Solar Wind During the Maunder Minimum

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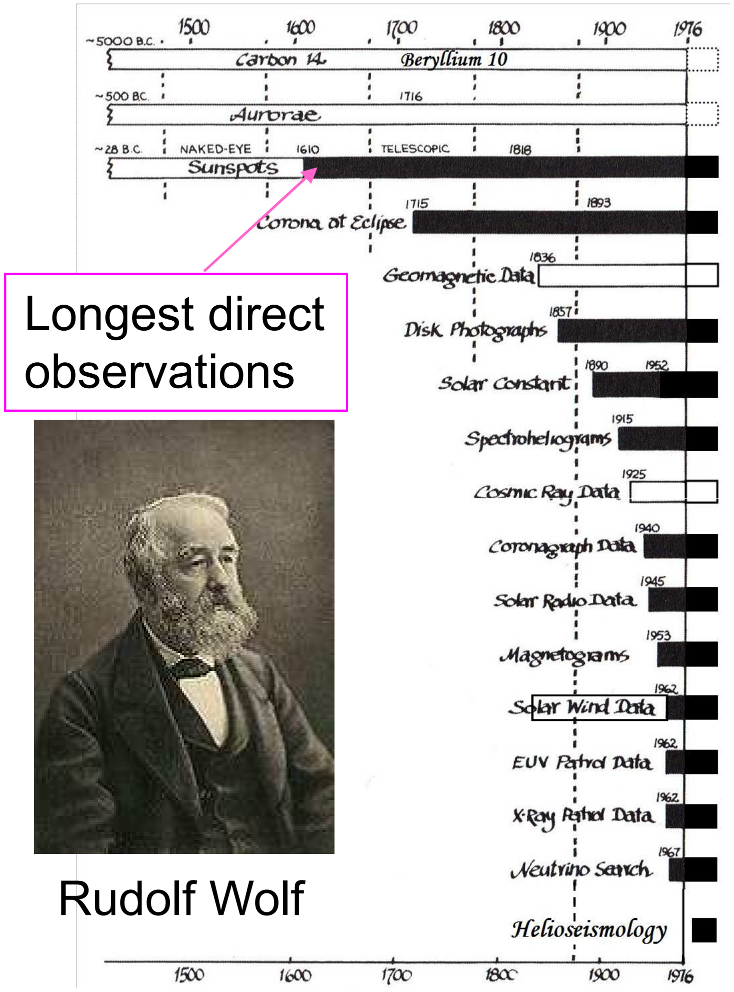
Predictive Science, San Diego, 4 Sept. 2012

Indicators of Solar Activity

- Sunspot Number (and Area, Magnetic Flux)
- Solar Radiation (TSI, UV, …, F10.7)
- Cosmic Ray Modulation
- Solar Wind
- Geomagnetic Variations
- Aurorae
- Ionospheric Parameters
- Climate?
- More…

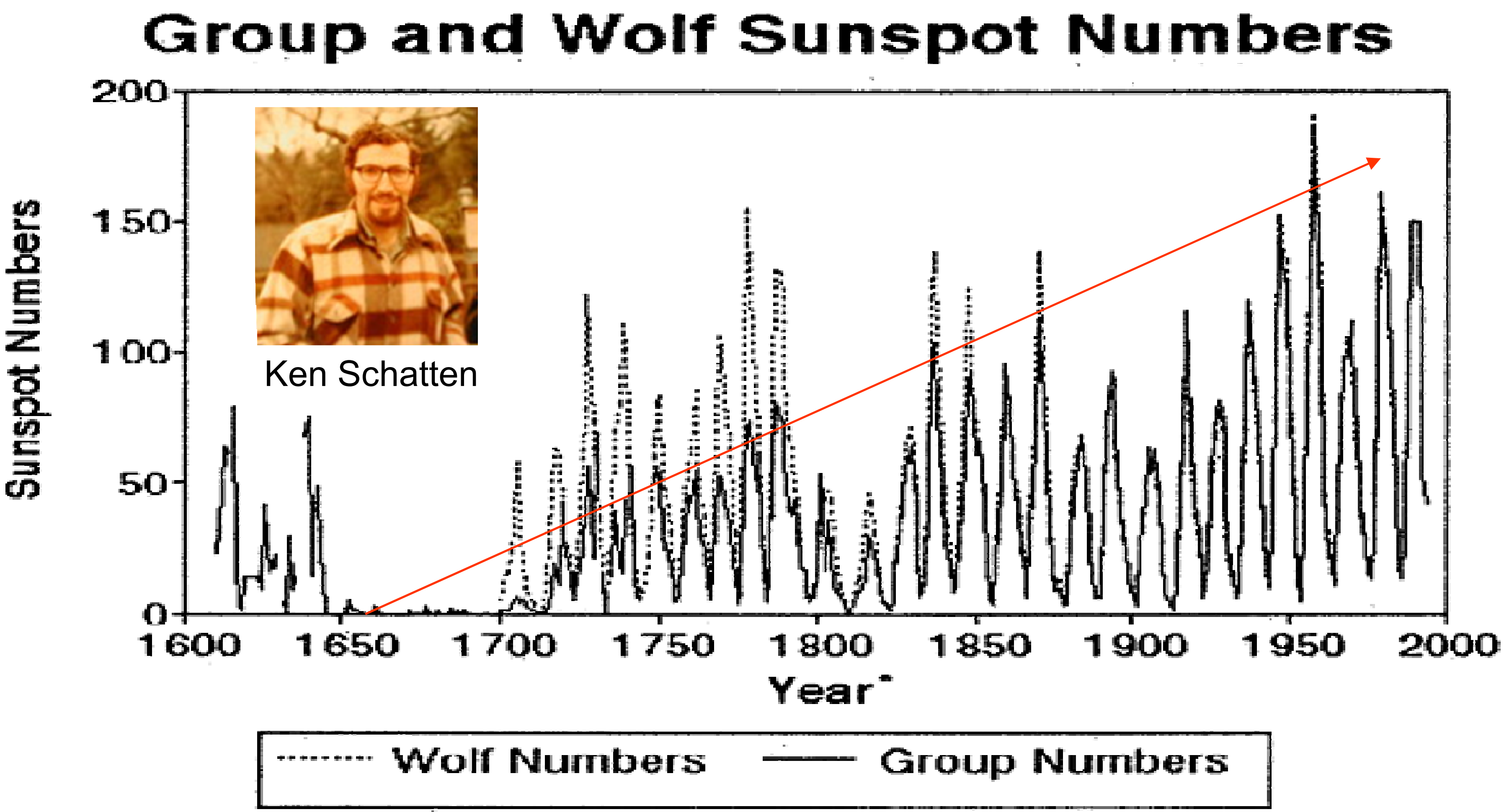


Rudolf Wolf

After Eddy, 1976

Solar Activity is *Magnetic* Activity

Unfortunately Two Data Series



Hoyt & Schatten, GRL *21*, 1994

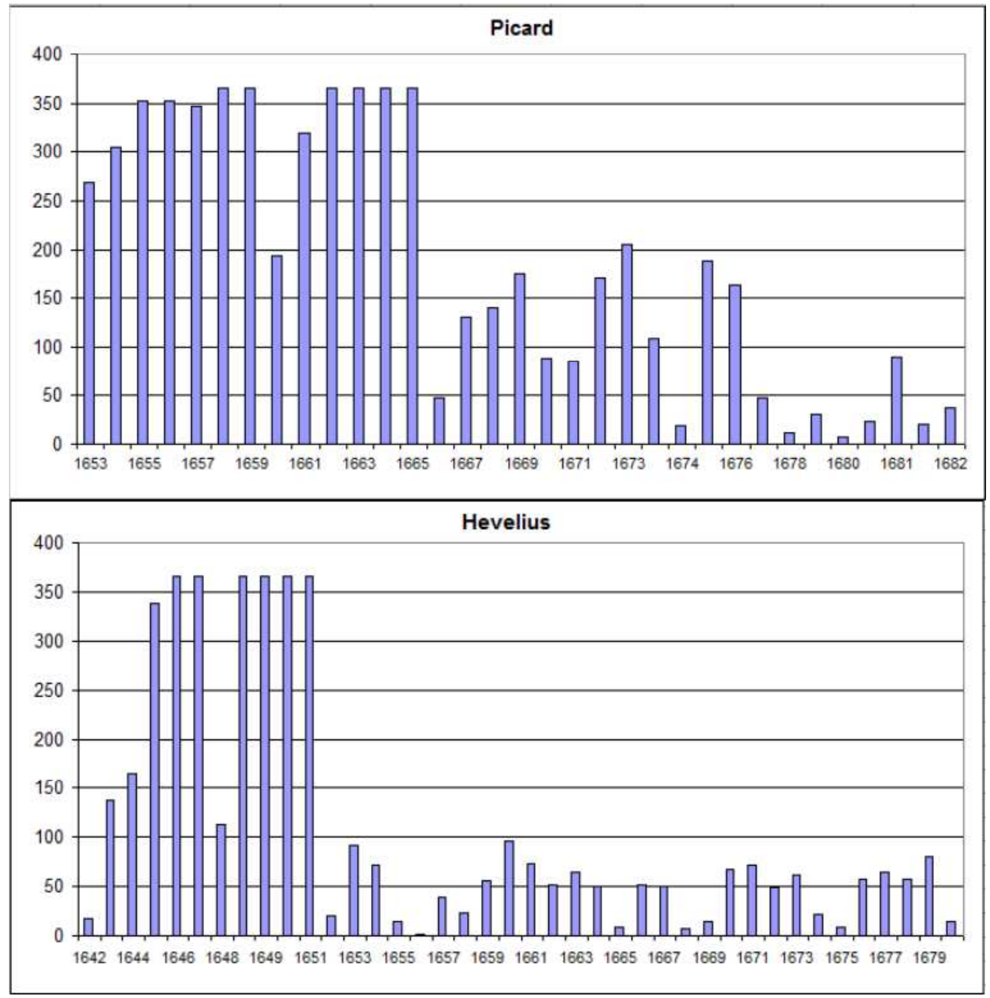
How Well was the Maunder Minimum Observed?

NUMBER OF SUNSPOT GROUPS FOR THE YEAR: 1658
AS OBSERVED BY: PICARD/KEILL, PARIS

H&S

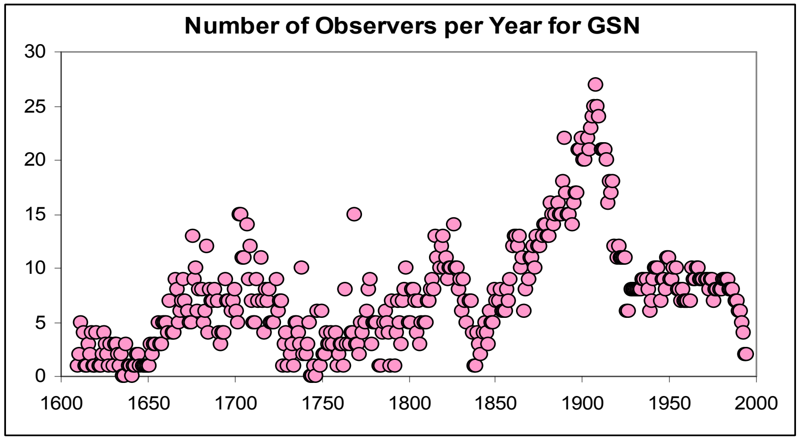
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	-99	0	0	0	0	0	0	0	0	0	0
30	0	-99	0	0	0	0	0	0	0	0	0	0
31	0	-99	0	-99	0	-99	0	0	-99	0	-99	0
means:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

It is not credible that for many years there were not a single day without observations



Number of days per year with 'observations'

More Realistic Assessment



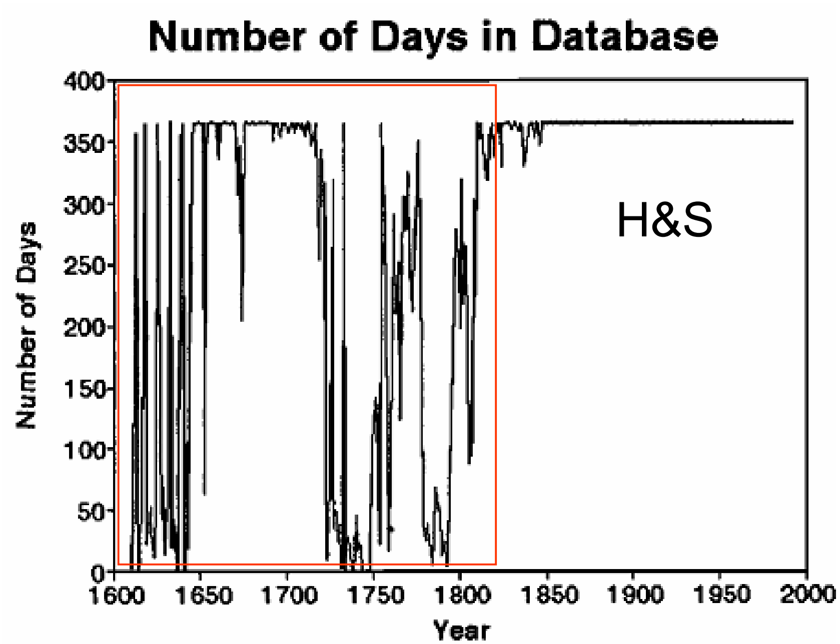
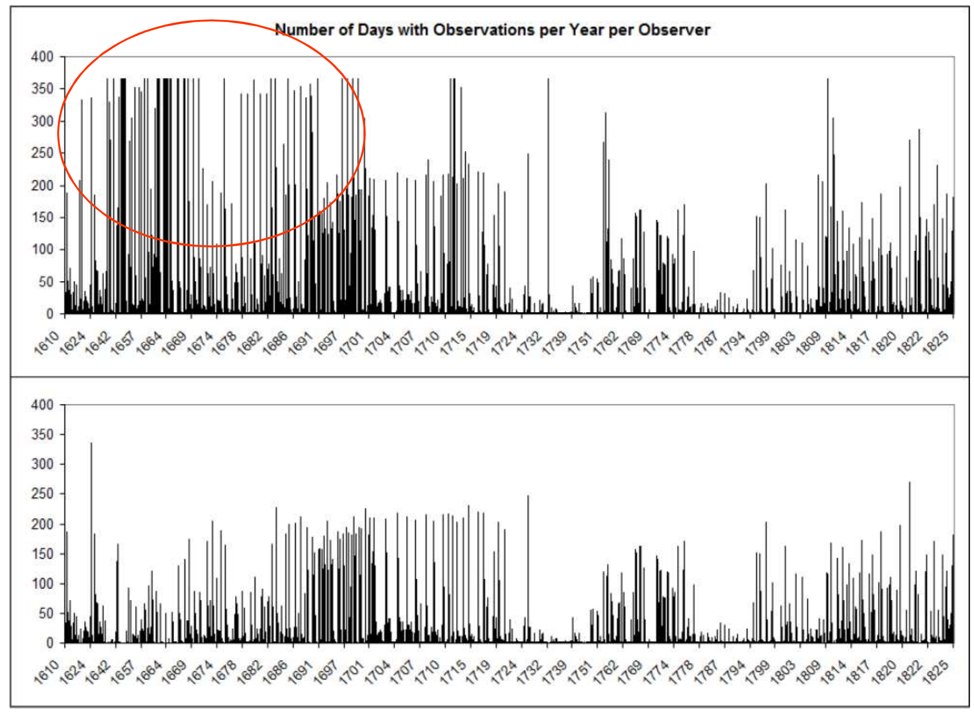


Figure 3. The number of days each year for we which have observations or interpolated values. If more than 5% of the days are observed in a year, a good yearly mean can usually be found. Most years meet this criteria. Note that the Sun was well observed during the Maunder Minimum.

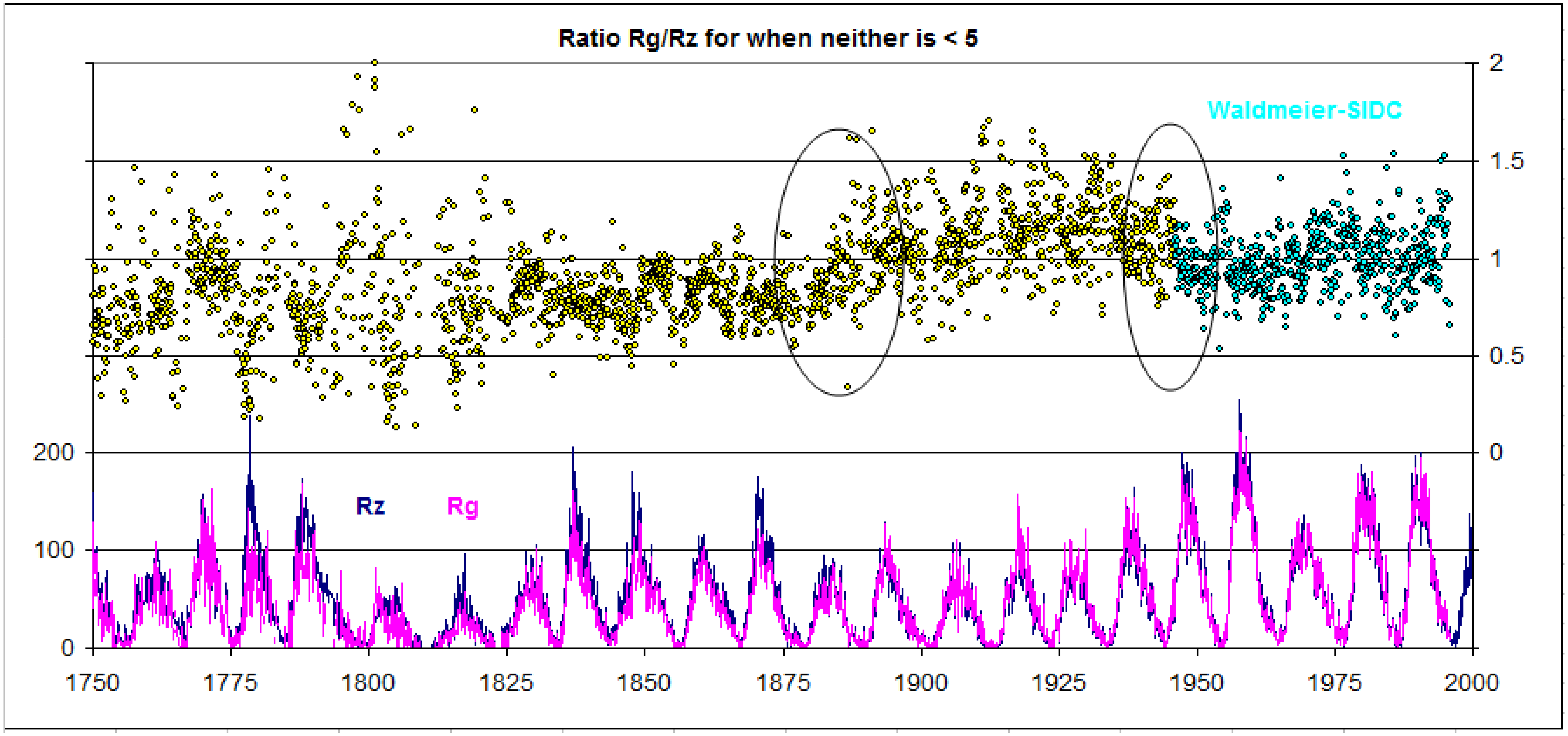
5% of 365 is ~20 days



1610 1700 1825

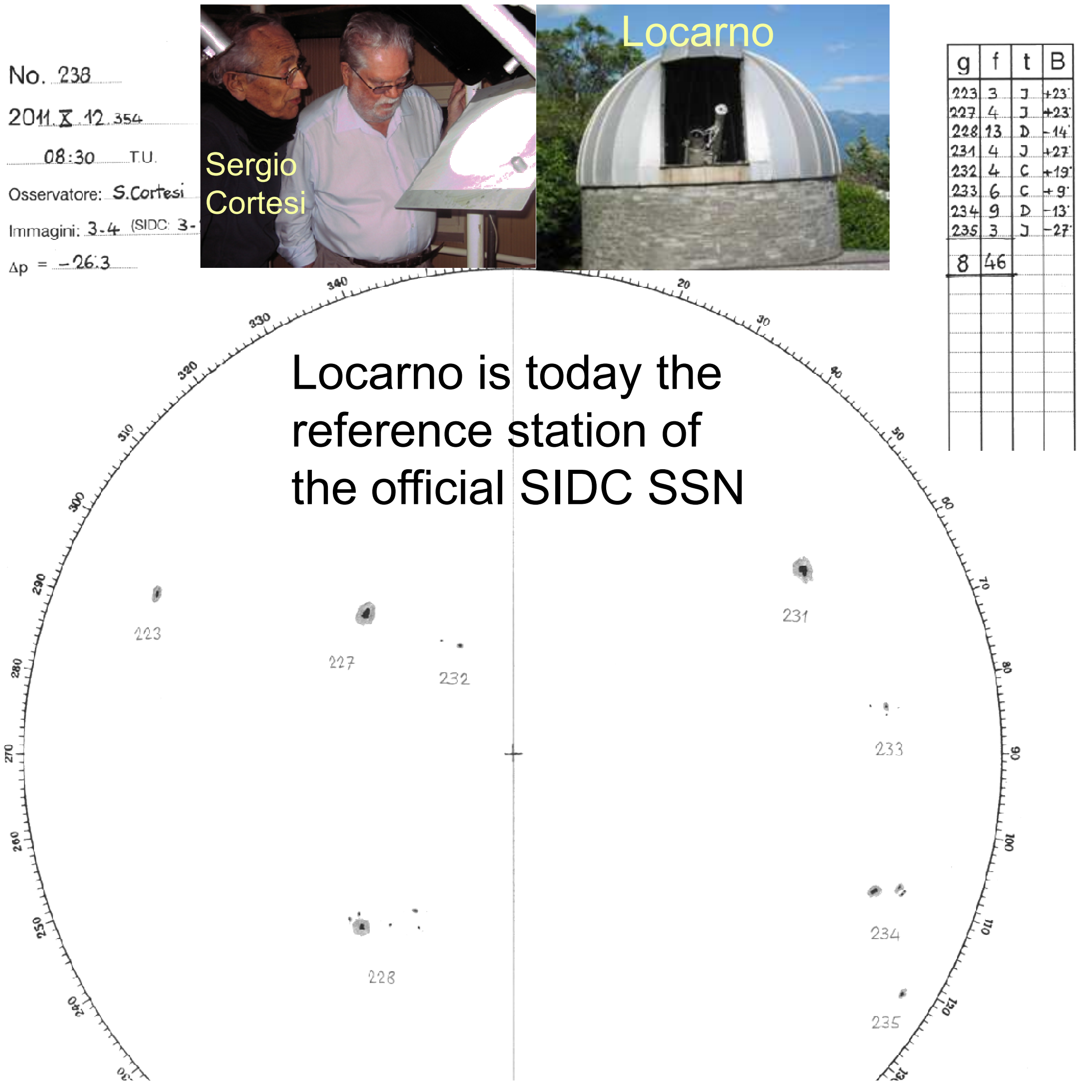
Even after eliminating the spurious years with ‘no missing data’ there are enough left to establish that the Maunder Minimum had very few visible sunspots and was not due to general lack of observations

