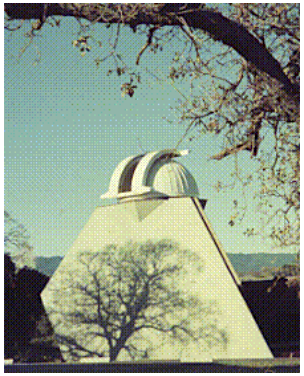
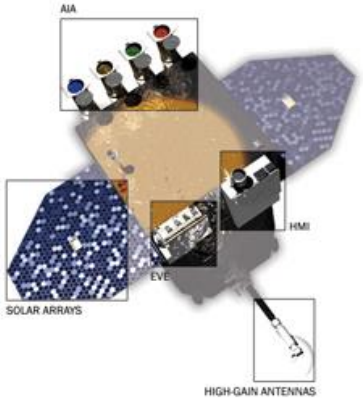




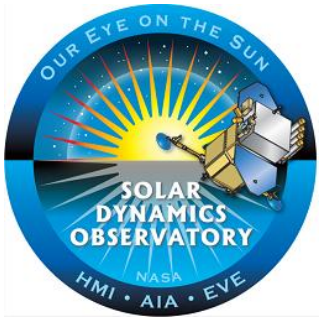
Variation of EUV Matches that of the Solar Magnetic Field and the Implication for Climate Research

Leif Svalgaard, Xudong Sun

Stanford University

15 Nov. 2016

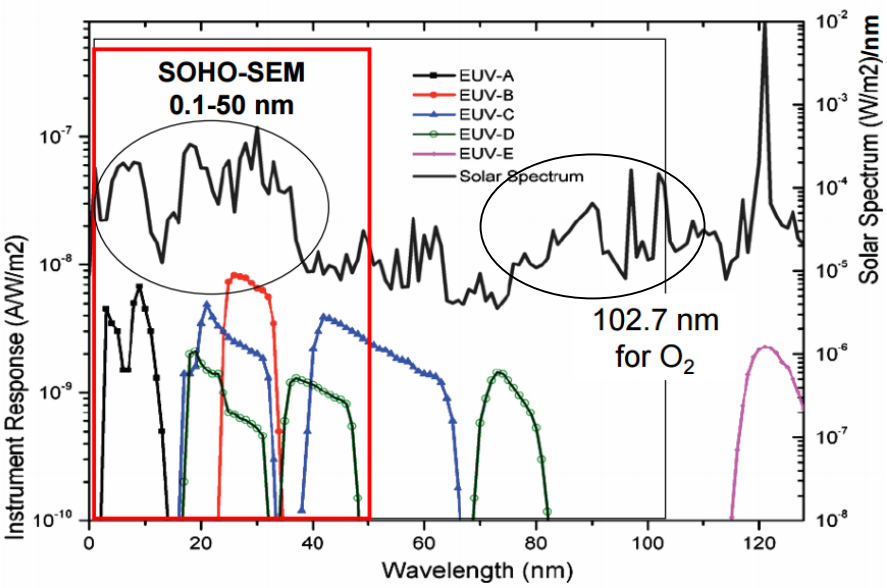
HAO, Boulder, CO



Outline

- Recent EUV, Magnetic Flux, and Solar Microwave flux records
- Deriving EUV [etc] from Geomagnetic Variations
- Deriving Solar Wind Magnetic Field from Geomagnetism and Sunspots
- Total Solar Irradiance, Magnetic Fields, and the Climate Data Record
- Calibration of TSI records

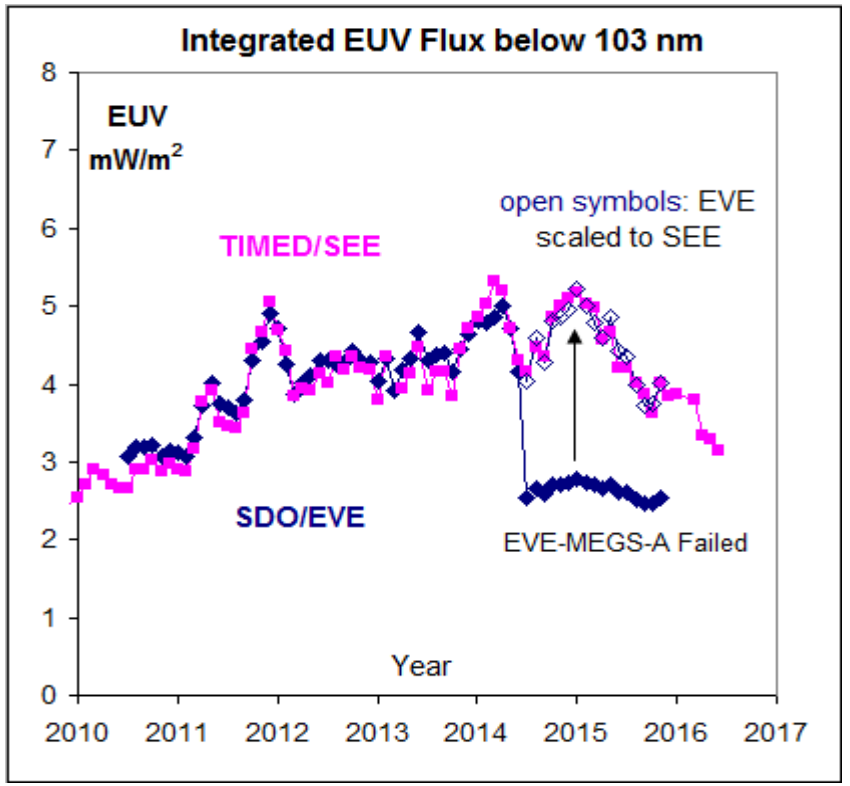
Sources of EUV Data: SEM, SEE, EVE



≤102.7 nm to ionize molecular Oxygen

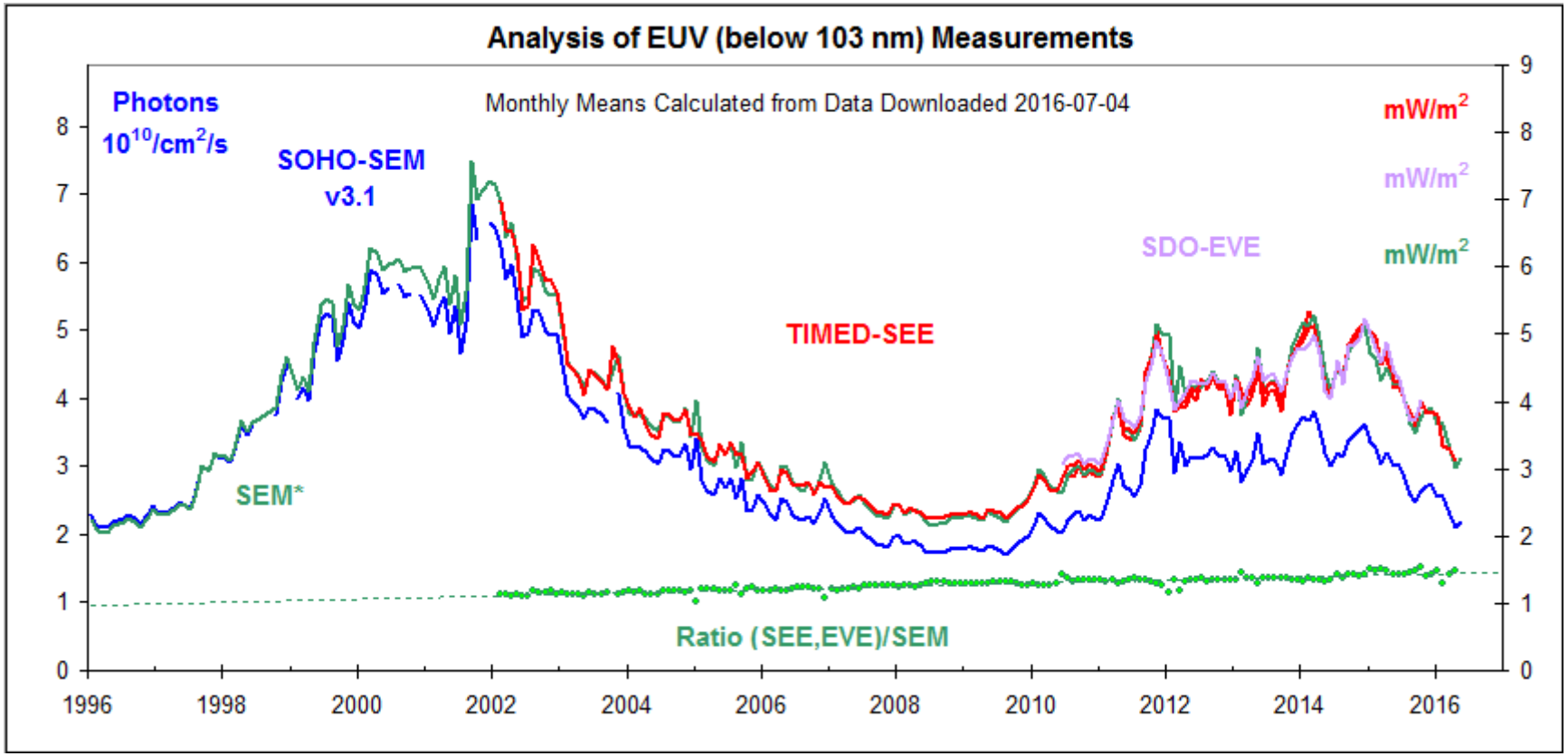
$$O_2 + h\nu \xrightarrow{J} O_2^+ + e^-$$

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



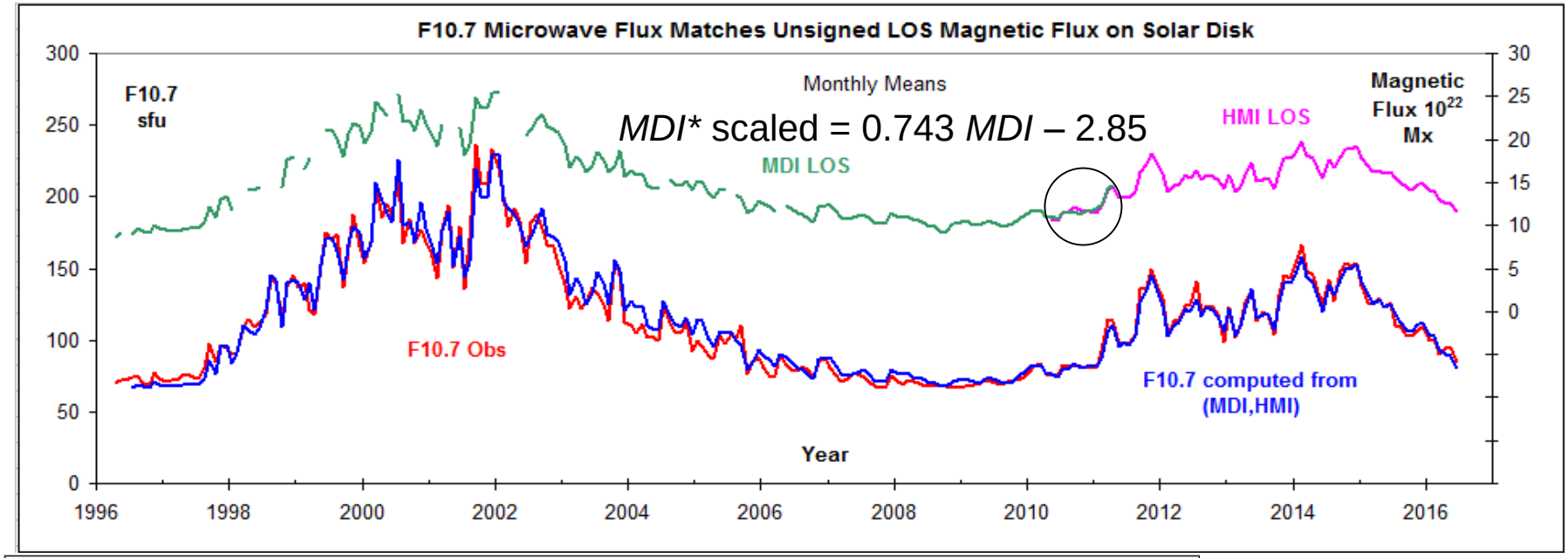
The detectors on the TIMED and SDO satellites agree well until the failure of the high-energy detector on EVE in 2014. We can still scale to earlier levels [open symbols]. 2016 not yet corrected.

