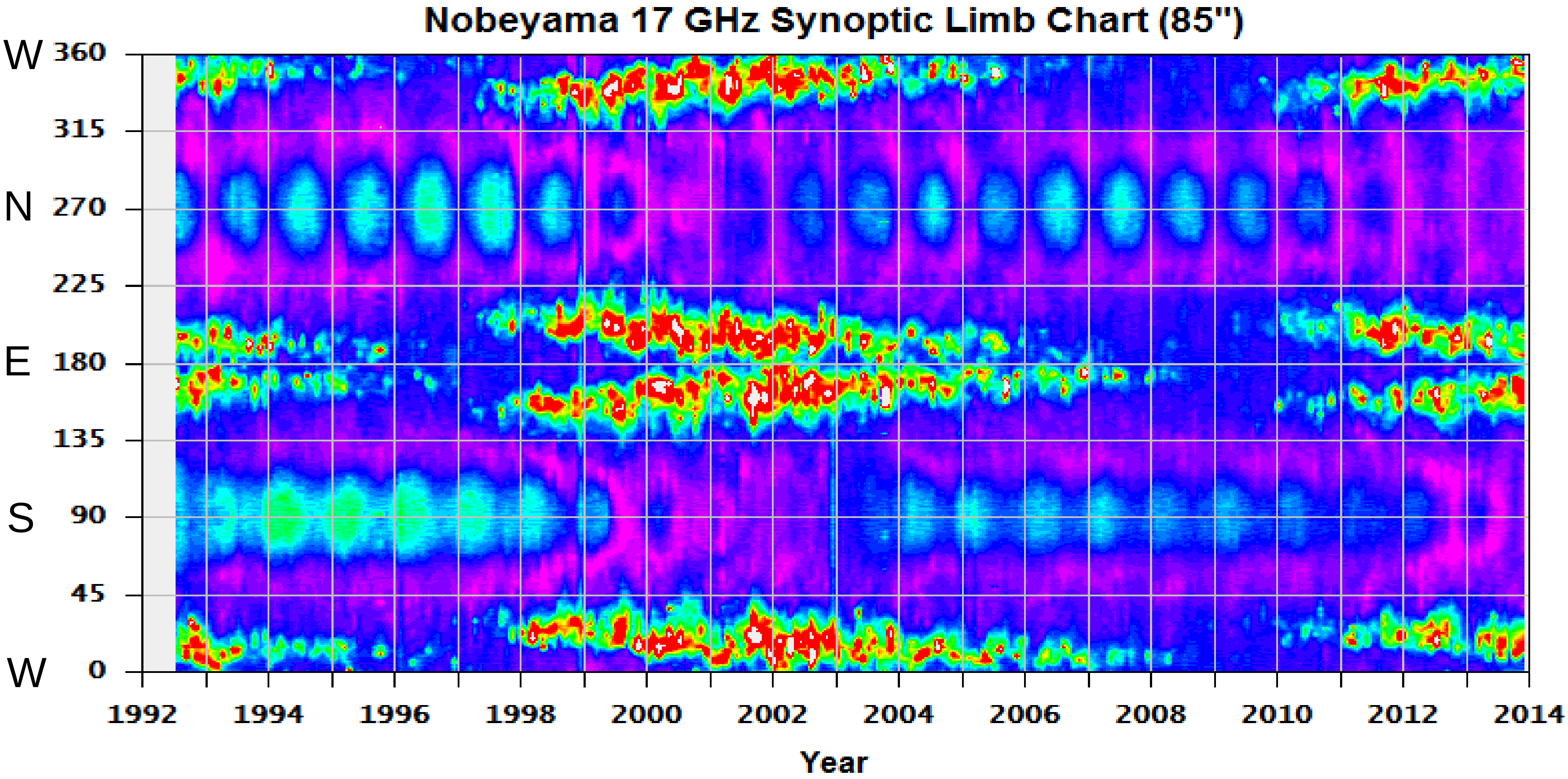




Make Synoptic Limb Chart

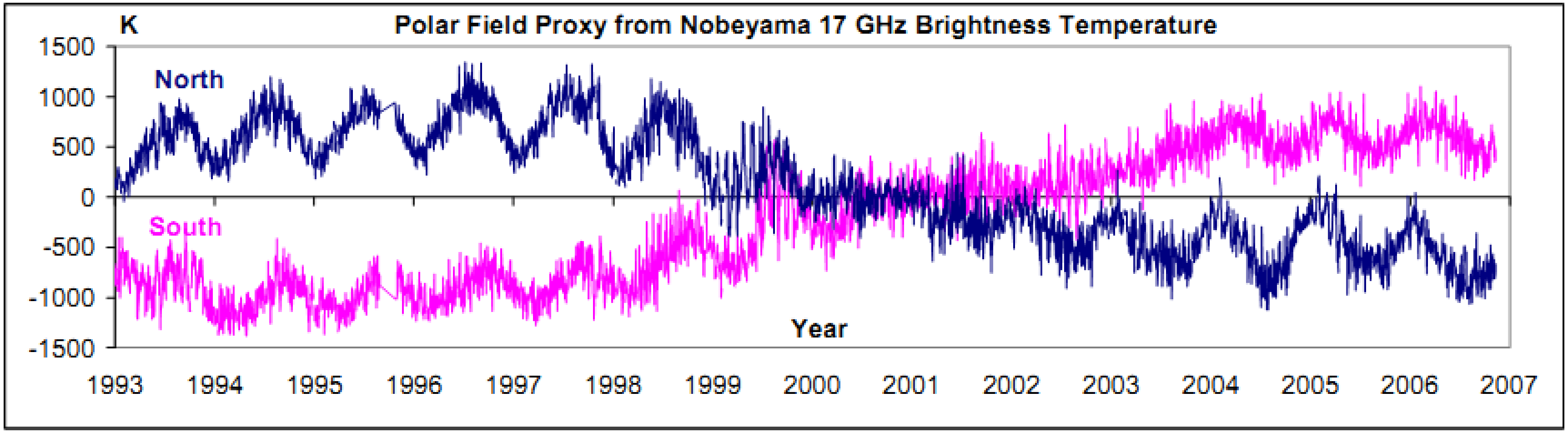


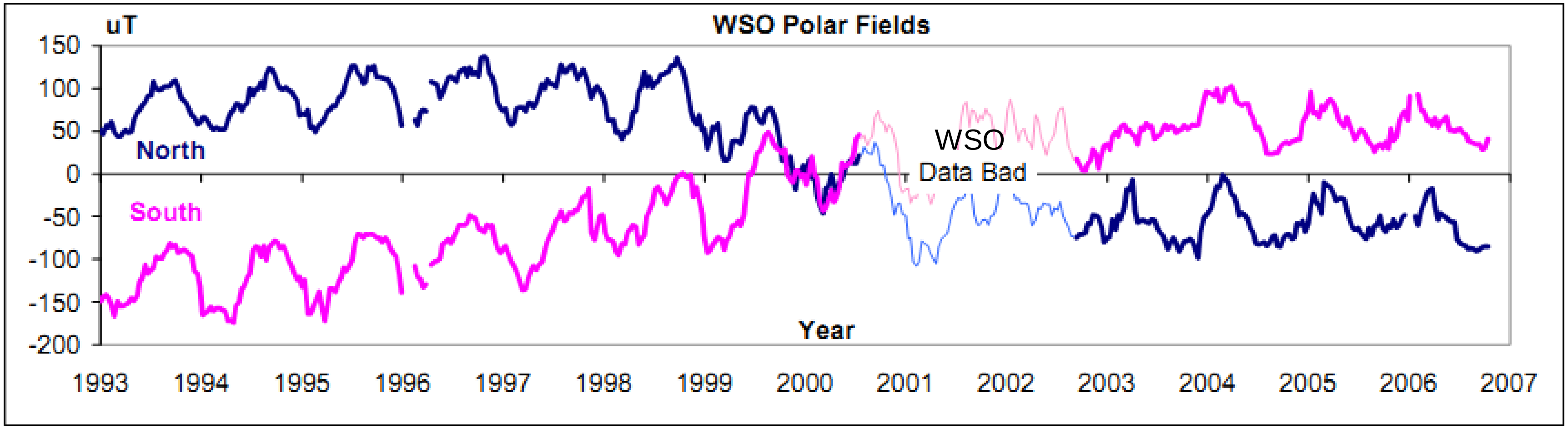
Compute average brightness temperature in ring of constant width just inside the limb


Nobeyama 17 GHz Synoptic Limb Chart (85")

Polar Emissions wax and wane over the cycle. Note annual variation and the weaker emissions in SC23/SC24 than in SC22/SC23

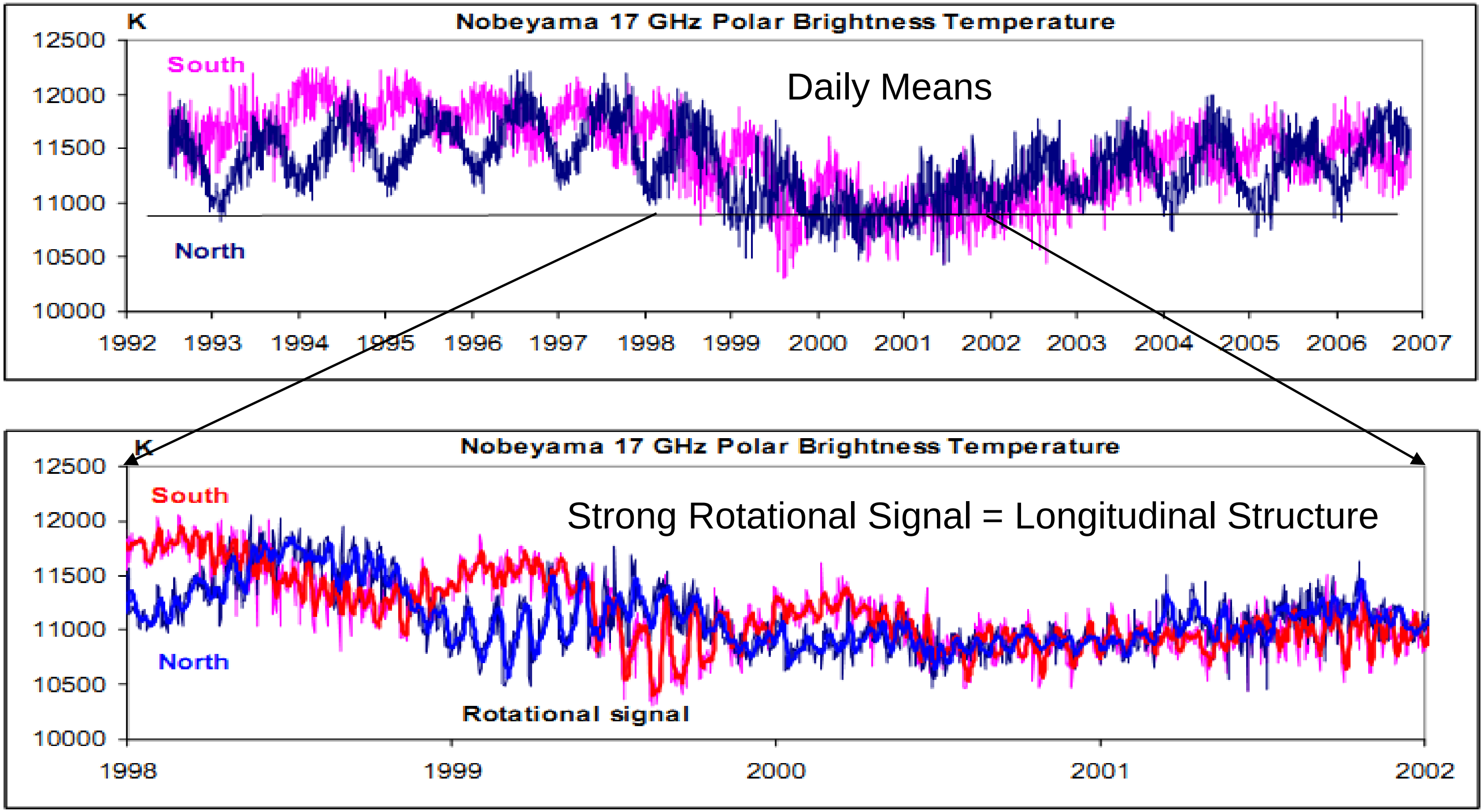
Signed Excess T_B Above 10,800K Matches WSO Polar Magnetic Field





Also shows strong rotational modulation

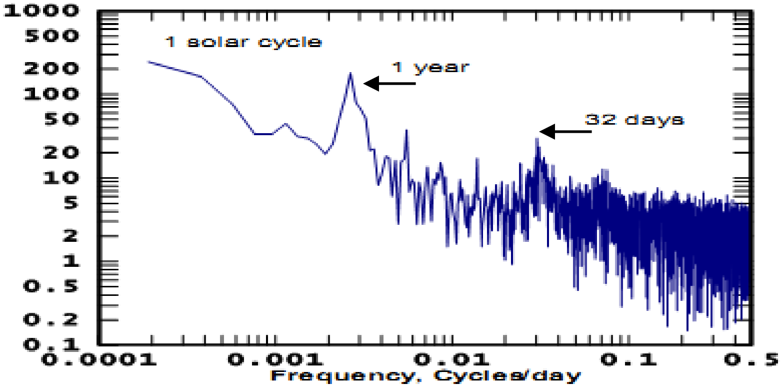
Strong Rotational Modulation


Daily Means

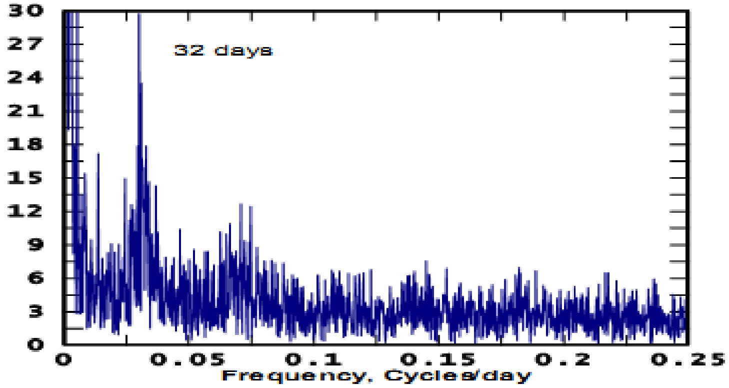
Strong Rotational Signal = Longitudinal Structure

Rotational Period: a 32-day Signal

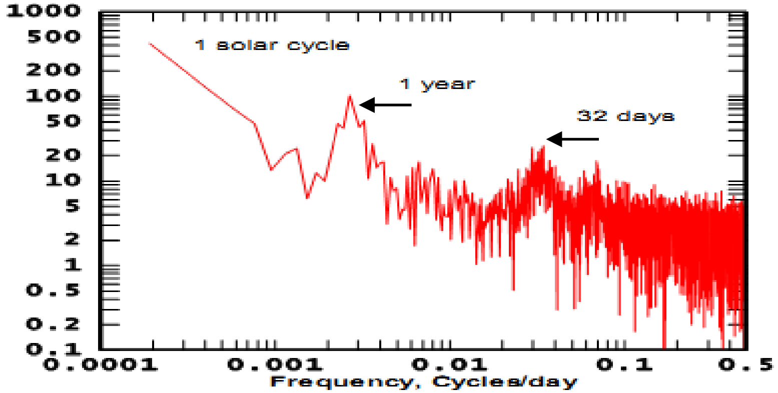
(FFT) Spectral Density (North)



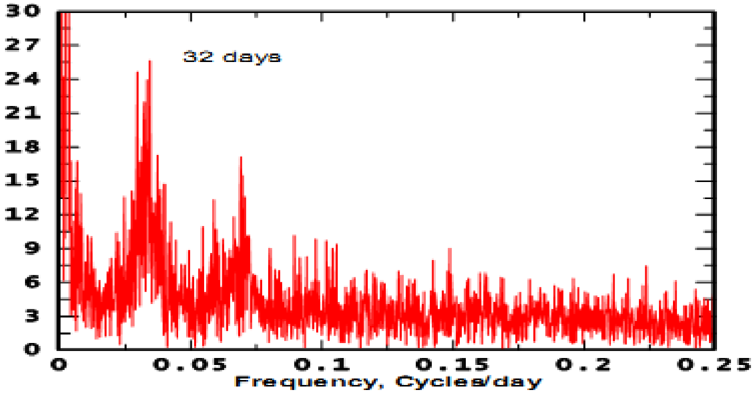
(FFT) Spectral Density (North)



(FFT) Spectral Density (South)

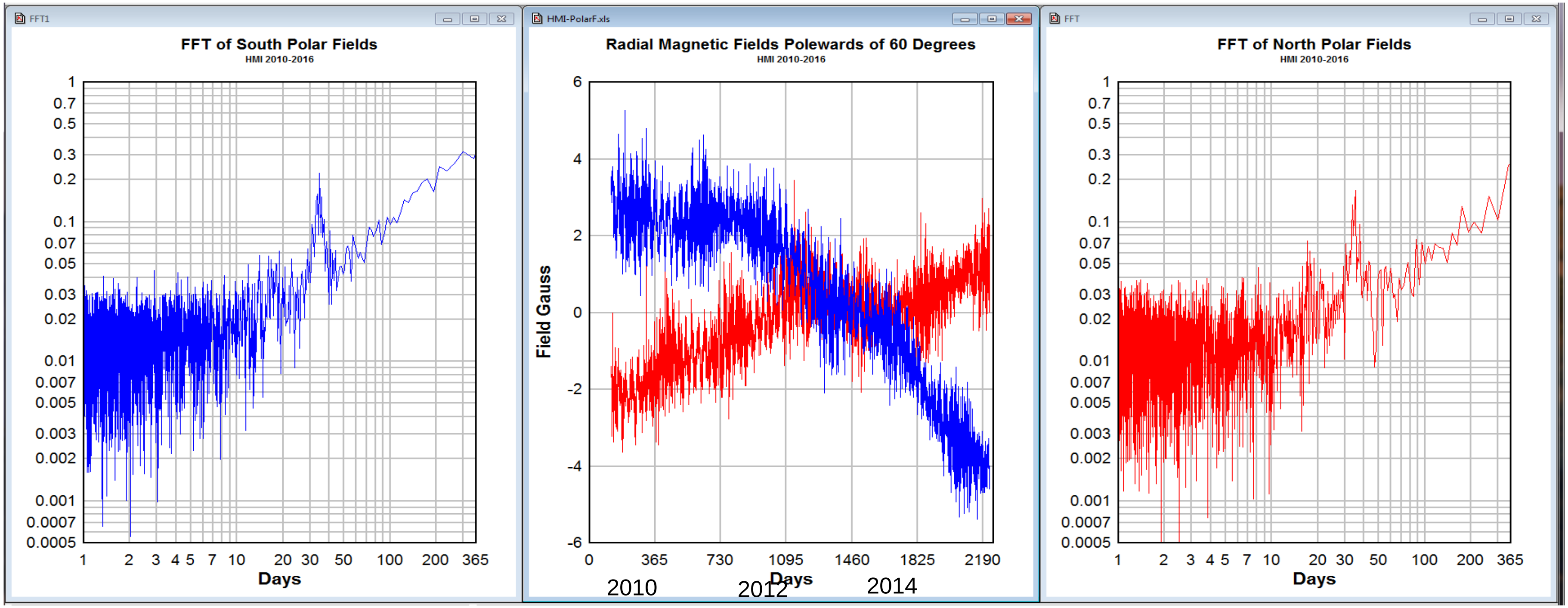


(FFT) Spectral Density (South)



Even hint of a 4-sector structure with period ~15 days

Also Fine Structure of HMI Polar Fields



The recurrence peak is at 34 days rather than at the Carrington synodic period. And a hint of a peak at half 34 days [4 ‘sectors’]

Strong rotational signal, especially when the very pole is best seen (red=North, in Sept; blue=South, in March)

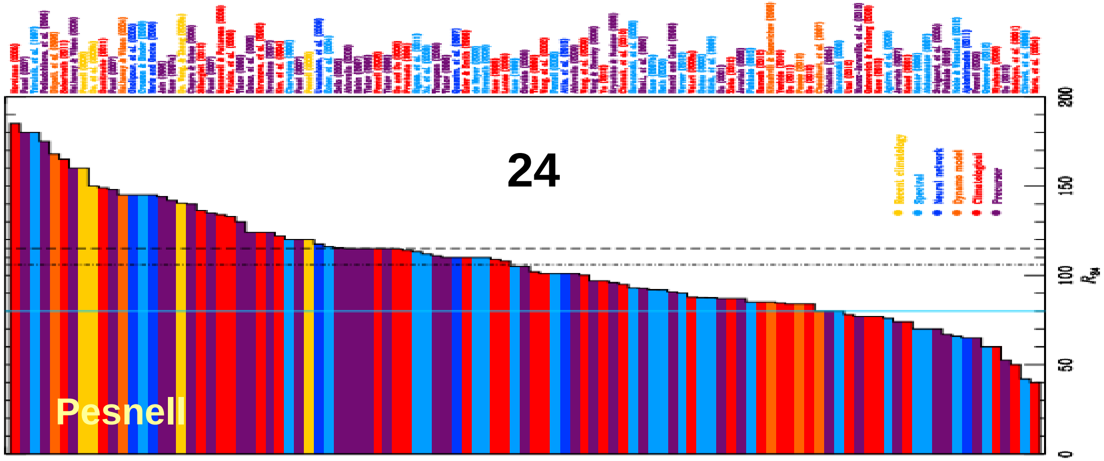
The recurrence peak is at 34 days rather than at the Carrington synodic period. And a peak at half 34 days [4 ‘sectors’].