The Ratio Group/Zurich SSN has Two Significant Discontinuities



At ~1946 (after Max Waldmeier took over) and at ~1885

Effect of Weighting of Sunspots



Locarno is today the reference station of the official SIDC SSN

223	3	**1**
227	4	**1**
228	13	**6**
231	4	**1**
232	4	**2**
233	6	**4**
234	9	**4**
235	3	**1**
8	46	**20**

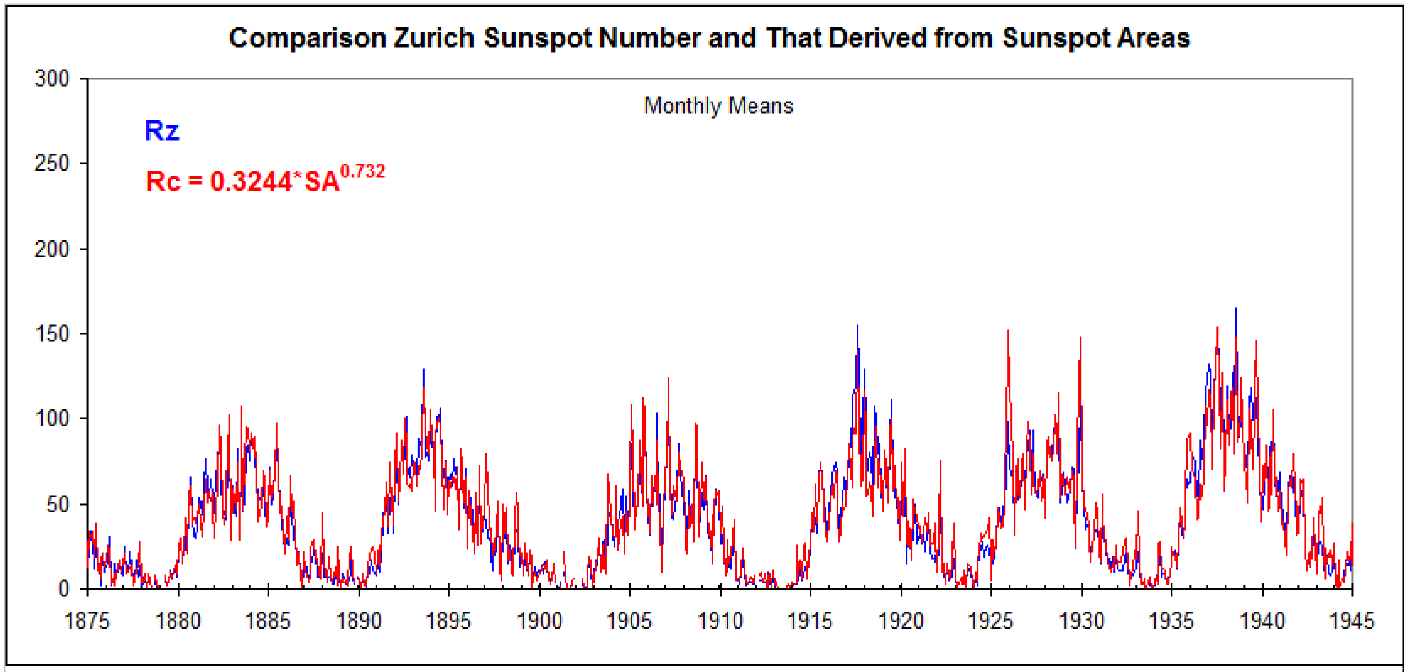
SSN = 10*G+S

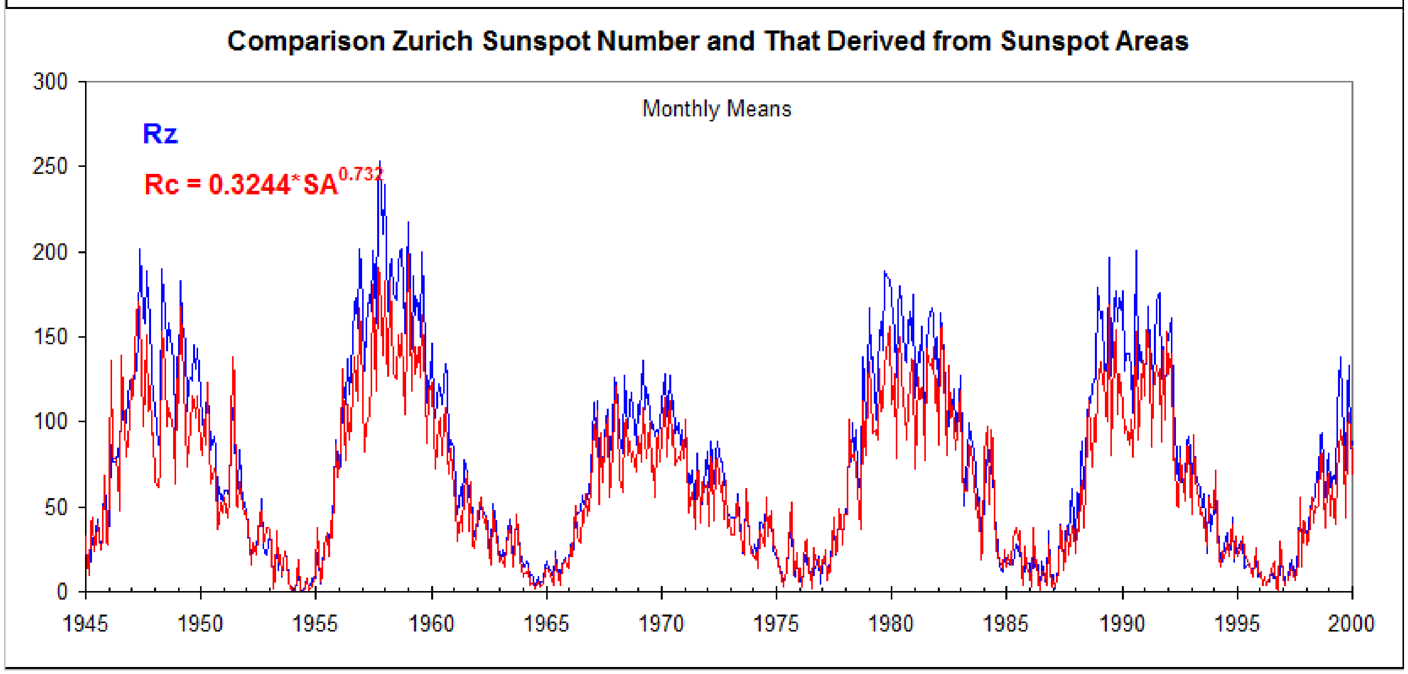
126 **100**

26% inflated

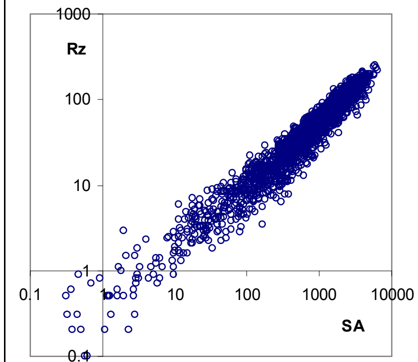
Unweighted count red

In the 1940s the observers in Zürich [and Locarno] began to Weight spots. The net result is a ~20% inflation of the official Zürich SSN since ~1945



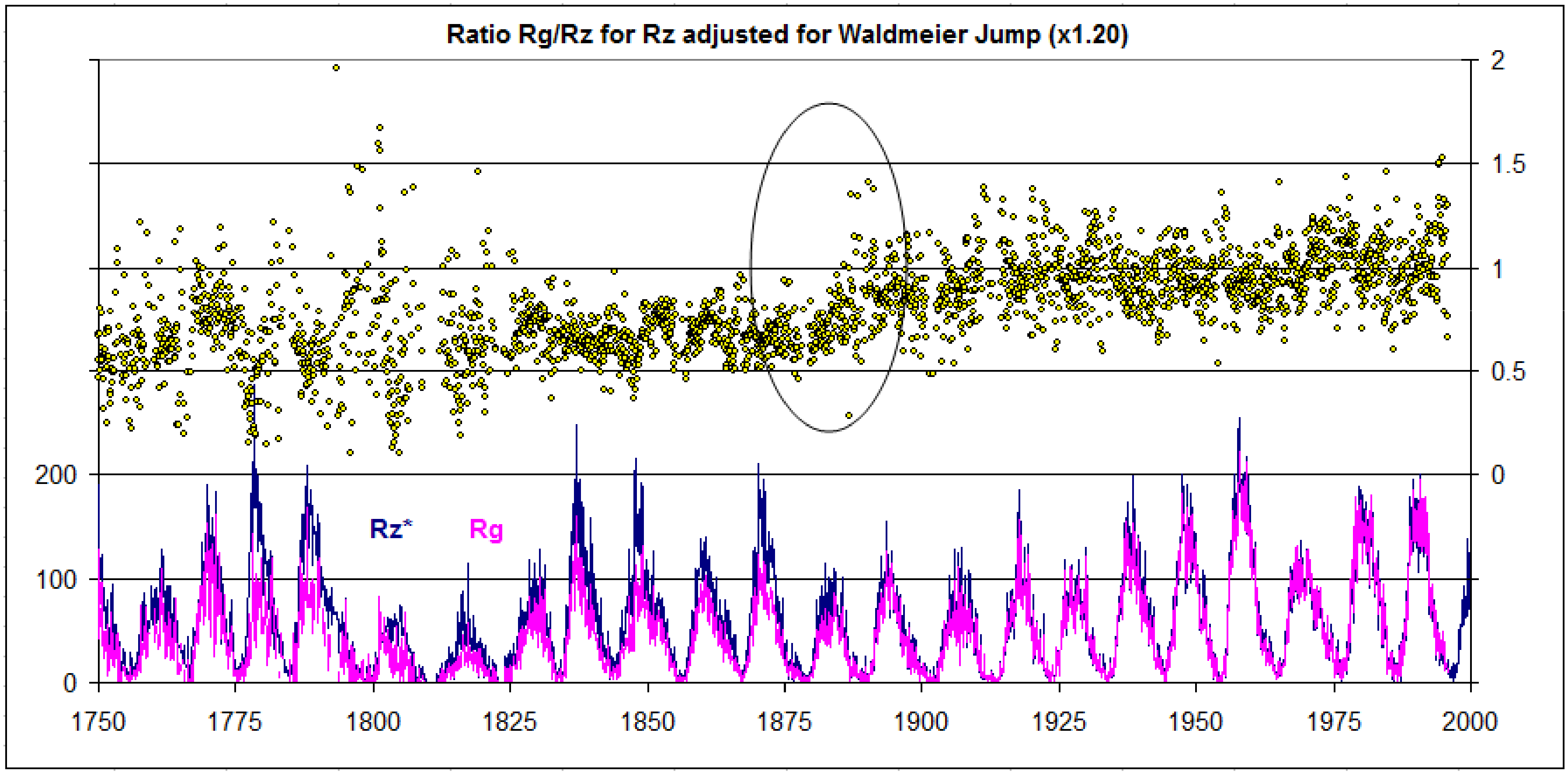


Compared with Sunspot Area (obs)



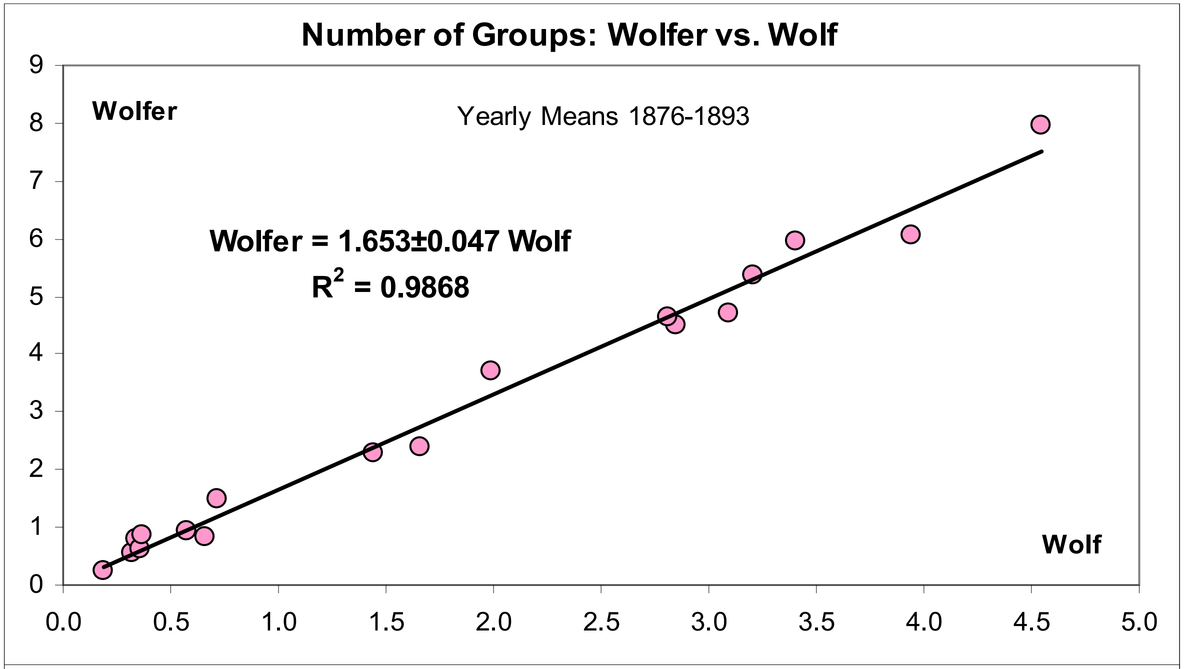
Not linear relation, but a nice power law with slope 0.732. Use relation for pre-1945 to compute Rz from Area, and note that the observed Rz after 1945 is too high [by 21%]

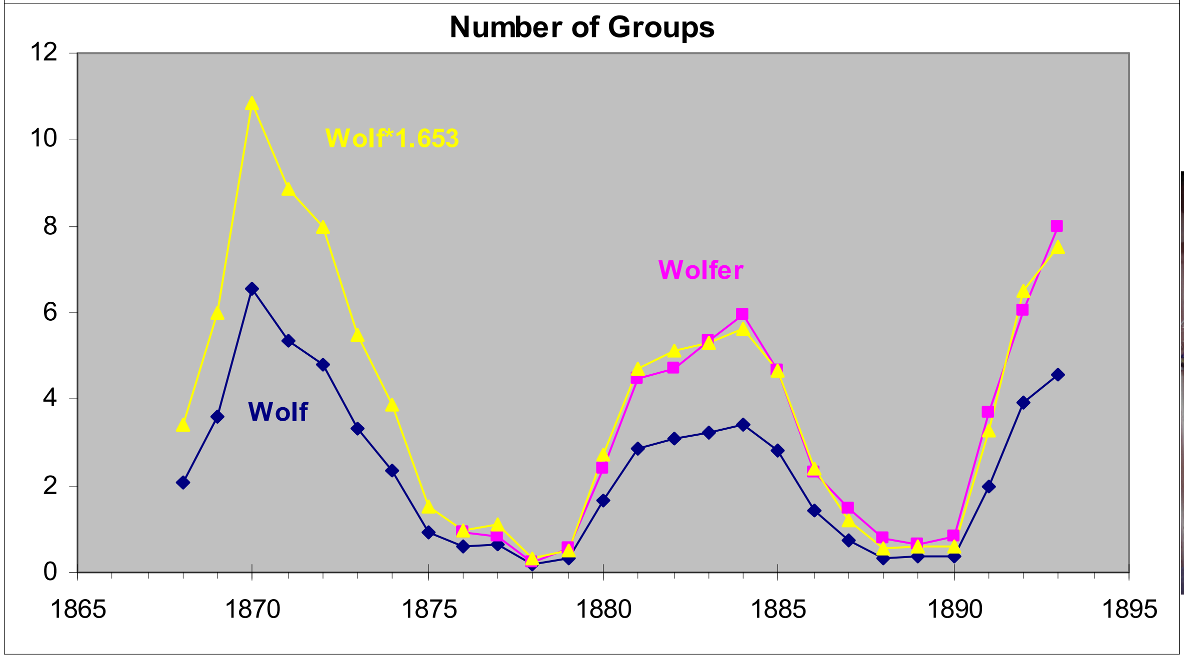
Removing the discontinuity in ~1946, by multiplying Rz before 1946 by 1.20, yields

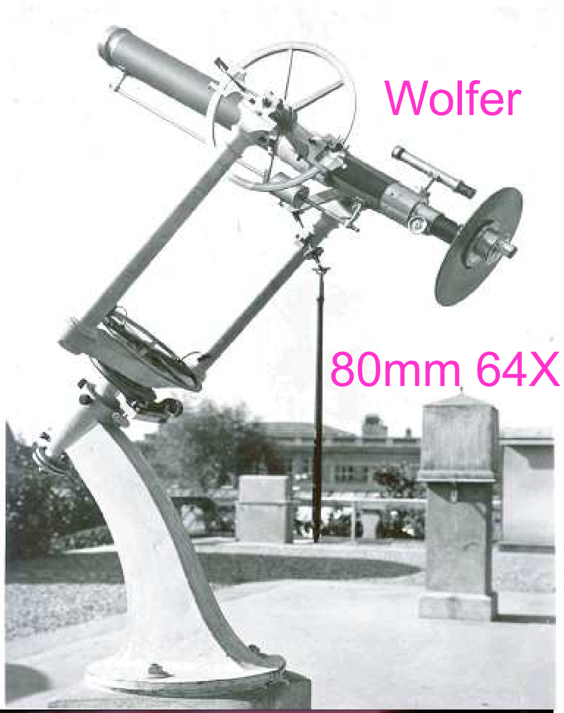


Leaving one significant discrepancy ~1885

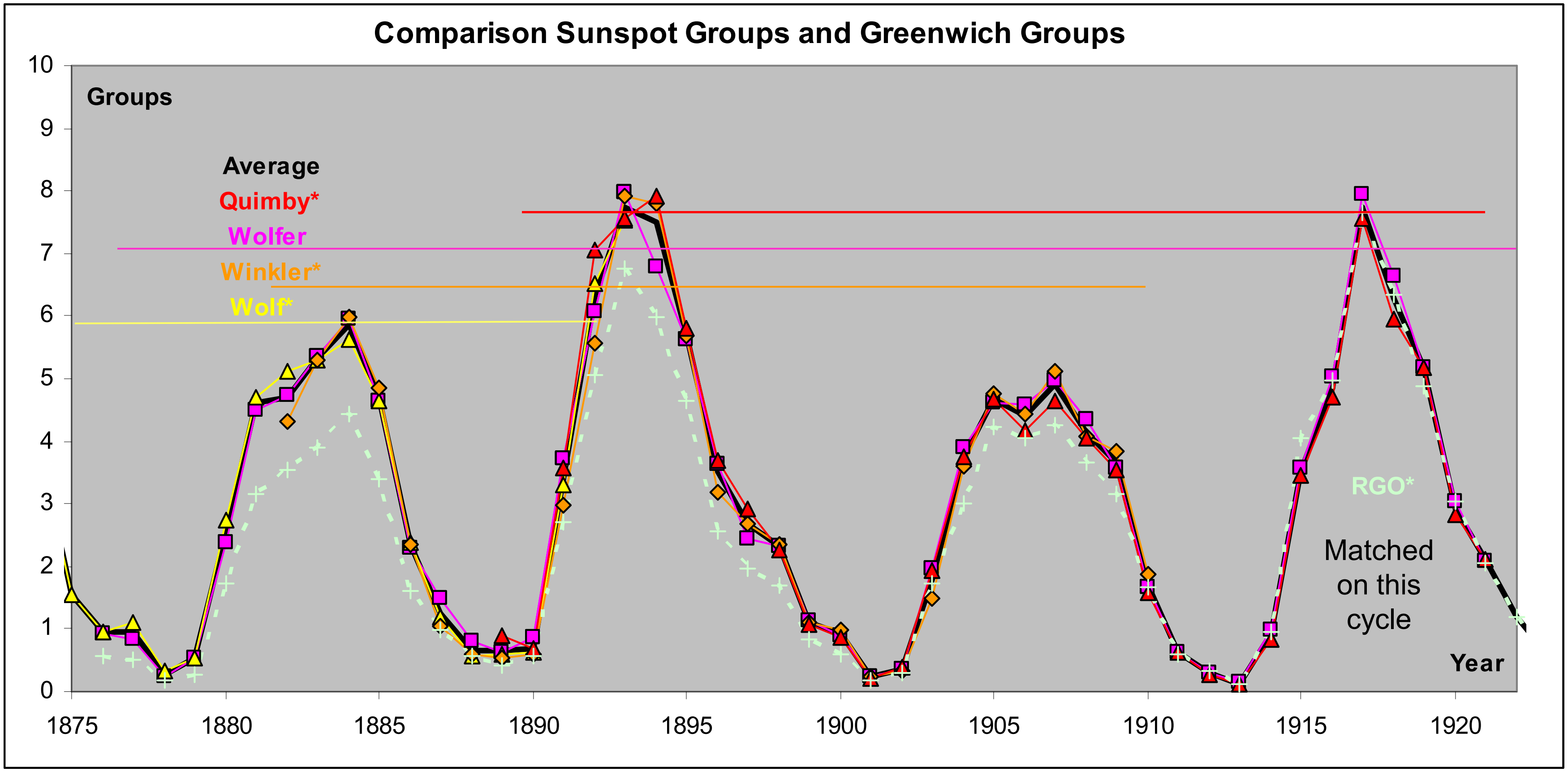
Wolf-Wolfer Groups







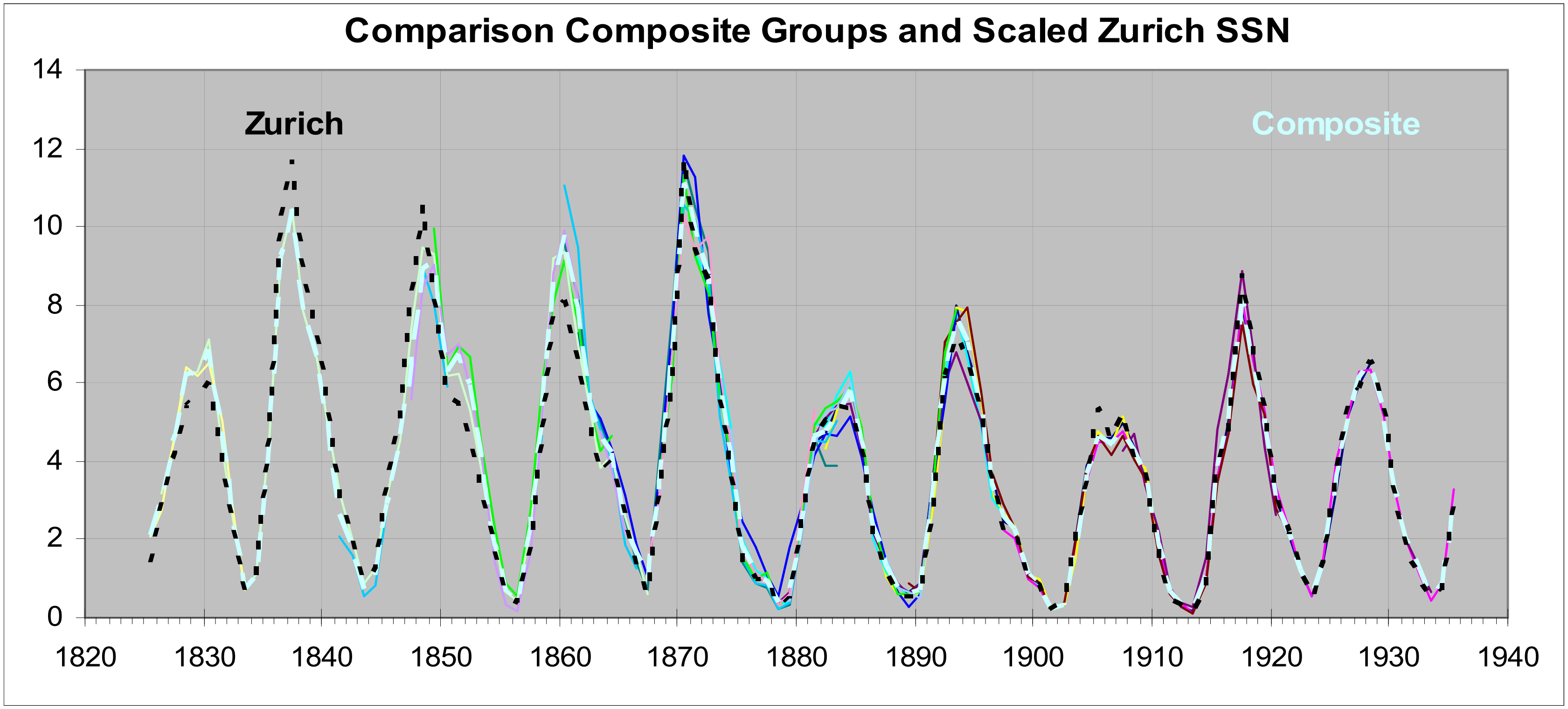
Making a Composite



Compare with group count from RGO [dashed line] and note its drift

Extending the Composite

Comparing observers back in time [that overlap first our composite and then each other] one can extend the composite successively back to Schwabe:

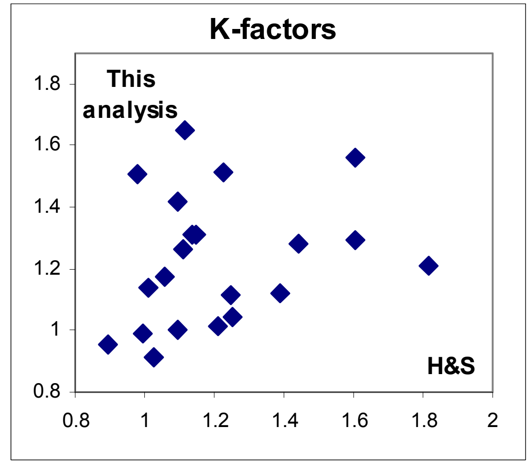


There is now no systematic difference between the Zurich SSN and a Group SSN constructed by not involving RGO.