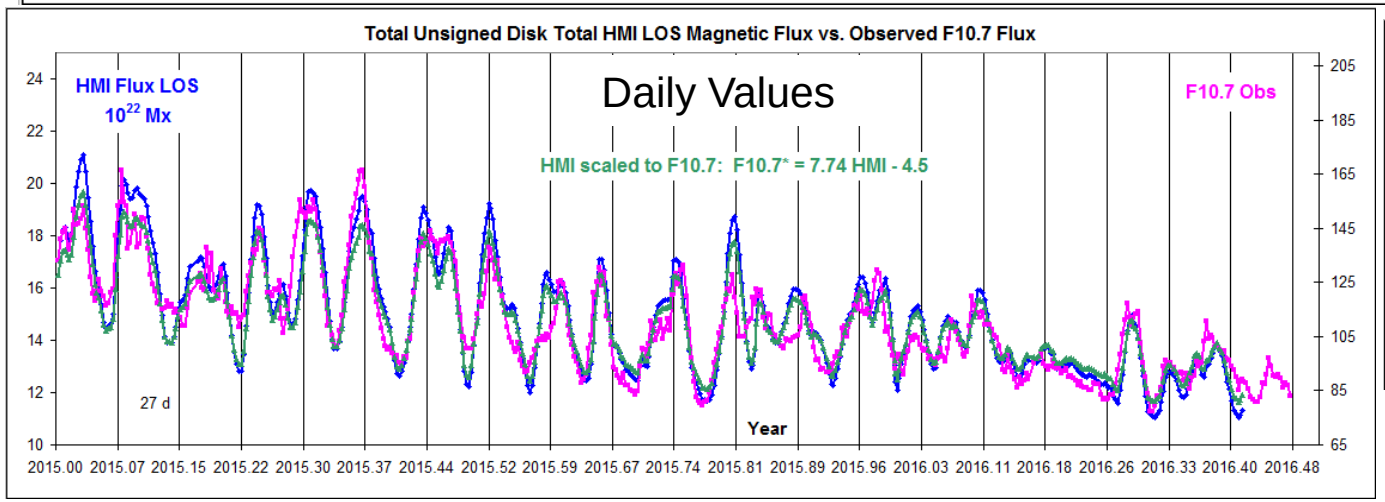
Creating an EUV (<103 nm) Composite

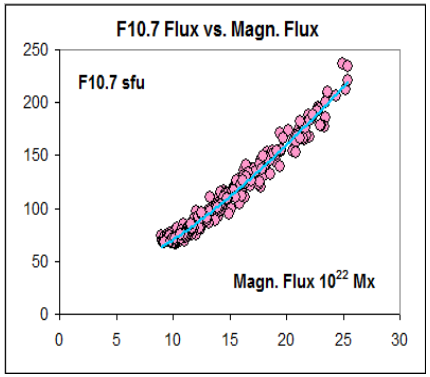


SEE and EVE agree nicely and we can form a composite (SEE,EVE) of them. SEM is on a different scale, but we can convert that scale to the scale of (SEE,EVE). The scale factor [green line] shows what to scale SEM with to match (SEE,EVE) [SEM*, upper green curve], to get a **composite** of all three (SEM*,SEE,EVE)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

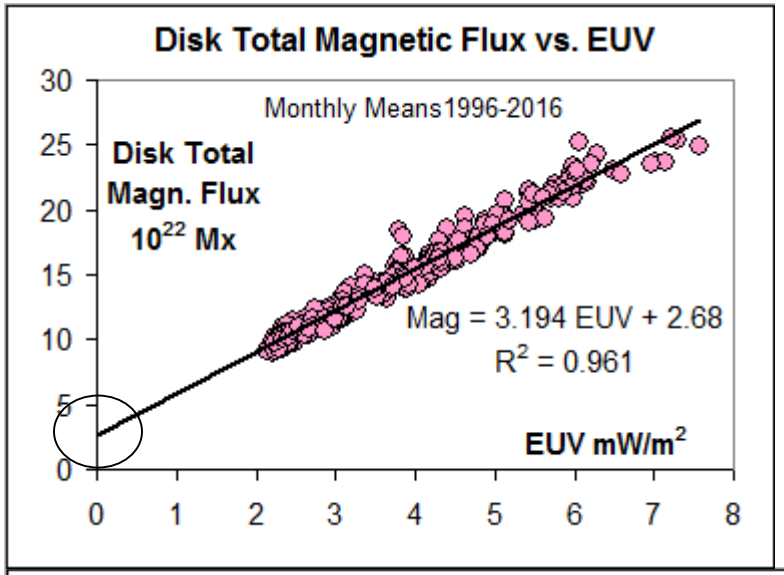
Magnetic Flux from MDI and HMI Match F10.7 Microwave Flux

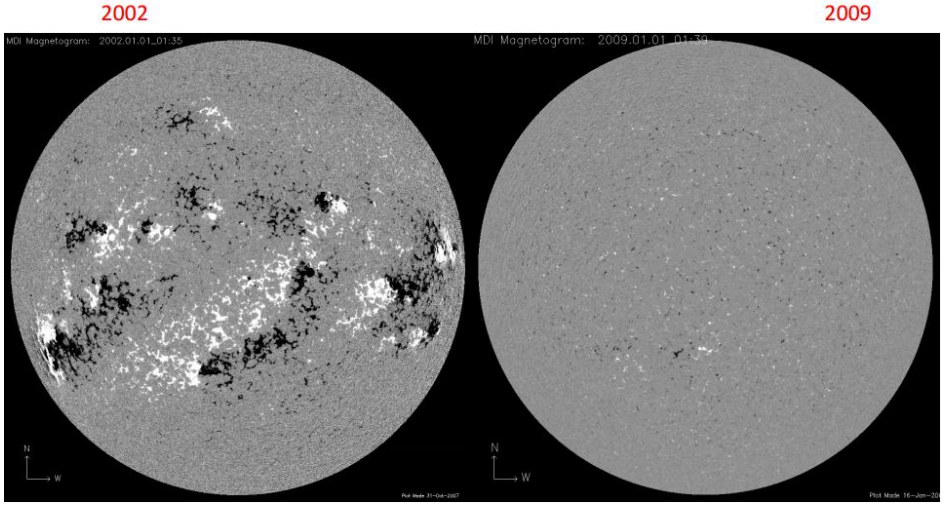




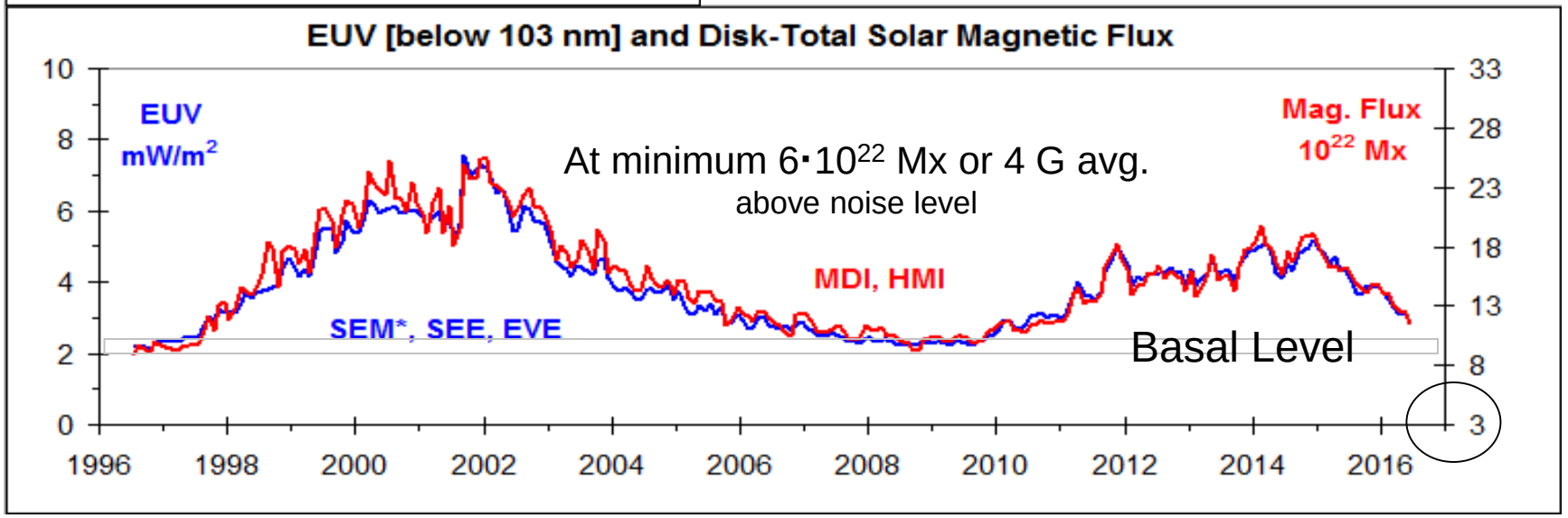


EUV Follows Total Unsigned Magnetic Flux



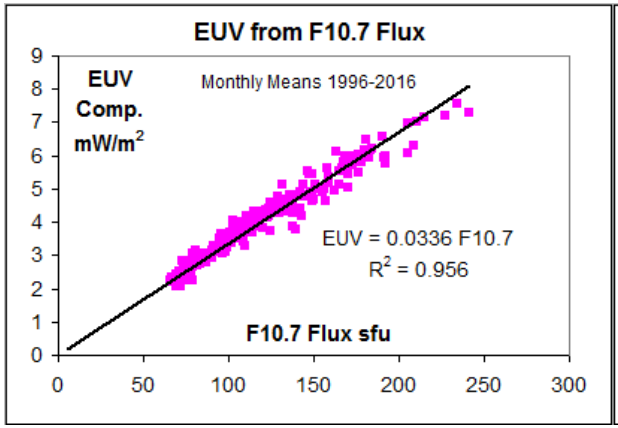


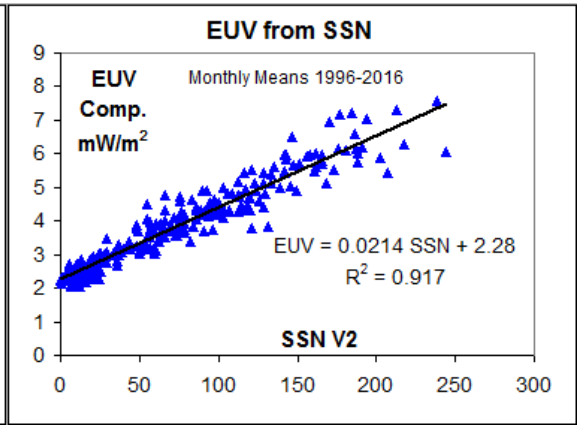
Offset interpreted as Noise Level ≈ 3·10^{22} Mx



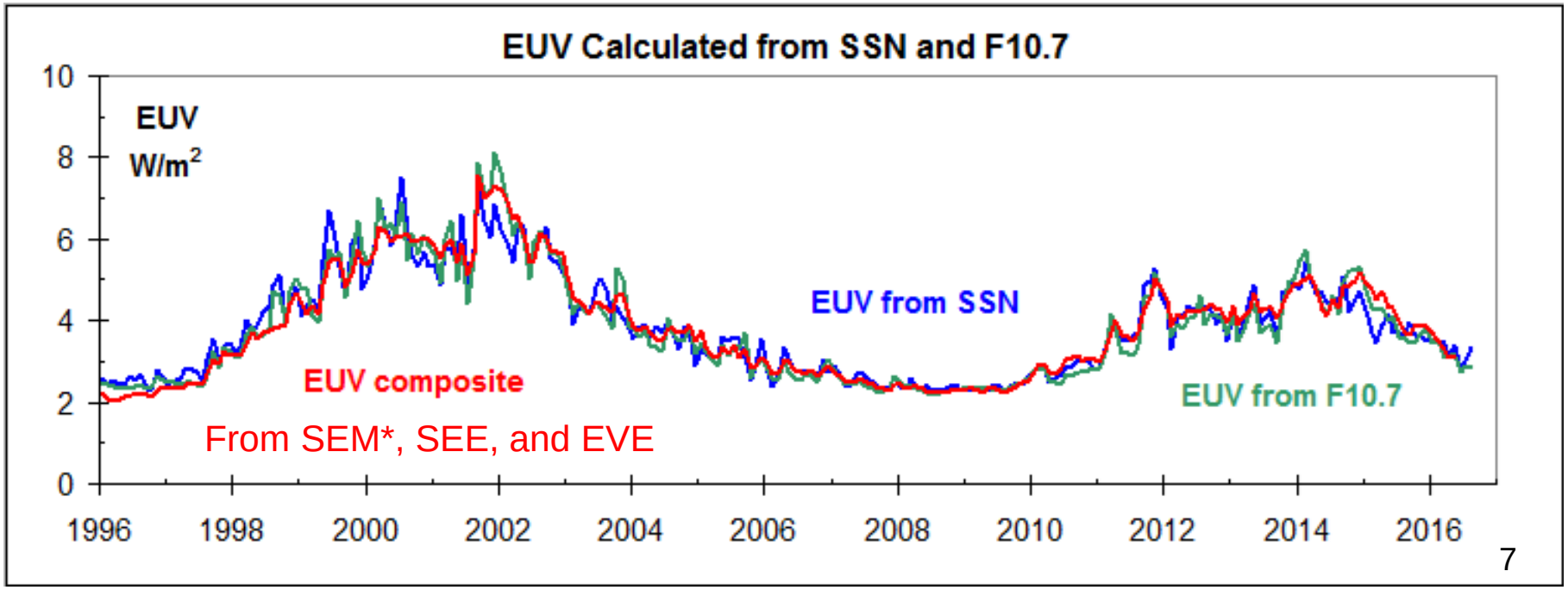
There is a 'basal' level at solar minima. Is this the case at every minimum?