We see strong rotational signals both in 17 GHz and HMI, indicating the arrival of narrow streams of flux from lower latitudes as we saw in the super-synodic charts

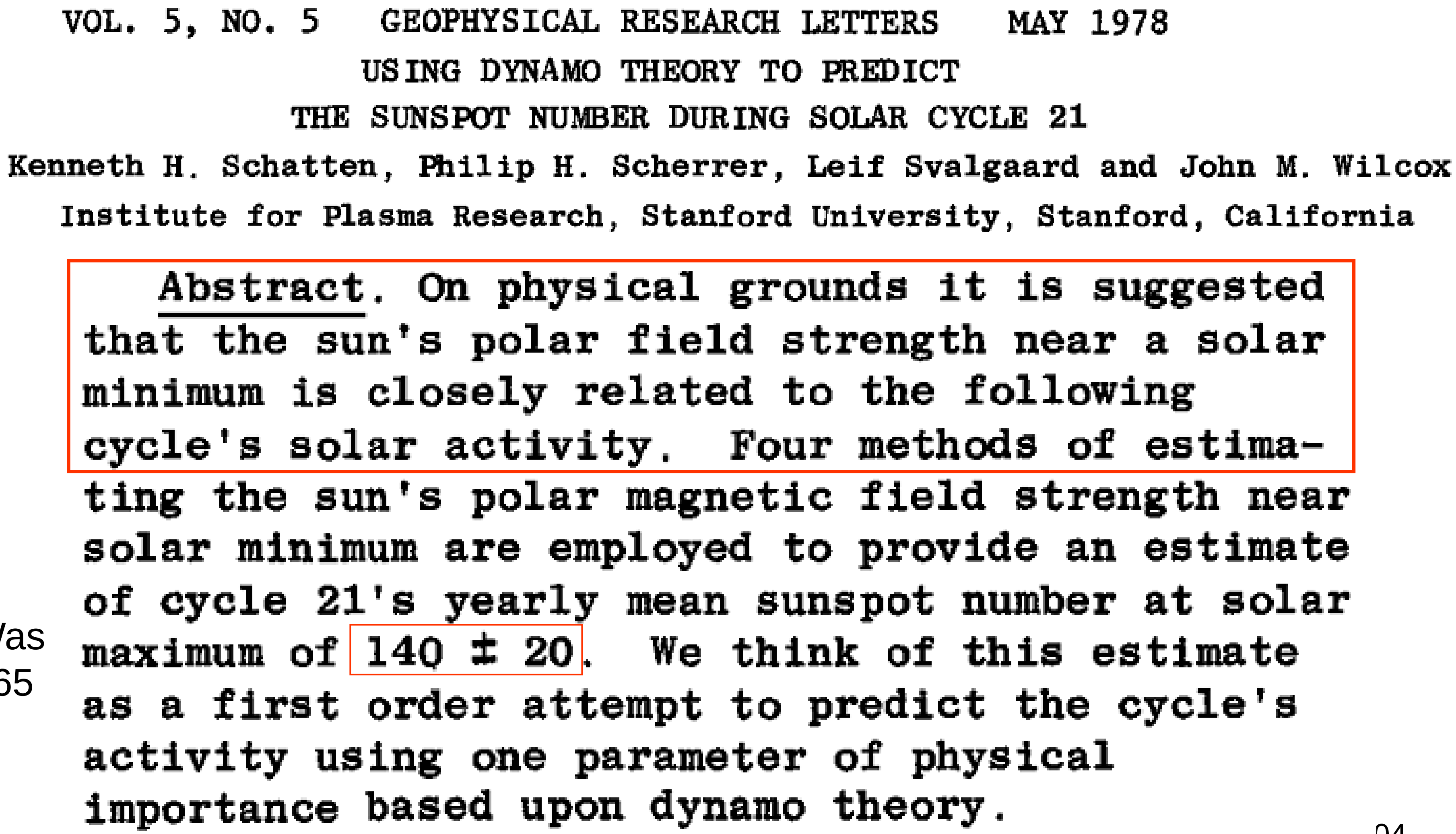
Summary V (Fine Structure of Polar Fields)

- Signed Excess Brightness Temperature Above 10,800K Matches WSO Polar Magnetic Field
- And shows a strong rotational modulation with period 32-35 days [and a hint of half that; 4 sectors?]
- HMI Polar Fields show the same modulation, indicating the arrival of narrow streams of flux from lower latitudes

The Polar Field Precursor Prediction Method



The Origin of the Polar Field Precursor Method



VOL. 5, NO. 5 GEOPHYSICAL RESEARCH LETTERS MAY 1978

USING DYNAMO THEORY TO PREDICT
THE SUNSPOT NUMBER DURING SOLAR CYCLE 21

Kenneth H. Schatten, Philip H. Scherrer, Leif Svalgaard and John M. Wilcox
Institute for Plasma Research, Stanford University, Stanford, California

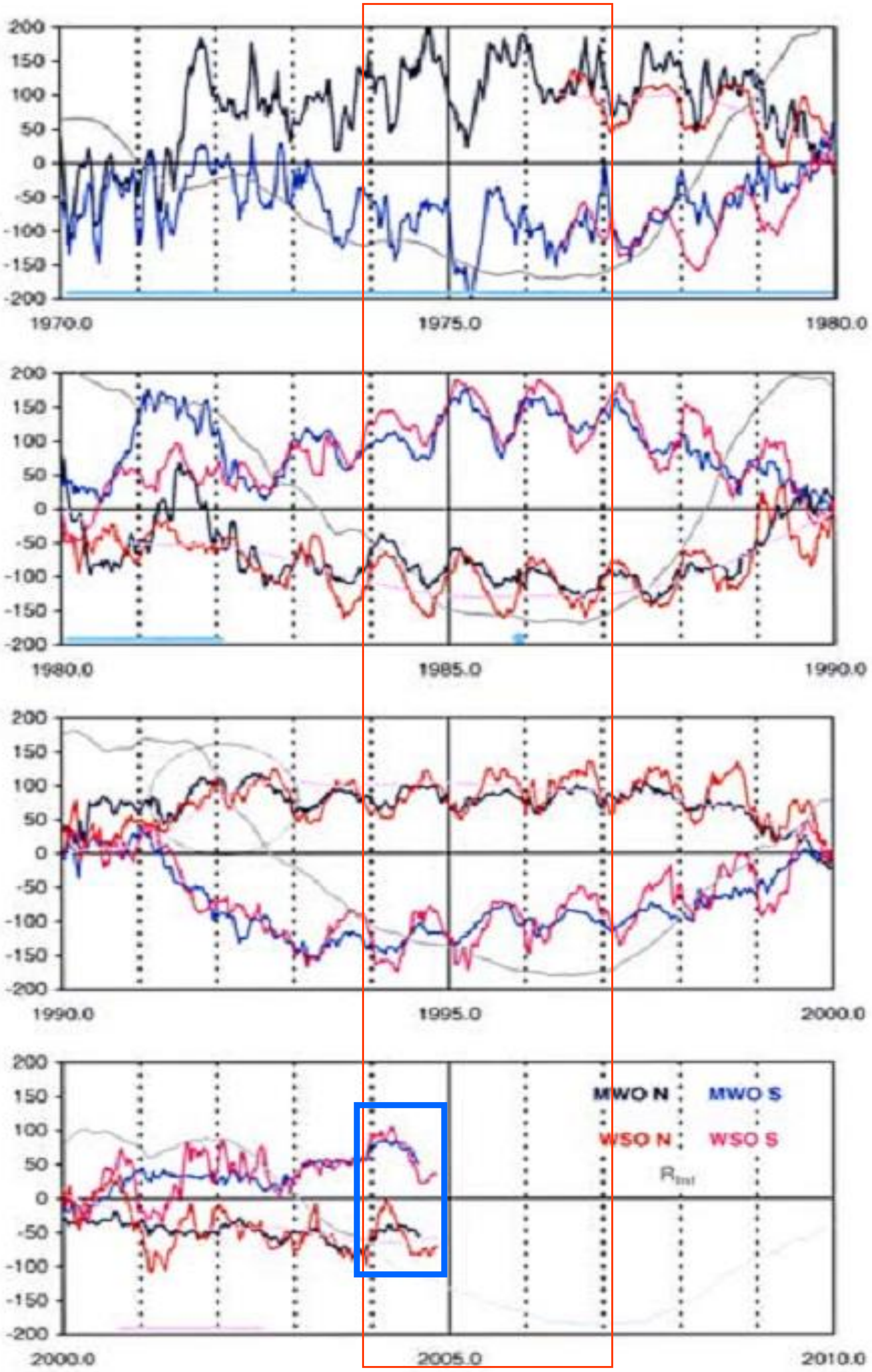
Abstract. On physical grounds it is suggested that the sun's polar field strength near a solar minimum is closely related to the following cycle's solar activity. Four methods of estimating the sun's polar magnetic field strength near solar minimum are employed to provide an estimate of cycle 21's yearly mean sunspot number at solar maximum of 140 ± 20. We think of this estimate as a first order attempt to predict the cycle's activity using one parameter of physical importance based upon dynamo theory.

Was
165

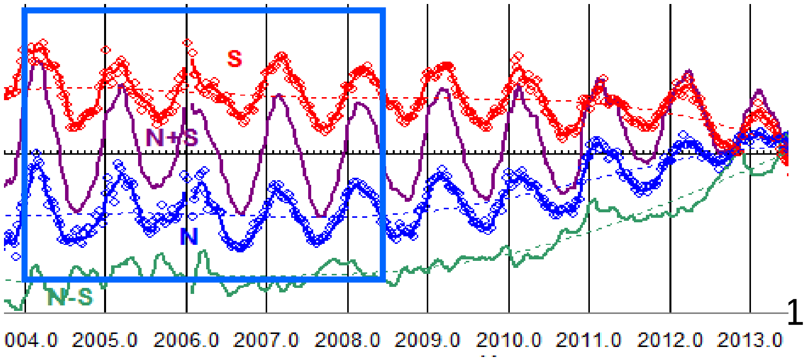
The Authors 31 years later

And now (2017) it is 39 years later

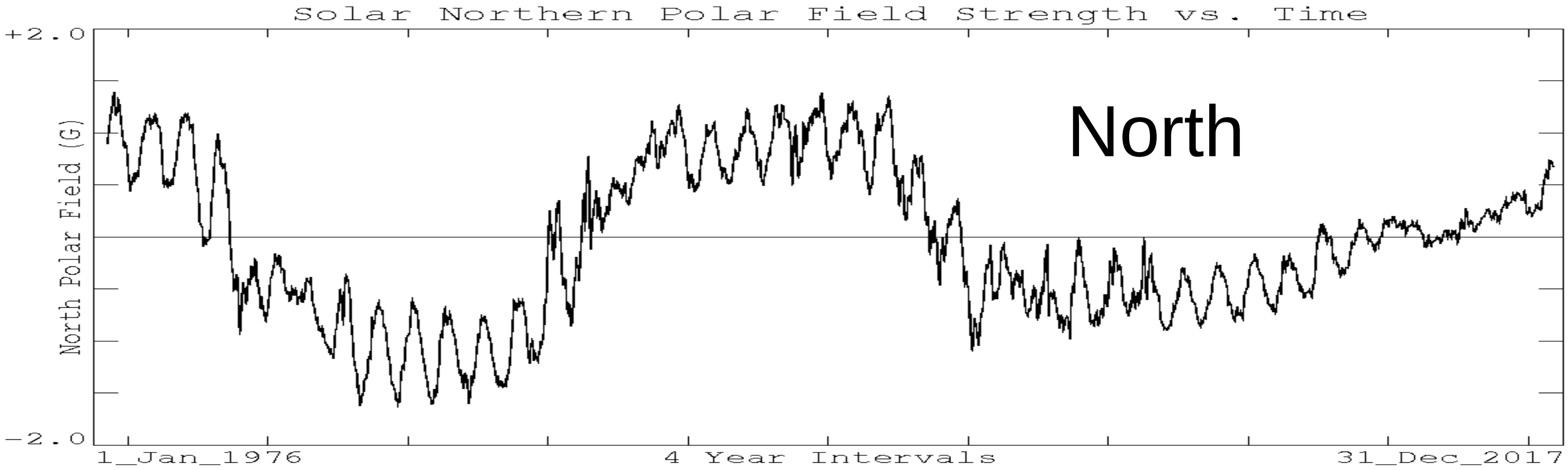
Using the Measurements of the Solar Polar Fields at MWO* and WSO we [Svalgaard, Cliver, Kamide] made a Prediction of the coming SC24 back in 2004

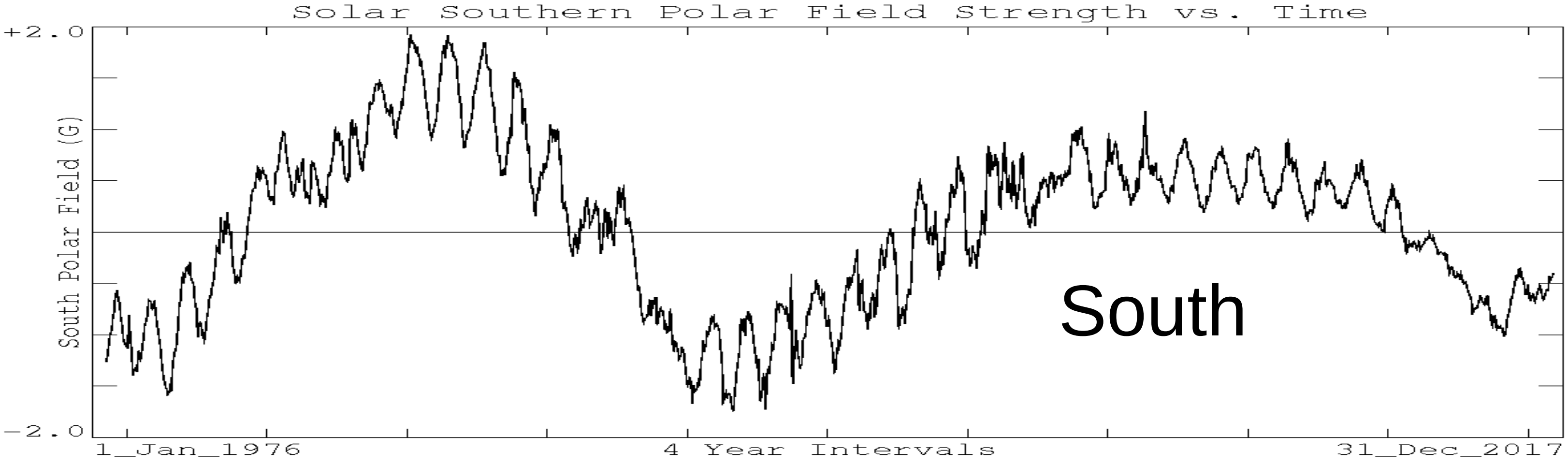


We noted that once a stable yearly variation was reached (3 to 4 years before minimum), the polar fields would not change much [the ‘plateau’] until the very minimum and might be used as a precursor for the size of the next cycle.