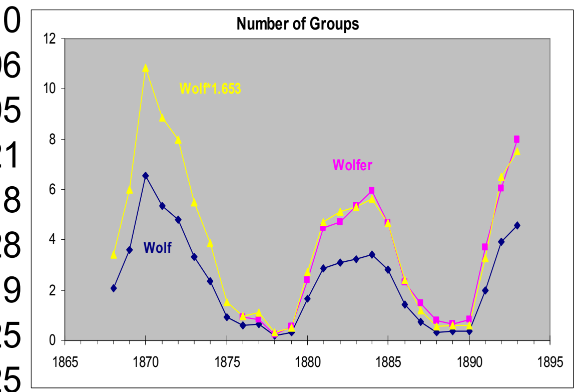
Why are these so different?

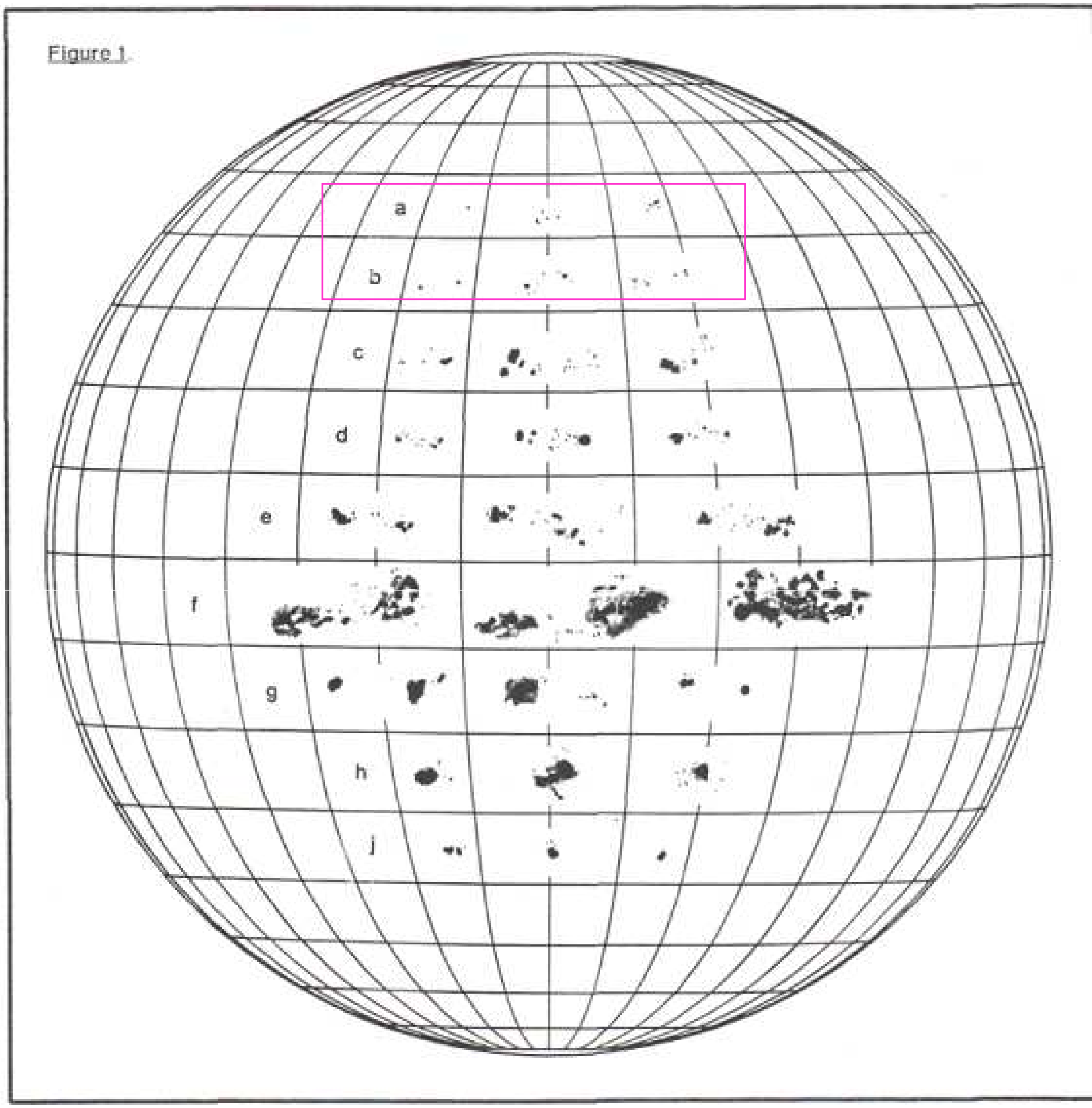
K-Factors

Observer		H&S RGO	to Wolfer	Begin	End
Wolfer, A., Zurich	2% diff.	1.094	1	1876	1928
Wolf, R., Zurich		1.117	1.6532	1876	1893
Schmidt, Athens		1.135	1.3129	1876	1883
Weber, Peckeloh		0.978	1.5103	1876	1883
Spoerer, G., Anclam		1.094	1.4163	1876	1893
Tacchini, Rome		1.059	1.1756	1876	1900
Moncalieri		1.227	1.5113	1876	1893
Leppig, Leibzig		1.111	1.2644	1876	1881
Bernaerts, G. L., England		1.027	0.9115	1876	1878
Dawson, W. M., Spiceland, Ind.		1.01	1.1405	1879	1890
Ricco, Palermo		0.896	0.9541	1880	1892
Winkler, Jena		1.148	1.3112	1882	1910
Merino, Madrid		0.997	0.9883	1883	1896
Konkoly, Ogylla		1.604	1.5608	1885	1905
Quimby, Philadelphia		1.44	1.2844	1889	1921
Catania		1.248	1.1132	1893	1918
Broger, M, Zurich		1.21	1.0163	1897	1928
Woinoff, Moscow		1.39	1.123	1898	1919
Guillaume, Lyon		1.251	1.042	1902	1925
Mt Holyoke College		1.603	1.2952	1907	1925



No correlation

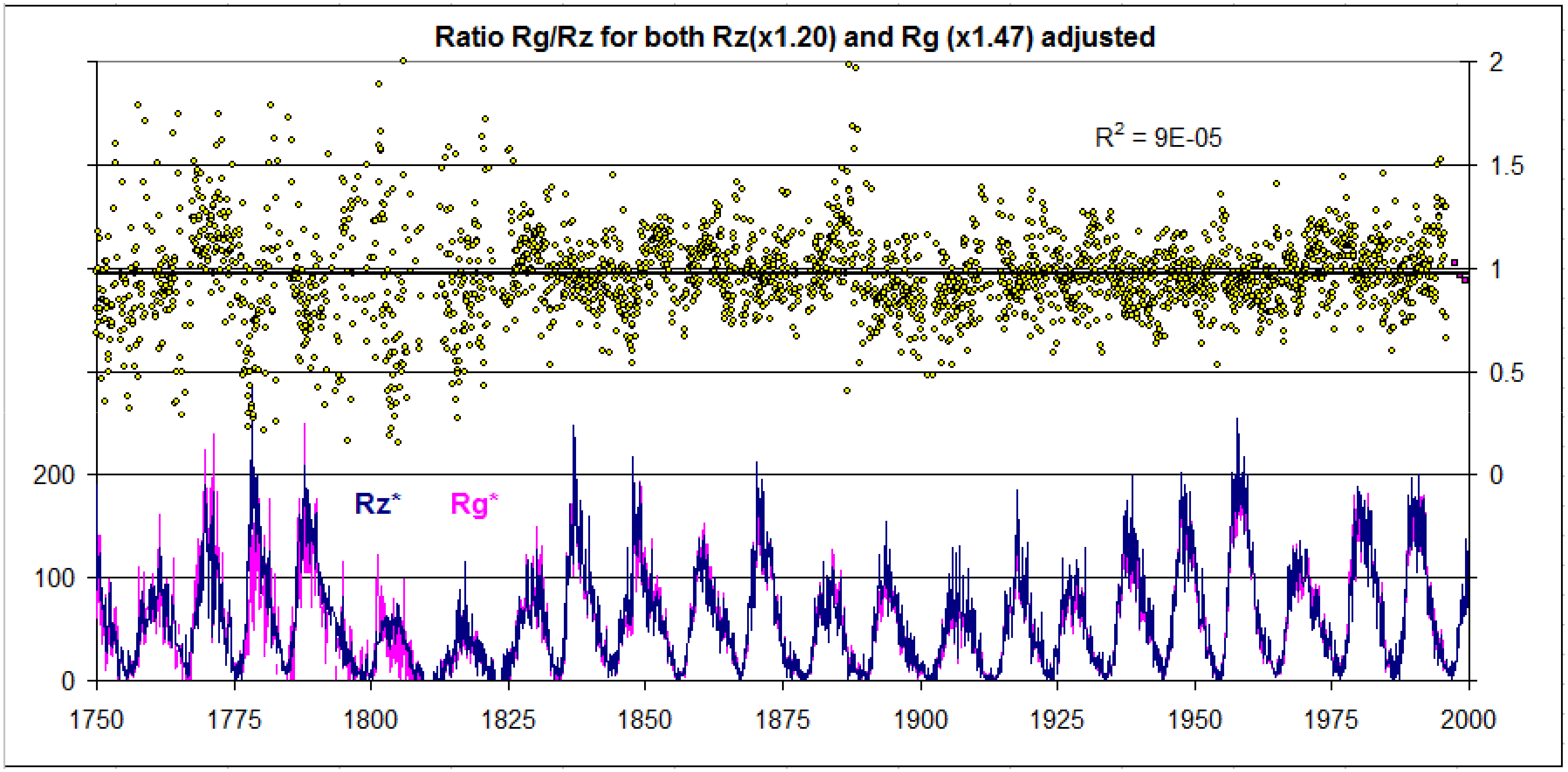




Why the large difference between Wolf and Wolfer?

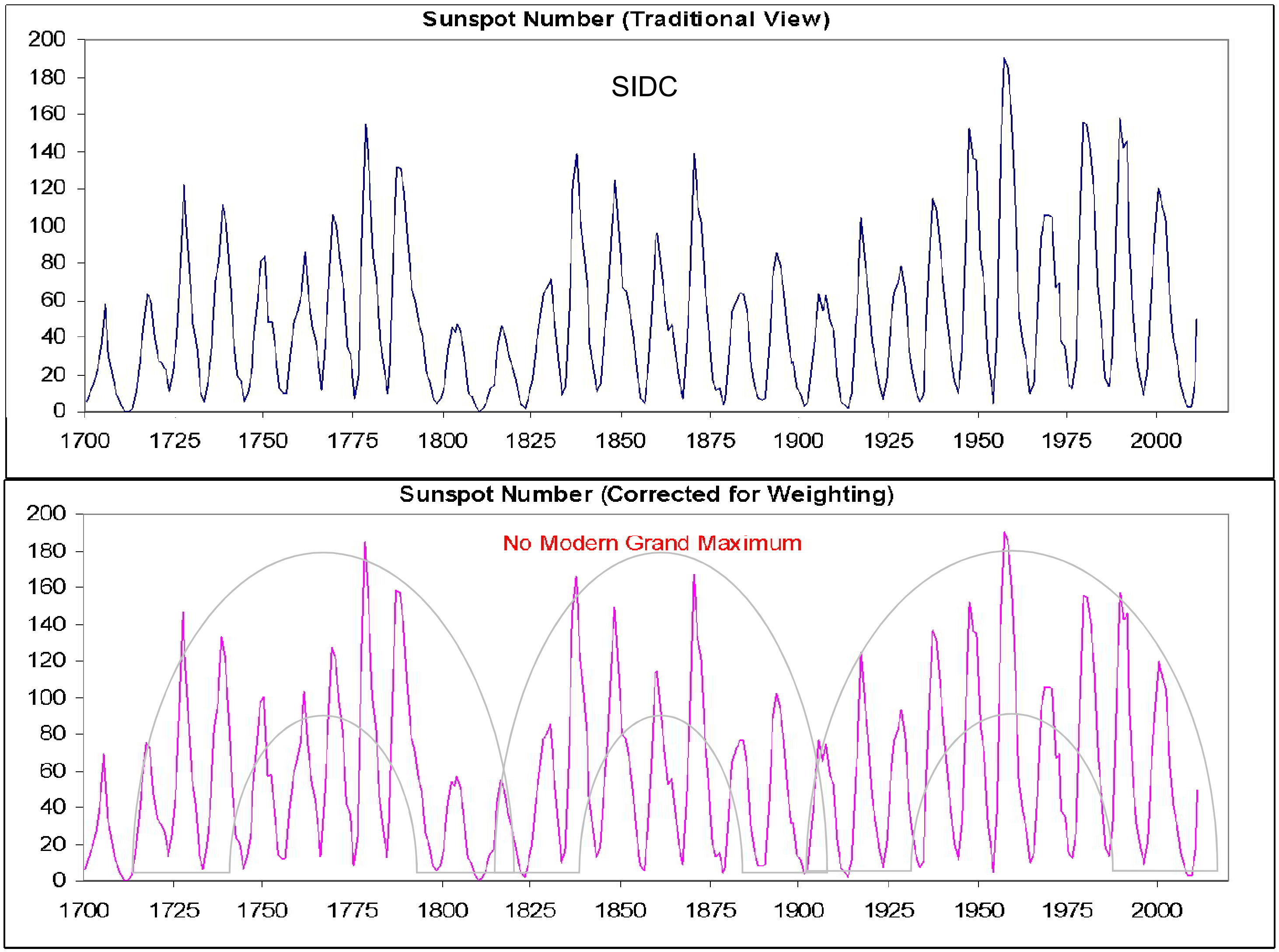
Because Wolf either could not see groups of Zurich classes A and B [with his small telescope] or deliberately omitted them when using the standard 80mm telescope. The A and B groups make up almost half of all groups

Removing the discontinuity in ~1885 by multiplying Rg by 1.47, yields



Only two adjustments remove most of the disagreement *and the evidence for a recent grand maximum (1945-1995)*

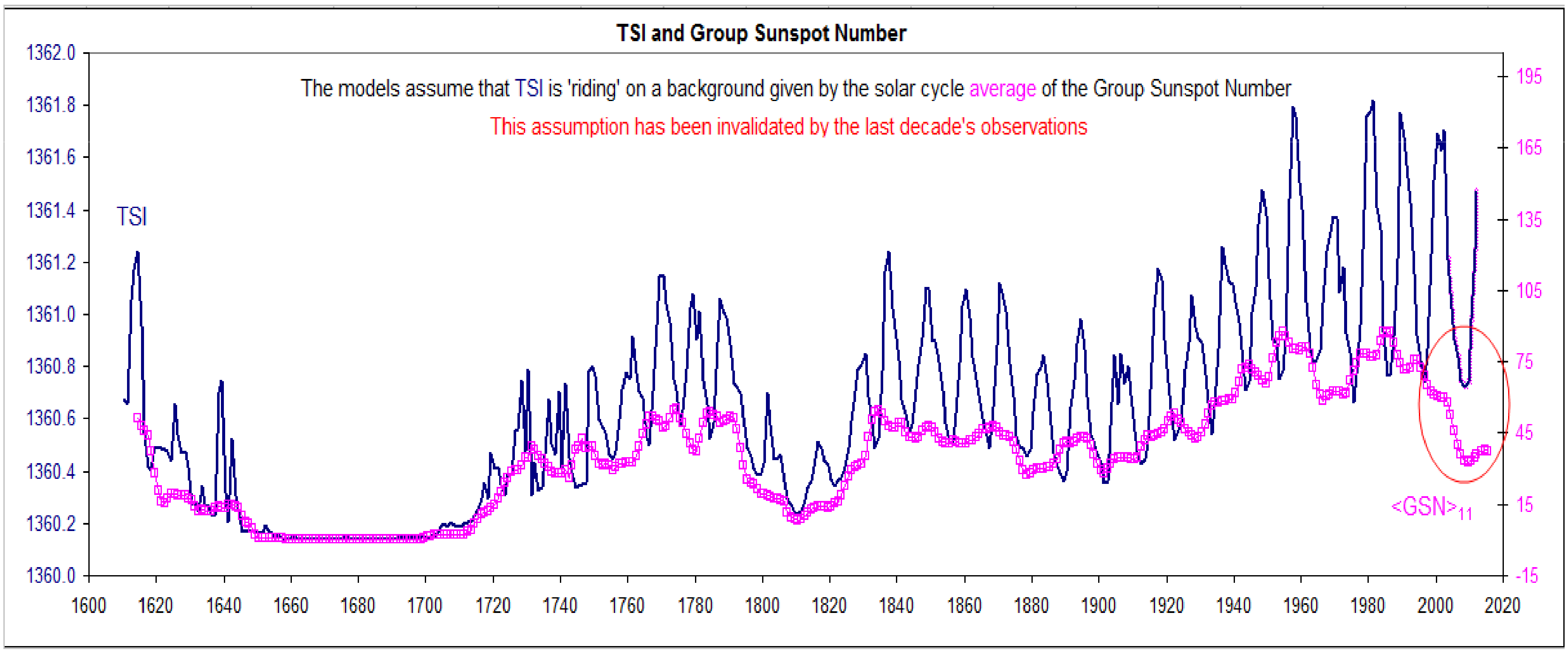
The Effect on the Sunspot Curve



No long-term trend the last 300 years

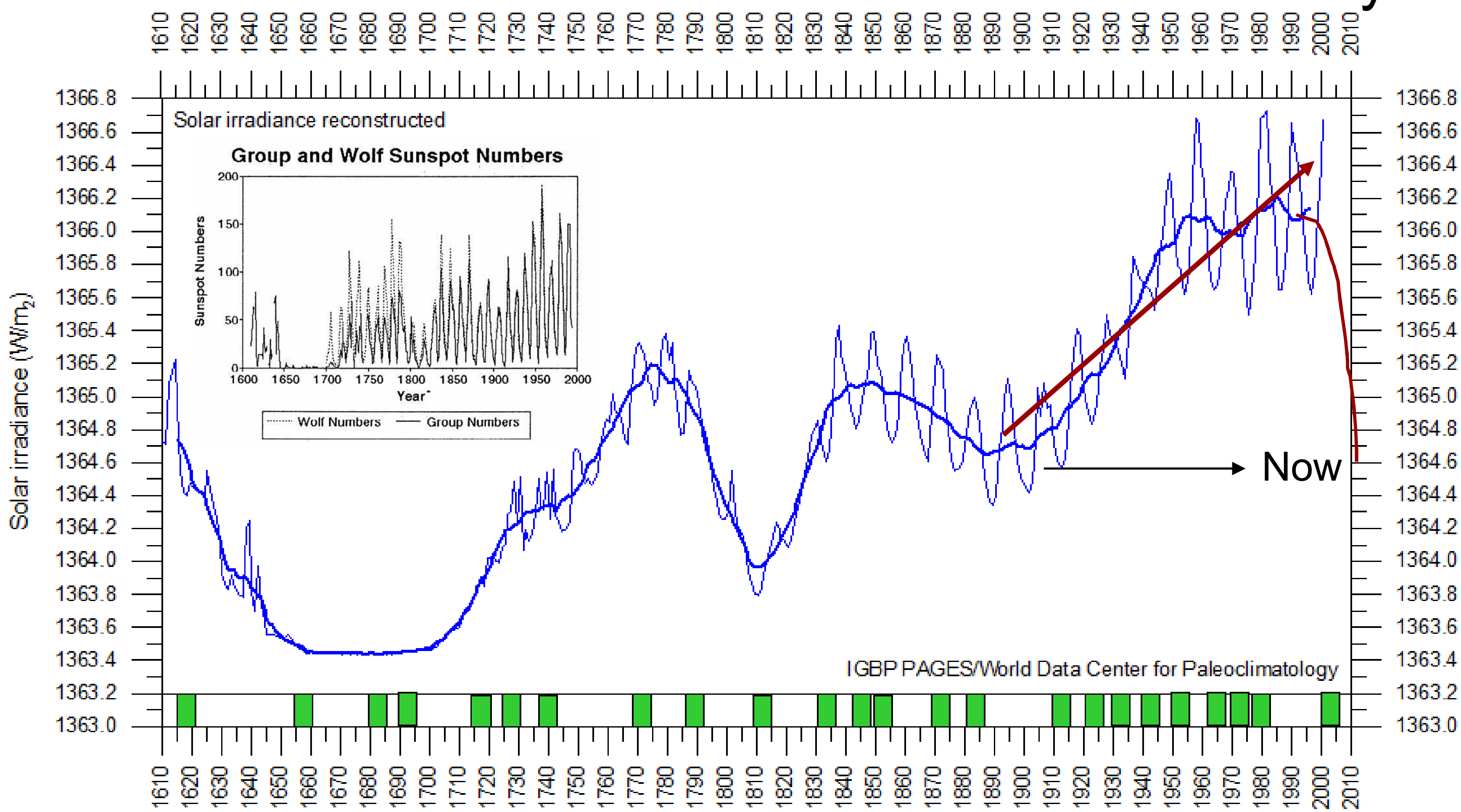
Removing the discrepancy between the Group Number and the Wolf Number removes the ‘background’ rise in reconstructed TSI