EUV Composite Matches F10.7 and Sunspot Numbers

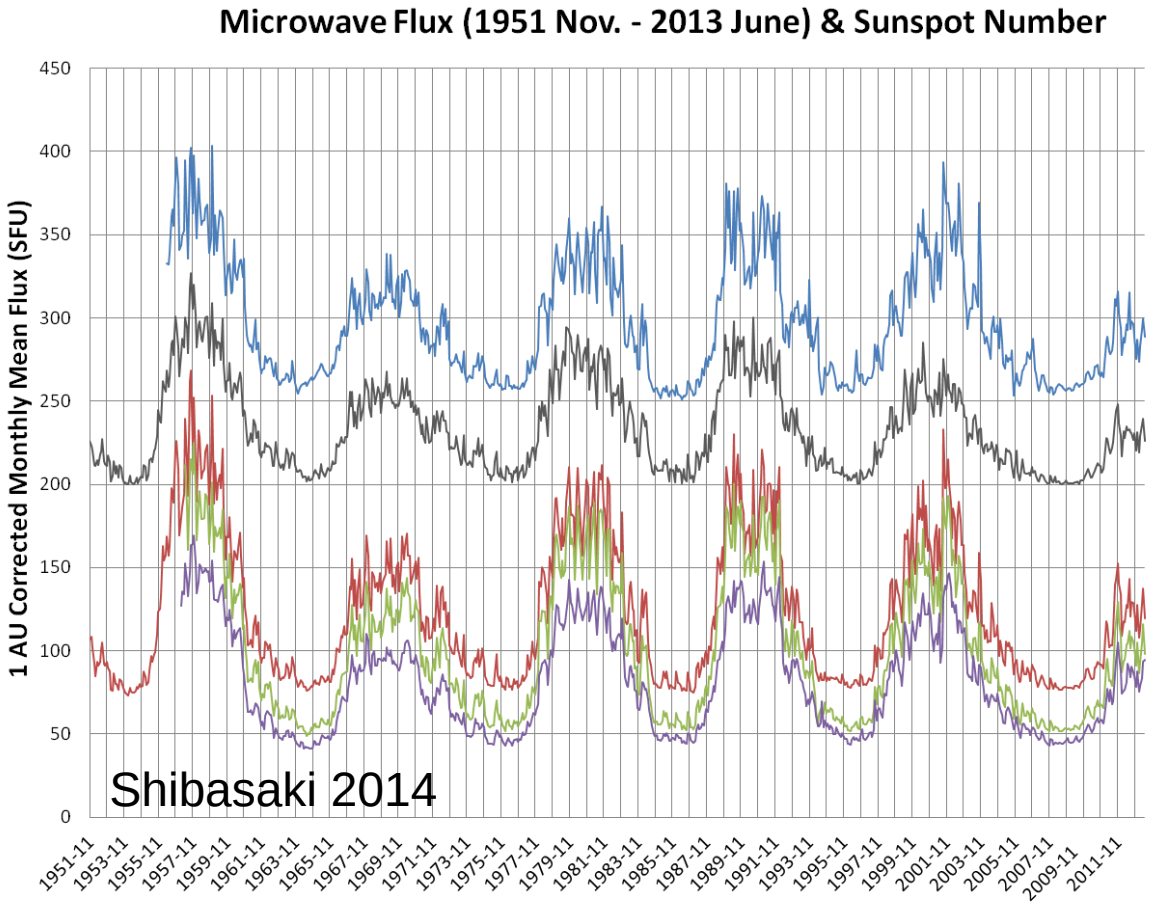


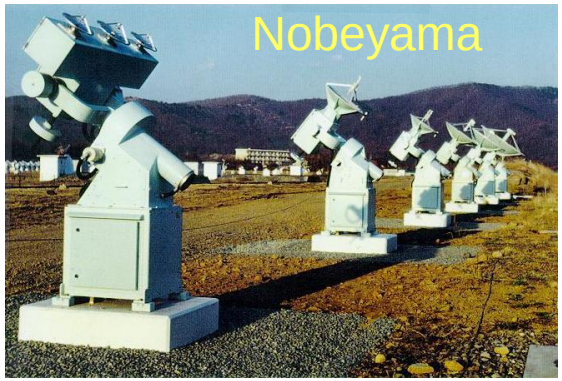


So, we can calculate the EUV flux both from the Sunspot Number and from the F10.7 flux which then is a good proxy for EUV [as is well-known].

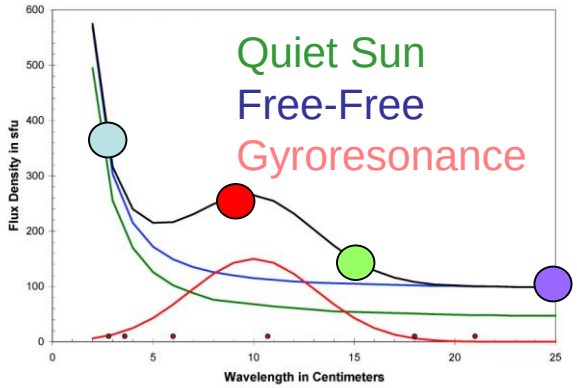


The Microwave Flux Record Extends 70 years in the Past





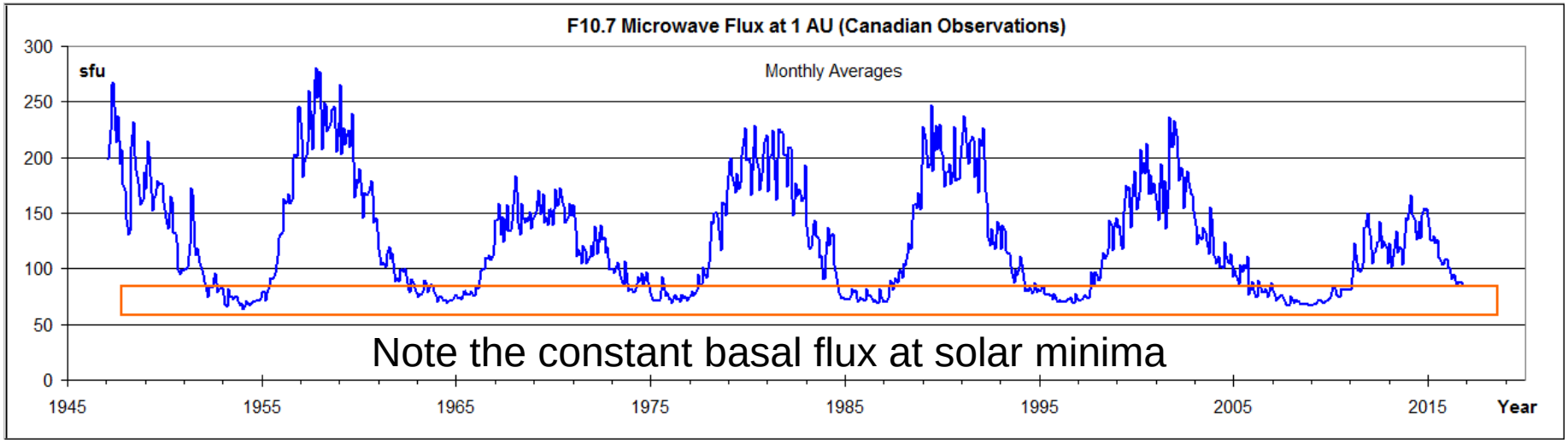
9.4GHz
3.75GHz
2.0GHz
1.0GHz
Spot/2+200

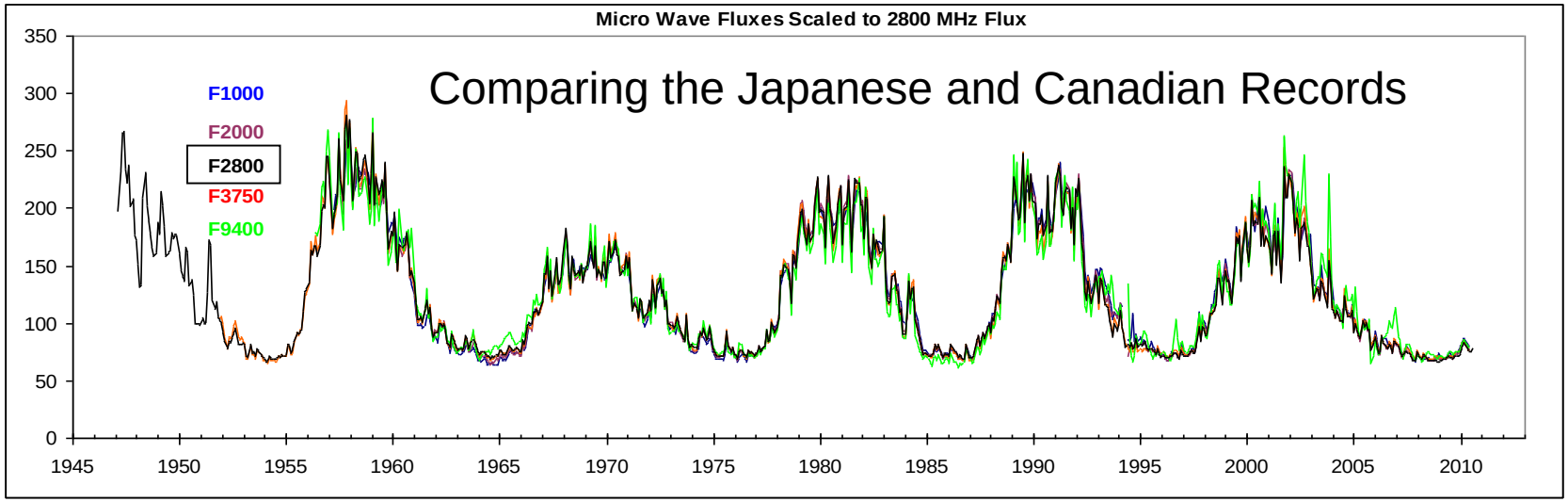


The microwave flux comes from the Transition Region

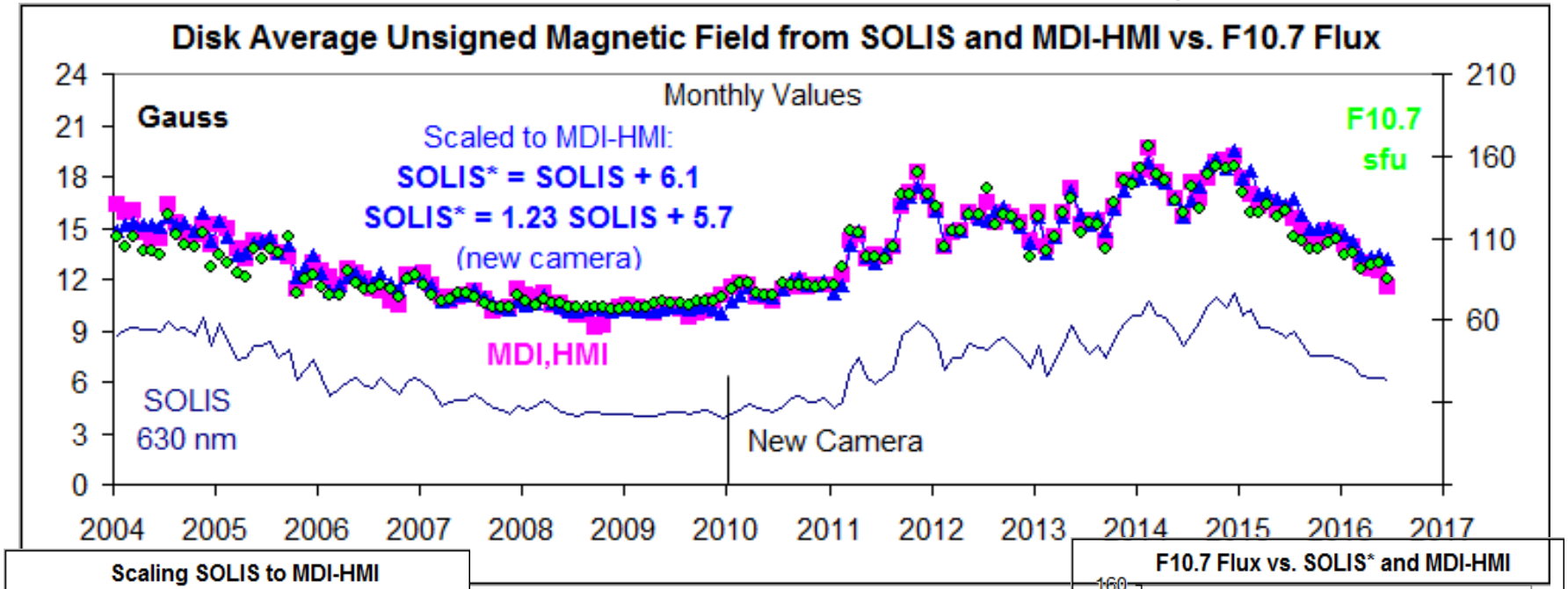
10.7

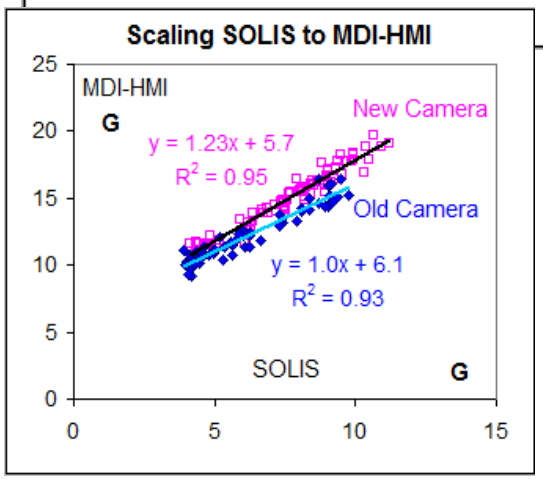
The Japanese and Canadian Microwave Records agree