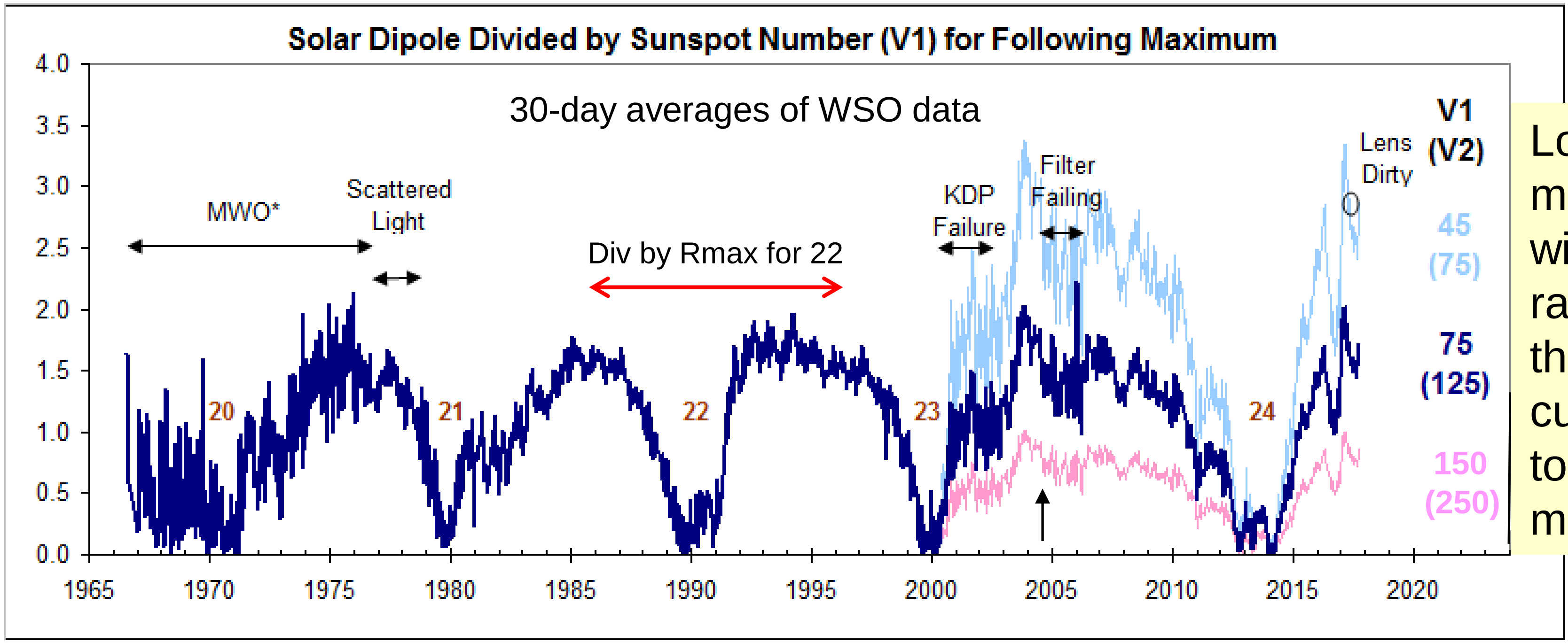


Just a Reminder How Different the Hemispheres Can Evolve (WSO)





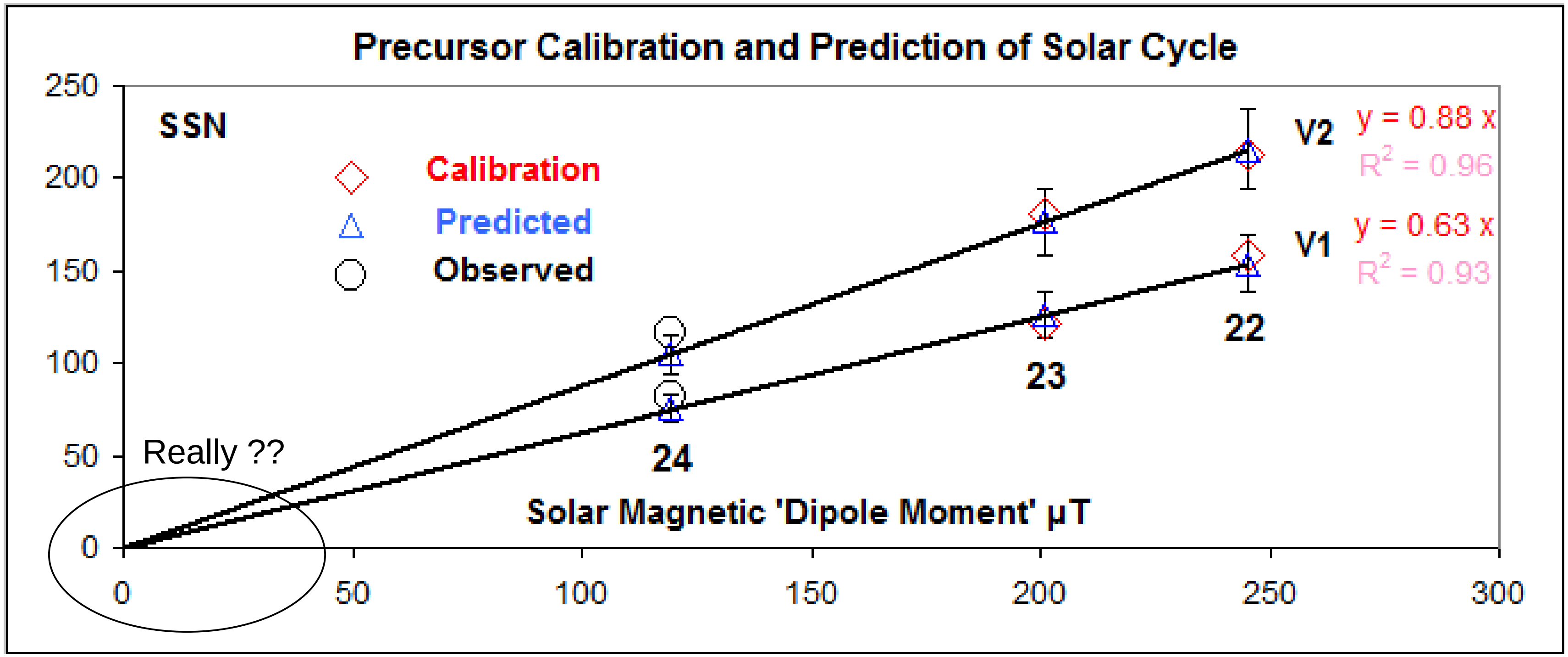
The Polar Field Precursor in Action



Low max will raise the curve too much

We divided the Dipole Moment [ABS(North-South) PF] from reversal to next reversal by the smoothed sunspot number for the cycle at that reversal (red arrow). We assume that the resulting curve (dark blue) is invariant (has about the same shape from cycle to cycle) and judge the size of cycle following the minimum between reversals (“the next cycle”) to be that [unknown] sunspot number that maintains the curve at the same level. The scatter of the points on the curve is taken as an indication of the error.

Calibration of the Precursor

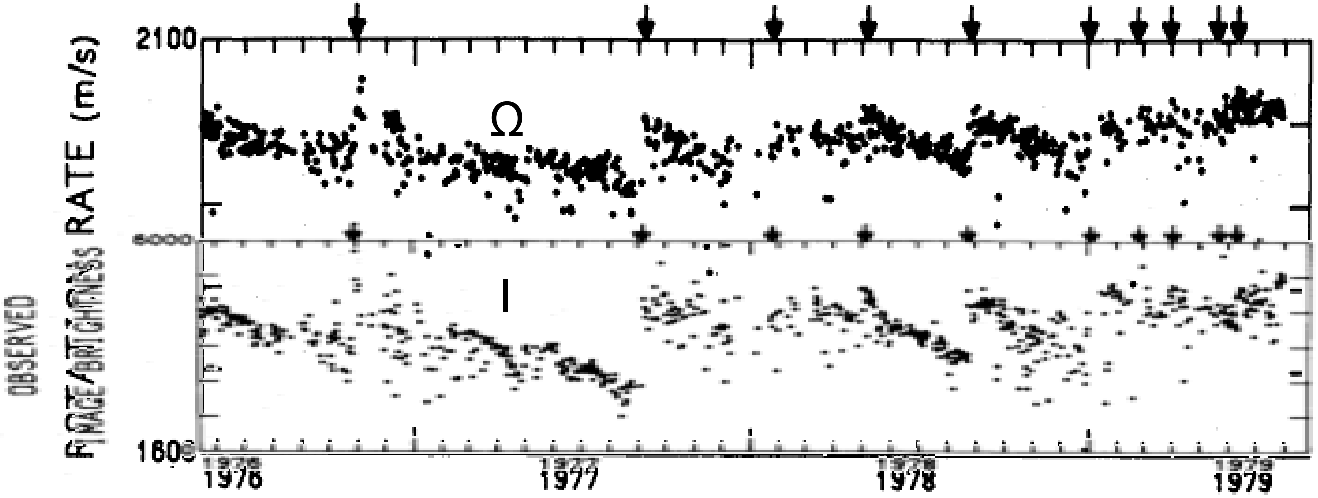


We assume that the polar field precursor method works and that we only need to calibrate the relationship. We use Cycles 22 and 23 for this and find that the prediction of Cycle 24 is correct within the 'error bar' [which is hard to estimate].

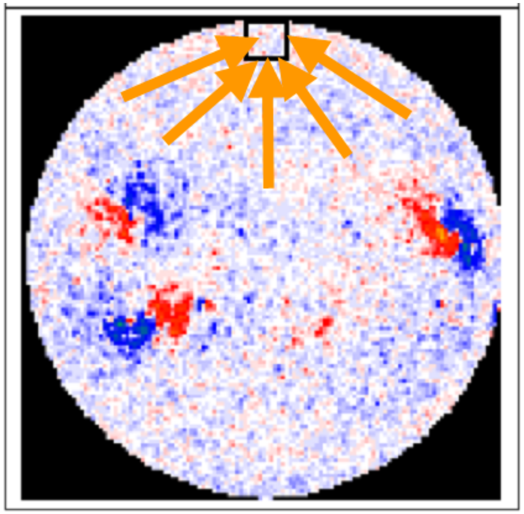
Why did we not use Cycle 21? One reason was that our WSO data only began in 1976. Another more serious problem [discovered later] was that of scattered light …

The Effect of Scattered Light

SCHERRER, WILCOX, AND SVALGAARD ApJ 1980

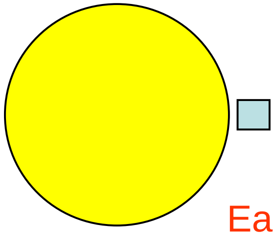


At WSO we also measure the rotation rate of the Sun. We found that the Sun rotated slower and slower as time went on, until we cleaned the mirrors and optics [arrows]. Dirty optics means scattered light. **In 1976-1977 that was particularly bad.**



Scattered light is the reason for the lower WSO fields, as light from mixed polarity areas are scattered into the polar aperture, diluting the measured polar field.

Making the mirrors dirty on purpose shows the effect very clearly:



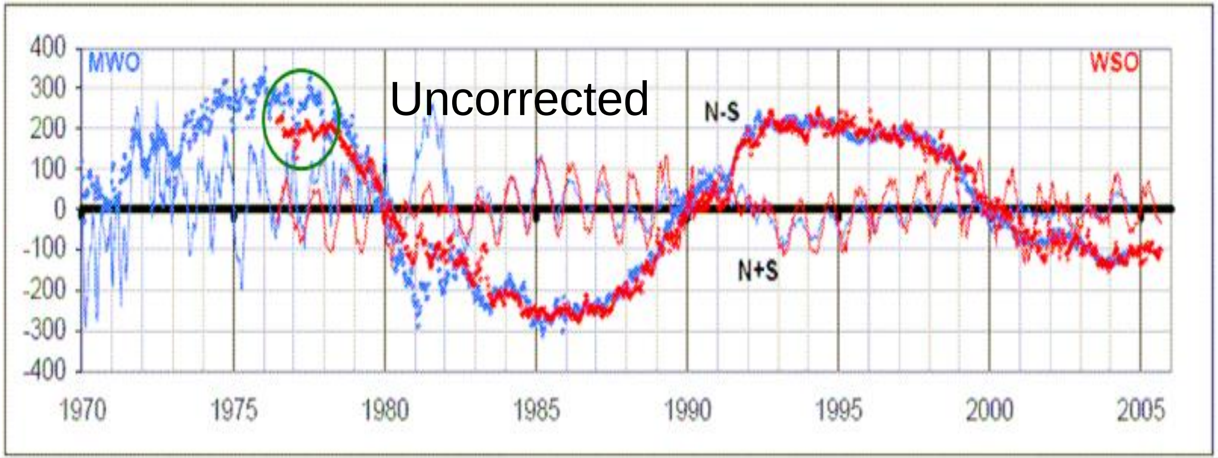
scattered %	Reduction
1.0	1.0000
3.0	0.8178
6.7	0.7402
11.1	0.5869
13.0	0.5424

In 1976-1977 scattered light was several %

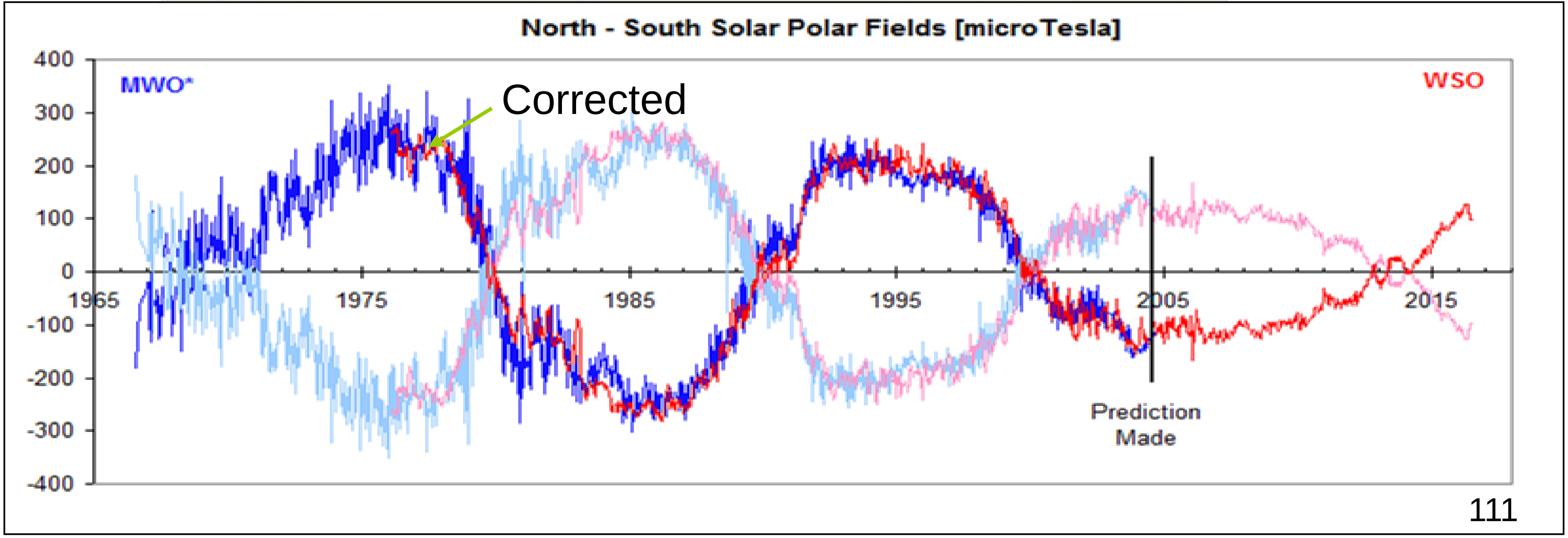
Each % of scattered light decreases the field by 4%

I didn’t think of that for the field until 2007, when we repeated the ‘dirty mirrors’ exercise (with J&J Baby Powder)

The Effect of Scattered Light Can Also Be Seen by Comparison with MWO



Polar fields should be 250 μT and not 200 μT back in 1976-1977



Recently we noticed a significant decline of WSO Mean Field compared with SOLIS

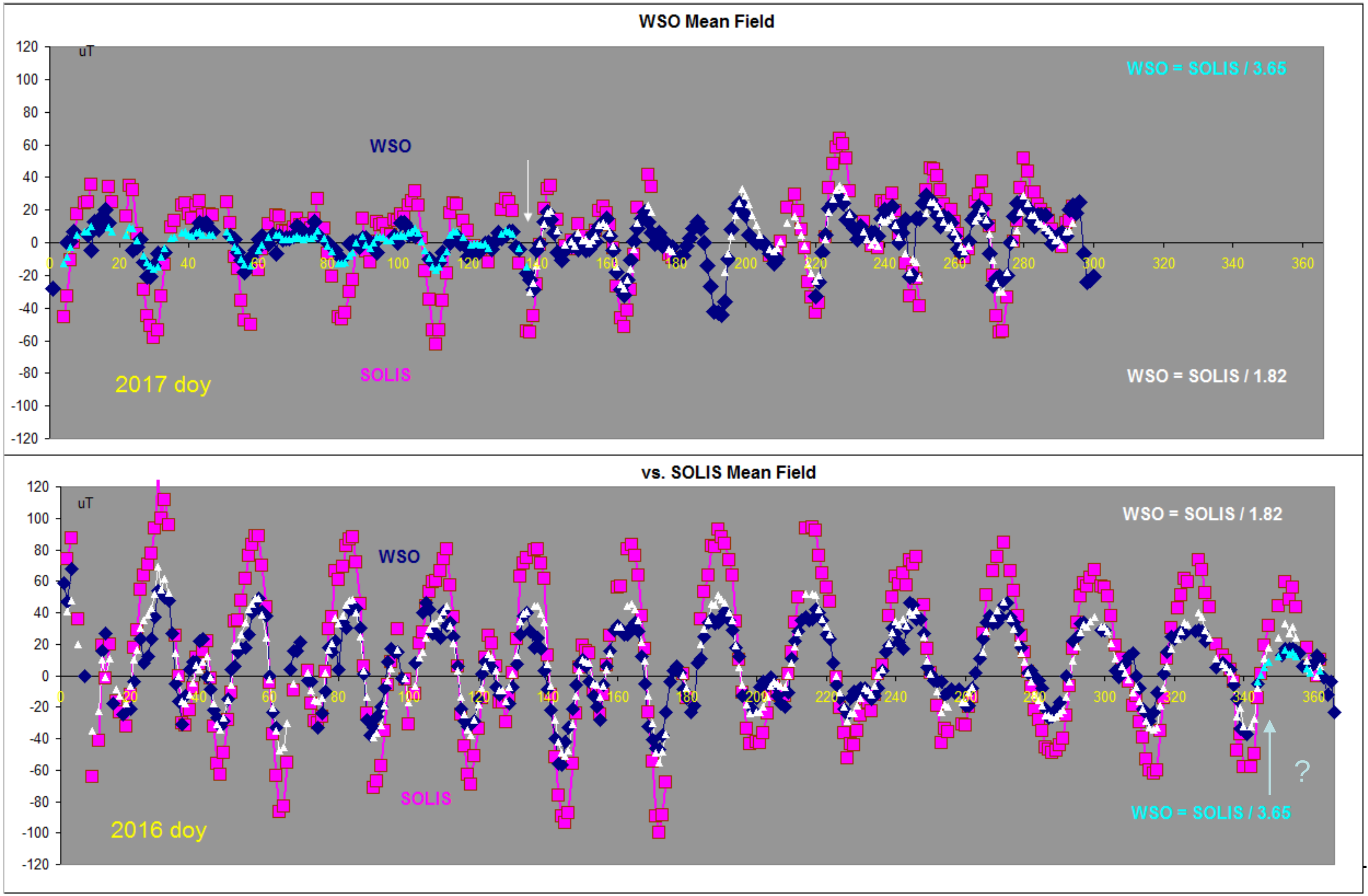
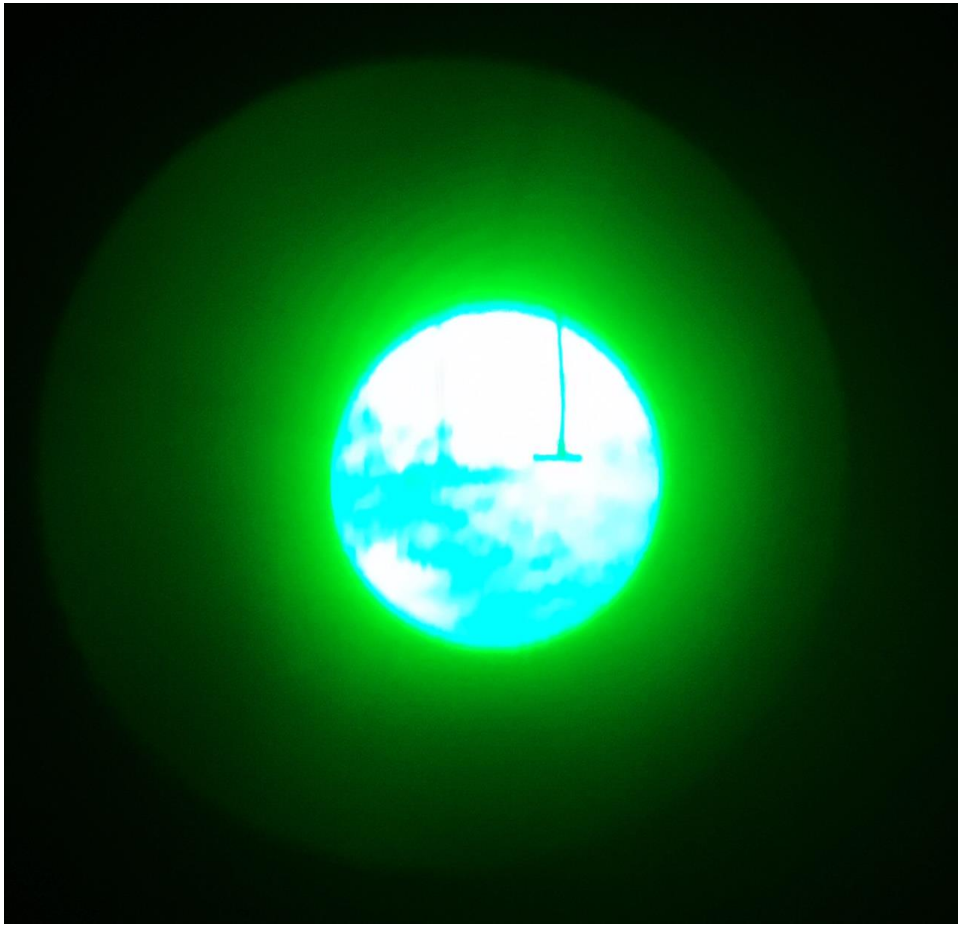