I expect a strong reaction against ‘fixing’ the GSN from people that ‘explain’ climate change as a secular rise of TSI and other related solar variables

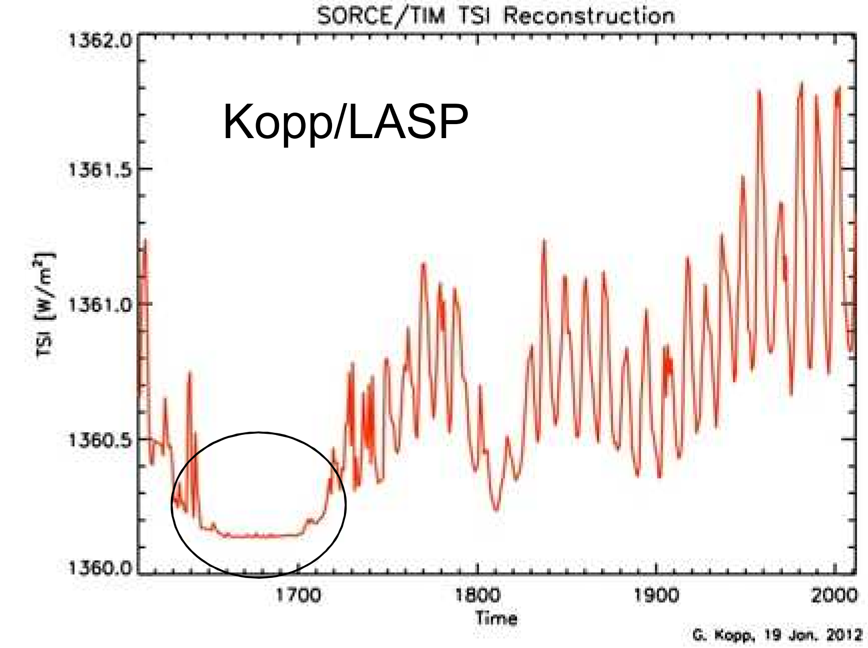


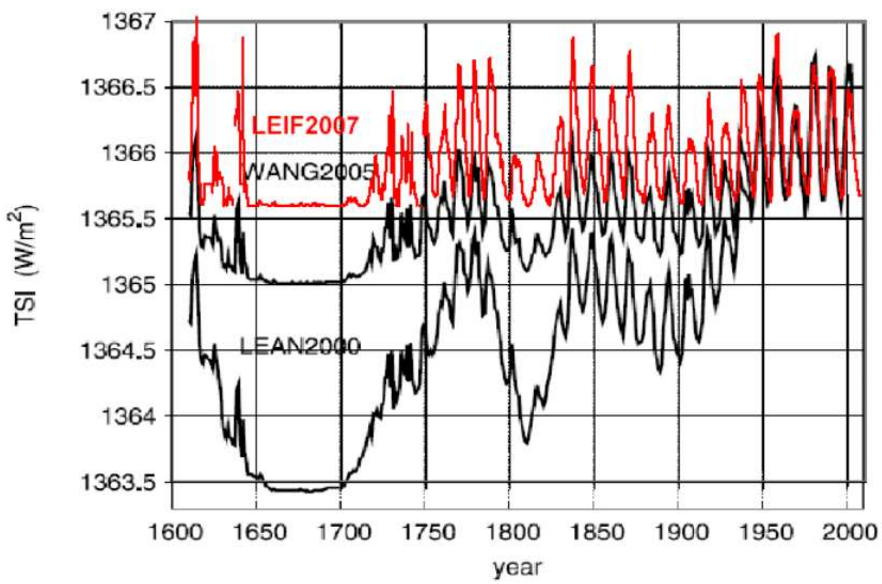
Typical Reconstruction

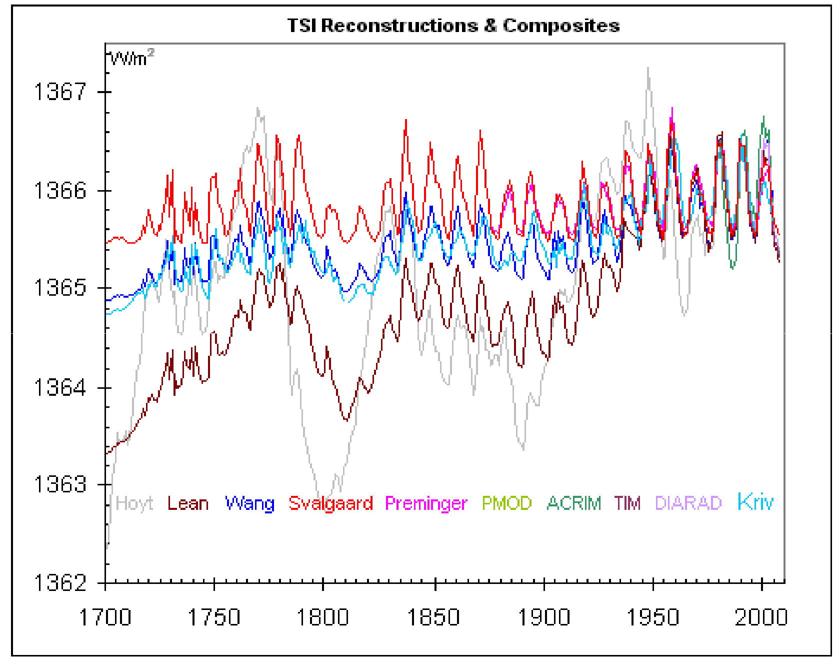
$TSI \sim TSI_0 + a \cdot GSN + b \cdot \langle GSN \rangle_{11yr}$



Some More TSI Reconstructions

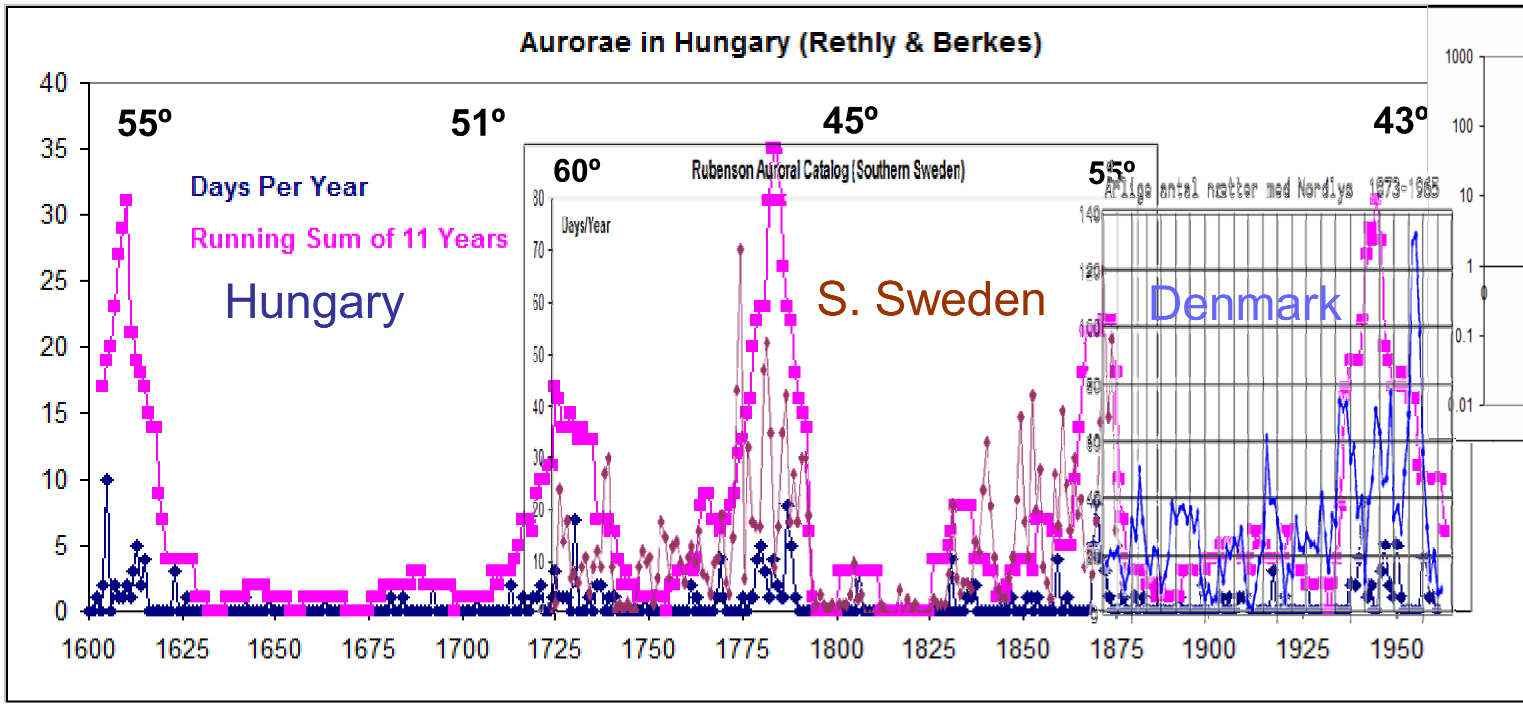


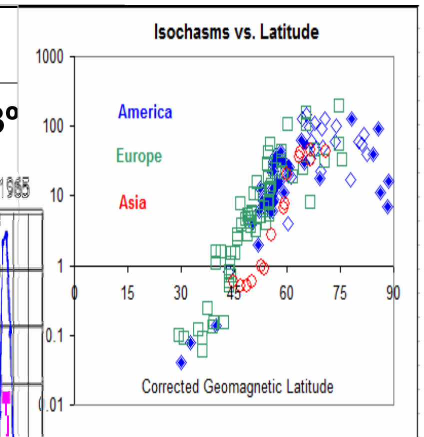




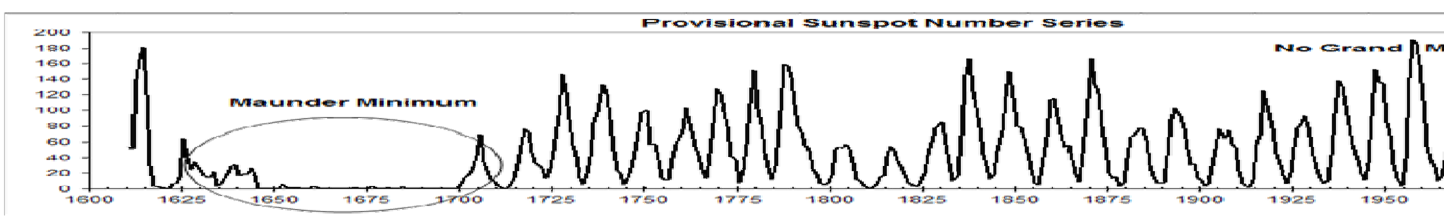
Crucial question: is there a slowly varying background? I think not.

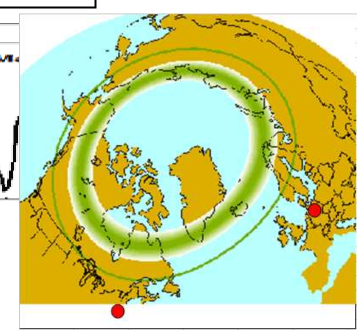
The Auroral Record in Europe





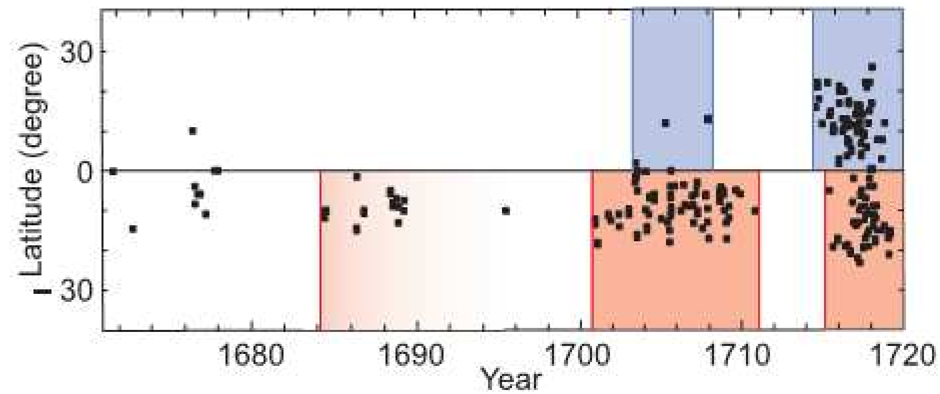
Effect of Changing Magnetic Latitude





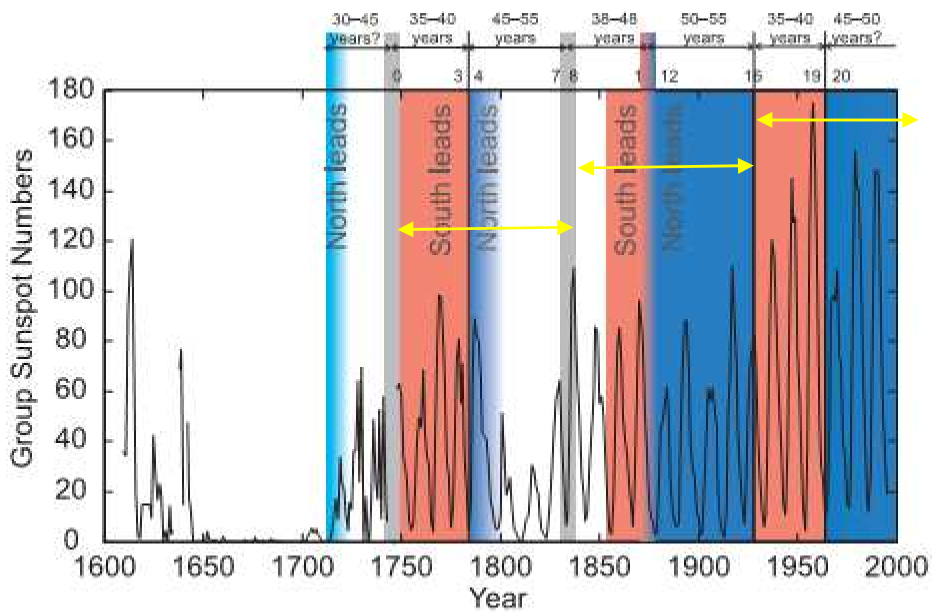
It is very difficult [impossible?] to calibrate accurately the auroral record because of the unknown ‘civilization’ correction.

80-110 Year 'Gleissberg Cycle' in Solar Activity Asymmetry?



Extreme Asymmetry during the Maunder Minimum…

There are various dynamo theoretical 'explanations' of N-S asymmetry. E.g. Pipin, 1999. I can't judge these…

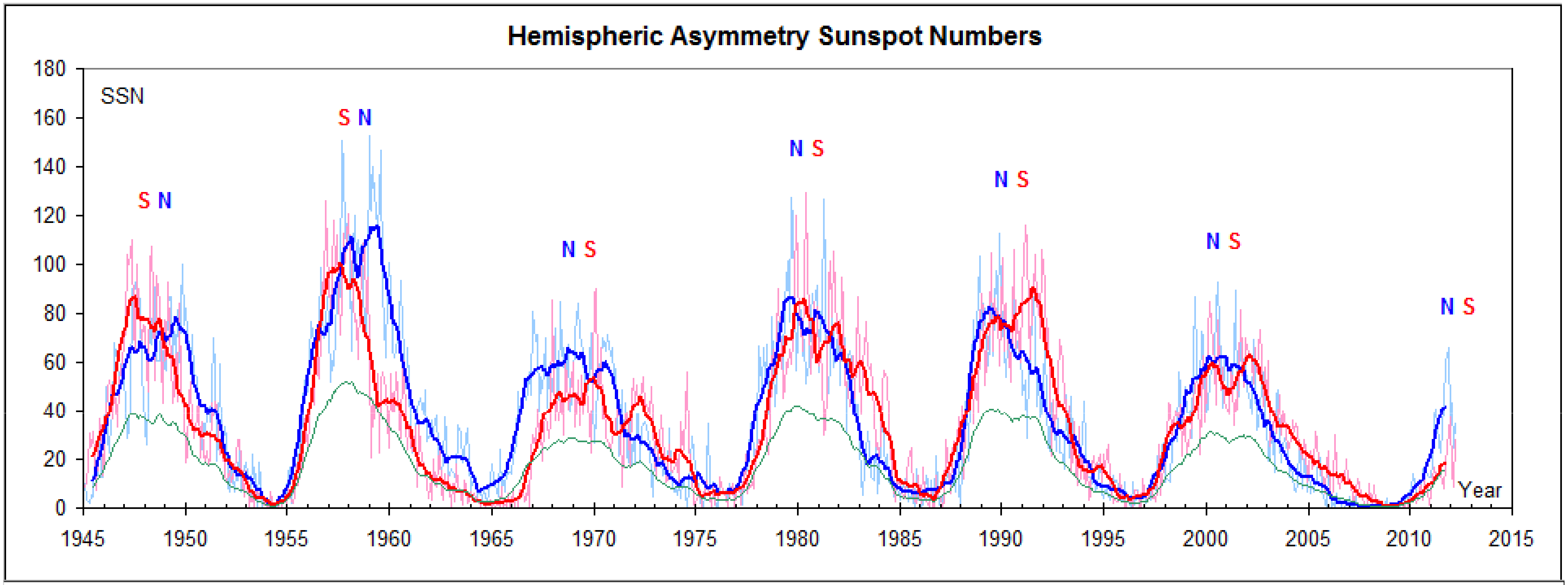


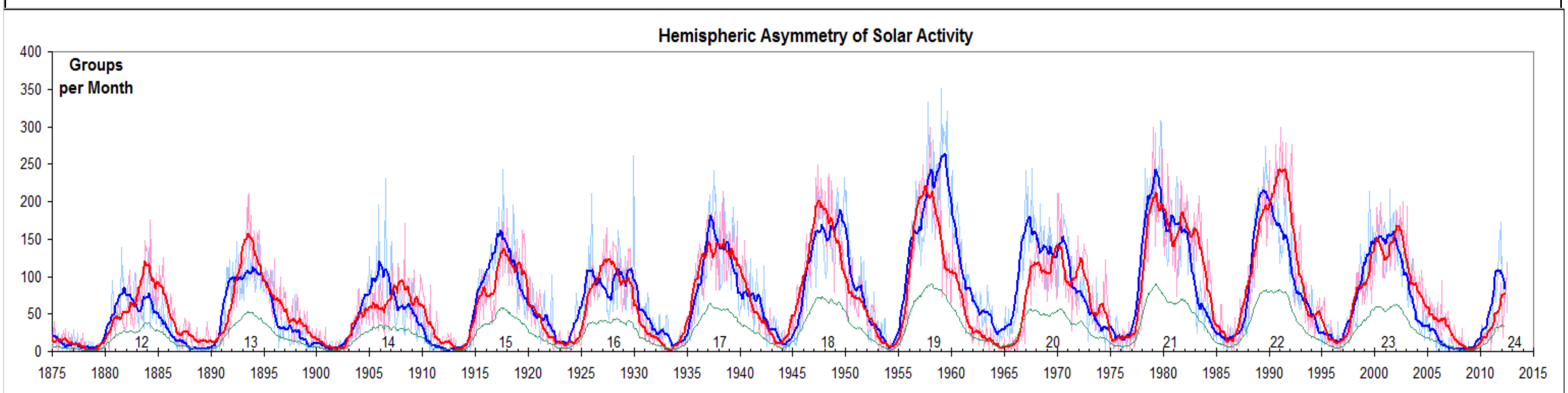
Zolotova et al., 2010

Is this a 'regular' cycle or just over-interpretation of noisy data [like Waldmeier's]?