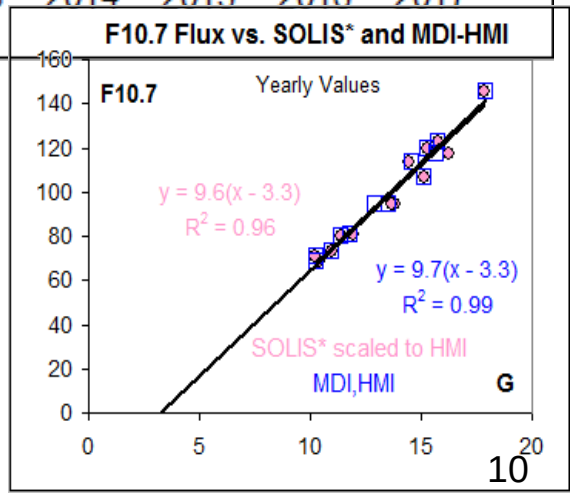


Even Ground-based Observations [SOLIS] Match F10.7 Nicely, but …

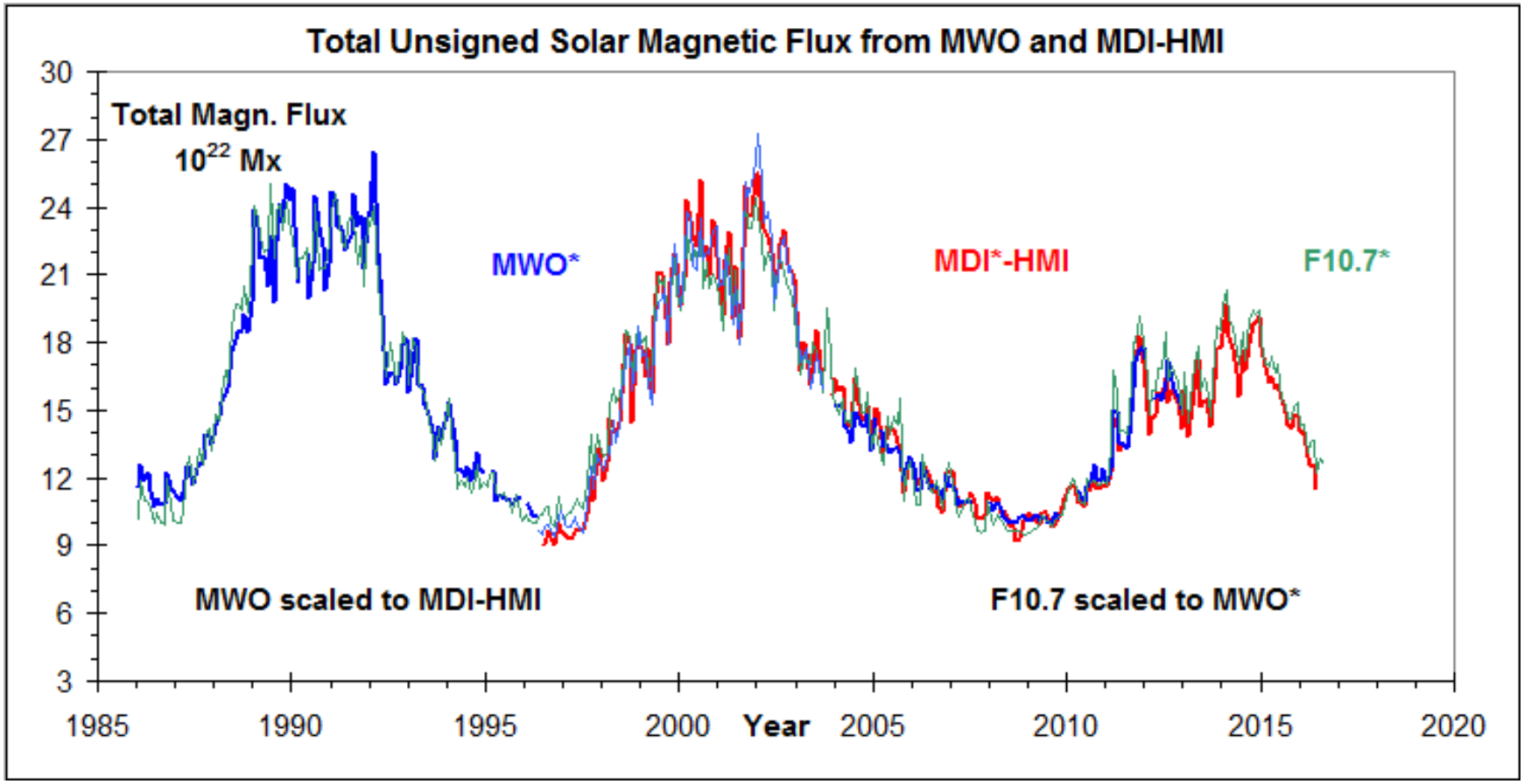




the upgrade to the new camera meant a change of calibration. Luckily, the F10.7 record can also serve as a reference series

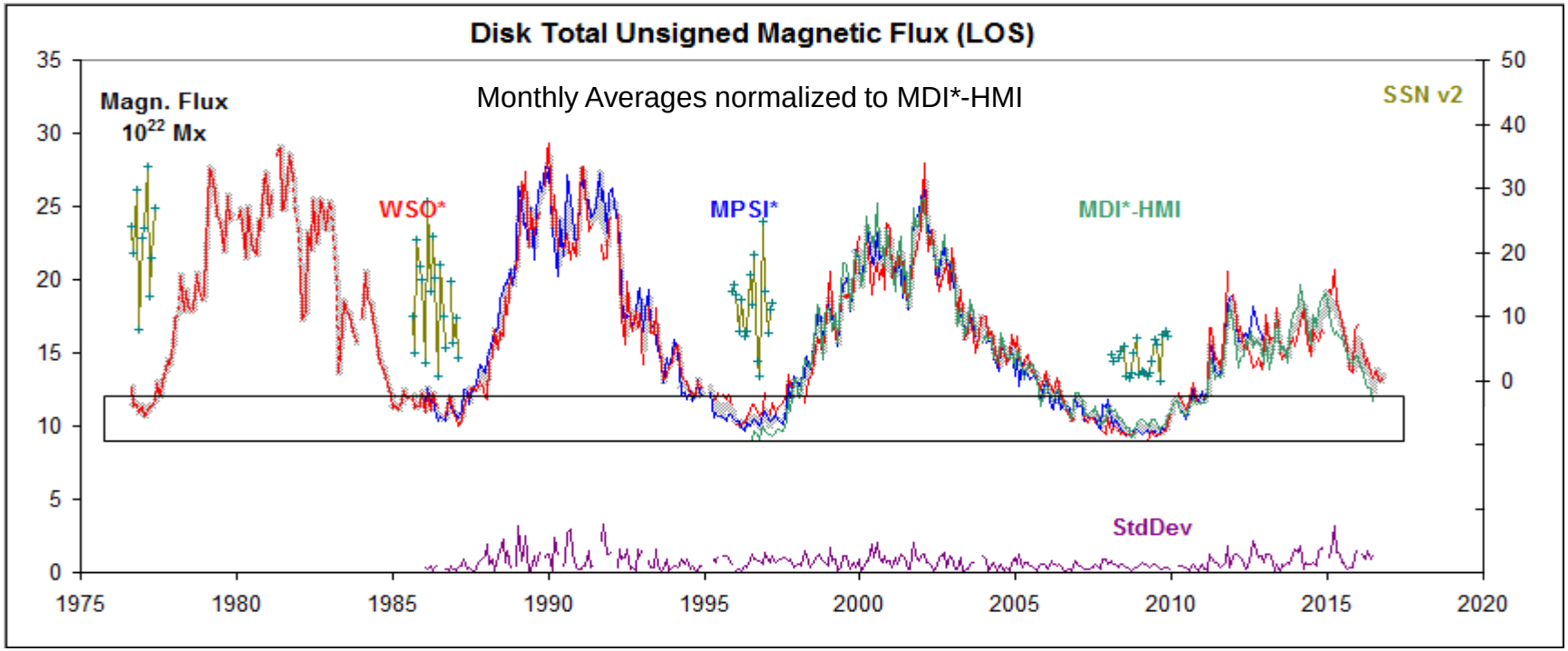


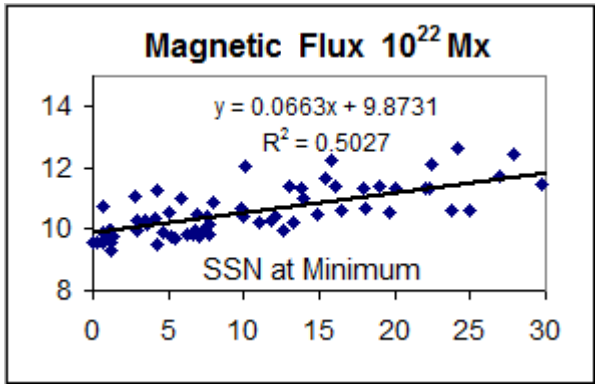
Magnetic Flux from MWO Tracks MDI-HMI and the F10.7 Flux



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]

What do we have so far? #1

- We can construct an observed EUV composite back to 1996
- We can construct an observed Magnetic Flux composite back to 1976
- The EUV matches the Magnetic Flux
- The Microwave Flux [1-10 GHz] matches the EUV, Magnetic Flux, and Sunspot Number
- There is no good evidence of activity at solar minima being different between minima the past 70 years, except for tiny residual sunspot-effects

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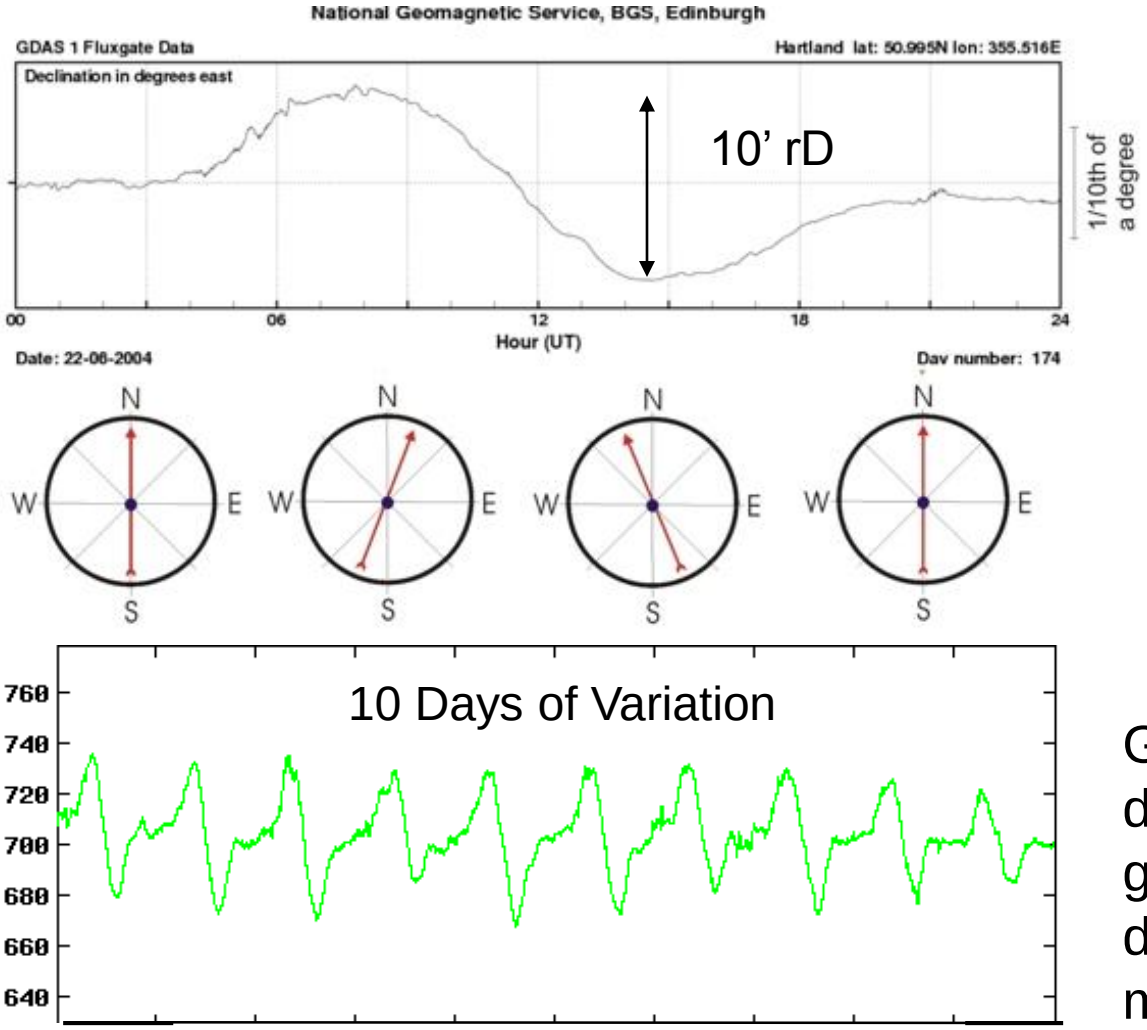
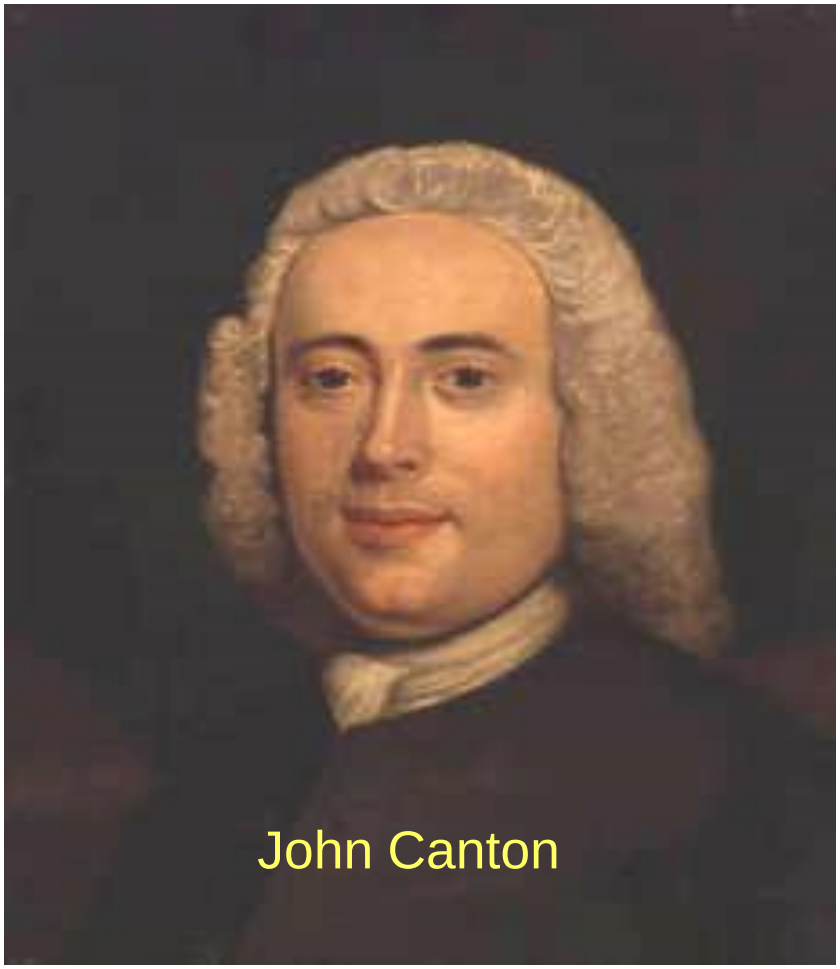
The Diurnal Variation of the Direction of the Magnetic Needle