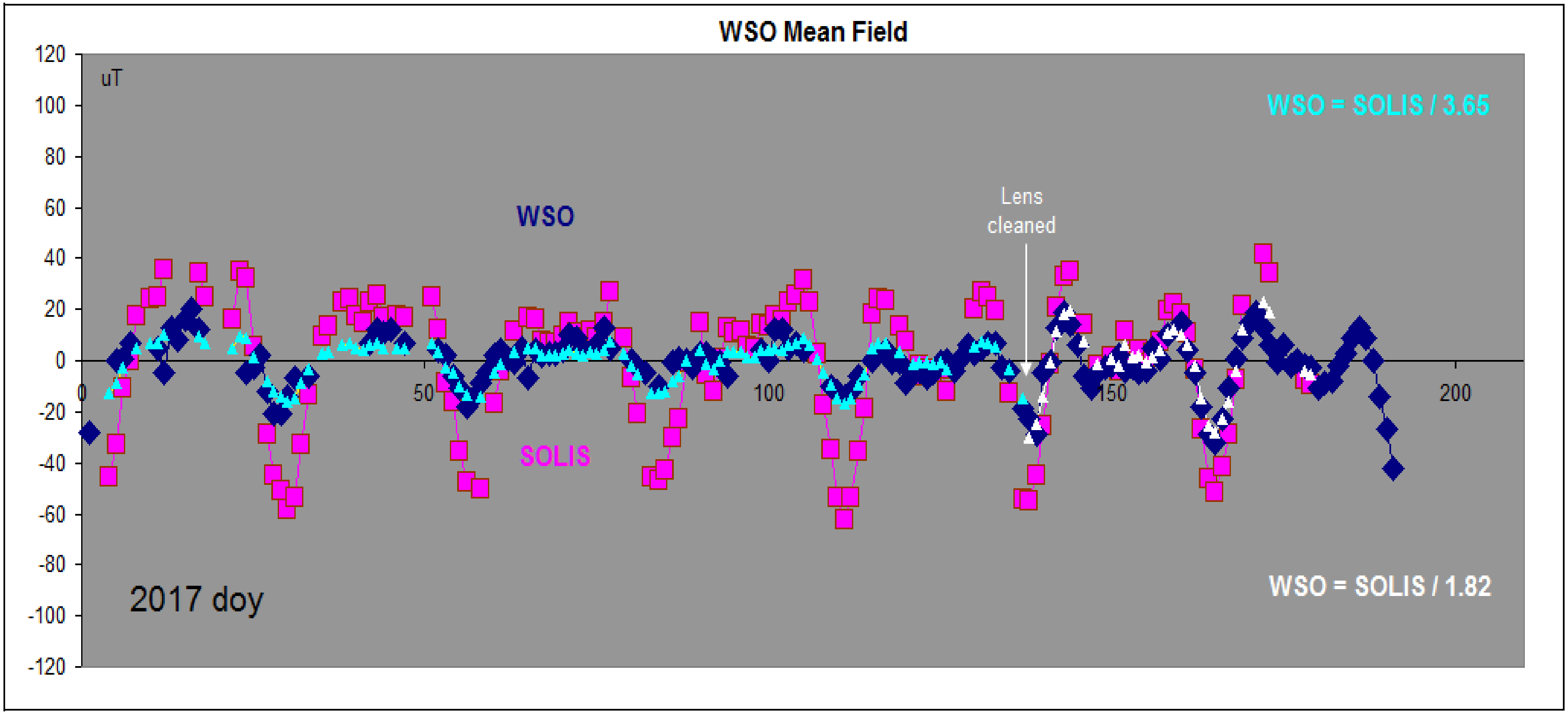
Image of the Littrow Lens



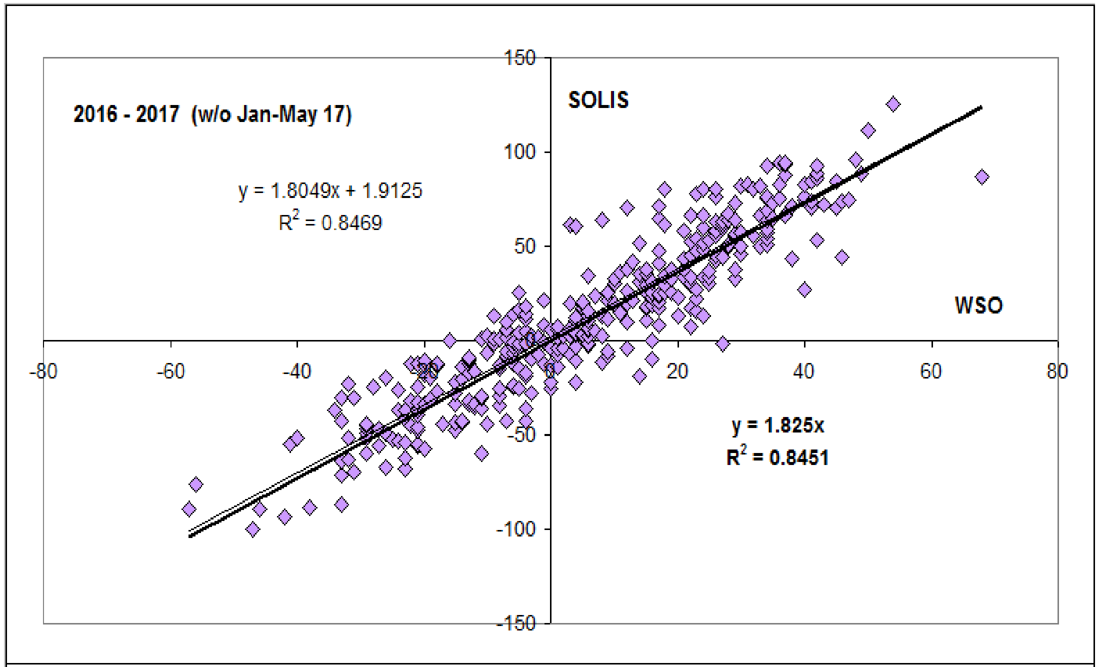
There is a lens in front of the grating in the pit. The lens makes the incoming light rays parallel before they hit the grating and collimates the dispersed light retuning to focus at the sensors in the observing room. Todd Hoeksema pointed his iPhone at the lens and imaged it. The image showed that the lens was very dirty.

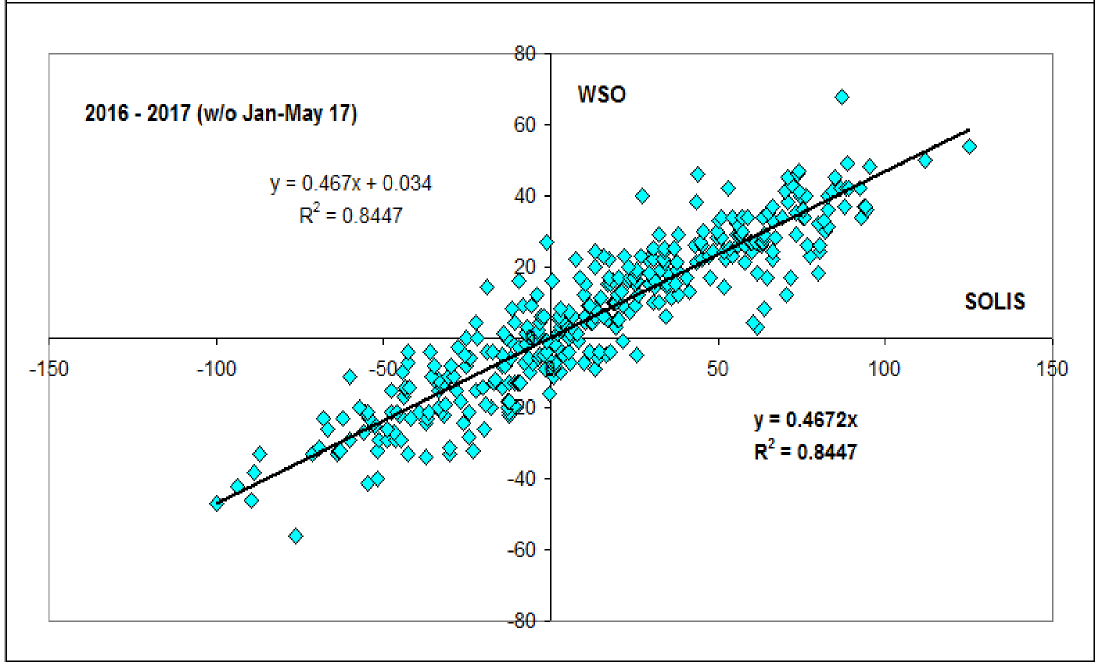
Cleaning the Littrow Lens

Cleaning the lens seems to have solved the problem



The Mean Field after the cleaning [marked with white triangles] are now again following the SOLIS measurements with the usual factor of ~2 instead of the ~4 we had when the lens was dirty.





Compare SOLIS and WSO Mean Fields Outside the 2017 Glitch

SOLIS = 1.825 WSO

WSO = 0.548 SOLIS (=1/1.825)

WSO = 0.4672 SOLIS

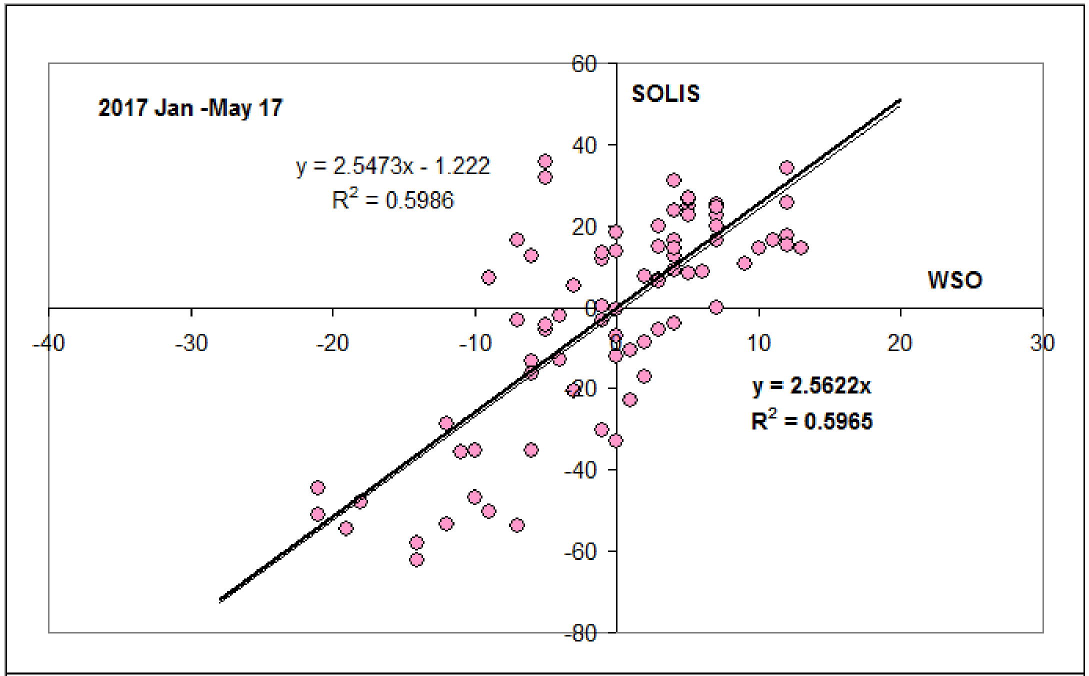
SOLIS = 2.14 WSO (=1/0.4672)

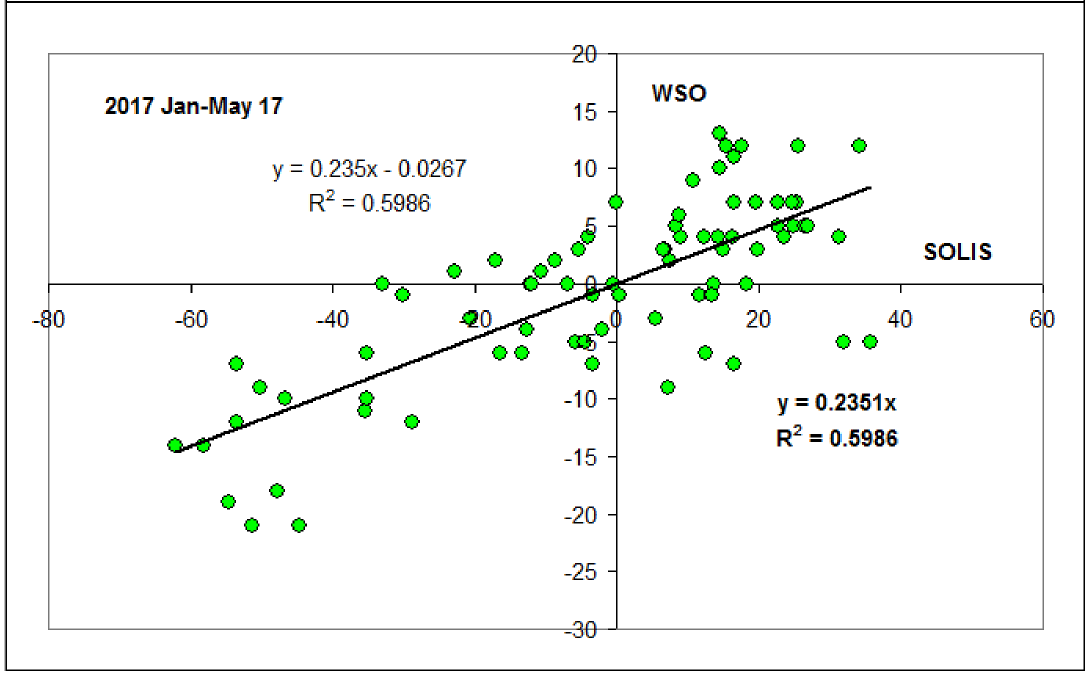
Average

WSO = 0.51 SOLIS

SOLIS = 1.97 WSO (=1/0.51)

Compare SOLIS and WSO Mean Fields During the 2017 Glitch





SOLIS = 2.5622 WSO

WSO = 0.390 SOLIS (=1/2.5622)

WSO = 0.2351 SOLIS

SOLIS = 4.254 WSO (=1/0.2351)

Average

WSO = 0.303 SOLIS

SOLIS = 3.303 WSO (=1/0.303)

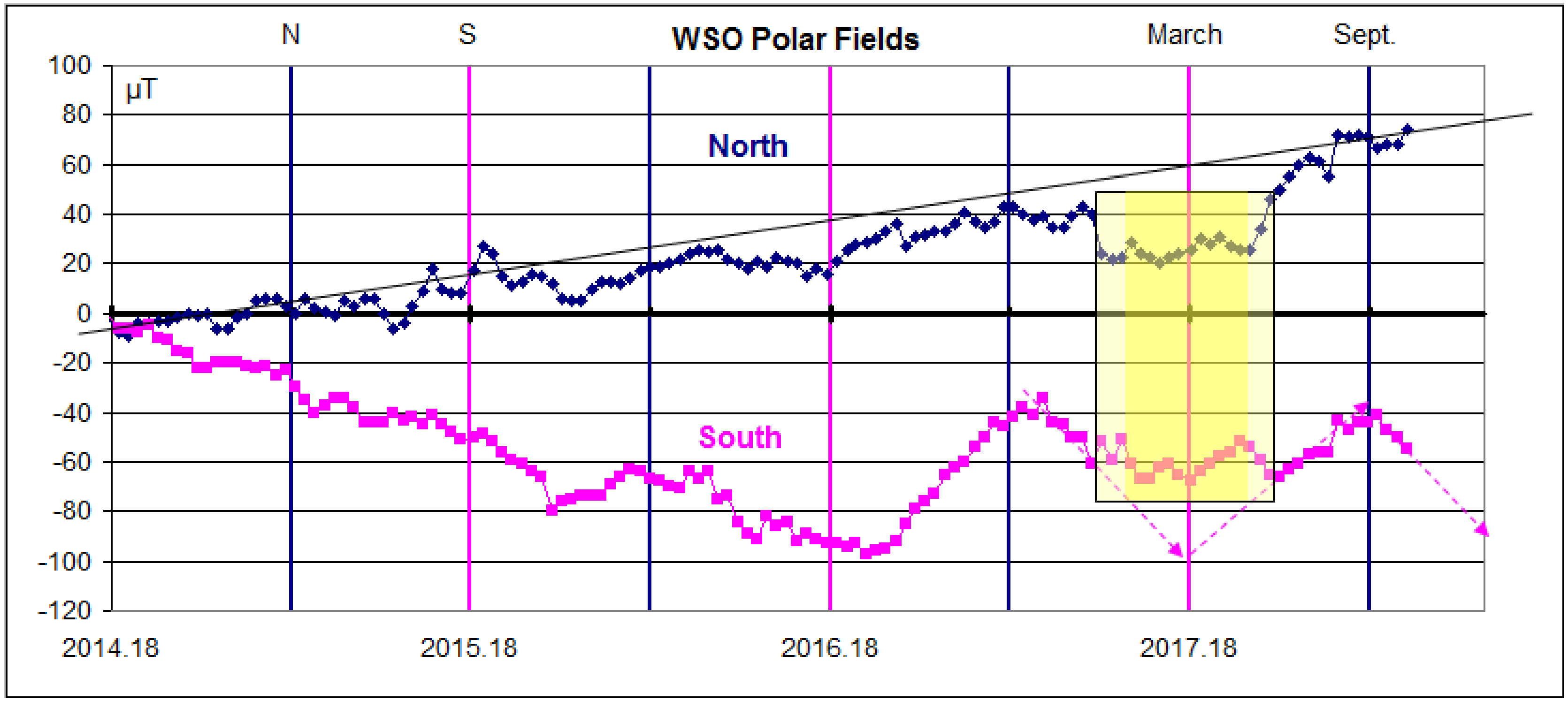
The Magnitude of the Glitch

SOLIS => WSO	WSO => SOLIS	When
0.30	3.30	During Glitch
0.51	1.91	No Glitch
1.70	**1.73**	Ratio

So, I adopt the correction factor for the mean field to be 1.73±0.16 (95%) with the error being mostly determined by the spread of the points during the glitch (run a standard regression on the points). WSO mean fields should then be multiplied by the constant 1.73.