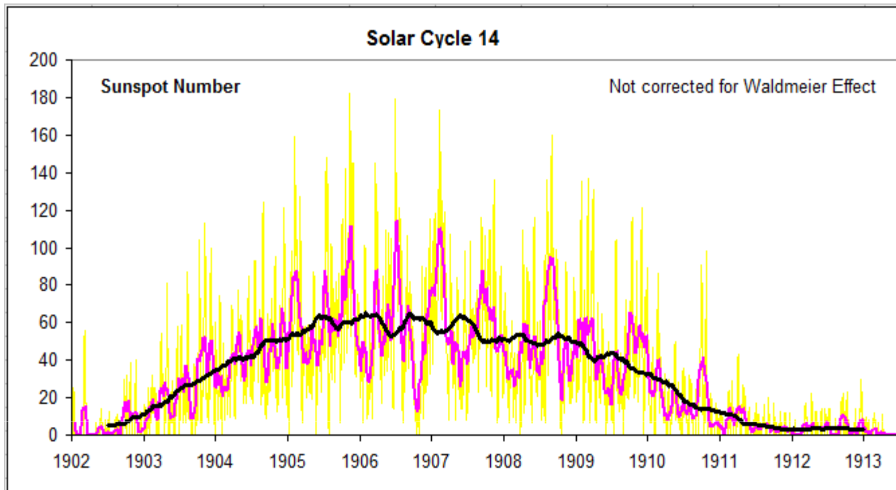
'Prediction' from this: South will lead in cycle 25 or 26 and beyond. We shall see…

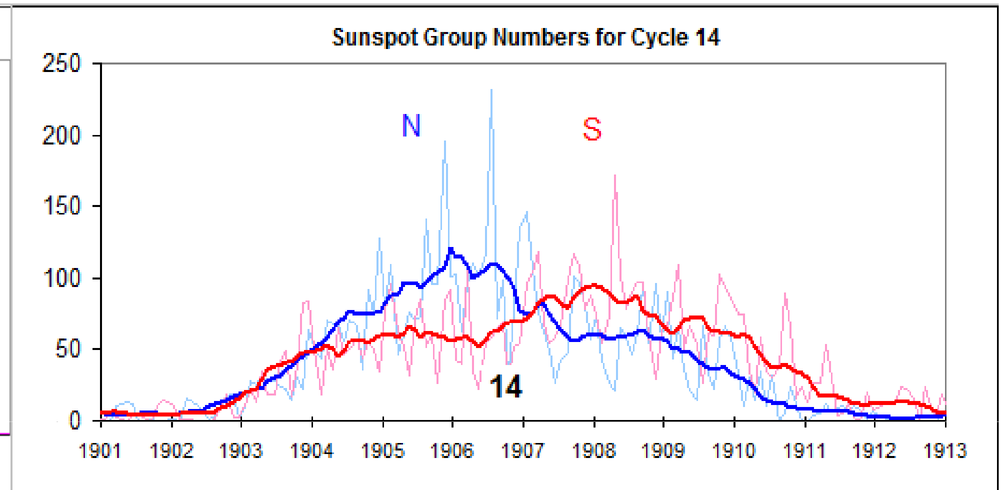
Asymmetric Solar Activity

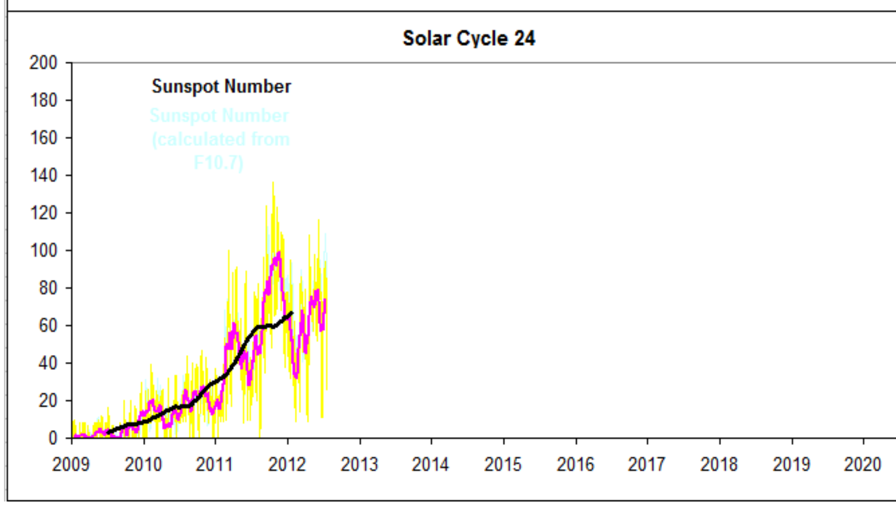


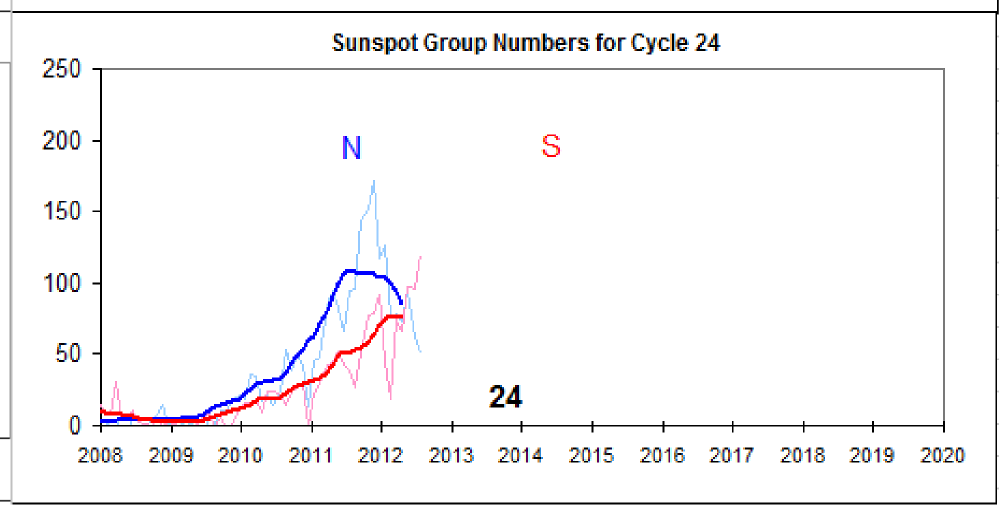


Comparing Cycles 14 and 24

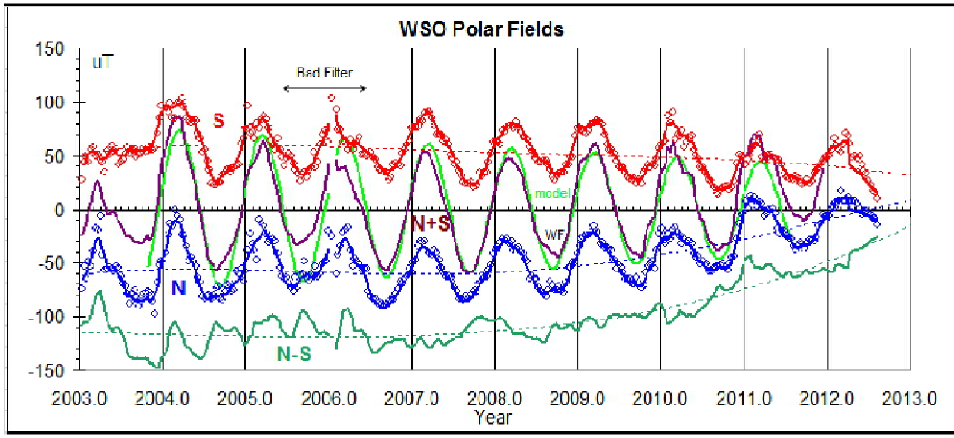


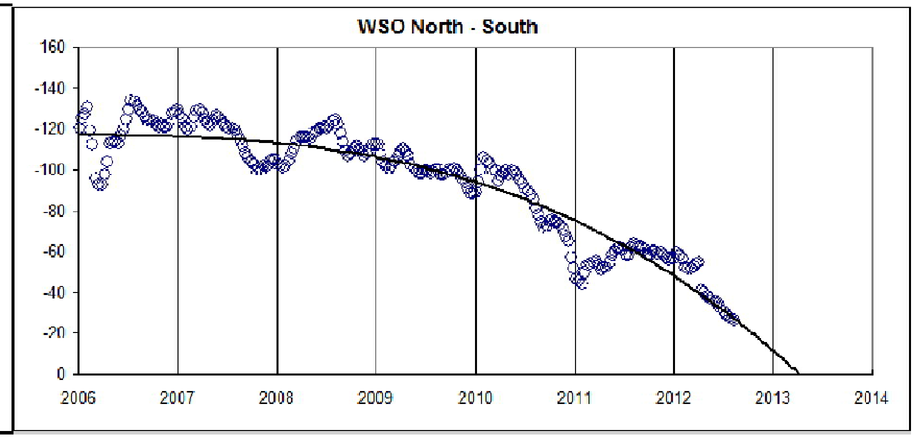


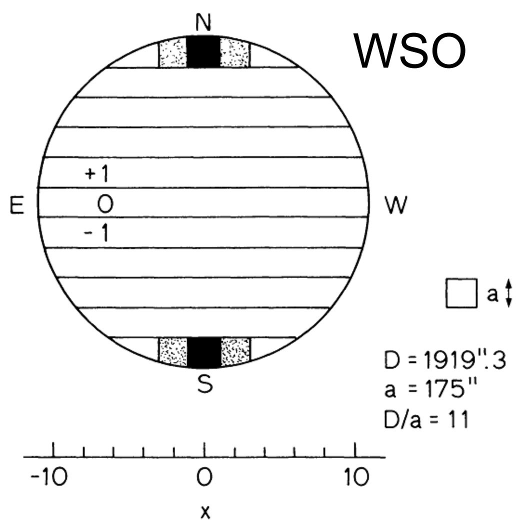




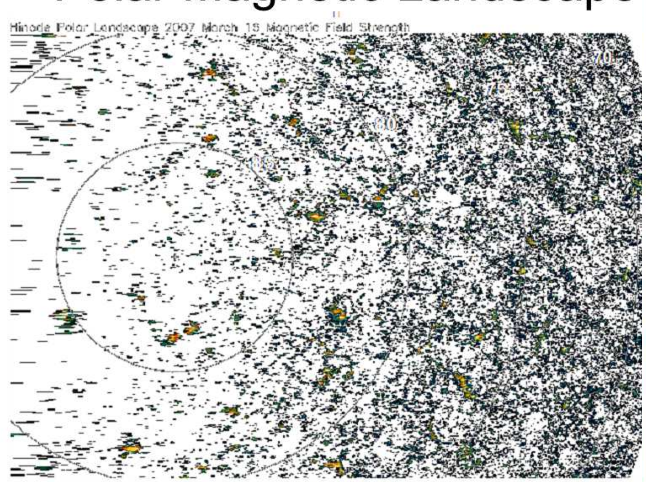
Polar Field Reversal SC24

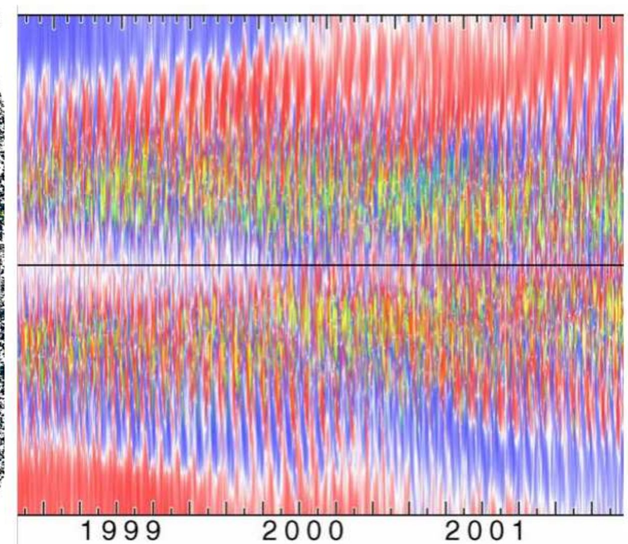




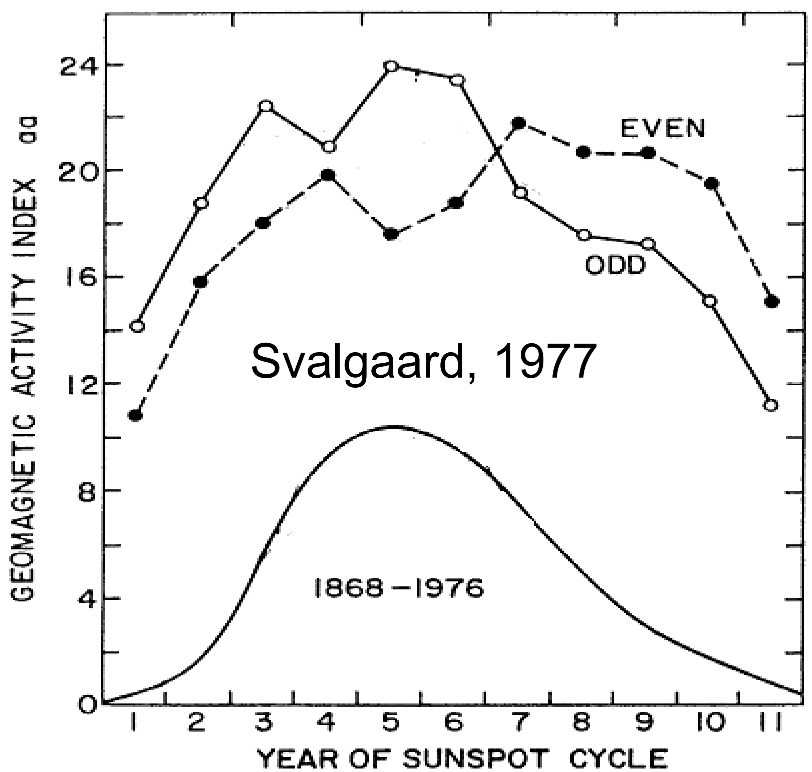


Polar Magnetic Landscape


Tsuneta et al. ApJ, 2008



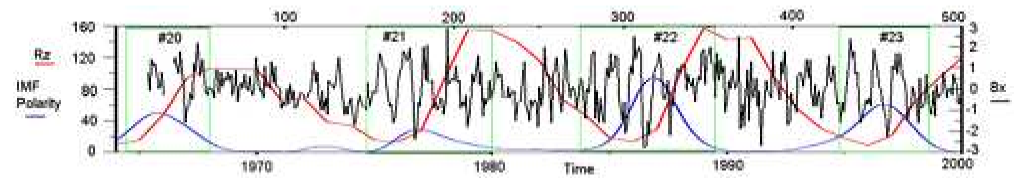
How do we Know that the Poles Reversed Regularly before 1957?



Svalgaard, 1977

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.

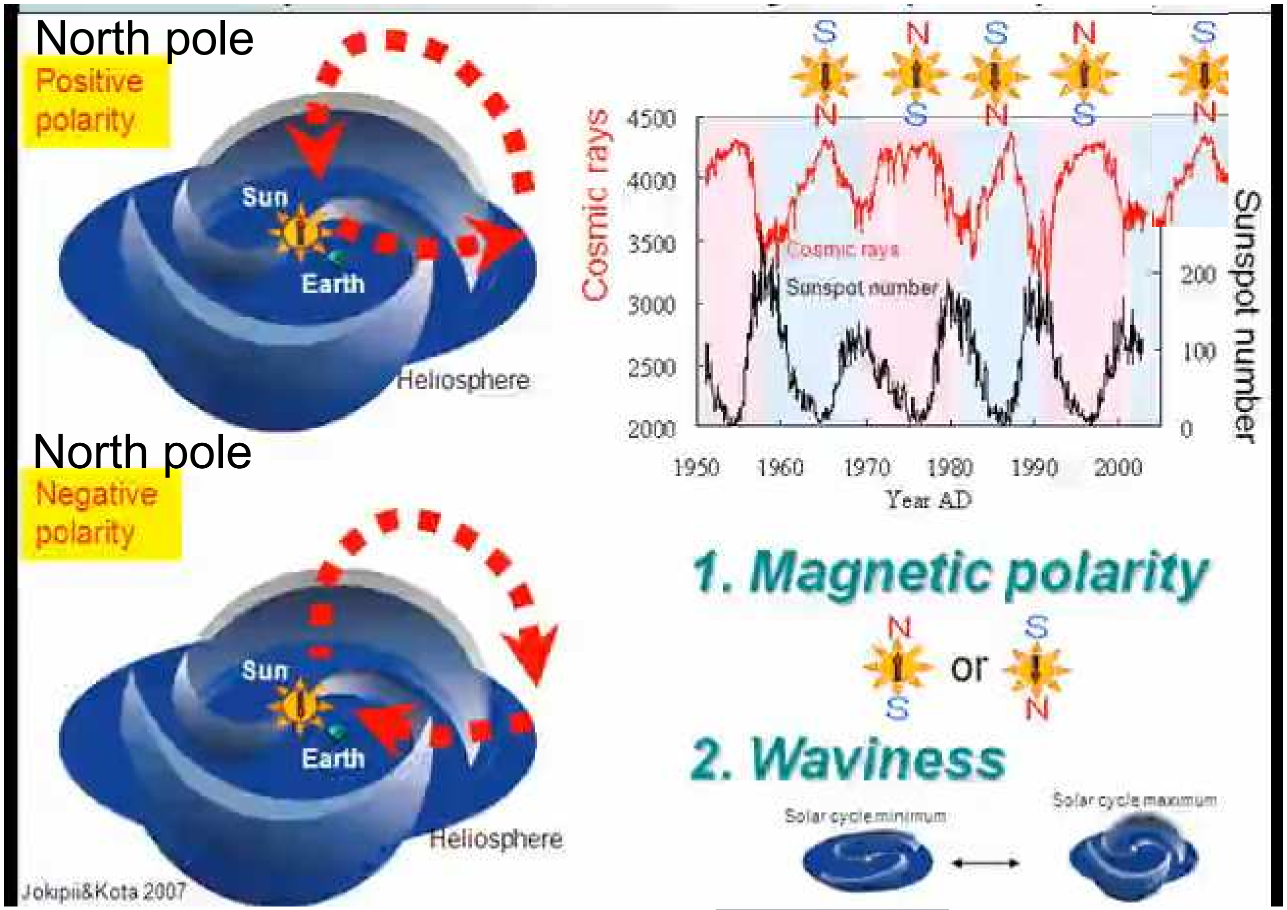


This effect combined with the Russell-McPherron effect [geomagnetic activity enhanced by the Southward Component of the HMF] predicts a 22-year cycle in geomagnetic activity synchronized with polar field reversals, as observed (now for 1840s-Present).

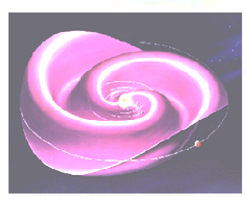
"Thus, during last eight solar cycles magnetic field reversals have taken place each 11 year period". S-M effect. Vokhmyanin & Ponyavin, 2012

L3

Cosmic Ray Modulation Depends on the Sign of Solar Pole Polarity



Miyahara, 2011



Svalgaard & Wilcox, 1976

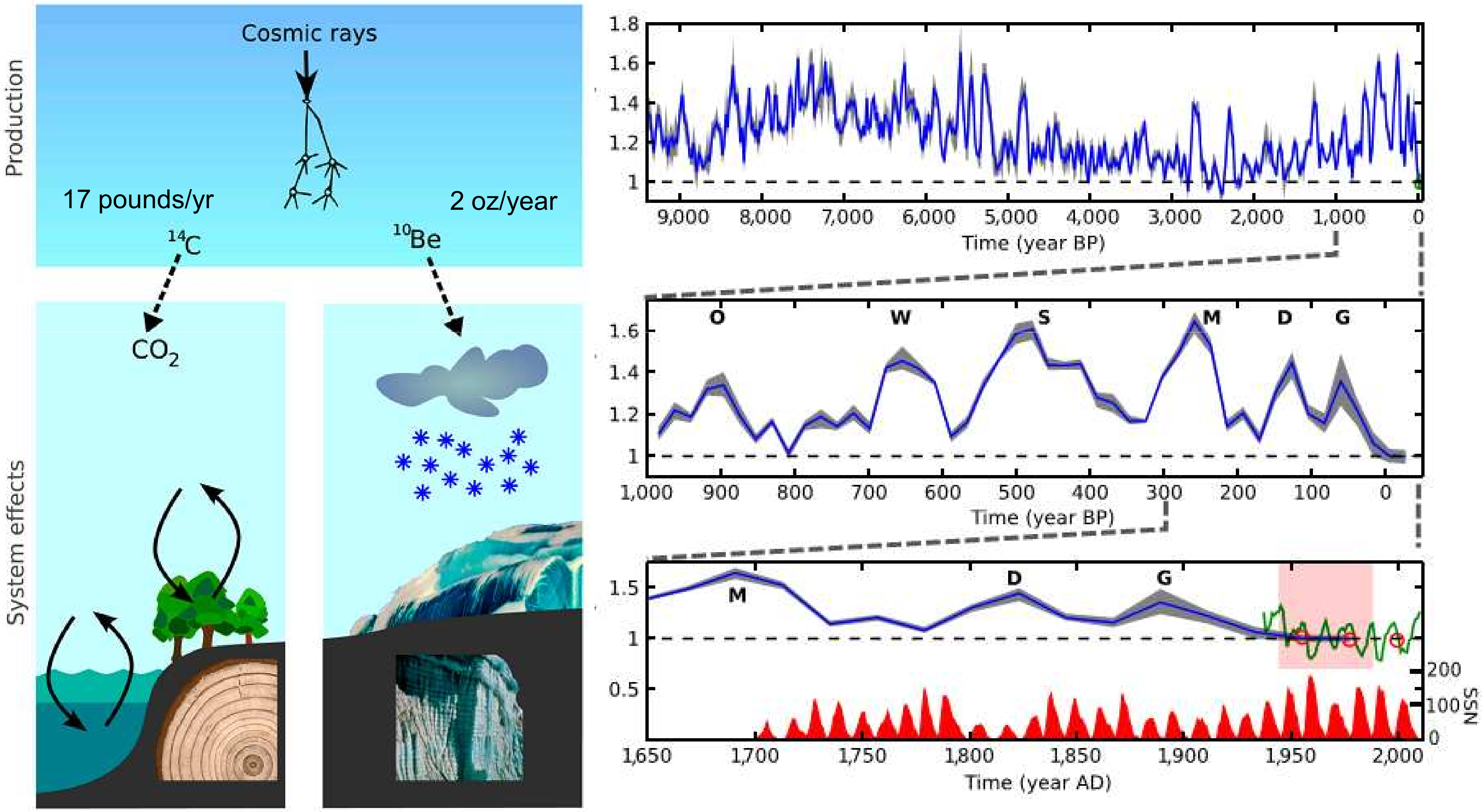
The shape of the modulation curve [alternating 'peaks' and 'flat tops'] shows the polar field signs.

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.