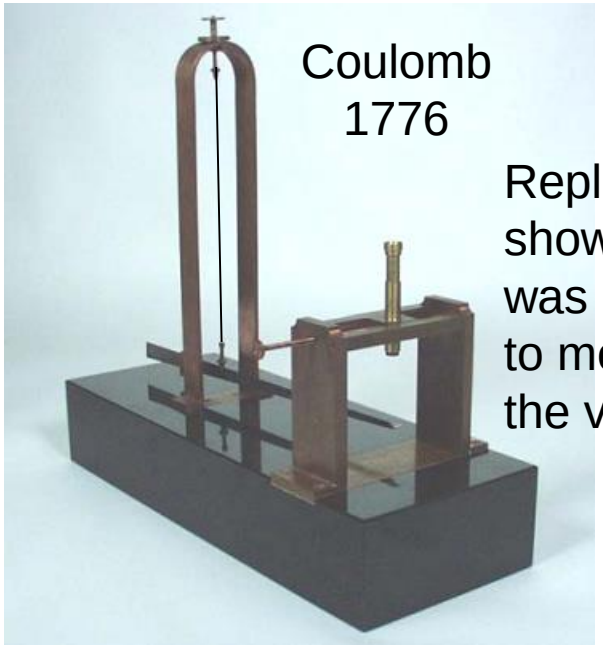


George Graham [London] discovered [1722] that the geomagnetic field varied during the day in a regular manner.

Even Rather Simple Instruments Could Readily Show the Variation

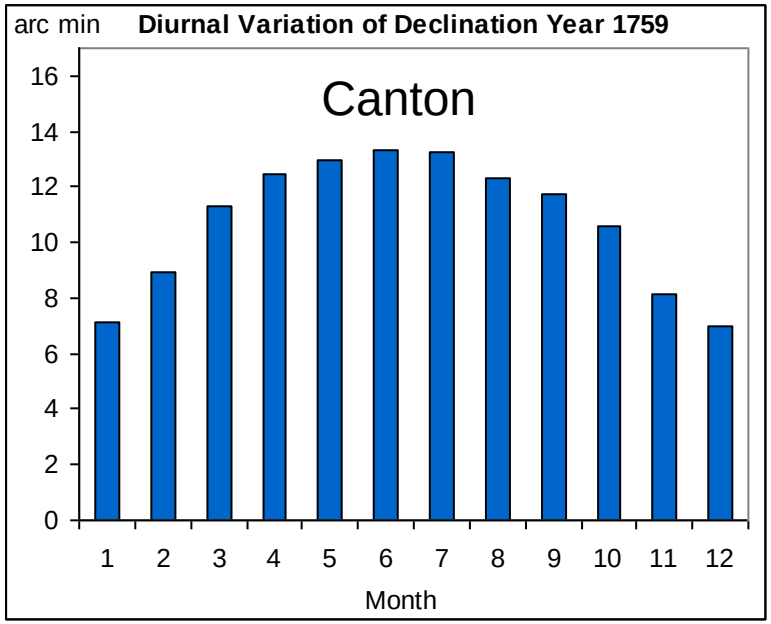


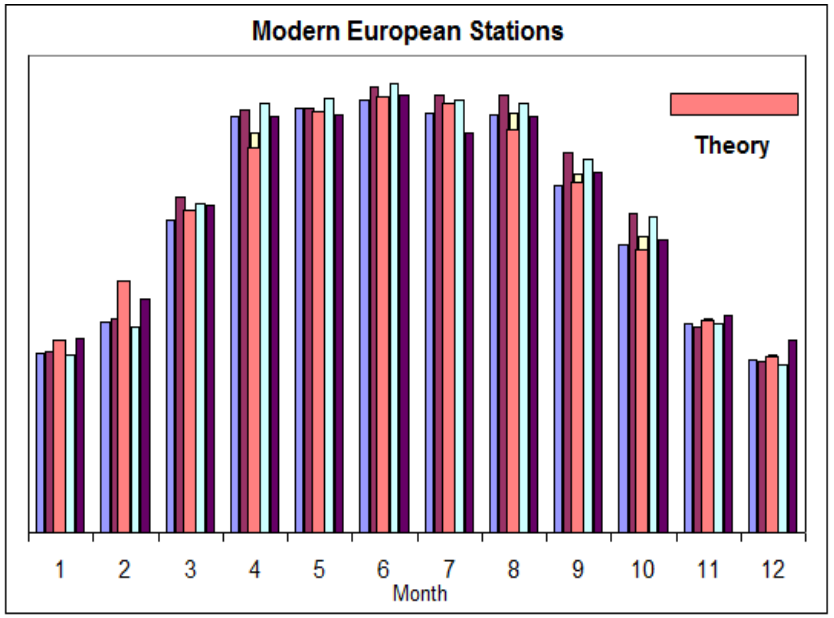
John Canton [1759] made ~4000 observations of the Declination on 603 days