The starting time of the glitch seems to be somewhere between Dec 6 and Dec 16, 2016. Say, Dec 10, 2016 without loss of ‘reality’. Ending time May 18, 2017

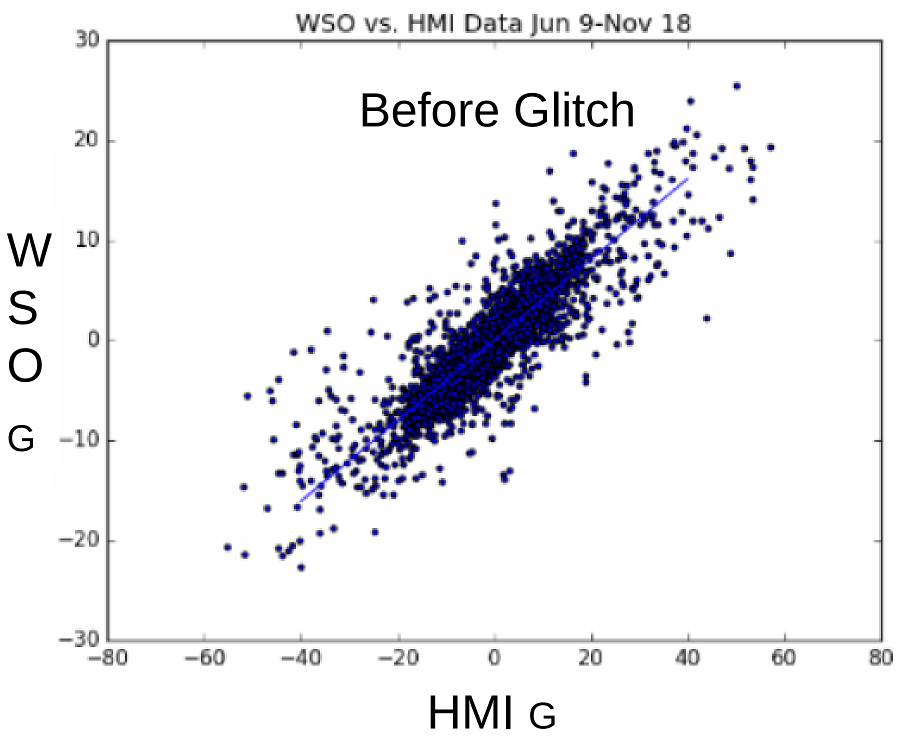
Recent WSO Measured Polar Fields

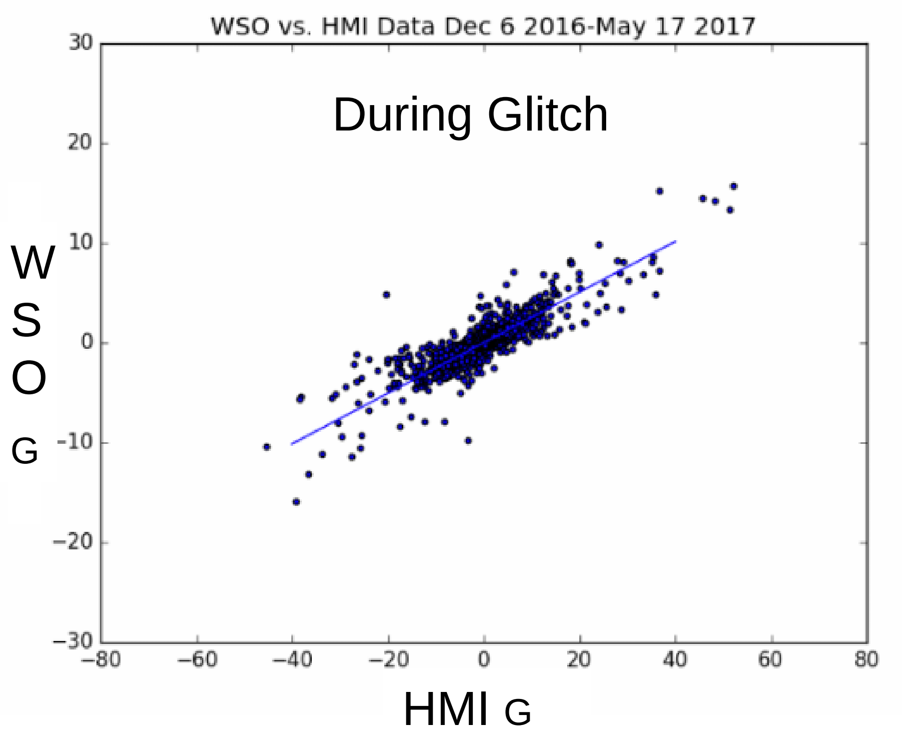


The South Pole [pink] has stabilized and is showing its usual B_0-angle variation, but the Glitch [yellow box] shows the problem, which also is seen in the North.

The polar fields are about a factor two too small and there may be a slight zero-level error as well.

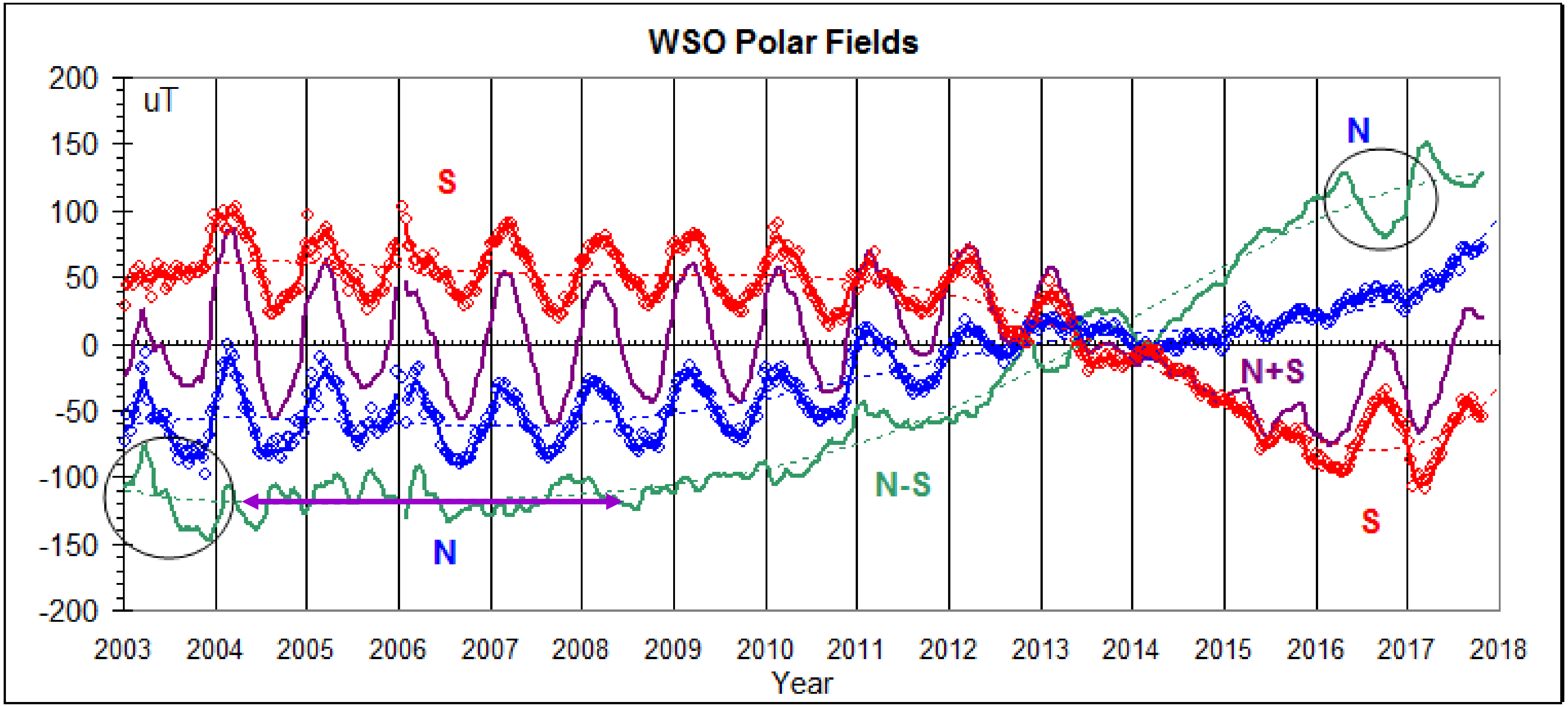
The Glitch on the Disk





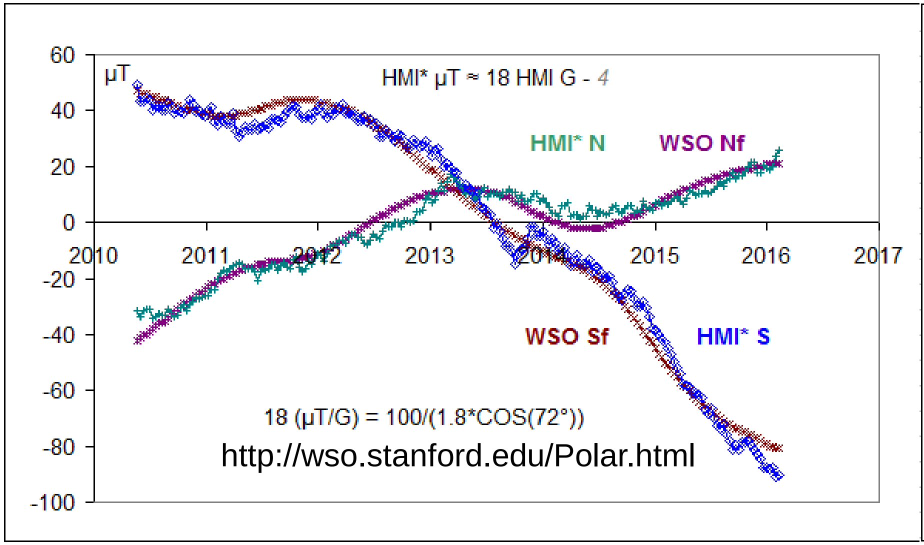
The HMI data on the disk were binned into the same ‘pixels’ [180’*180’] as WSO. The ratio of the slopes (including the inverse slopes) was 1.59. For the mean field it was 1.73, for a ‘grand average’ of 1.66 which is then taken to be the magnitude of the correction we need to make to the WSO values during the ‘glitch’

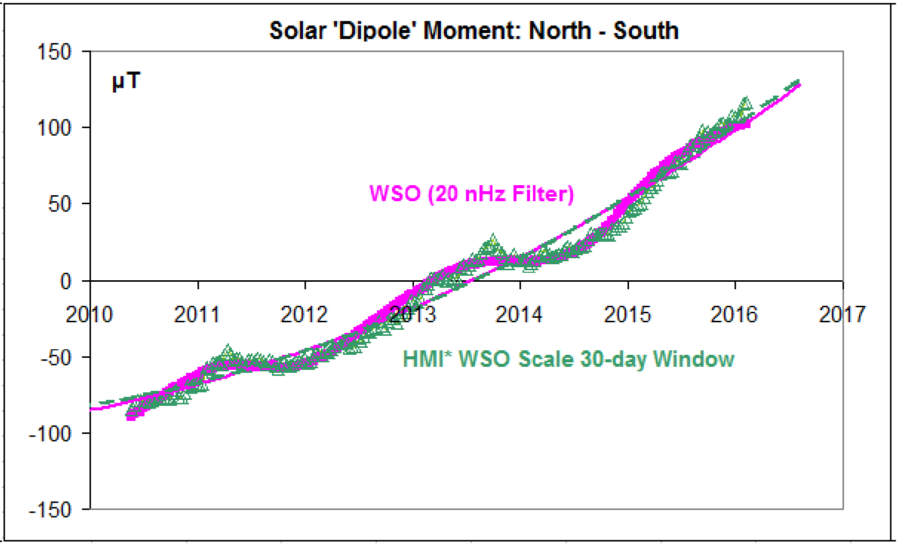
Corrected WSO Polar Fields



The ‘bite’ taken out of the Dipole Moment [North – South] shown by the circle in 2016 is similar to the bite takne out back in 2003 and for the same reason: one pole had stabilized but the other one had not yet.

Comparing HMI and WSO Polar Field Data



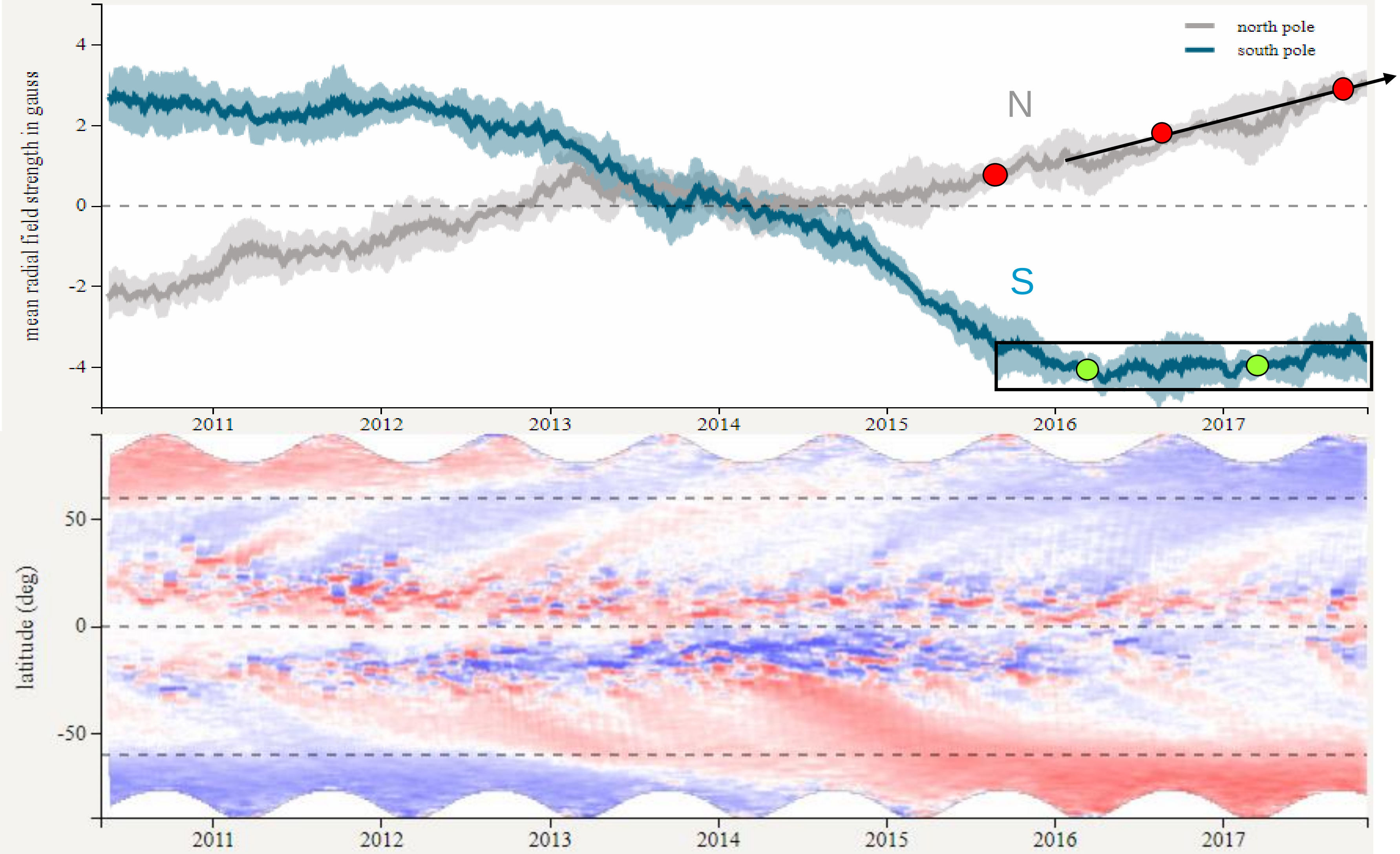


WSO: The pole-most aperture measures the line-of-sight field between about 55° and the poles. Each 10 days the usable daily polar field measurements in a centered 30-day window are averaged. A 20nHz low pass filter eliminates yearly geometric projection effects.

HMI: The raw (12-hour) data have been averaged into the same windows as WSO's and reduced to the WSO scale taking saturation (the 1.8) and projection (the COS(72°)) into account.