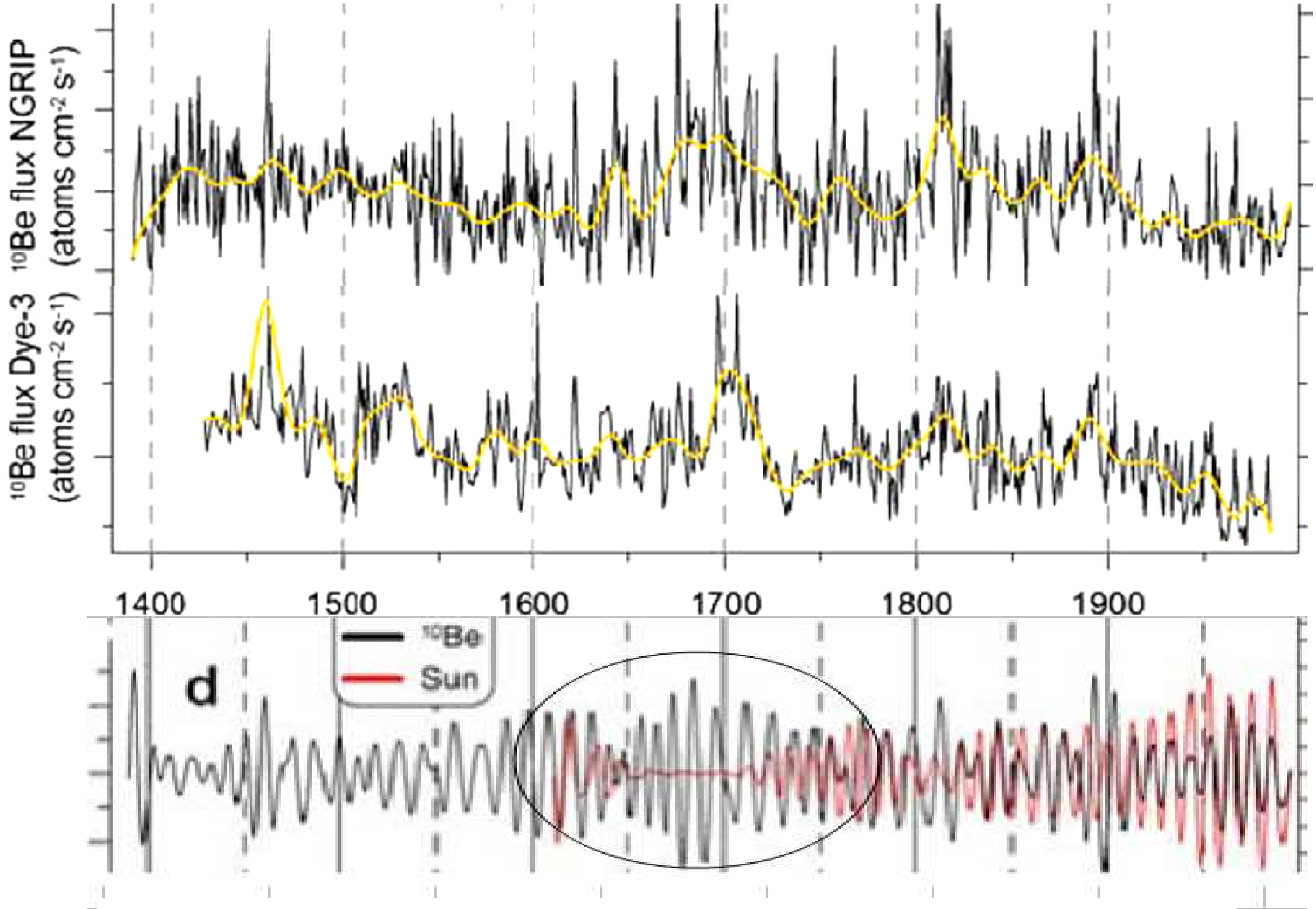
Slide 26

L3 The cosmic ray modulation by solar activity bears a signature of the polarity of the polar fields. The explanation is too long to give here [a topic for another talk, perhaps]. Ice cores hold a many millennium-long record of Beryllium 10 produced by cosmic ray spallation of Nitrogen and Oxygen in the Earth's atmosphere [globally the annual production is 2 ounces!]. In principle [and with future refinement of the data acquisition] we should be able to determine polar field reversals using 10Be. The data is not quite good enough yet.
Leif, 7/26/2012

The Cosmic Ray Record

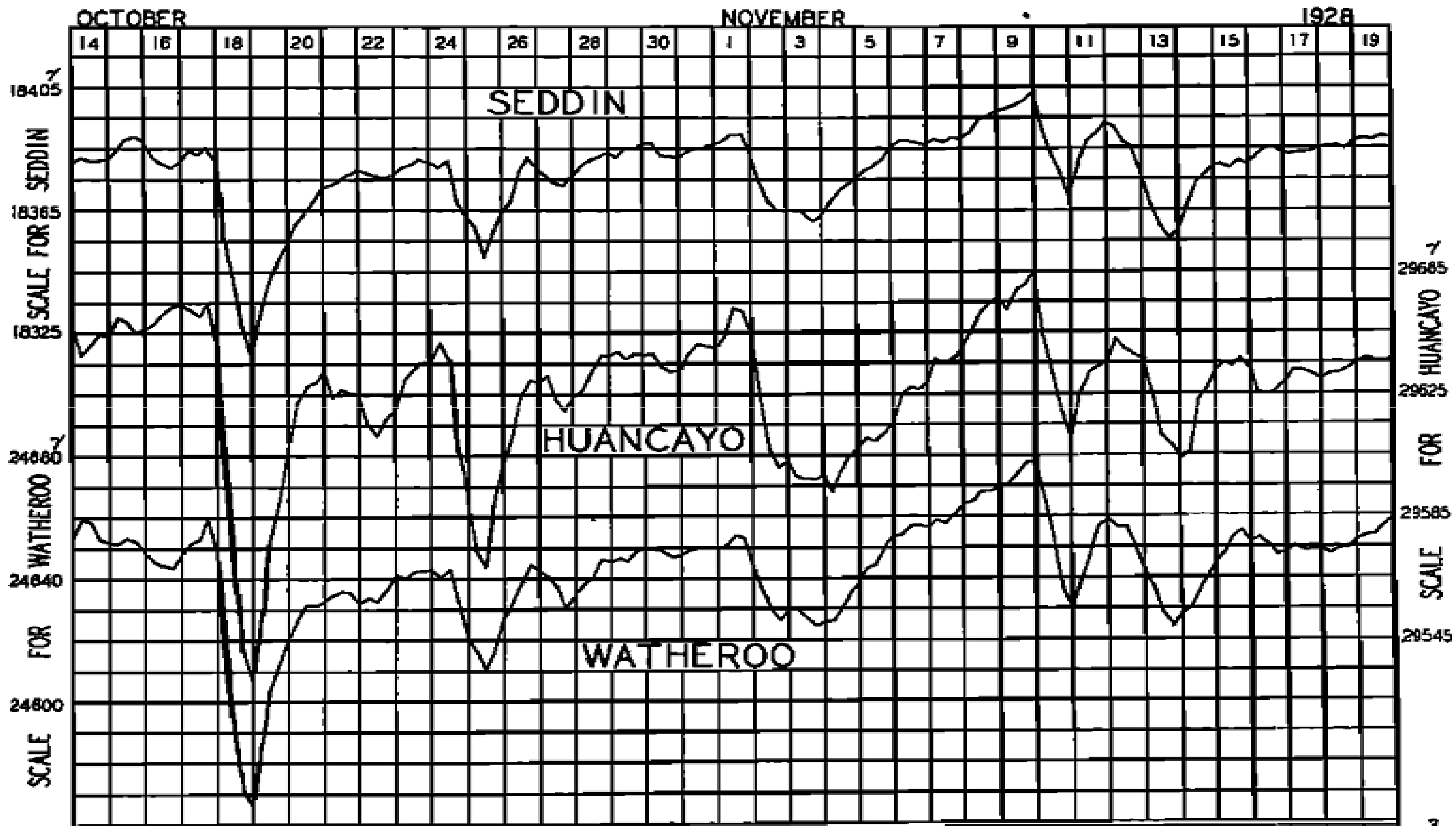


Steinhilber et al. 2012



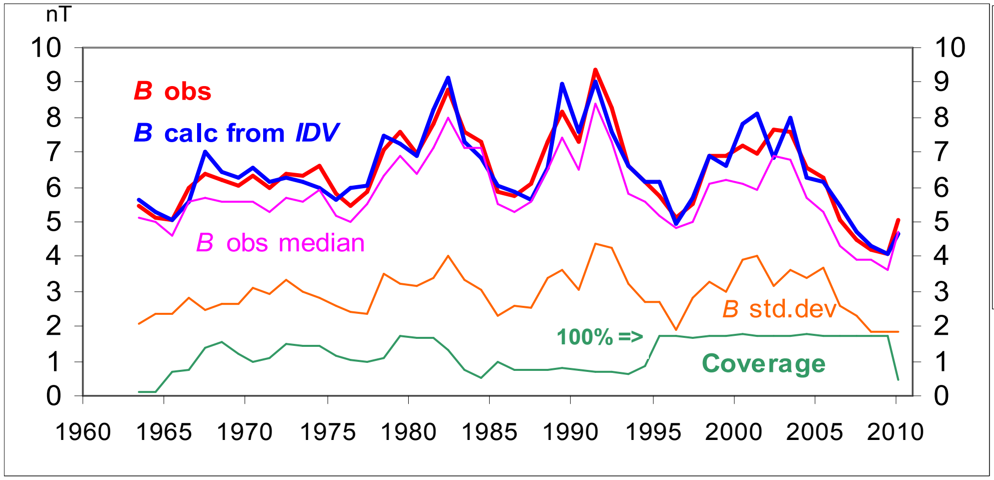
Cosmic Ray Proxy [Berggren et al.]

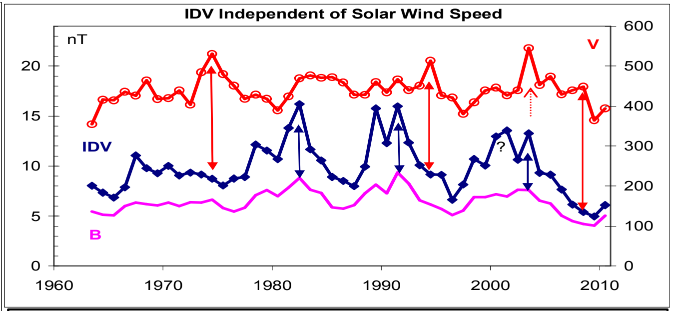
24-hour running means of the Horizontal Component of the low- & mid-latitude geomagnetic field remove most of local time effects and leaves a Global imprint of the Ring Current [Van Allen Belts]:

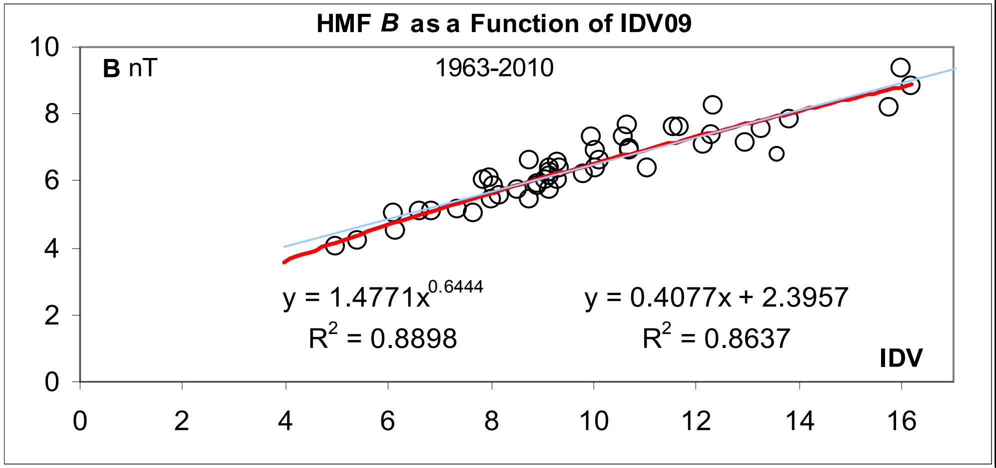


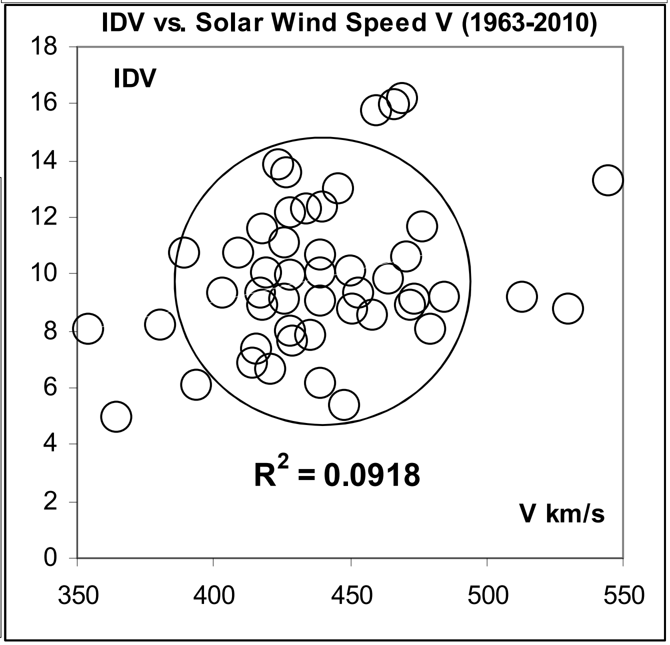
A quantitative measure of the effect can be formed as a series of the unsigned differences between consecutive days: The InterDiurnal Variability, IDV-index

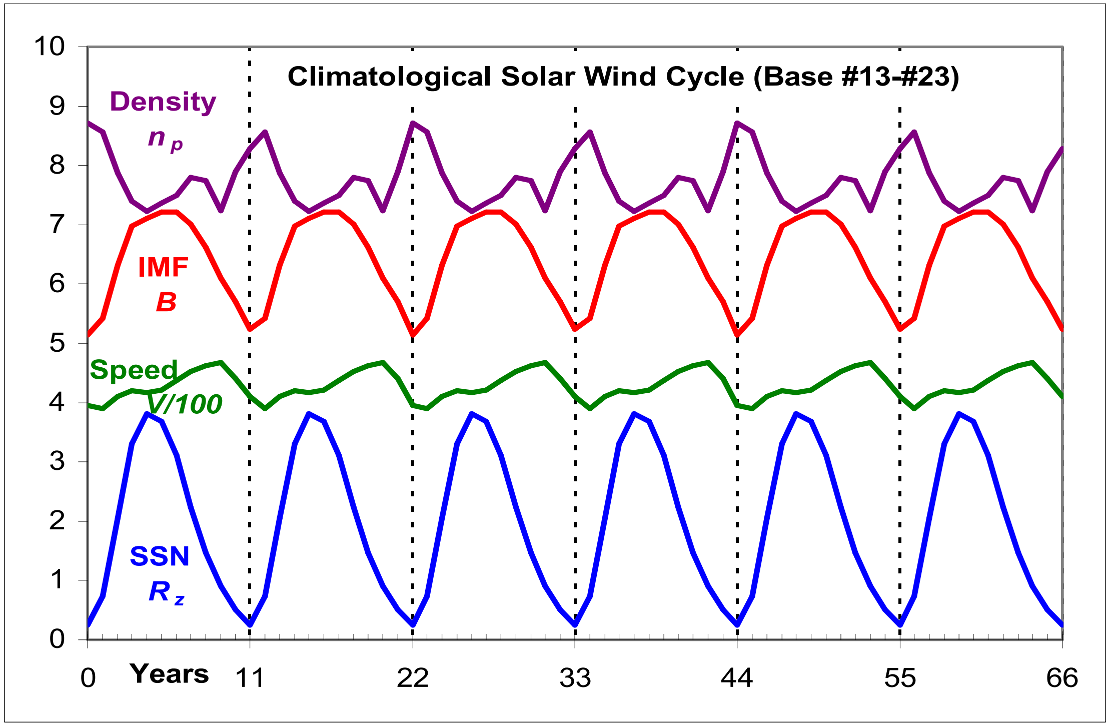
IDV is strongly correlated with HMF B, but is blind to solar wind speed V





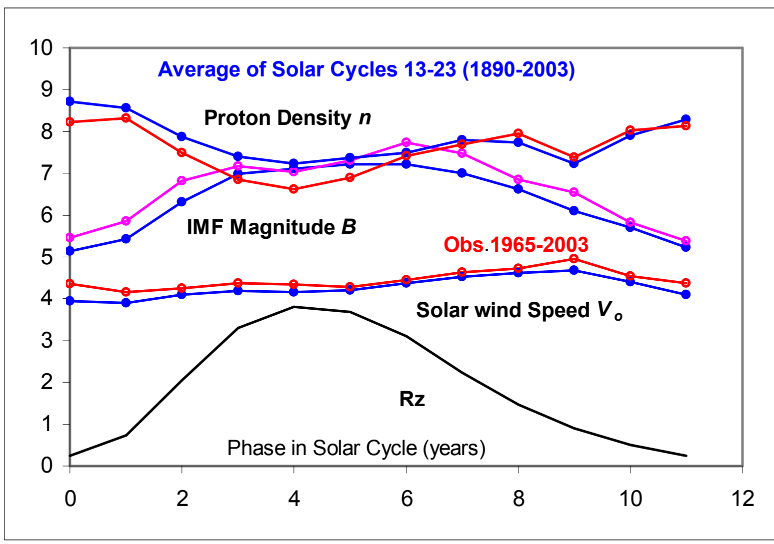


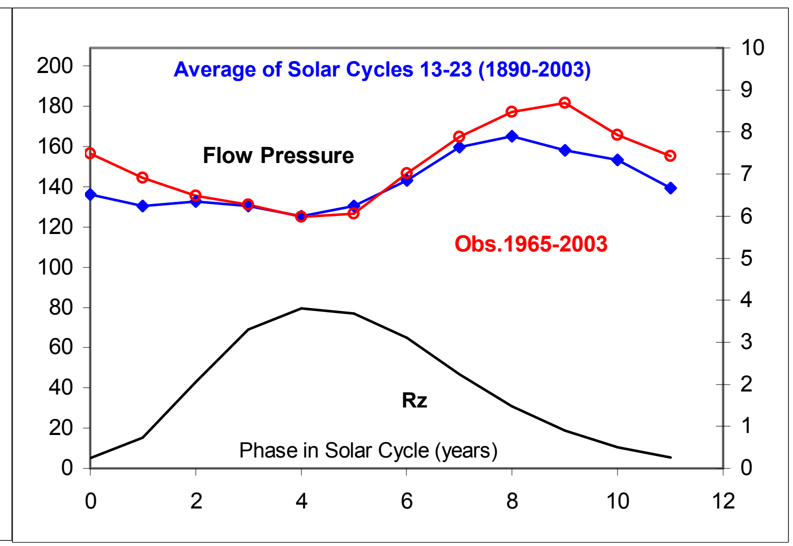




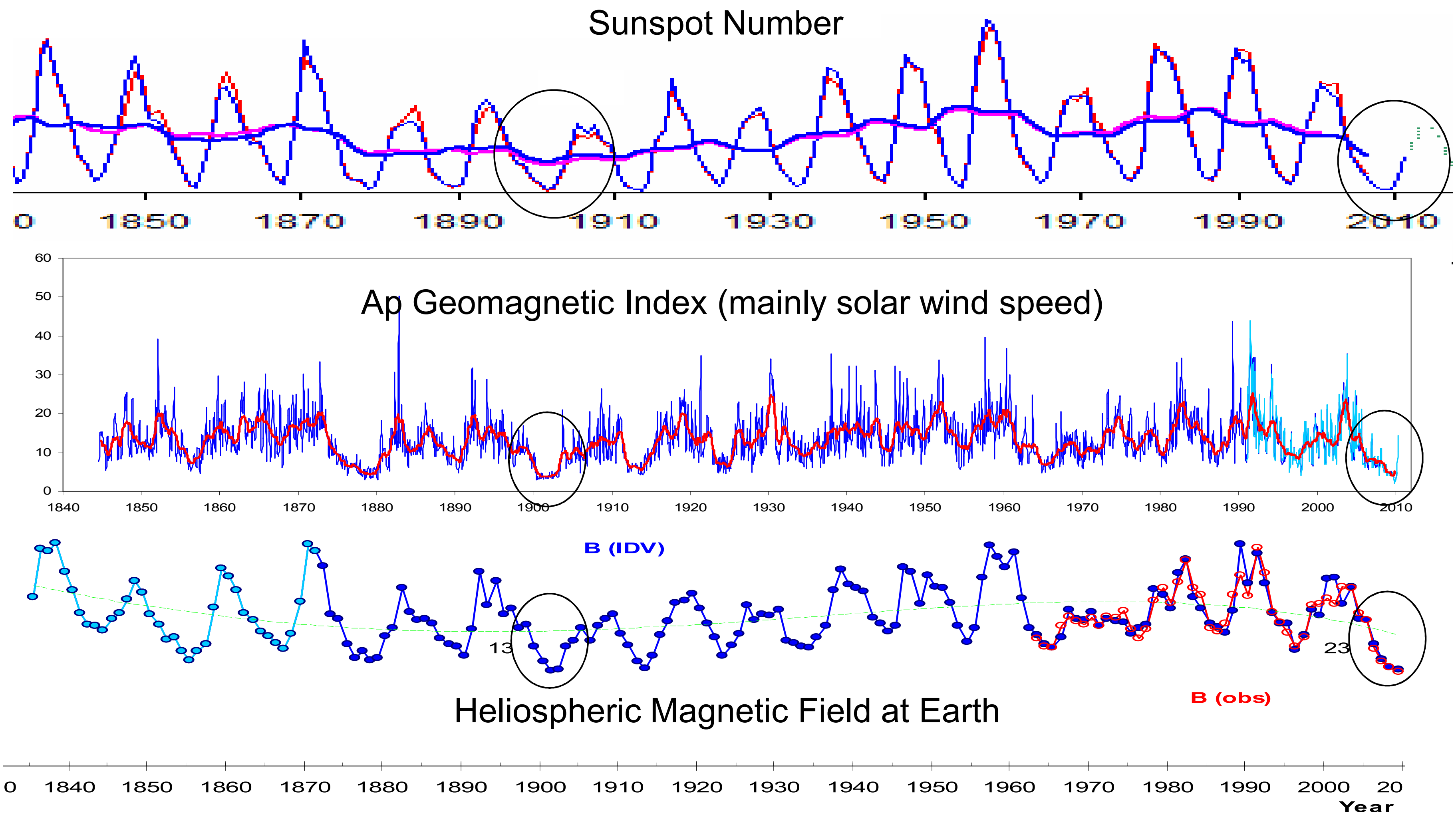
Space Climate

Since we can reconstruct B, V, and n for 11 solar cycles we can determine an ‘average’ profile of the solar wind through the solar cycle