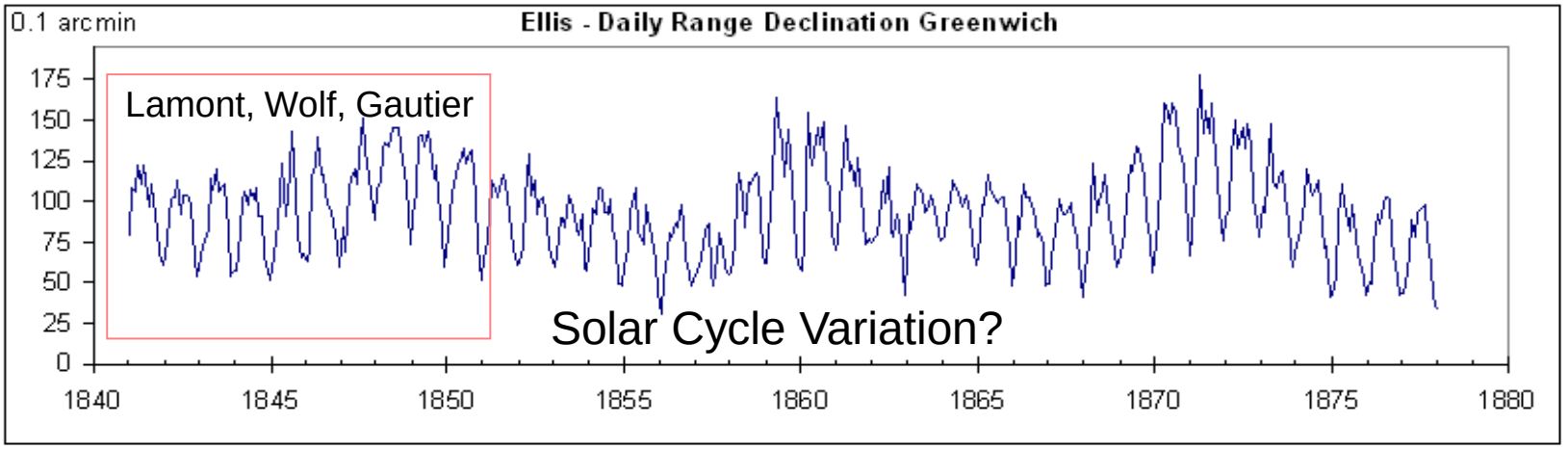


Replicas show that it was possible to measure the variation

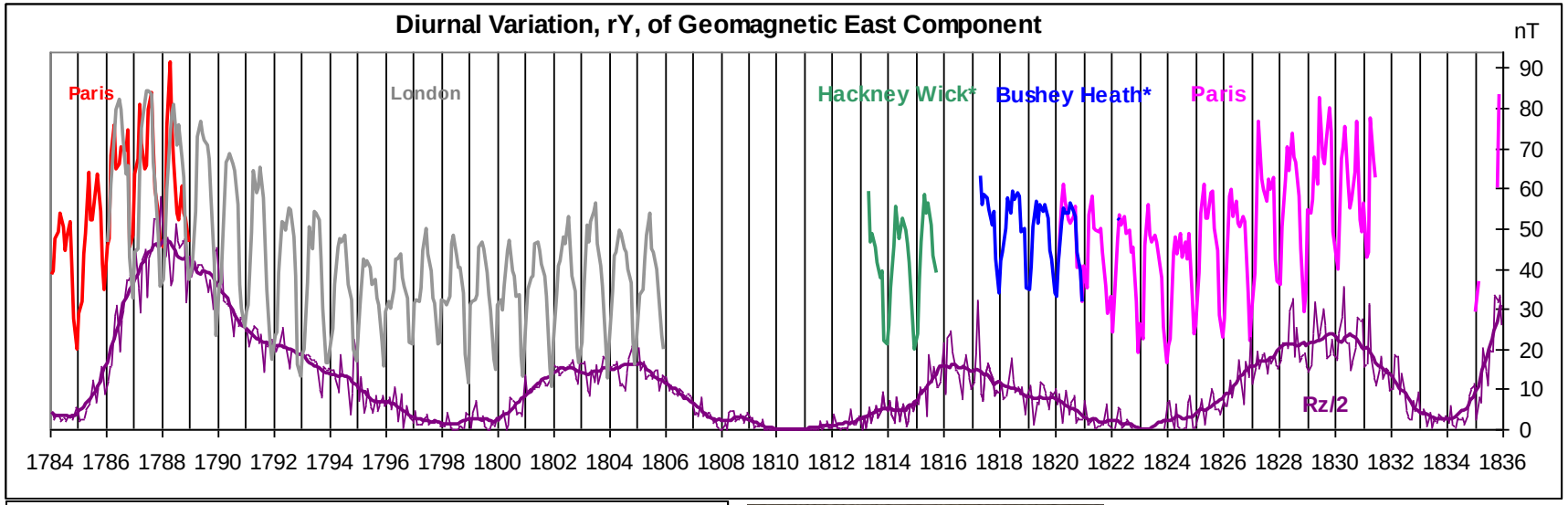
Zenith Angle Dependence Confirmed

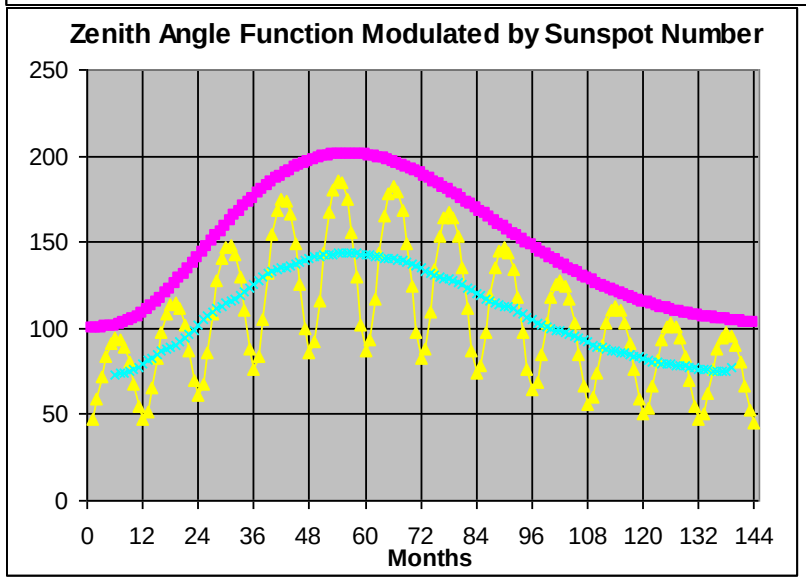






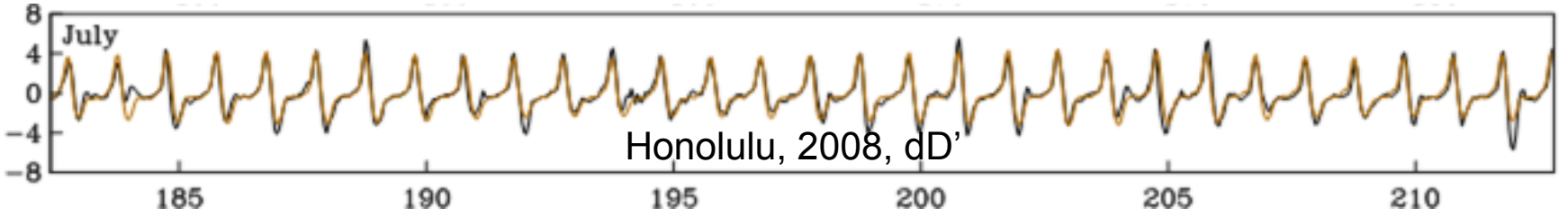
Solar Cycle and Zenith Angle Control



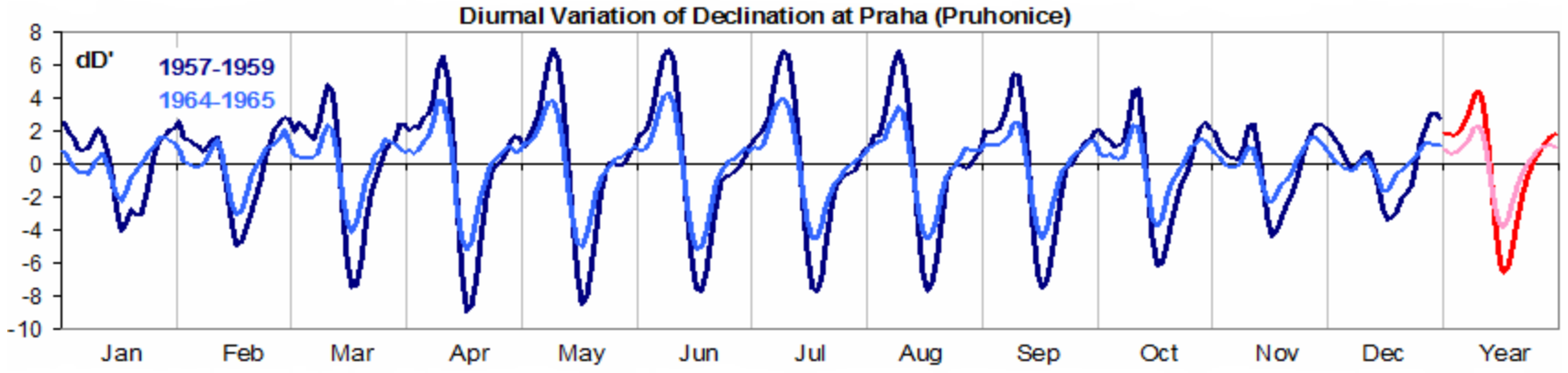


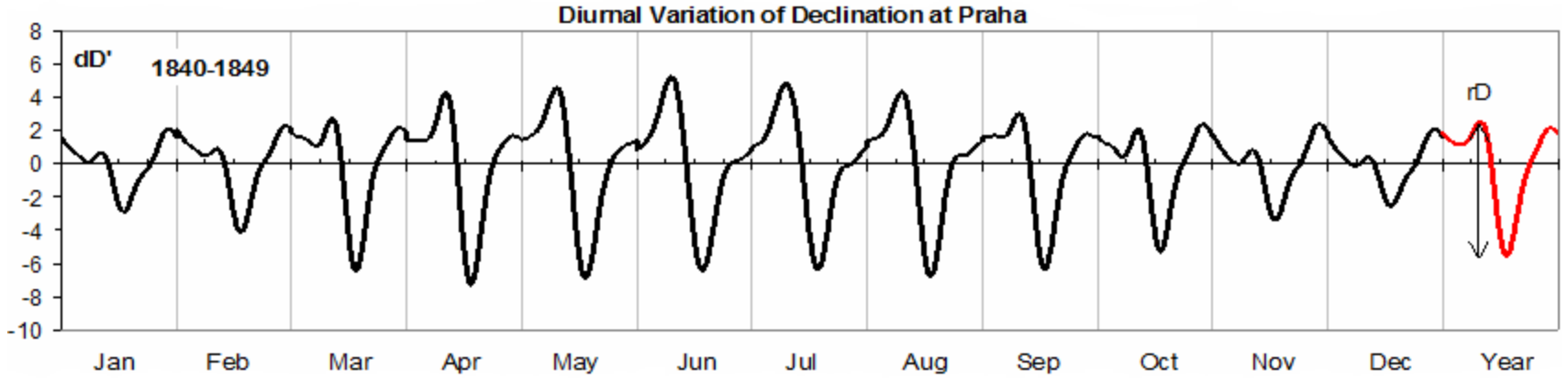
Rudolf Wolf and
J-A Gautier,
1852

The Diurnal Variation of Declination



Honolulu, 2008, dD'



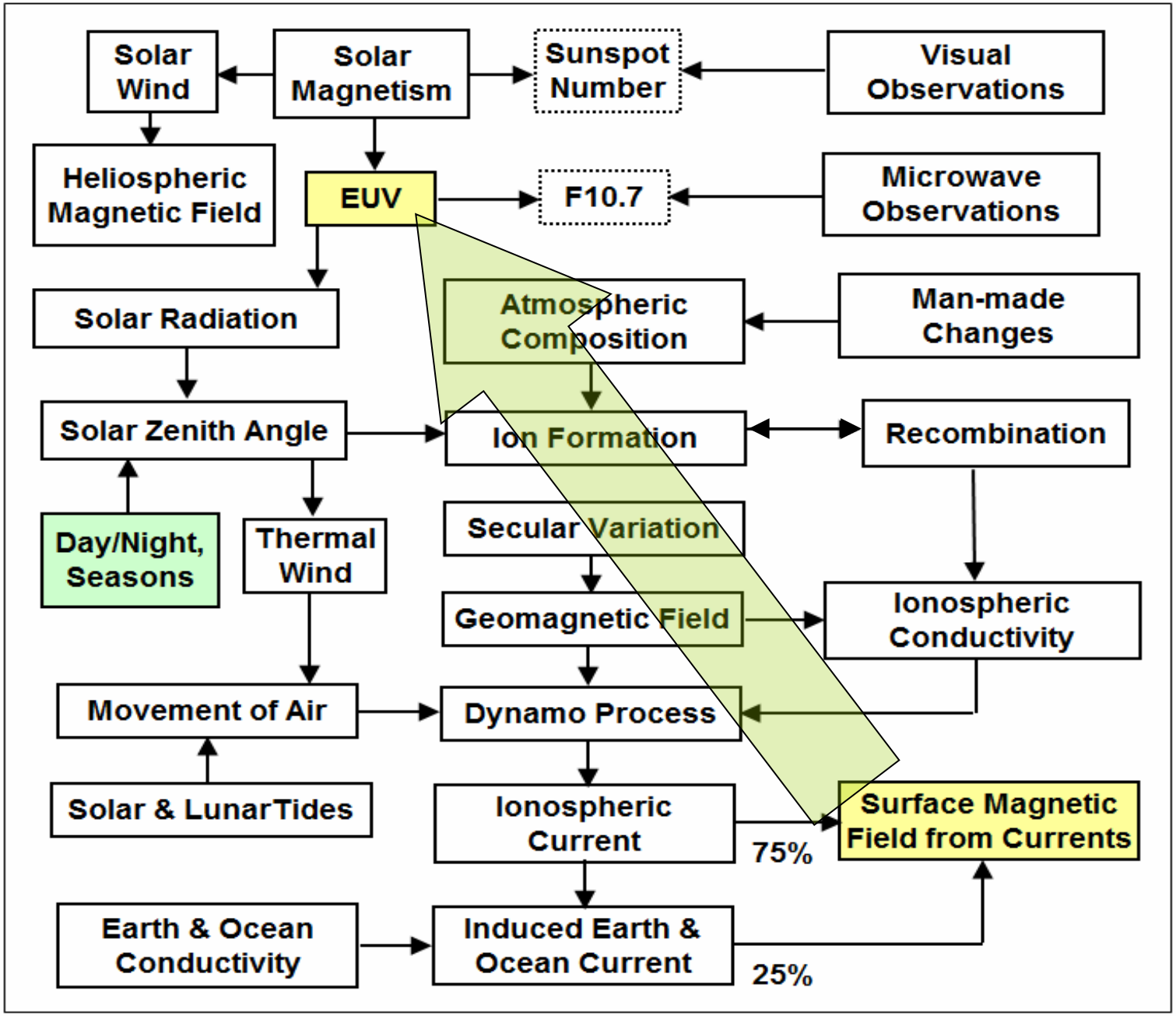


Balfour Stewart, 1882, Encyclopedia Britannica, 9th Ed.

"The various speculations on the cause of these phenomena [daily variation of the geomagnetic field have ranged over the whole field of likely explanations. (1) […], (2) It has been imagined that convection currents established by the sun's heating influence in the **upper regions of the atmosphere are to be regarded as conductors moving across lines of magnetic force, and are thus the vehicle of electric currents which act upon the magnet**, (3) […], (4) […].

Balfour Stewart
1828-1887

"there seems to be grounds for imagining that their **conductivity may be much greater than has hitherto been supposed**."

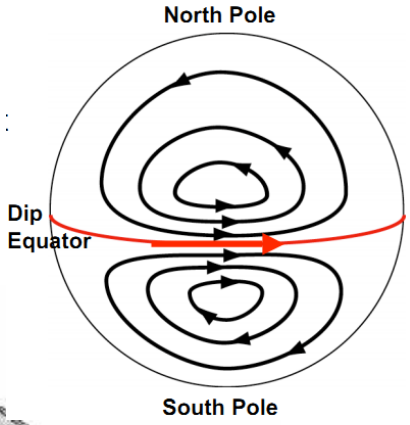


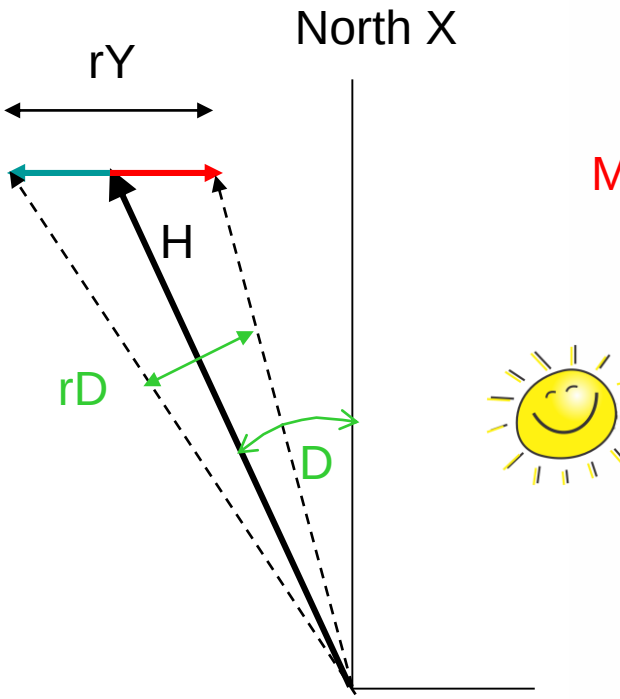
Determining EUV Flux from the magnetic effect of dynamo currents in the E-region of the ionosphere