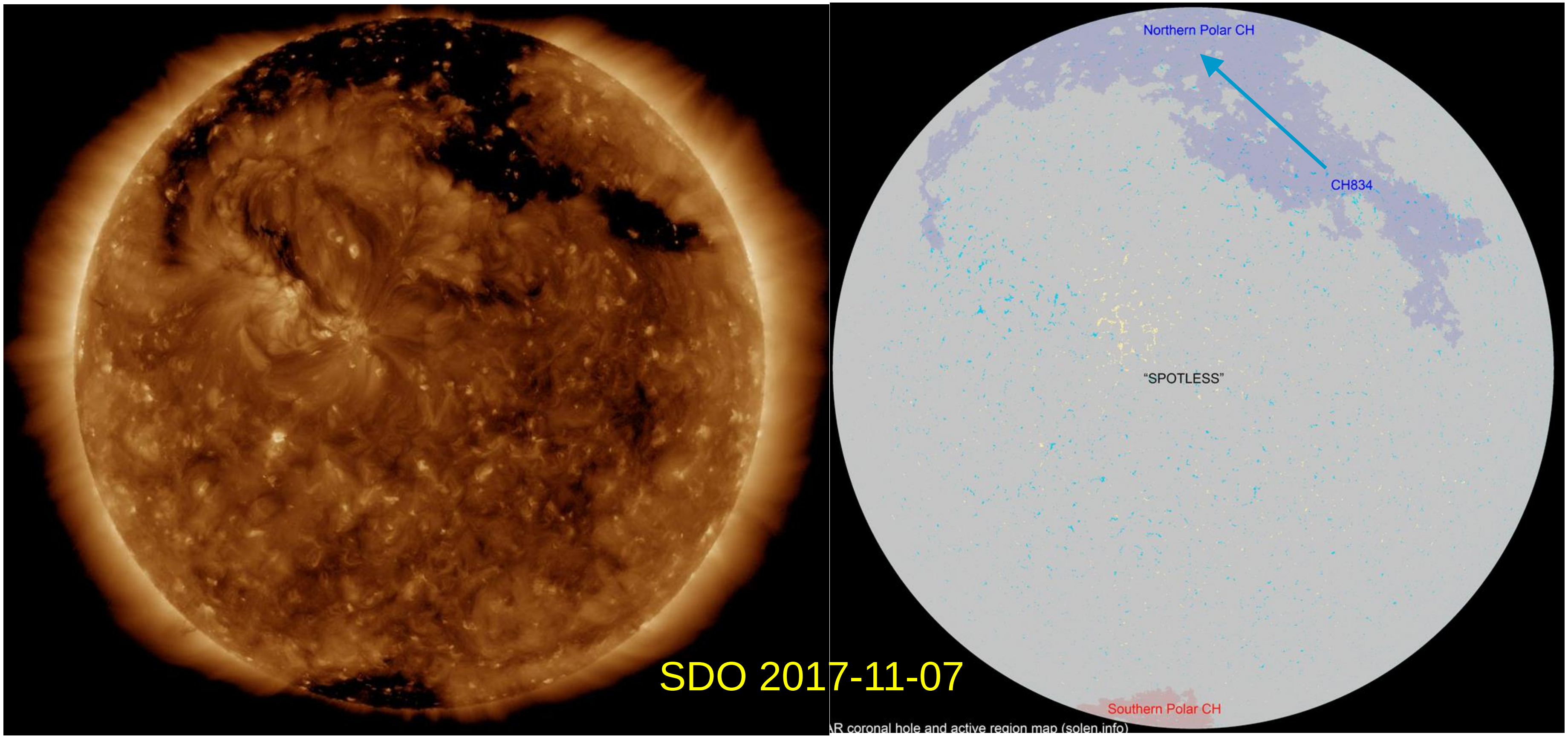
We have argued that the 'poloidal' field in the years leading up to solar minimum is a good proxy for the size of the next cycle (SNmax≈ DM [WSO scale μT]). The successful prediction of Cycle 24 seems to bear that out, as well as the observed success from previous cycles. We used the average 'Dipole Moment', i.e. the difference, DM, between the fields at the North pole and the South pole. The 20nHz filtered WSO DM matches well the HMI DM on the WSO scale using the same 30-day window as WSO. So, we can extend WSO using HMI into the future as needed. This is **good**!

HMI Polar Fields Up-to-Date



The South has stabilized and the North is still growing.

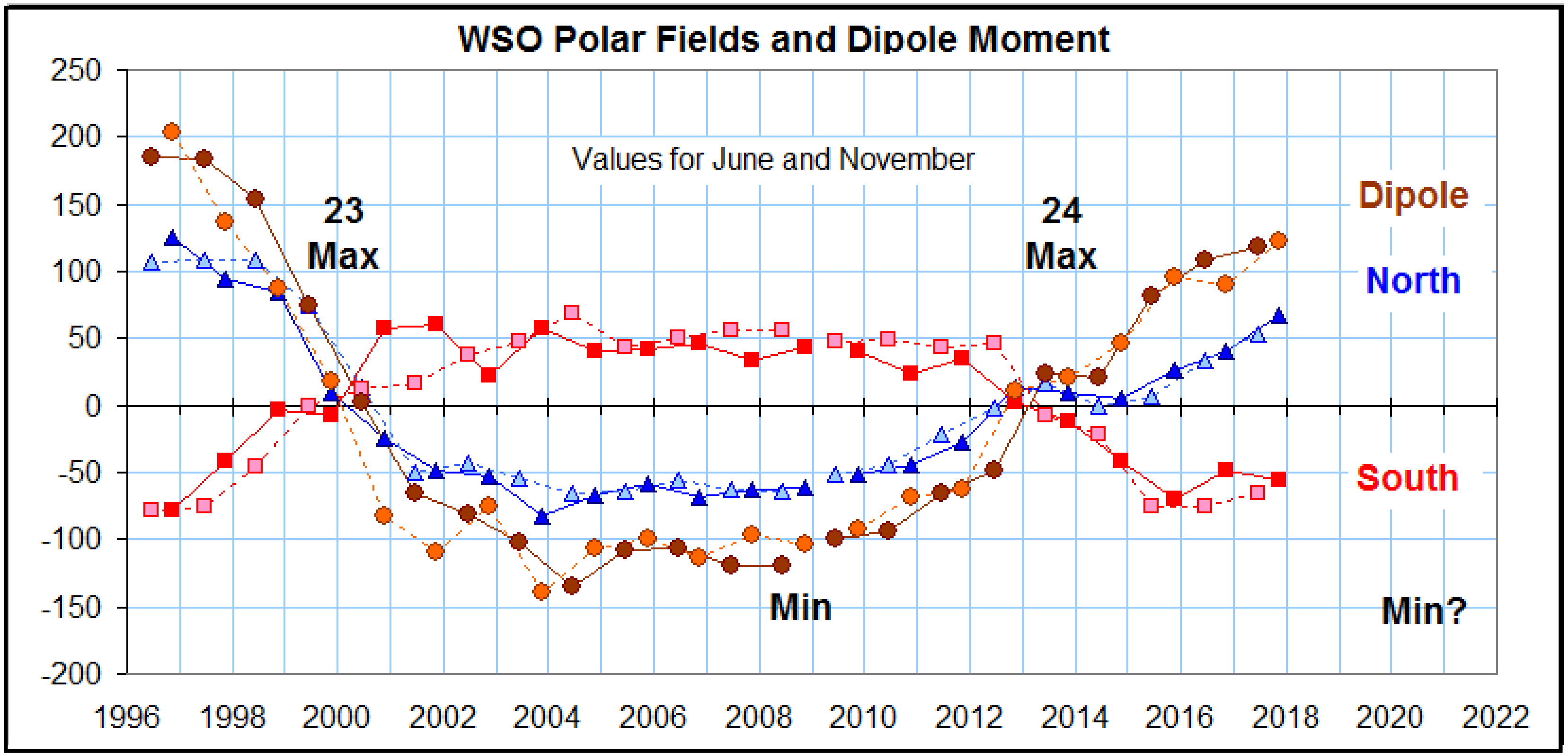
Lots of Positive Flux Still on its Way to the Solar North Pole



SDO 2017-11-07

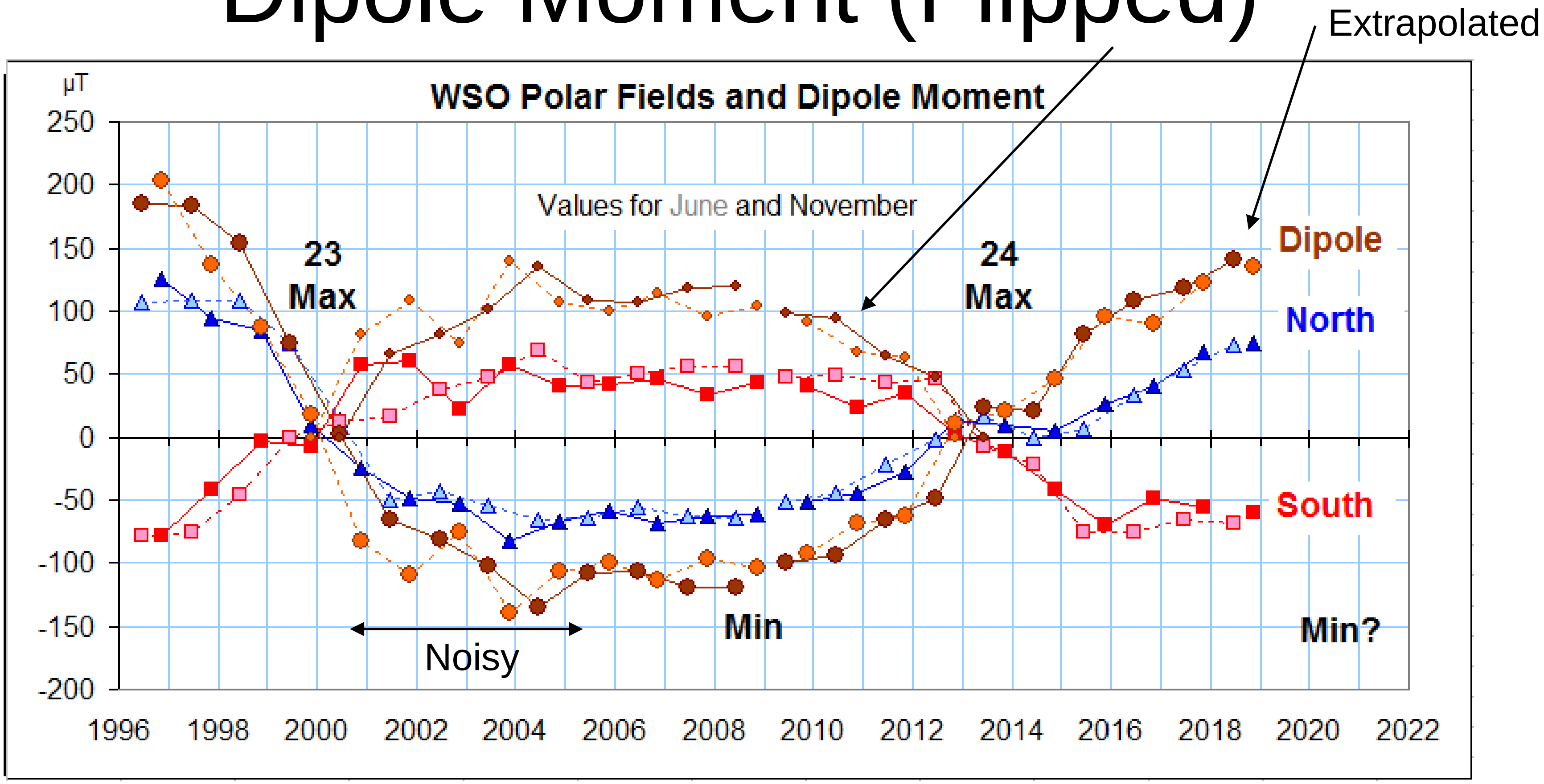
AR coronal hole and active region map (solen.info)

WSO Polar Fields and Dipole Moment



The Dipole Moment is calculated as the North Polar Field minus the South Polar Field at the same time of the year. Here I used the first two weeks of June (light symbols on dashed curve) and of November, respectively. That effectively removes the annual modulation.

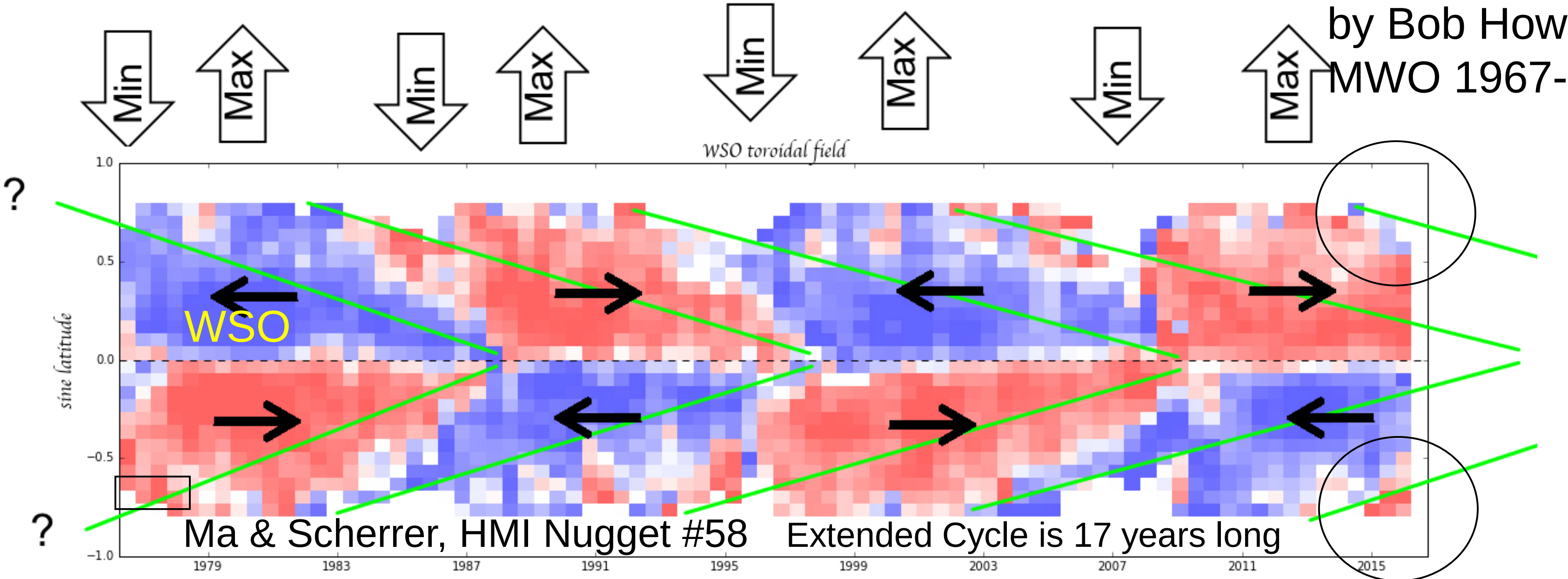
WSO Polar Fields and Dipole Moment (Flipped)



The Dipole Moment is calculated as the North Polar Field minus the South Polar Field at the same time of the year. Here I used the first two weeks of June (light symbols on dashed curve) and of November, respectively. That effectively removes the annual modulation.

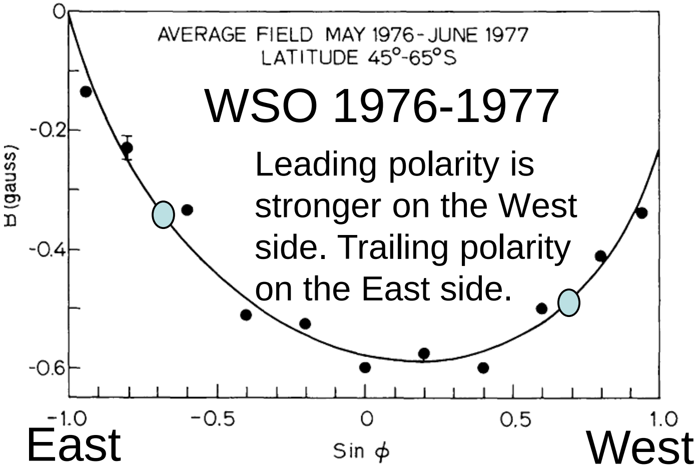
Toroidal Field Shows SC25 has Begun

Effect discovered by Bob Howard MWO 1967-1973

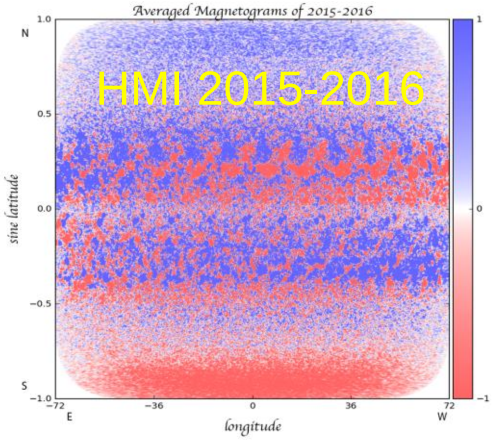


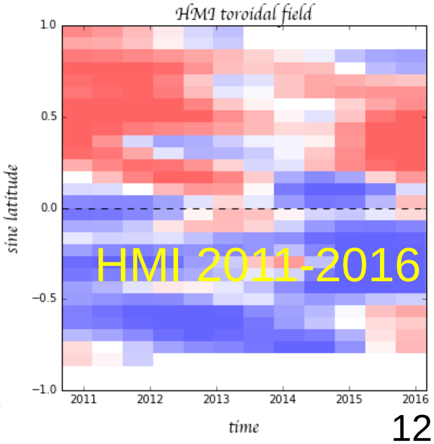
Ma & Scherrer, HMI Nugget #58

Extended Cycle is 17 years long



Leading polarity is stronger on the West side. Trailing polarity on the East side.