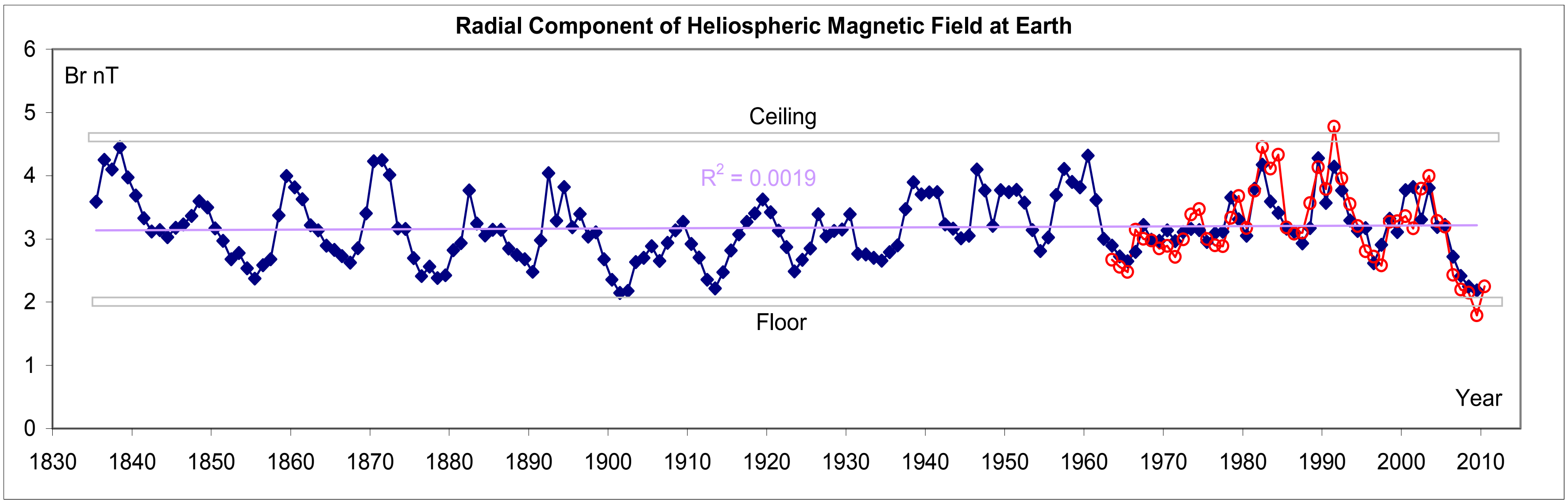


Solar Activity 1835-2011



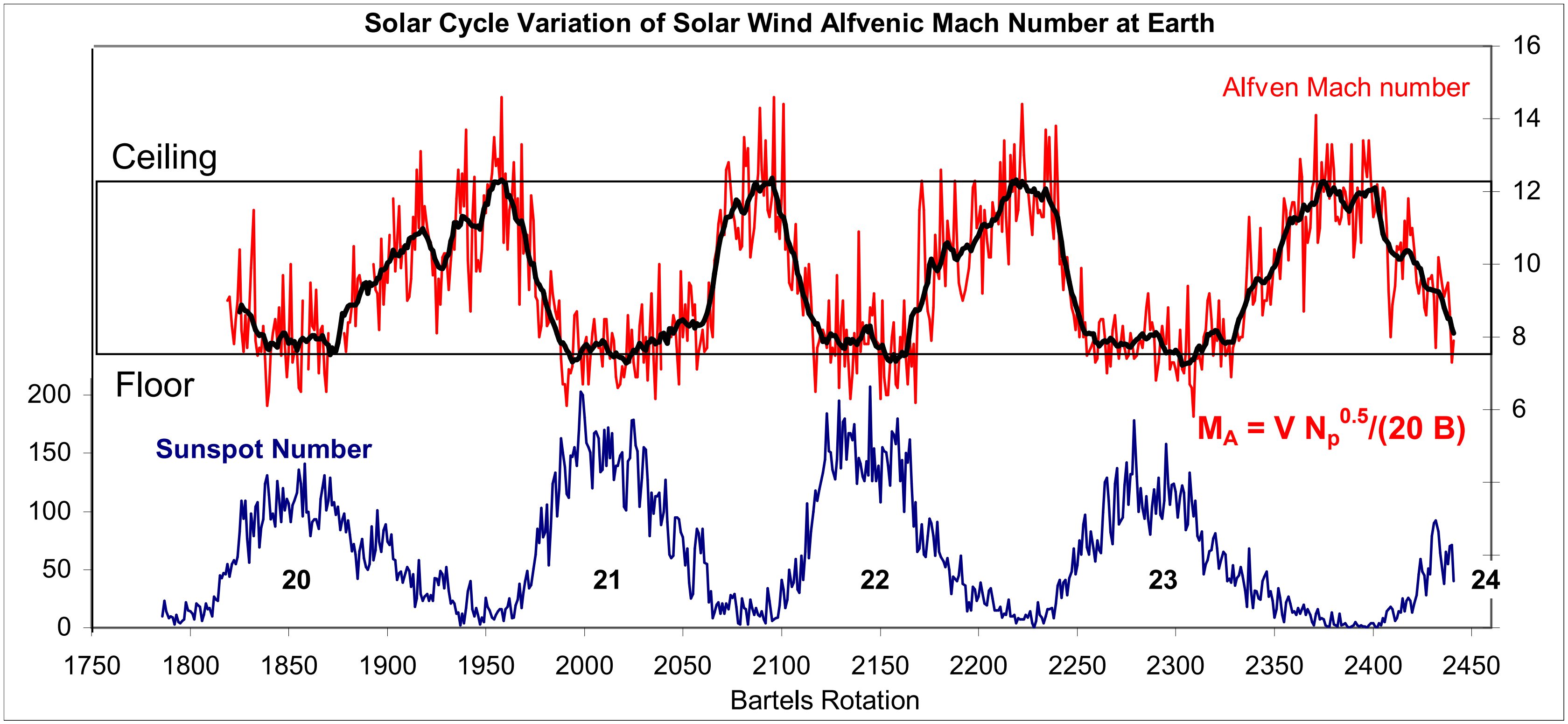
Variation of 'Open Flux'

Since we can also estimate solar wind speed from geomagnetic indices [Svalgaard & Cliver, JGR 2007] we can calculate the radial magnetic flux from the total B 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.

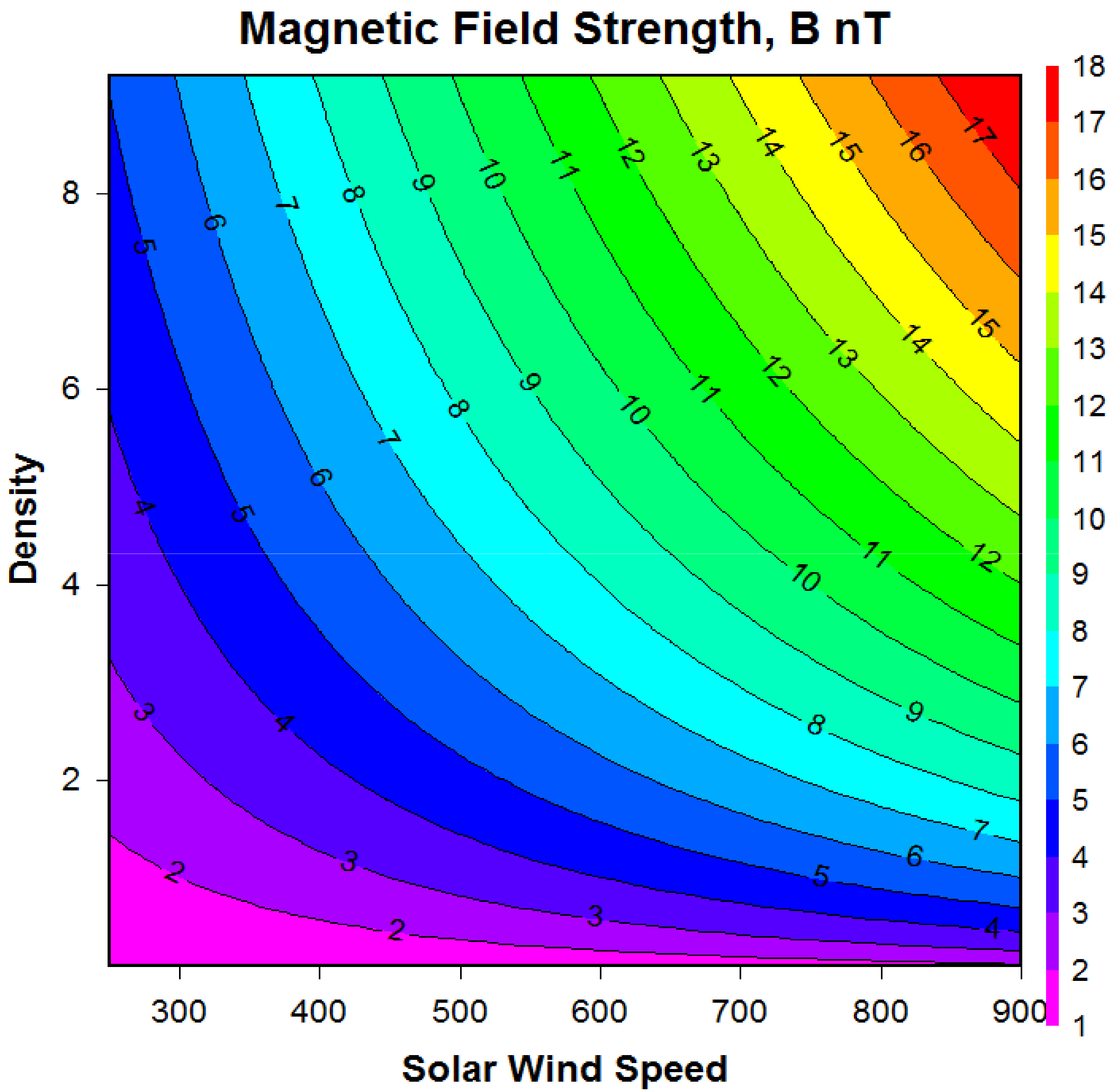
Floor and Ceiling of Solar Wind Alfvénic Mach number



Observations seem to suggest that the magnitude of the solar cycle variation is invariant, i.e. does not depend on the size of the cycle. In particular, that the value at solar minimum is the same, ~12.25, in every cycle.

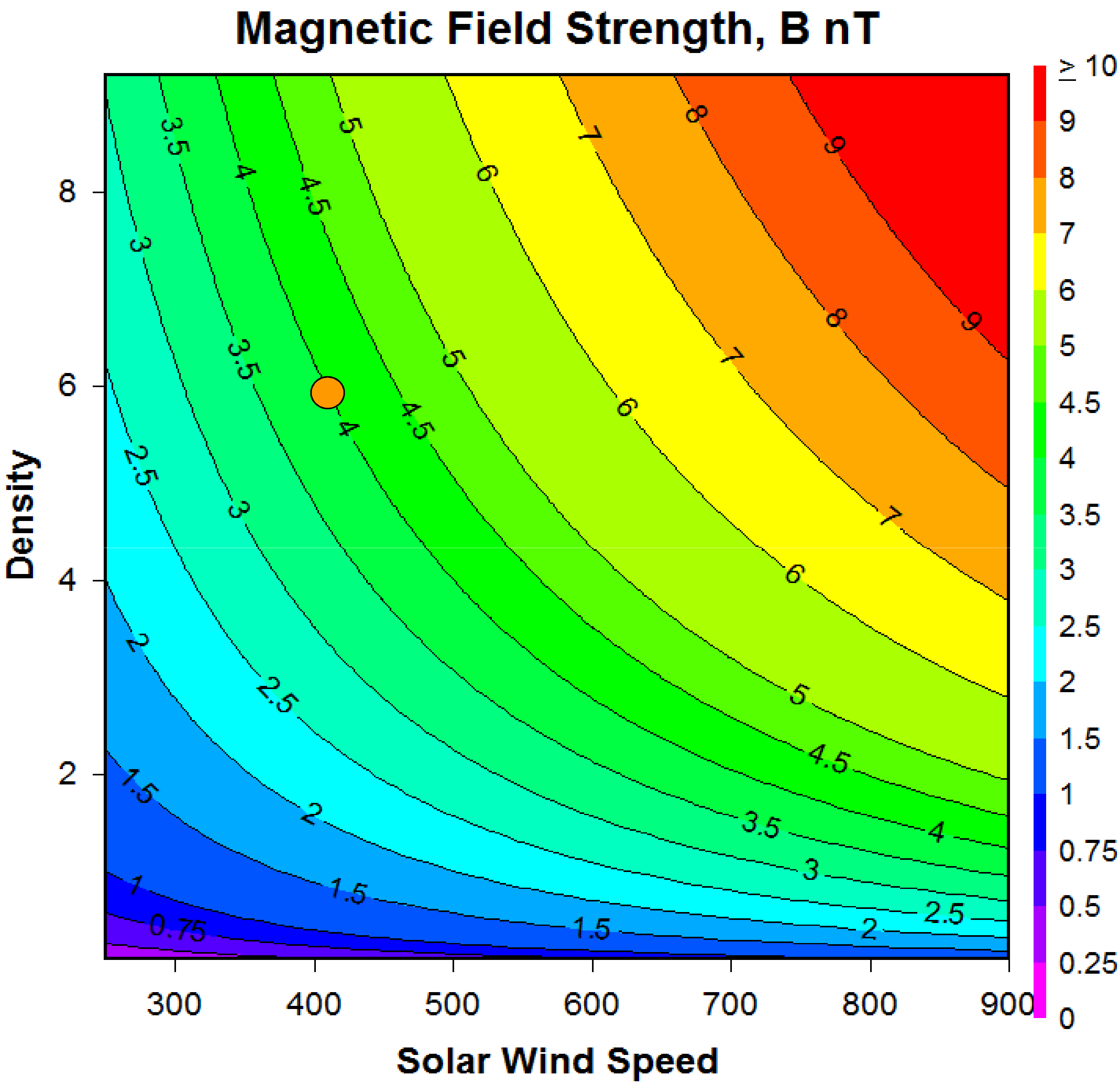
OMNI Explanation of M_A

Consider first the multi-species nature of the solar wind plasma: protons, alphas, electrons. We use subscripts p, a and e for these. N is density, T temperature, V flow speed, m mass Let Na = f*Np Ne = Np + 2*Na = Np*(1+2f) Mass density = mp*Np + ma*Na + me*Ne = mp*Np + 4*mp*f*Np = mp*Np * (1+4f) Thermal pressure = k * (Np*Tp + Na*Ta + Ne*Te) = k * (Np*Tp + f*Np*Ta + (1+2f)*Np*Te) = k*Np*Tp * [1 + (f*Ta/Tp) + (1+2f)*Te/Tp] Flow pressure = Np*mp*Vp**2 + Na*ma*Va**2 + Ne*me*Ve**2 = Np*mp*Vp**2 + f*Np*4*mp*Va**2 = Np*mp*Vp**2 * [l + 4f*(Va/Vp)**2] Rewrite: Mass density = C*mp*Np Thermal pressure = D*Np*k*Tp Flow pressure = E*Np*mp*Vp**2 Where C = 1+ 4f D = 1 + (f*Ta/Tp) + (1+2f)*Te/Tp E = 1 + 4f*(Va/Vp)**2 **Now, some issues.** 1. f is typically in the range 0.04-0.05, although there are significant differences for different flow types. 2. Ta/Tp is typically in the range 4-6. 3. What about Te? Feldman et al, JGR, 80, 4181, 1975 says that Te is almost always in the range 1-2*10**5 deg K. Te rises and falls with Tp, but with a much smaller range of variability. Kawano et al (JGR, 105, 7583, 2000) cites Newbury et al (JGR, 103, 9553, 1998) recommending Te = 1.4E5 based on 1978-82 ISEE 3 data. So we'll use Te = 1.4E5 deg K for our analysis. 4. What about (Va/Vp)**2? We should probably let this be unity always. If we let f=0.05, Ta=4*Tp, Va=Vp, and Te=1.4*10**5, we'd have C = 1.2 D = 1.2 + 1.54E5/Tp E = 1.2 **Characteristic speeds:** Sound speed = Vs = (gamma * thermal pressure / mass density)**0.5 = gamma**0.5 * [D*Np*k*Tp /C*mp*Np]**0.5 = gamma**0.5 * (D/C)**0.5 *(k*Tp/mp)**0.5 With the above assumptions for f, Ta, Va, and Te, and with gamma = 5/3, we'd get Vs (km/s) = 0.12 * [Tp (deg K) + 1.28*10**5]**0.5 Alfven speed = VA = B/(4pi*mass_density)**0.5 = B/(4pi*C*mp*Np)**0.5 With the above assumptions, we'd get VA (km/s) = 20 * B (nT)/Np**0.5 and **MA = V/Va = (V * Np**0.5) / 20 * B**



For M_A = 7.5 at all Maxima

Question: Where would the MHD calculations fall in this diagram?



For M_A = 12.25 at all Minima

$M_A = (V N_p^{0.5})/(20 B)$

The ● marks the B = 4 nT contour of the 'Floor' in HMF

‘Burning Prairie’ => Magnetism

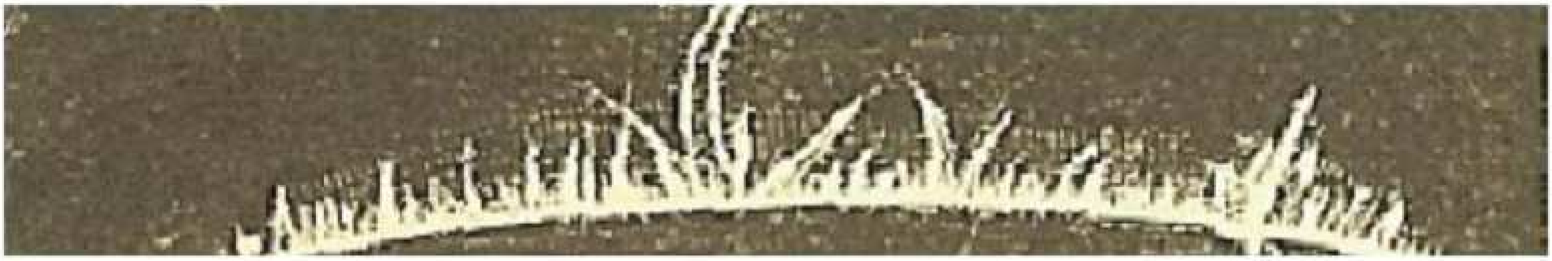
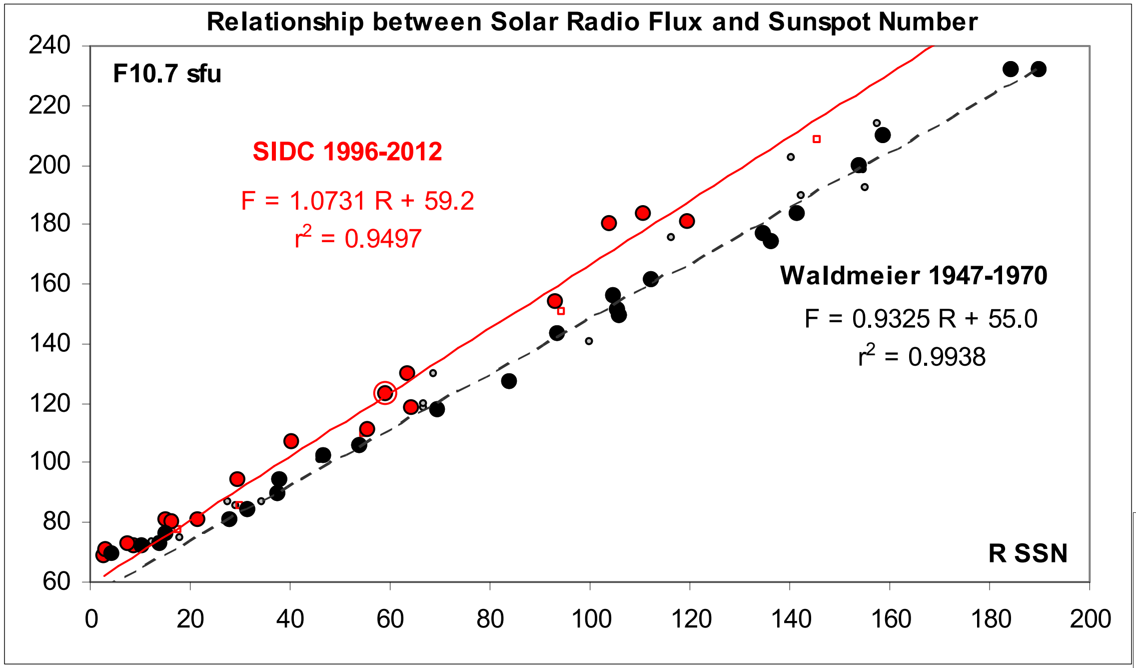


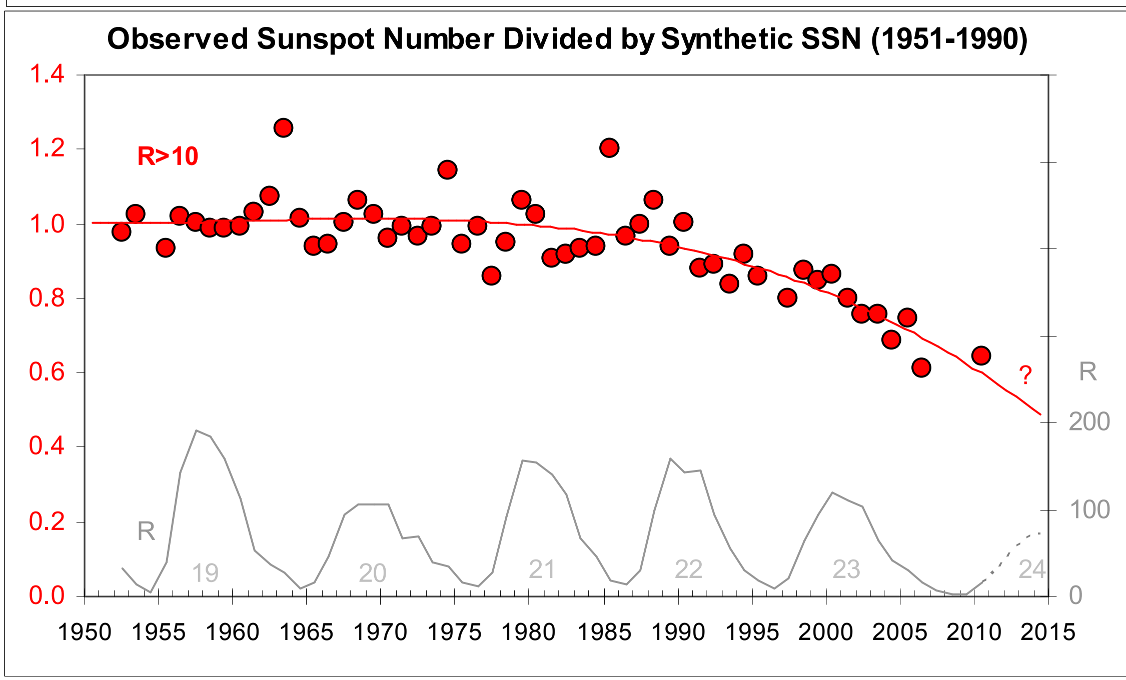
Figure 1 An early drawing of the “burning prairie” appearance of the Sun’s limb made by C.A. Young, on 25 July 1872. All but the few longest individual radial structures are spicules.

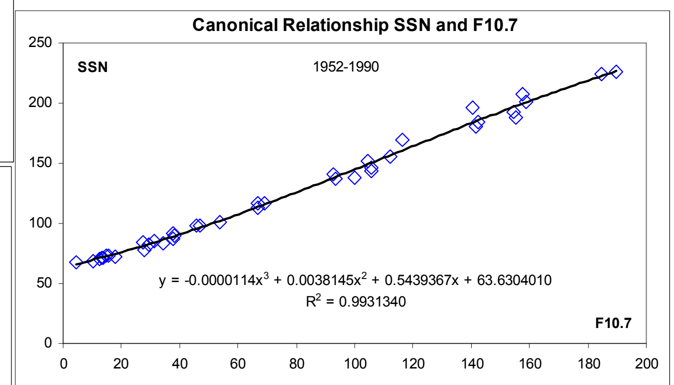
It is now well known (see, *e.g.*, the overview in Foukal, 2004) that the spicule jets move upward along magnetic field lines rooted in the photosphere outside of sunspots. Thus the observation of the red flash produced by the spicules requires the presence of widespread solar magnetic fields. Historical 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.