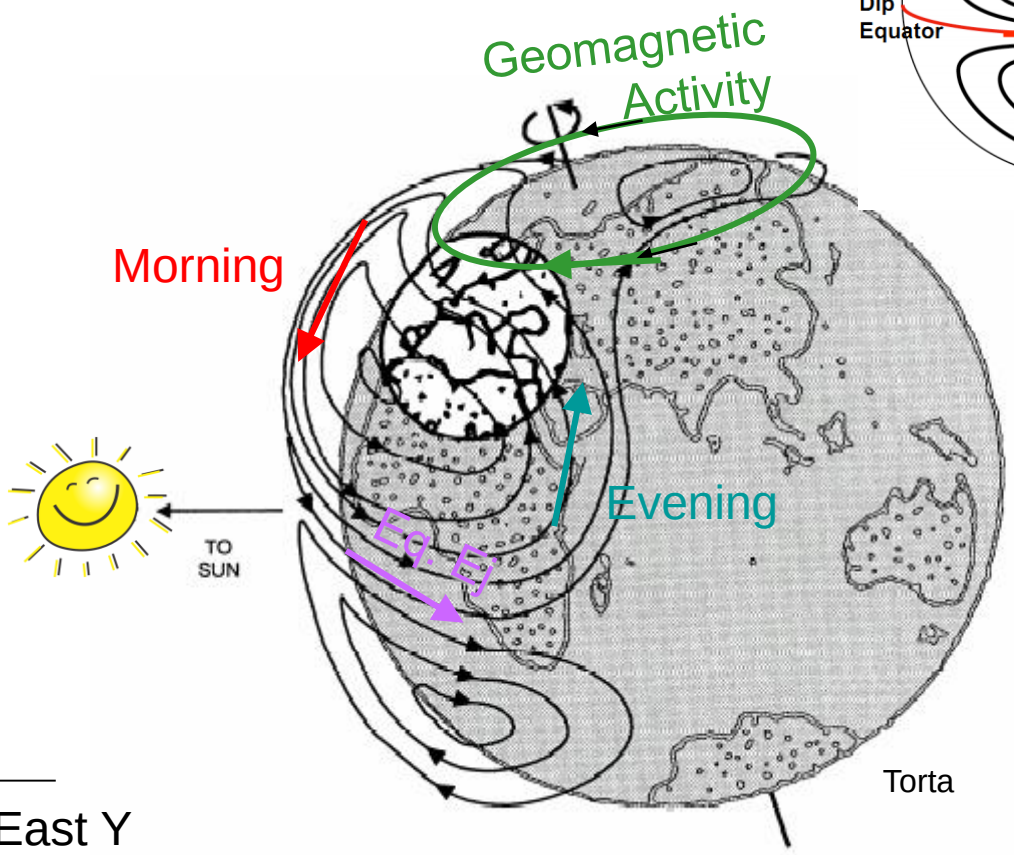
The physics of the boxes is generally well-known

We shall determine the EUV from the magnetic effects

The E-layer Current System







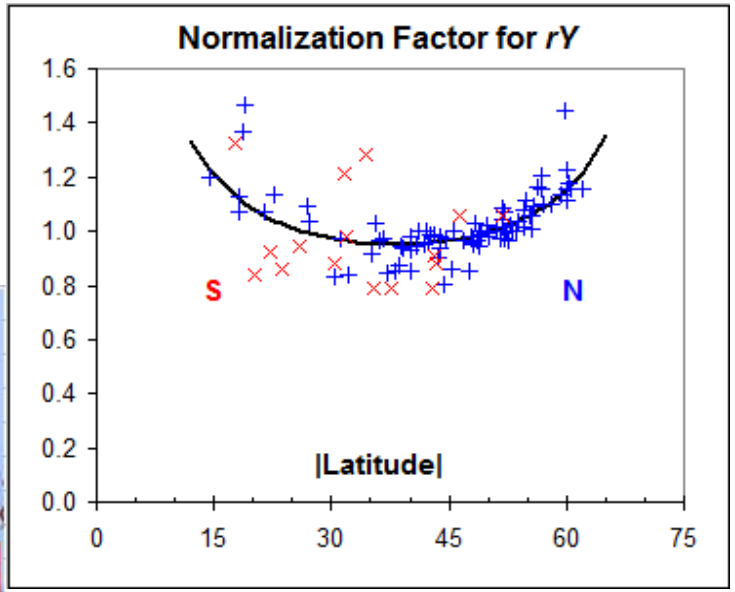
$Y = H \sin(D)$

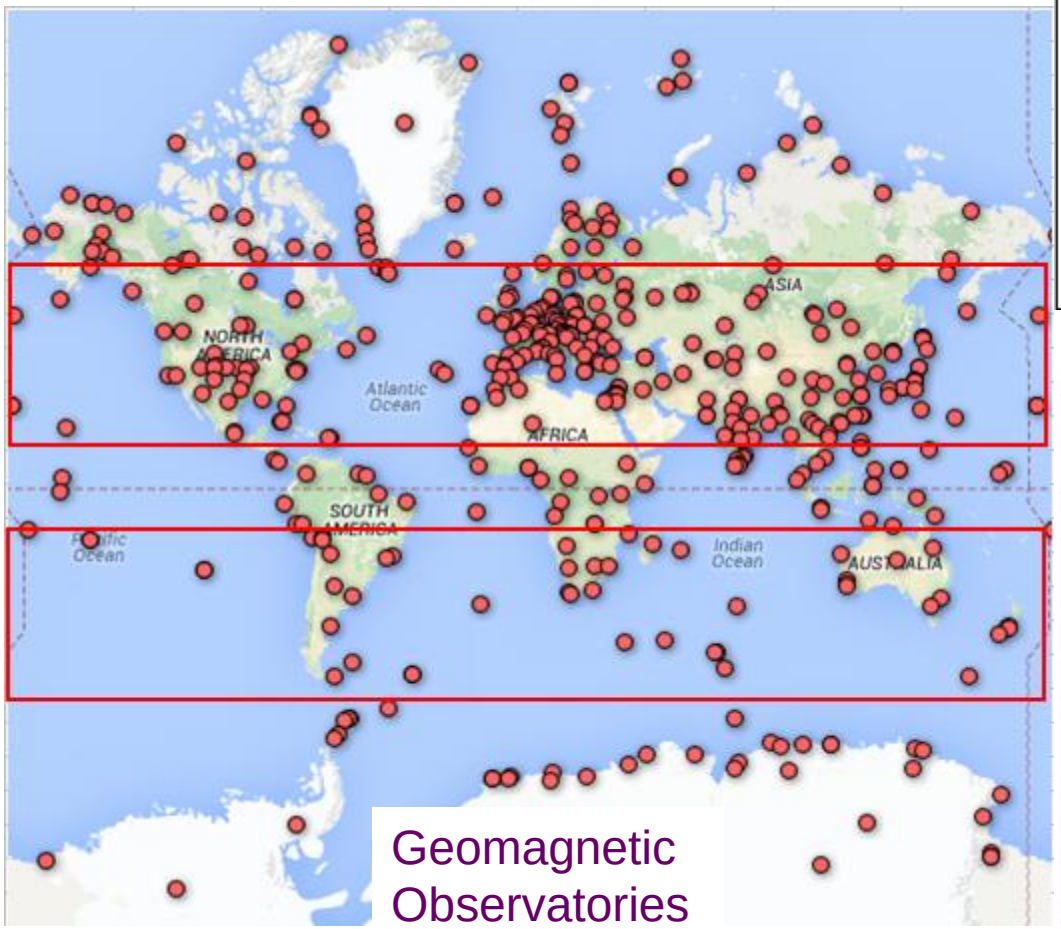
$dY = H \cos(D)\, dD$ For small dD

A current system in the ionosphere is created and maintained by solar EUV radiation

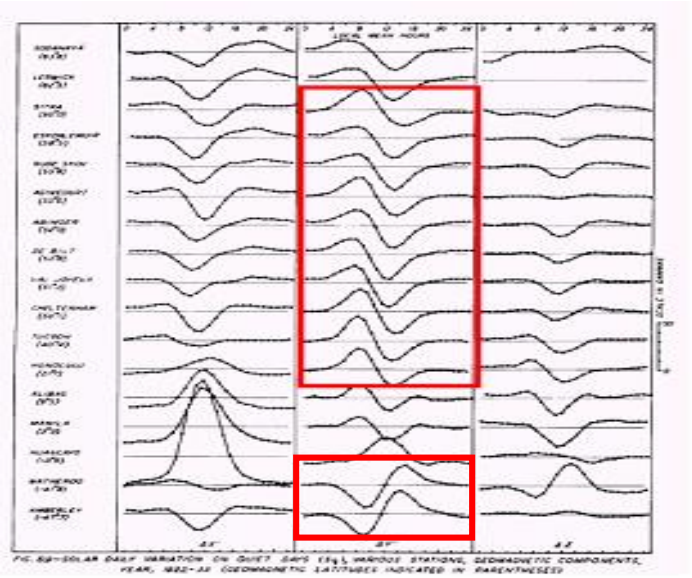
The magnetic effect of this system was what George Graham discovered

The Magnetic Signal at Midlatitudes



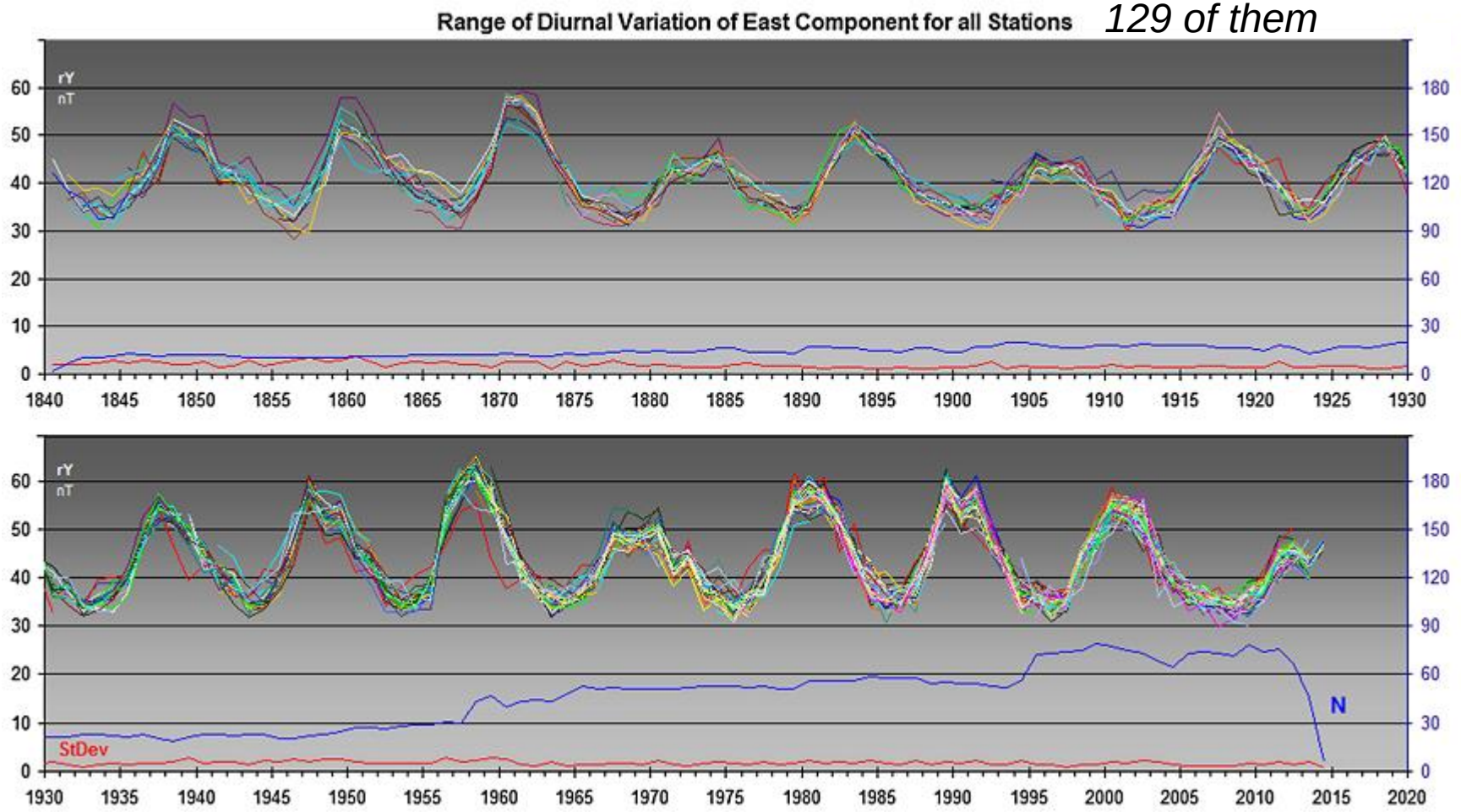


X Y Z



The effect in the Y-component is rather uniform for latitudes between 20º and 60º

Observed Diurnal Ranges of the Geomagnetic East Component since 1840



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

Electron Density due to EUV

< 102.7 nm

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

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

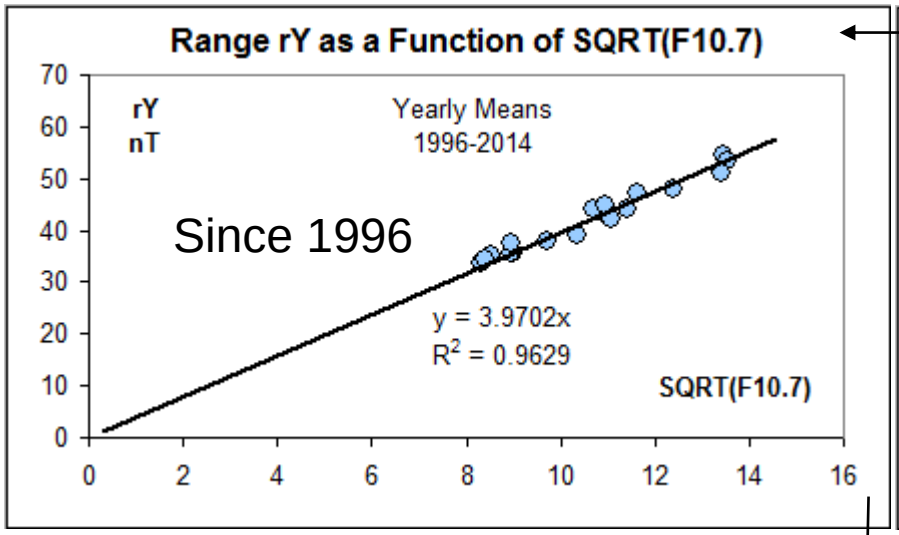
The conductivity at a given height is proportional to the electron number density N_e. In the dynamo region the ionospheric plasma is largely in photochemical equilibrium. The dominant plasma species is O^+_2, which is produced by photo ionization at a rate J (s^{-1}) and lost through recombination with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