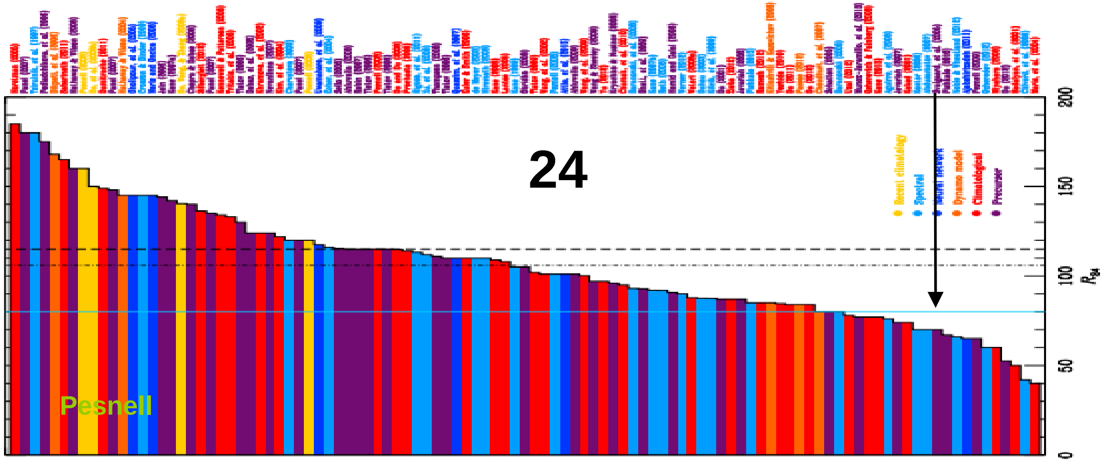




Summary VI (The Polar Field Precursor Hypothesis)

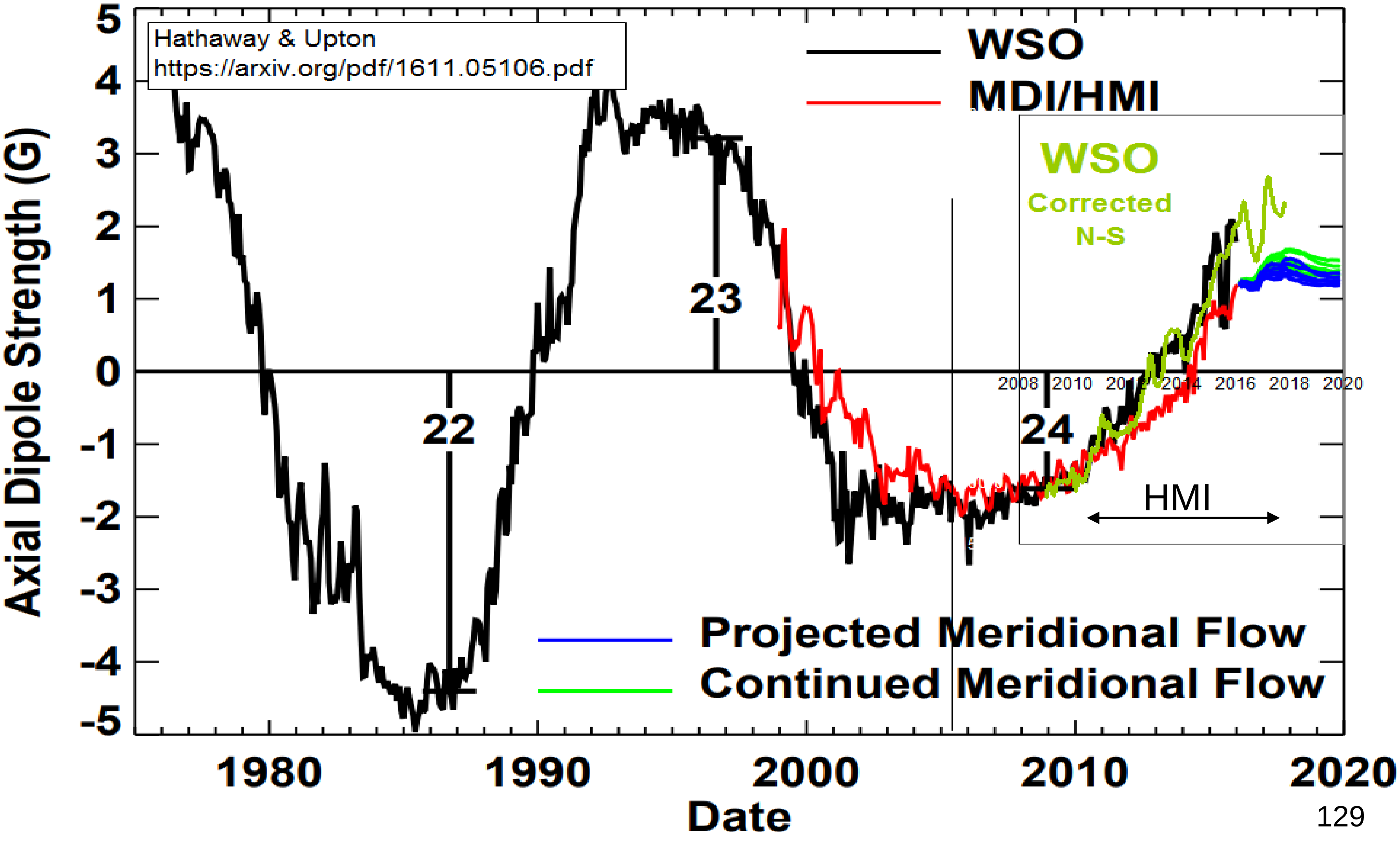
- Began with the 1978 GRL paper by S+S+S+W
- A stable yearly variation ~3 years before minimum suggested that the polar fields might be used as a precursor for the size of the next cycle [S+C+K 2005]
- Scattered light diminished the polar fields in 1976-1977
- In 2017, dirt on the Littrow Lens cut the polar fields in half
- Scaled HMI polar fields match filtered WSO field very well [with no ‘shifts’]
- The South Pole is now stable, the North is still growing
- So the dipole moment [N-S] may grow larger than for the previous minimum, suggesting that SC25 will be somewhat larger than SC24

Predictions of Solar Cycle 25

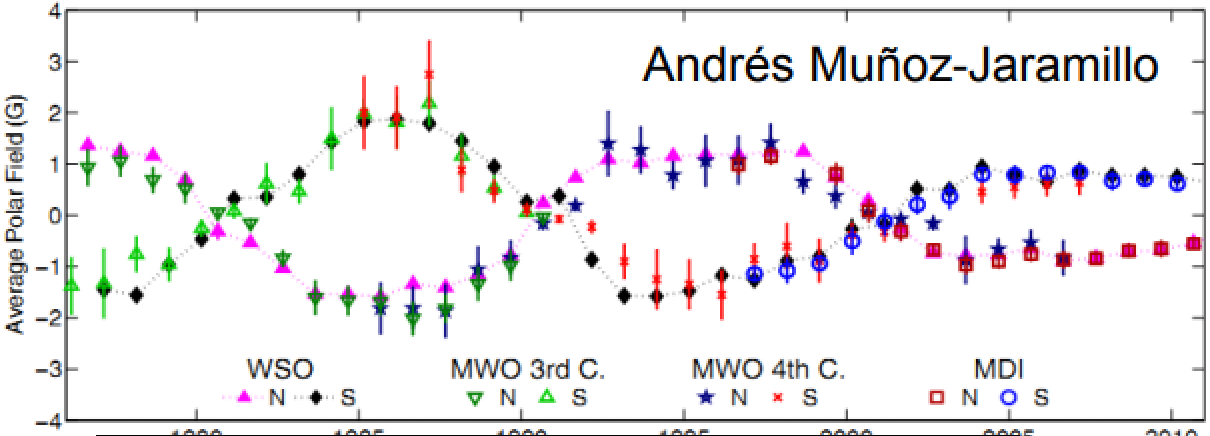


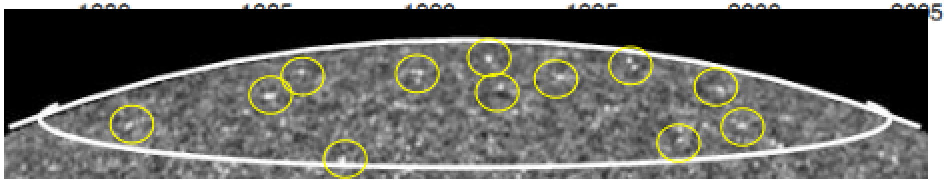
Extrapolations Often do Not Work

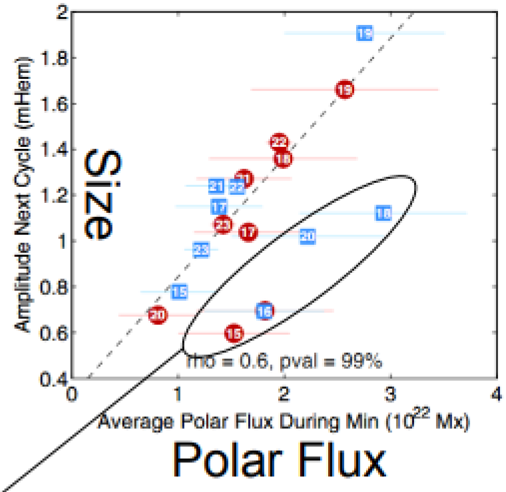
A SFT Prediction of Solar Cycle 25

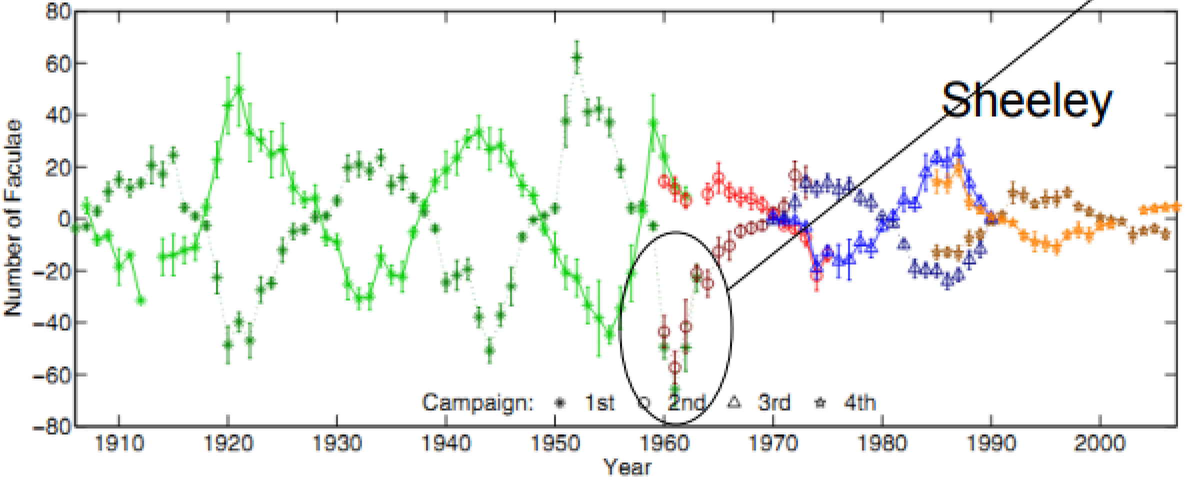


Polar Faculae as Proxy for Polar Magnetic ‘Field’ [Flux] and Predictor


Andrés Muñoz-Jaramillo



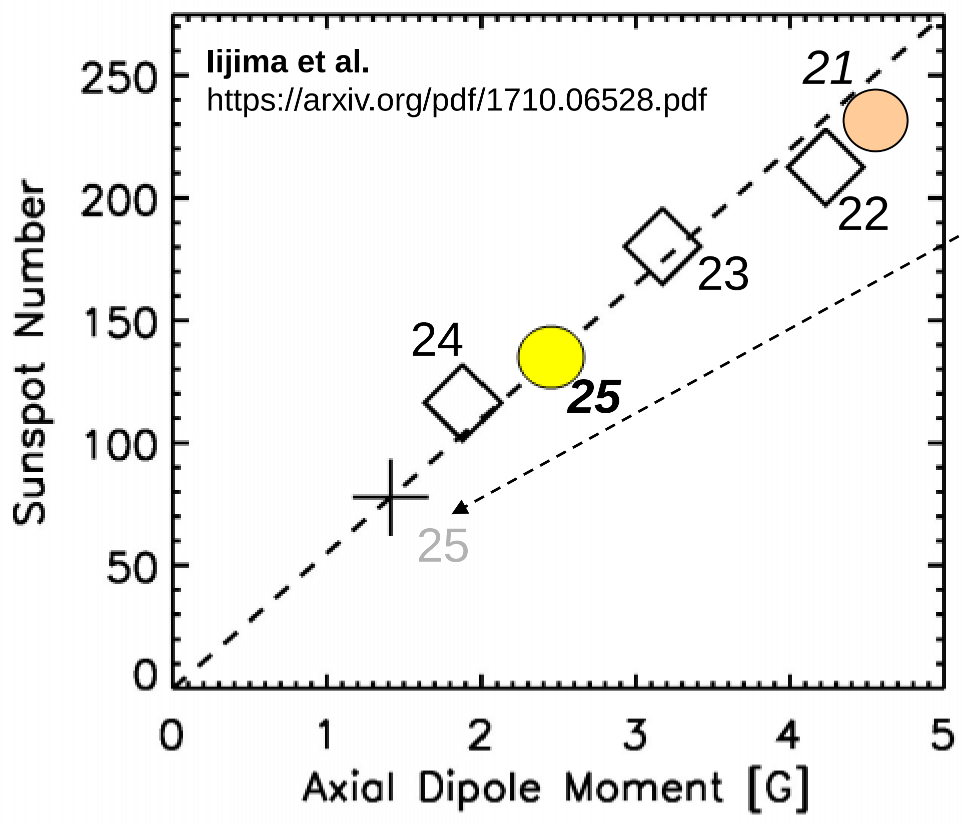



Sheeley

The inferred polar flux at minimum is a fair proxy for the size of the next solar cycle.

Some outliers are due to ‘spikes’ (surges) in the faculae count.

Simulations are Hostages to Assumptions and Over-Confidence


Iijima et al.
https://arxiv.org/pdf/1710.06528.pdf

Iijima et al. 2017: “We predict that the strength of the axial dipole moment at Cycle 24/25 minimum will be several tens of percent weaker than the previous minimum.”

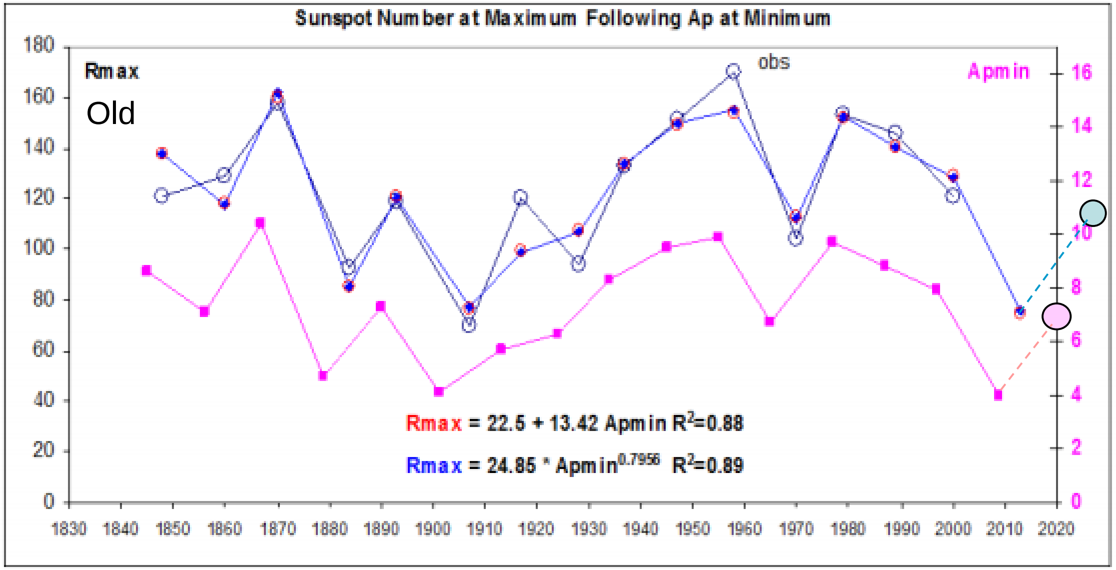
But:

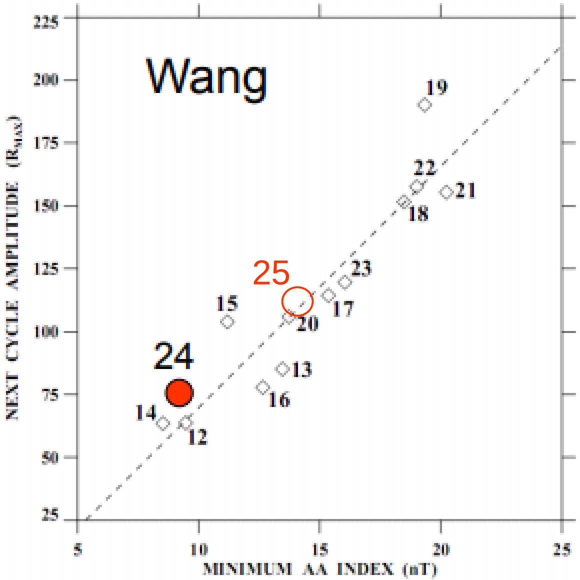
Cameron et al. 2016: “The empirical correlation between the dipole moment during solar minimum and the strength of the subsequent cycle thus suggests that Cycle 25 will be of moderate amplitude, not much **higher** than that of the current cycle.”

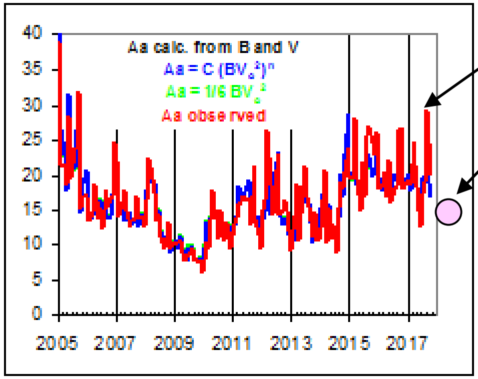
For Cycle 21 🟠, I used the Dipole Moment corrected for scattered light. For Cycle 25 🟡 I used the latest (corrected) WSO data.