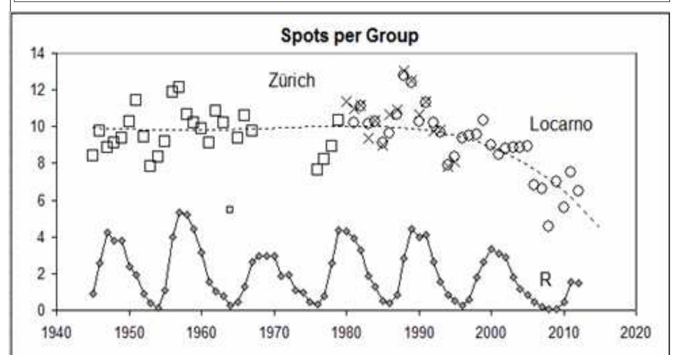
Foukal & Eddy, Solar Phys. 2007, *245*, 247-249

Growing Deficiency of Sunspots

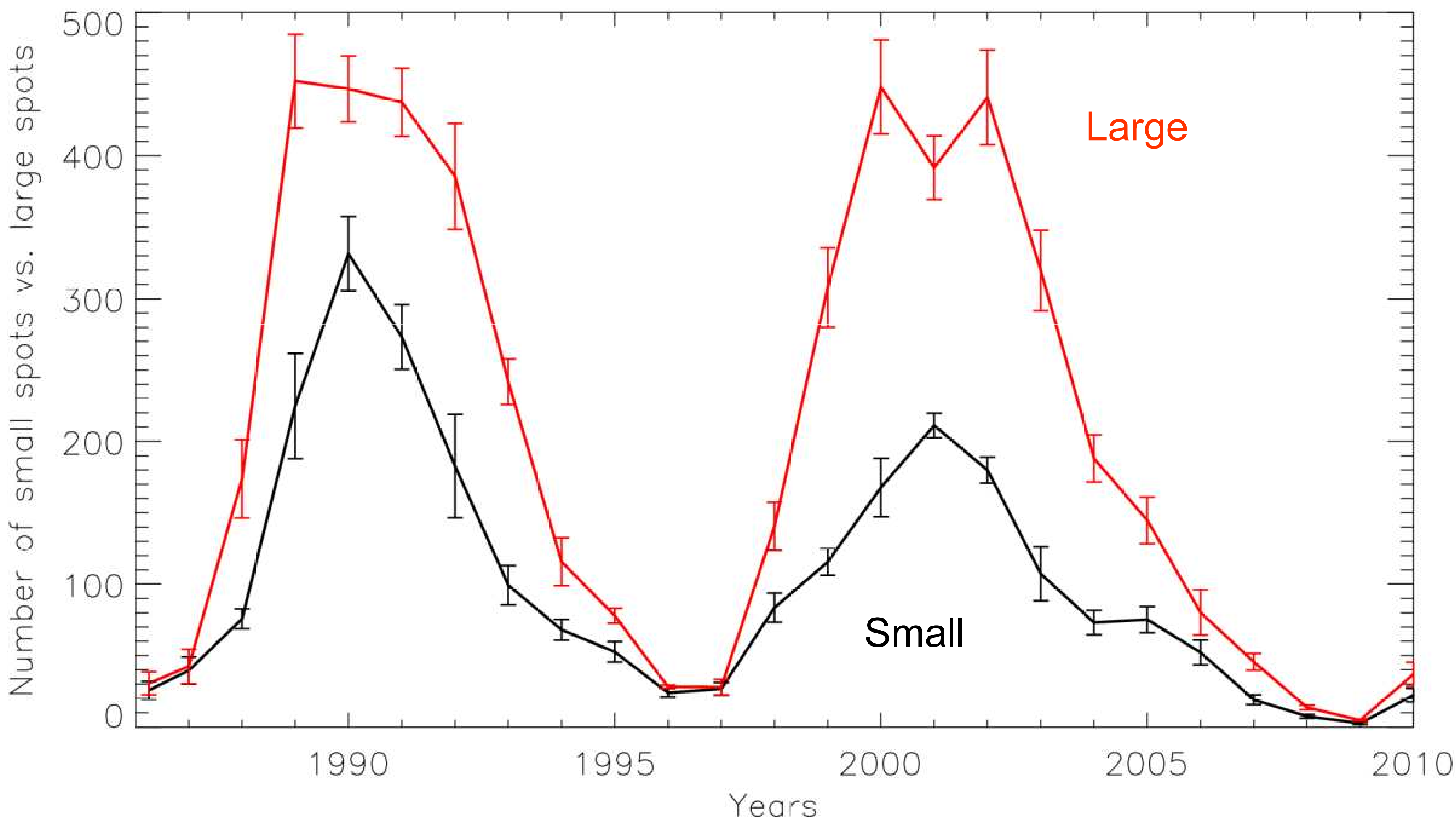






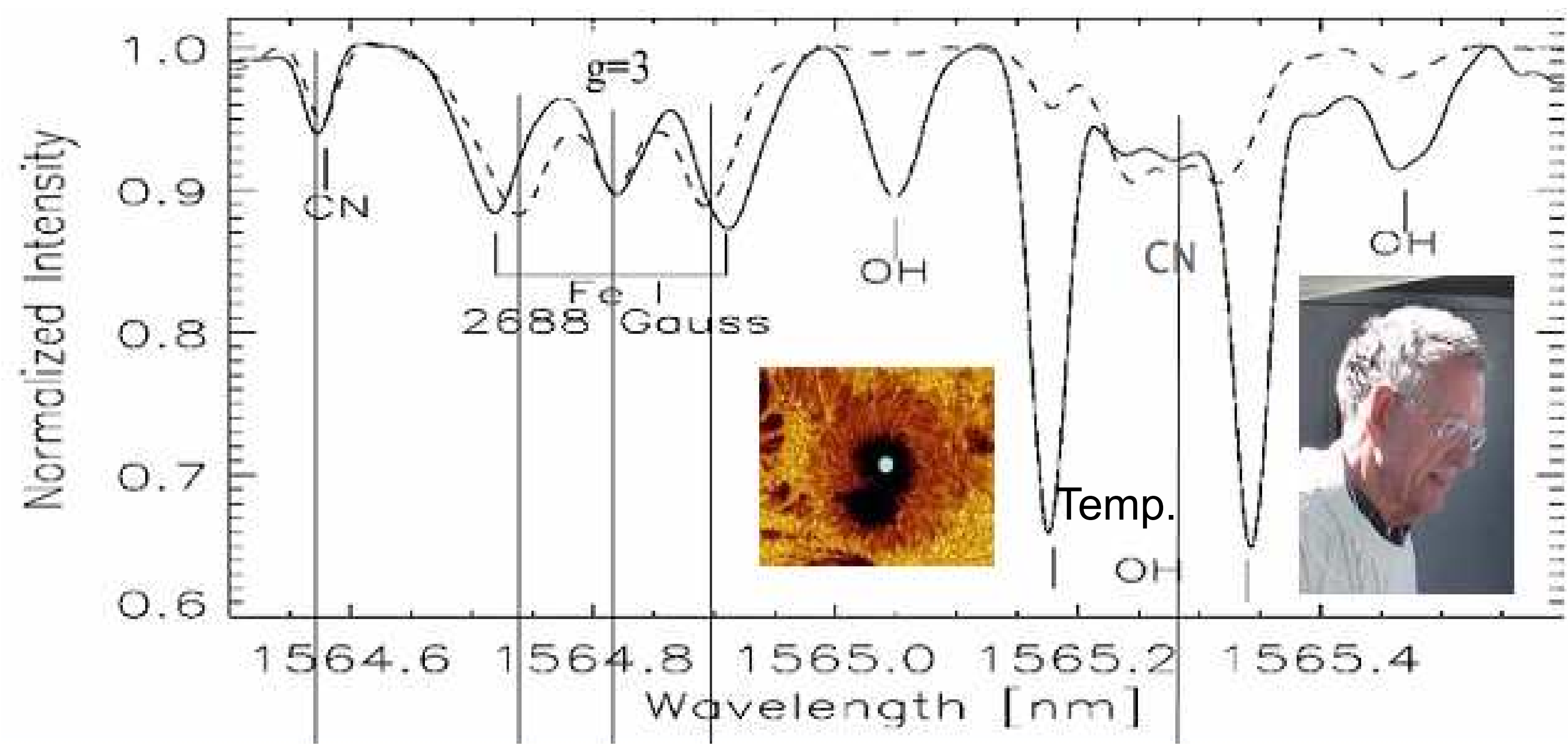


Deficit of Small Spots

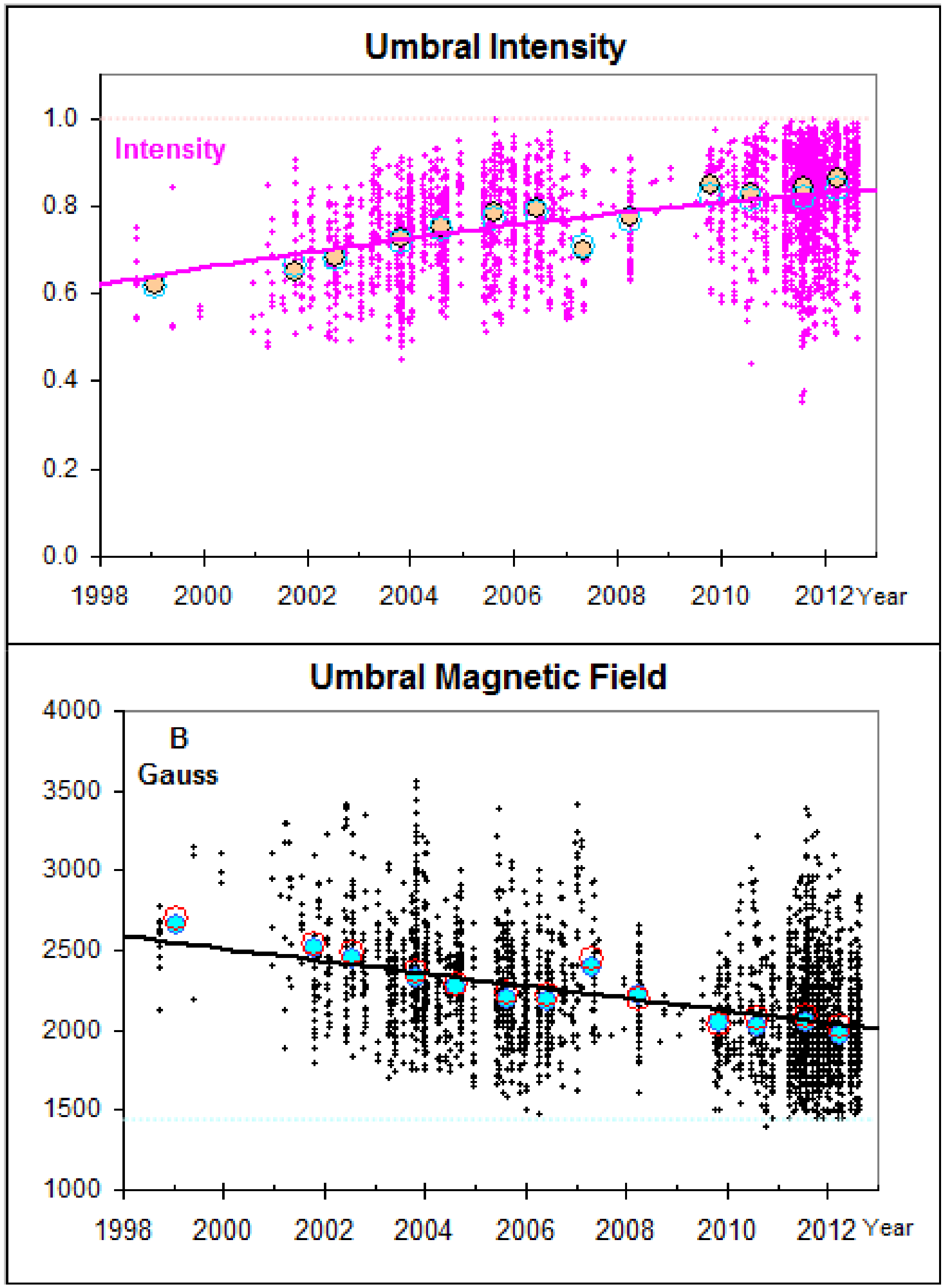


Lefevre & Clette, SIDC

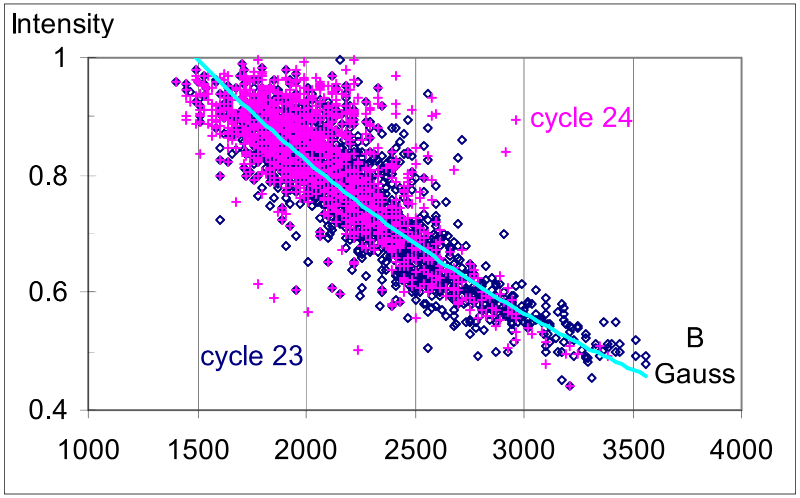
The Livingston & Penn Data

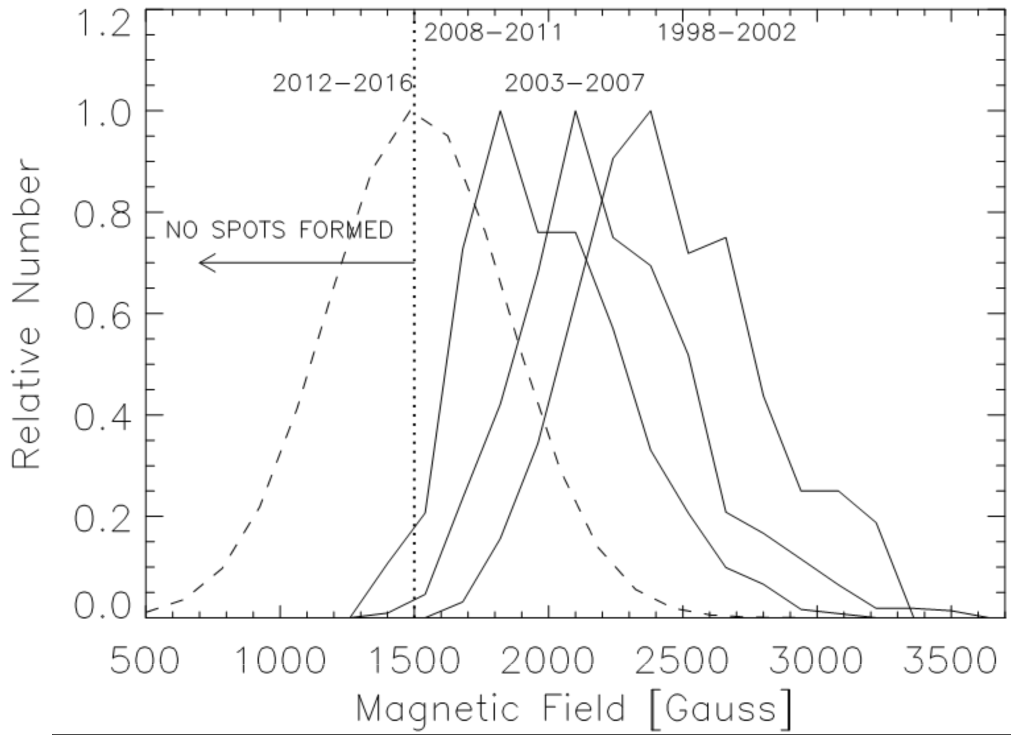


From 2001 to 2012 Livingston and Penn have measured field strength and brightness at the darkest position in umbrae of 1843 spots using the Zeeman splitting of the Fe 1564.8 nm line. Most observations are made in the morning [7h MST] when seeing is best. Livingston measures the absolute [**true**] field strength averaged over his [small: 2.5″x2.5″] spectrograph aperture, and not the Line-of-Sight [LOS] field.

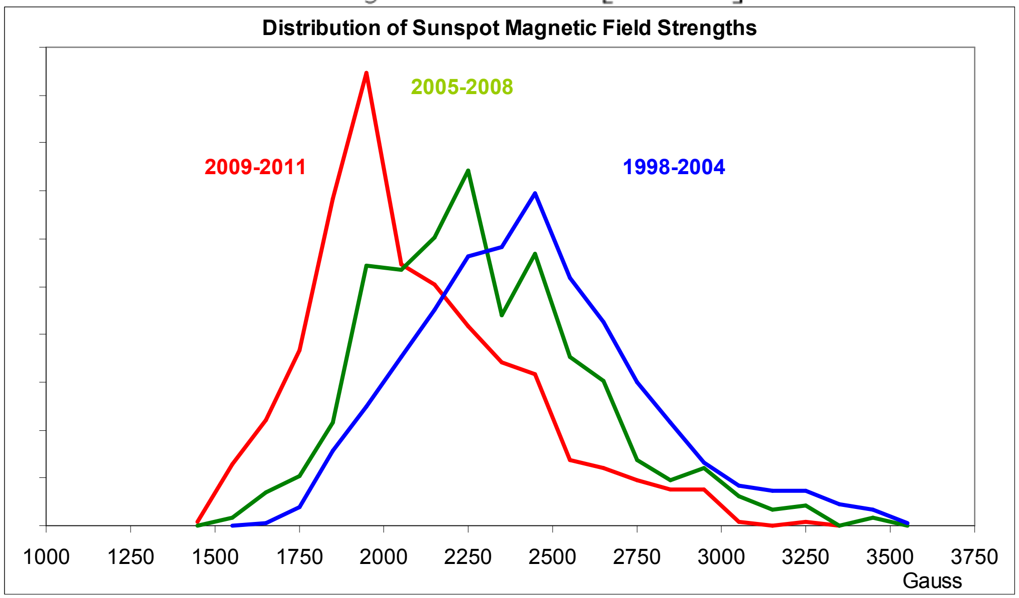


Umbral Intensity [Temperature] and Magnetic Field



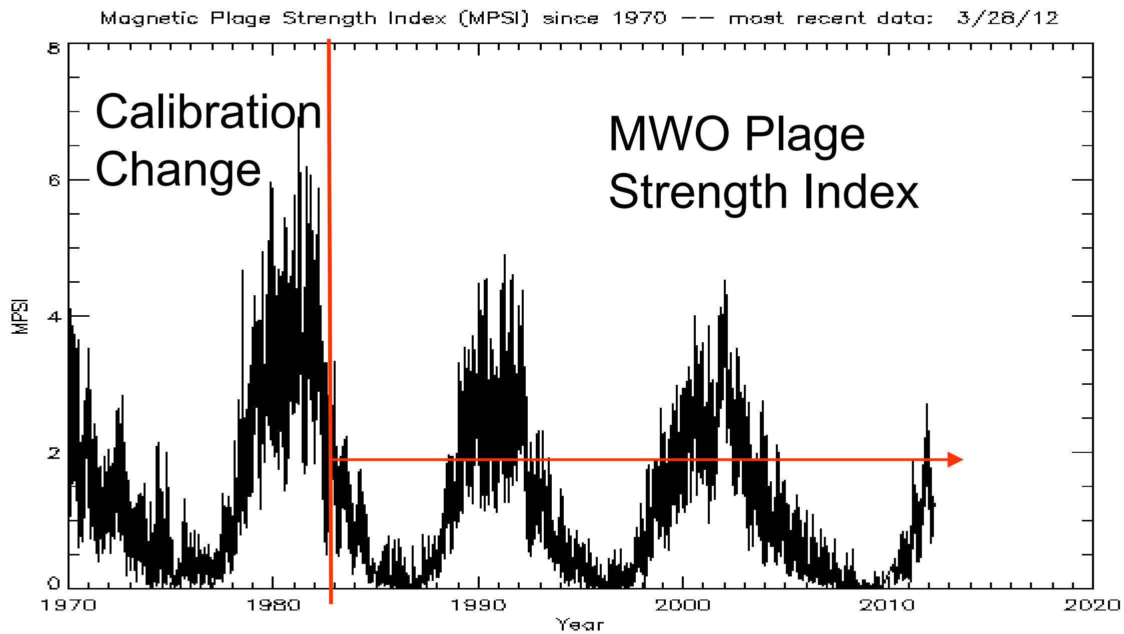


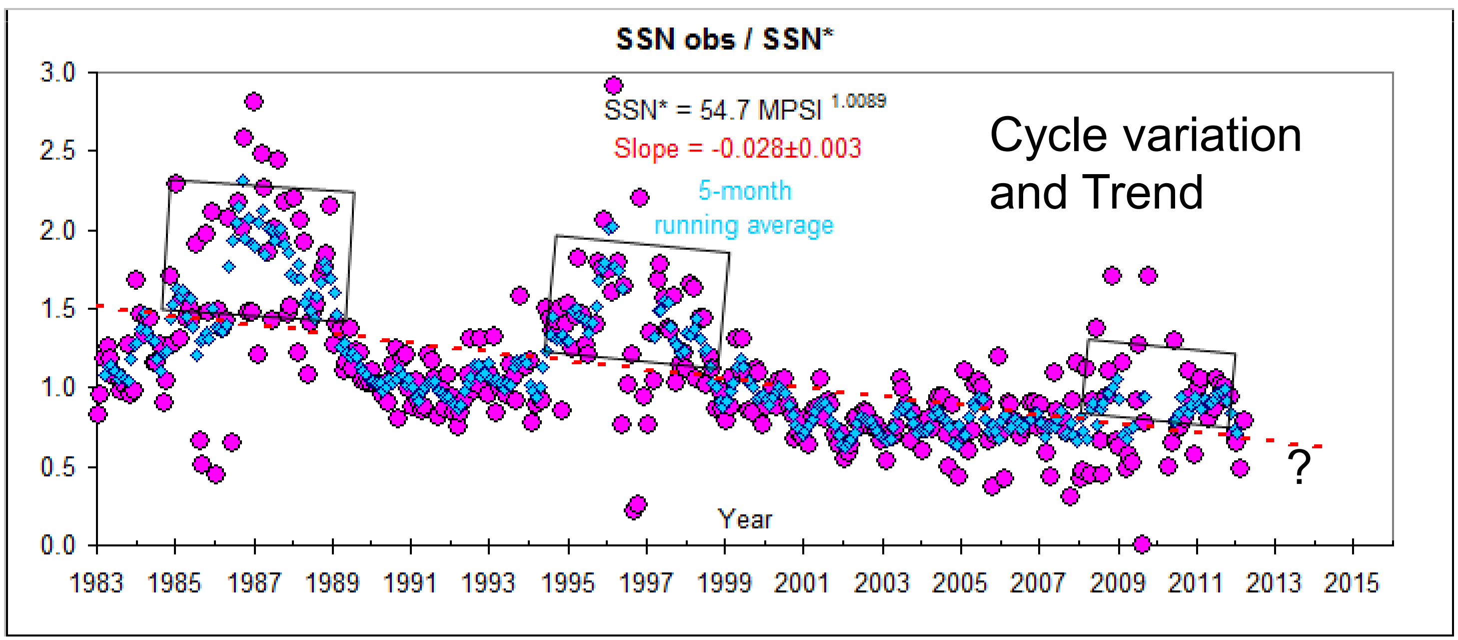
Evolution of Distribution of Magnetic Field Strengths



Sunspots form by assembly of smaller patches of magnetic flux. As more and more magnetic patches fall below 1500 G, fewer and fewer spots will form

We see fewer sunspots for given MPSI





Working Hypothesis

- The Maunder Minimum was not a deficit of magnetic flux, but
- A lessening of the efficiency of the process that compacts magnetic fields into visible spots
- This may now be happening again
- If so, there is new solar physics to be learned