Thus not much **lower**…

Geomagnetic Activity Seems to be a Decent Precursor as Well







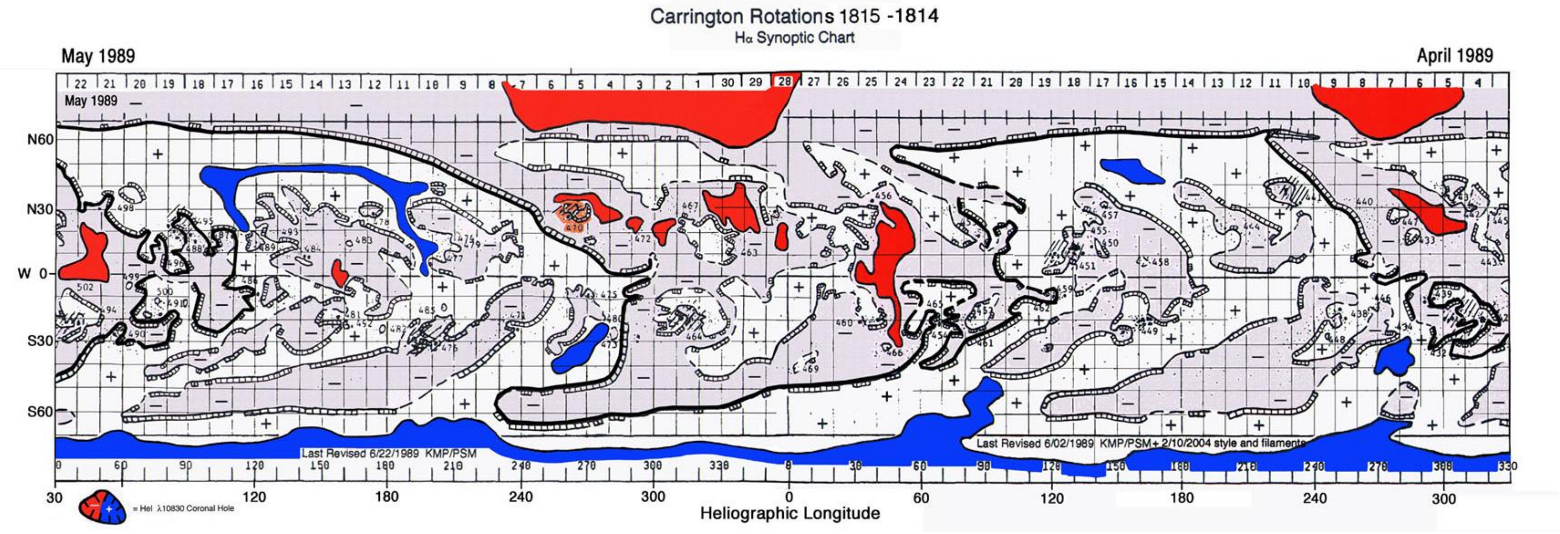
Highest in SC24

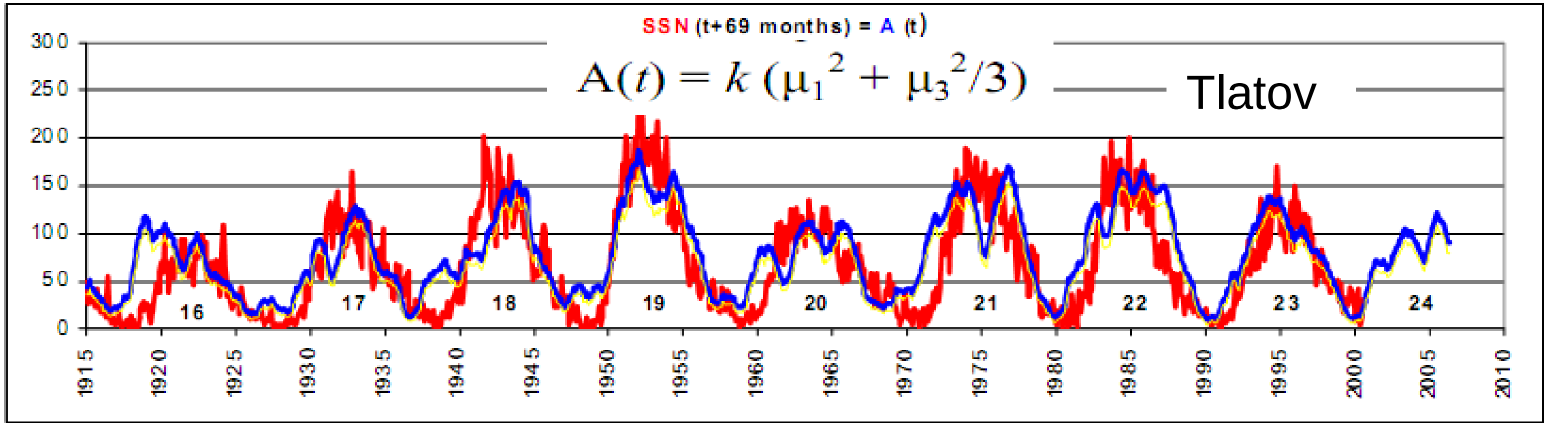
Extrapolate (!) ap [or aa] 2 to 3 years into the future

The idea is that the polar fields at sunspot minimum makes up most of the magnetic flux in the heliosphere and that geomagnetic activity depends on that flux.

SC25 perhaps like SC20

‘Large-Scale’ Fields are also a Precursor



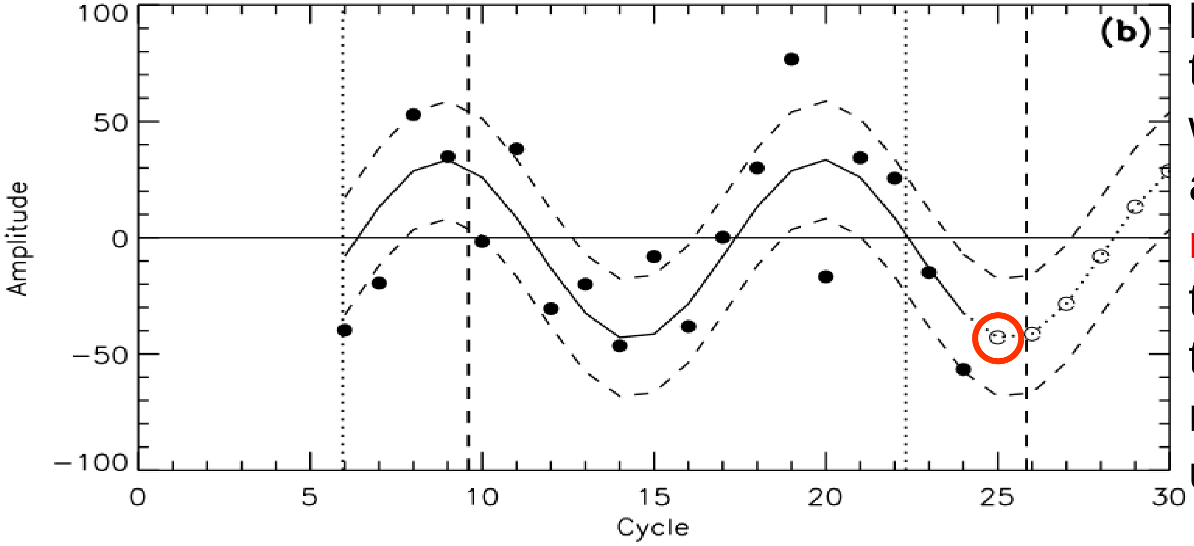


Assign fields of +1 and -1 to areas between neutral lines and calculate the global dipole μ1 and octupole μ3 components. They predict the cycle 69 months ahead

Anything Goes?

arXiv:1711.04117 “Will Solar Cycles 25 and 26 Be Weaker than Cycle 24?”
J. Javaraiah, Solar Physics Vol. 292, p. 172, November 2017:

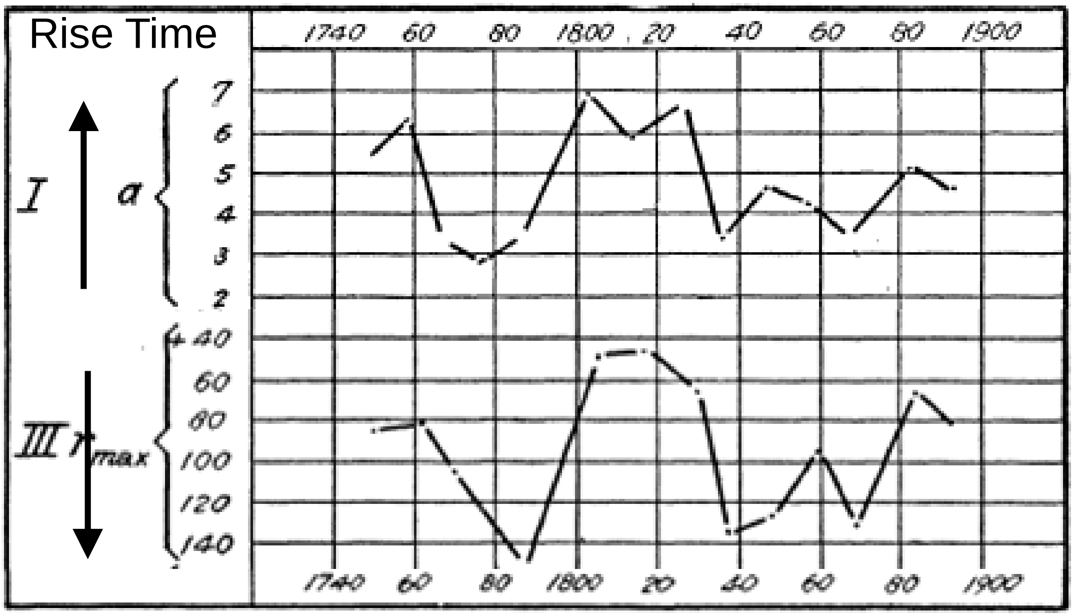
“We fitted a cosine function to the amplitudes and times of the solar cycles after subtracting a linear fit of the amplitudes. The best cosine fit shows overall properties (periods, maxima, minima, etc.) of Gleissberg cycles, but with large uncertainties. We obtain a pattern of the rising phase of the upcoming Gleissberg cycle, but there is considerable ambiguity. Using the epochs of violations of the Gnevyshev-Ohl rule (G-O rule) and the ‘tentative inverse G-O rule’ of solar cycles during the period 1610-2015, and also **using the epochs where the orbital angular momentum of the Sun is steeply decreased** during the period 1600-2099, we infer that Solar Cycle 25 will be weaker than Cycle 24. Our analysis also suggests a much lower value (30-40 [on the old scale or 40-70 on the revised scale]) for the maximum amplitude of the upcoming Cycle 25.”

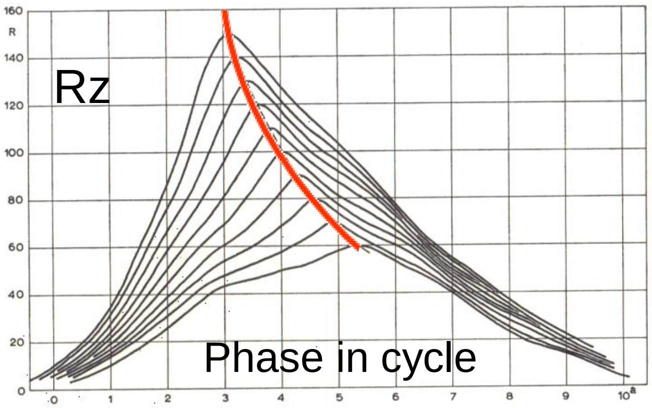


Half of SC24

The (Misnamed) Waldmeier Effect

Although Max Waldmeier today is credited with “the Waldmeier Effect” for the finding that **large sunspot cycles have shorter rise times than do small cycles**, this fact was known already to Wolf (we are still basically using his determinations of the times of early minima and maxima) and was seriously discussed around the turn of the 20th century (e.g. Halm 1901, 1902; Lockyer 1901; and Wolfer 1902 [Figure below]) and taken as evidence for an ‘eruption-type’ sunspot cycle freed from ‘the shackles of unduly close adherence to harmonic analysis’ (Milne 1935), although the allure of ‘oscillators’ still rears it (ugly) head today…

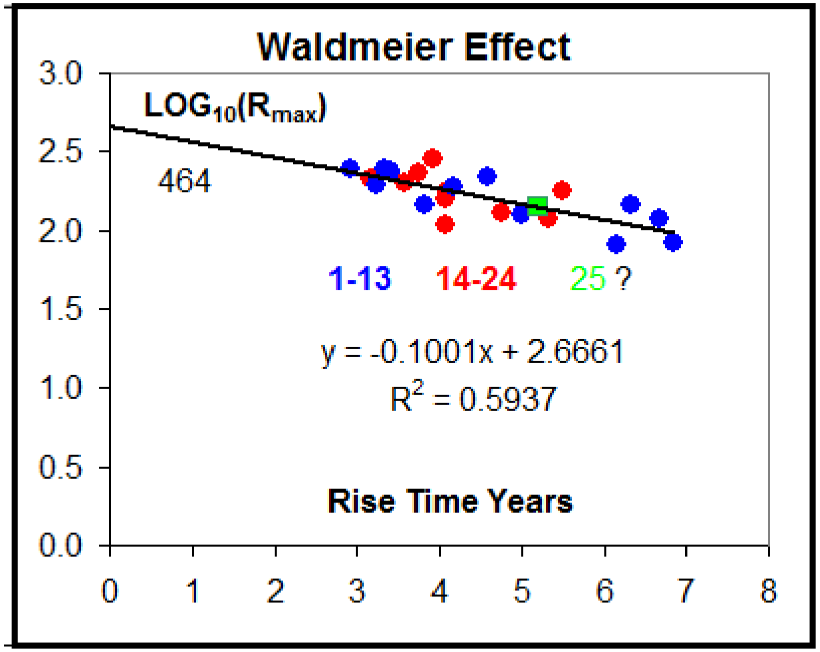


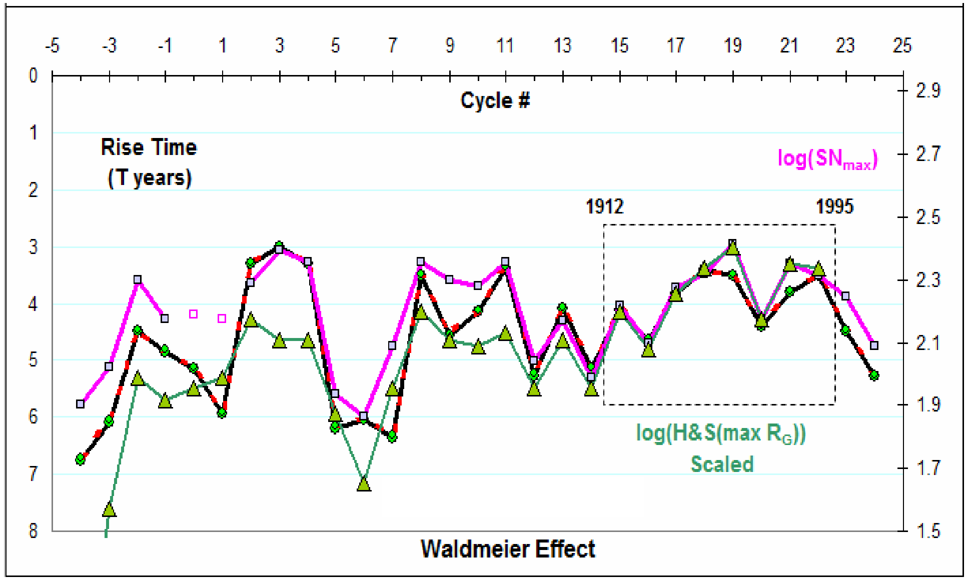


Waldmeier’s one-parameter curve family for the sunspot number through the cycle (Waldmeier 1968)

Waldmeier's Insight (1978)

"There is a relationship between the rise time T (in years) from minimum to maximum and the maximum smoothed monthly sunspot number R_{Max}. The times of the extrema can be determined **without knowledge of the reduction (or scale) factors**. Since this relationship also holds for the years from 1750 to 1848 we can be assured that the **scale value of the relative sunspot number over the last more than 200 years has stayed constant** or has only been subject to insignificant variations"





We can use the effect to get the rise time and thus when maximum will occur

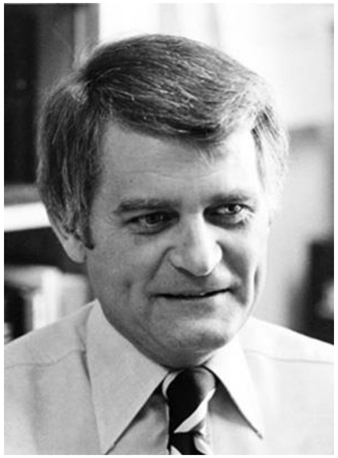
My *Guess* about Cycle 25

- Somewhat stronger than SC 24
- Perhaps on Par with SC 20
- No Maunder Minimum this Time
- Still too early to put a firm number on the prediction not to speak about an error bar
- Ask me next year when the North Pole has stabilized
- "It is better to be lucky than to be good"

Summary VII (Prediction of Solar Cycle 25 and Beyond)

- Polar Faculae may be an indicator for the Polar Fields and thus be used as precursors
- Simulations and assimilations with Flux Transport Models have promise
- Geomagnetic Activity at minimum seems to work as precursors
- HMF strength at or near minimum seems to be correlated with the Polar Fields and thus work as precursors
- Planetary Control of the solar cycle has been invoked ever since Wolf's first attempts in the 1850s, but lack credible physical mechanisms
- Monitoring of the Polar Fields may be the simplest and most effective path to go. My current guess is for a cycle with amplitude somewhere between SC20 and SC24

Caveat Auditor



The listener beware

"It cannot be said that much progress has been made towards the disclosure of the cause, or causes, of the sunspot cycle. Most thinkers on this difficult subject provide a quasi-explanation of the periodicity through certain assumed vicissitudes affecting internal processes. In all these theories, however, the course of transition is arbitrarily arranged to suit a period, which imposes itself as a fact peremptorily claiming admittance, while obstinately defying explanation"

Agnes M. Clerke, A Popular History of Astronomy During the Nineteenth Century, page 163, 4th edition, A. & C. Black, London, 1902.

Have we made Progress? Perhaps Some, but maybe not Much. Cycle 25 might give us needed confidence, except we, full of hope, say that for every new cycle…

A society that travels to other planets needs forecasts of the solar activity visible from any point in the solar system several years in advance. Given the wide range of the predictions for the amplitude of Solar Cycle 24 and the many methods that were used to produce them, we look forward to this cycle [25?] answering important questions about how to predict solar activity at the Earth and throughout the solar system (Pesnell, 2016)

We need imagination, but not too much of it

“Progress is more often made by re-examining what had been looked at, and sometimes ignored, by generations of earlier students, but with new insights and new reasons and even new prejudice. To improve the historical record we must probably rely most on what we already have at hand. *After 130 years it is probably time to repeat Wolf’s analysis of the earliest sunspot records*. The period of the Little Maunder Minimum, between 1800 and 1820, seems one that needs more study. The rich auroral history deserves deeper and repeated attention in the light of our rapidly-developing understanding of coronal holes, and the solar wind, and the pictures now emerging of the real nature of the earth’s magnetosphere. It is probably tied more closely to what we read in radiocarbon, since both deal with features of solar particles and fields.

What is probably needed, for both re-analysis and in the search for new historical sources, is imagination, but not too much of it.”

John A. Eddy, The historical record of solar activity, in The Ancient Sun, pg 119 (Geocosmica et Cosmochimica Acta, Suppl. 13, 1980)

Alfvén's Nobel Acceptance Speech

On the 75th anniversary this year of his 1942 Nature paper on the foundations of MHD it seems appropriate to cite Hannes Olof Alfvén: "it is only the plasma itself which does not understand how beautiful the theories are and absolutely refuses to obey them". Alfvén's criticisms of the dangers of allowing theory to run too far from experiment and observation, or of becoming seduced by one's own models, were, and still are, extremely sensible.

We should all keep that in mind when we pretend to know what is going on.

The End