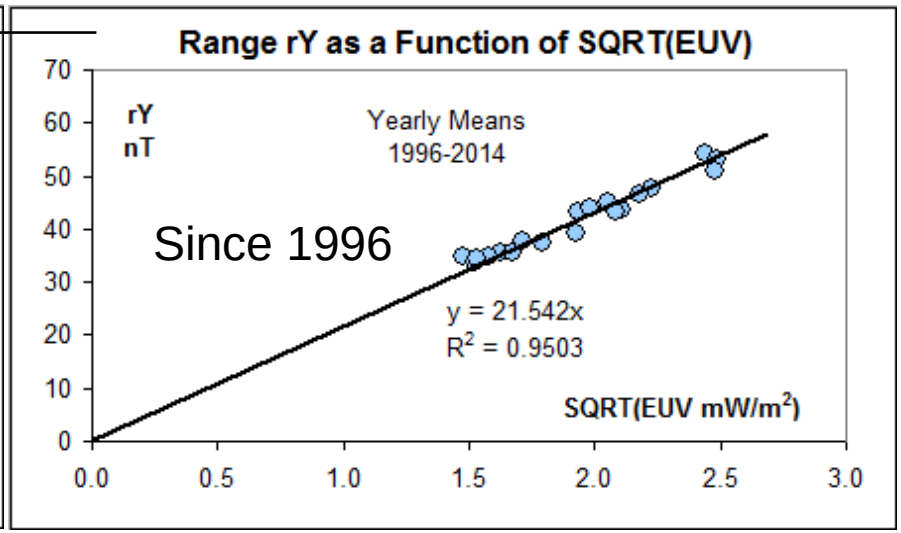
The rate of change of the number of ions N_i, dN_i/dt and in the number of electrons N_e, dN_e/dt are given by $dN_i/dt = J\cos(\chi) - \alpha N_i N_e$ and $dN_e/dt = J\cos(\chi) - \alpha N_e N_i$. Because the Zenith angle χ changes slowly we have a quasi steady-state, in which there is no net electric 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

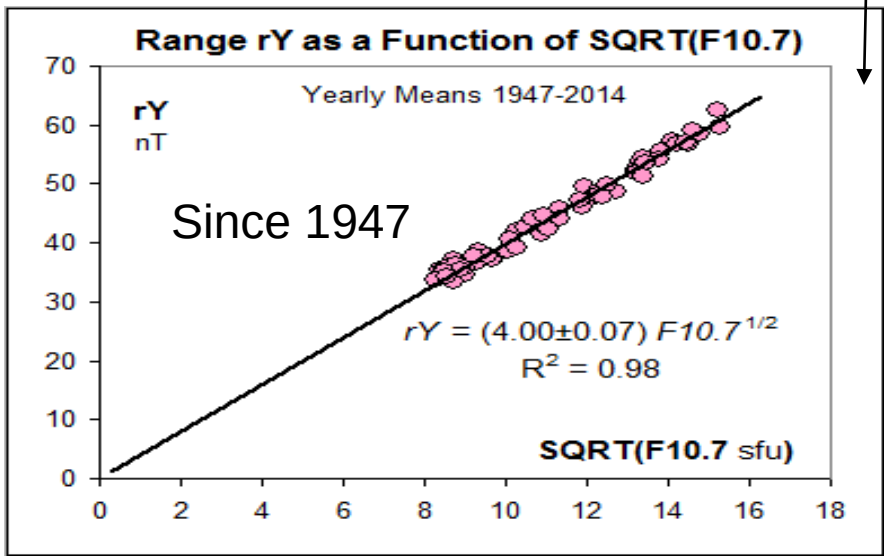
$$N = \sqrt{(J\,\alpha^{-1}\cos(\chi))}$$

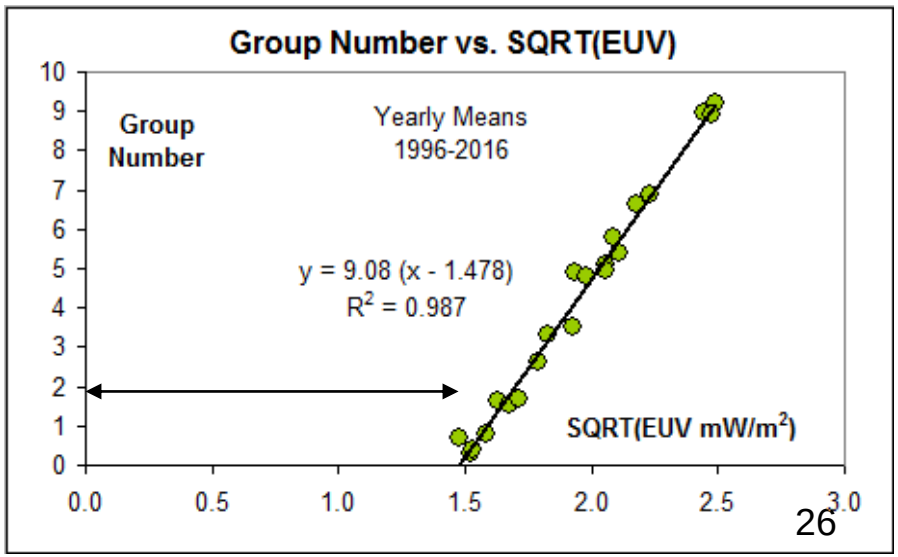
Since the conductivity, Σ, depends on the number of electrons N, we expect that Σ scales with the square root $\sqrt{(J)}$ of the overhead EUV flux with $\lambda < 102.7$ nm.

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:

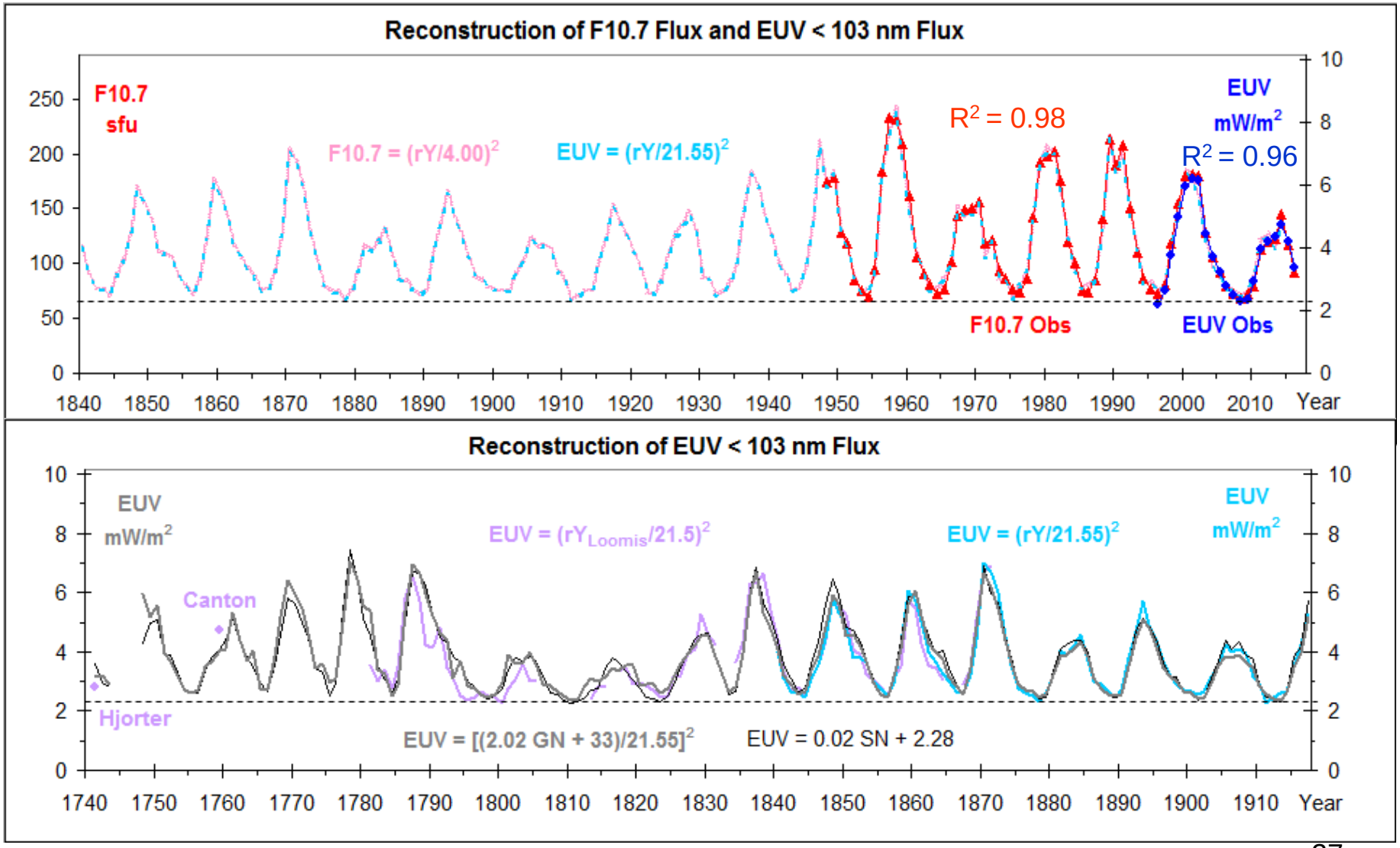






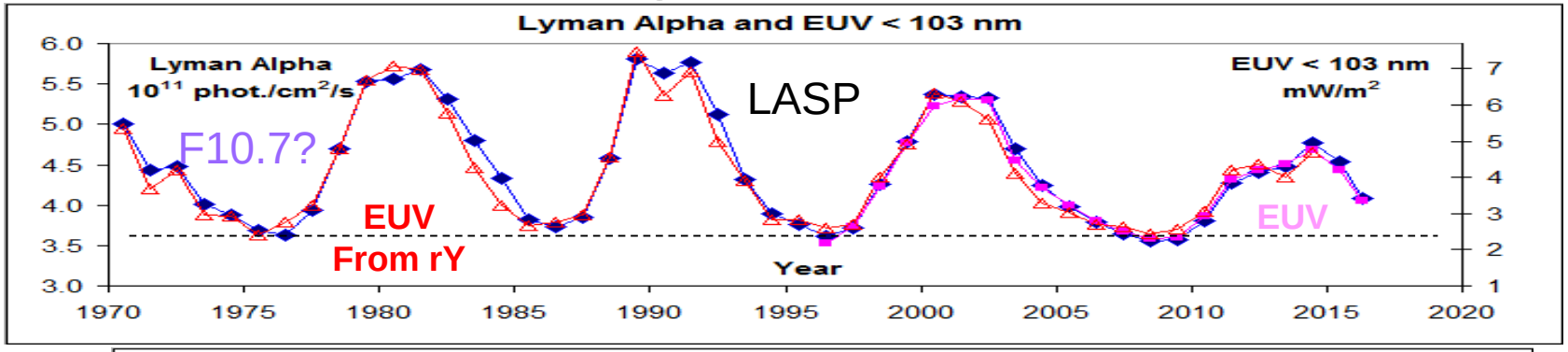


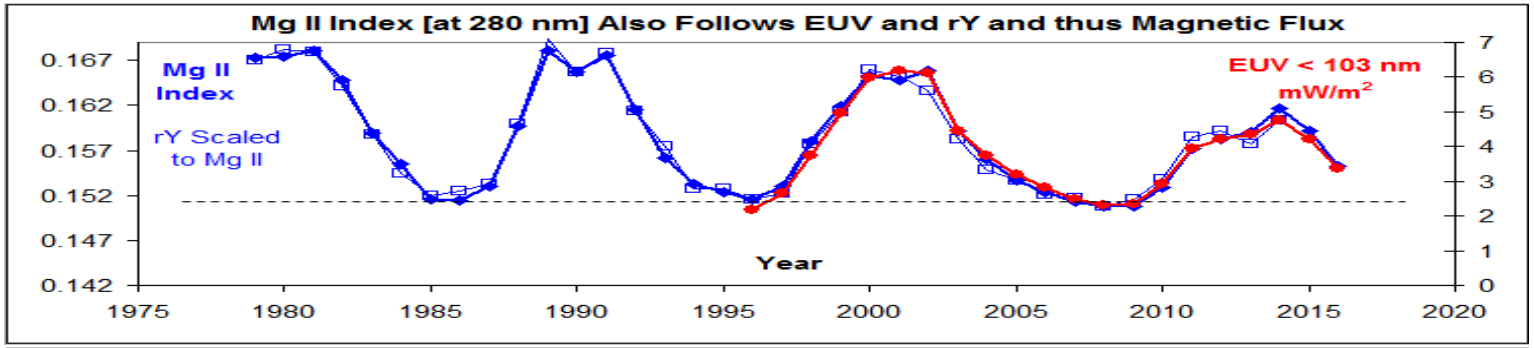
Reconstructions of EUV and F10.7

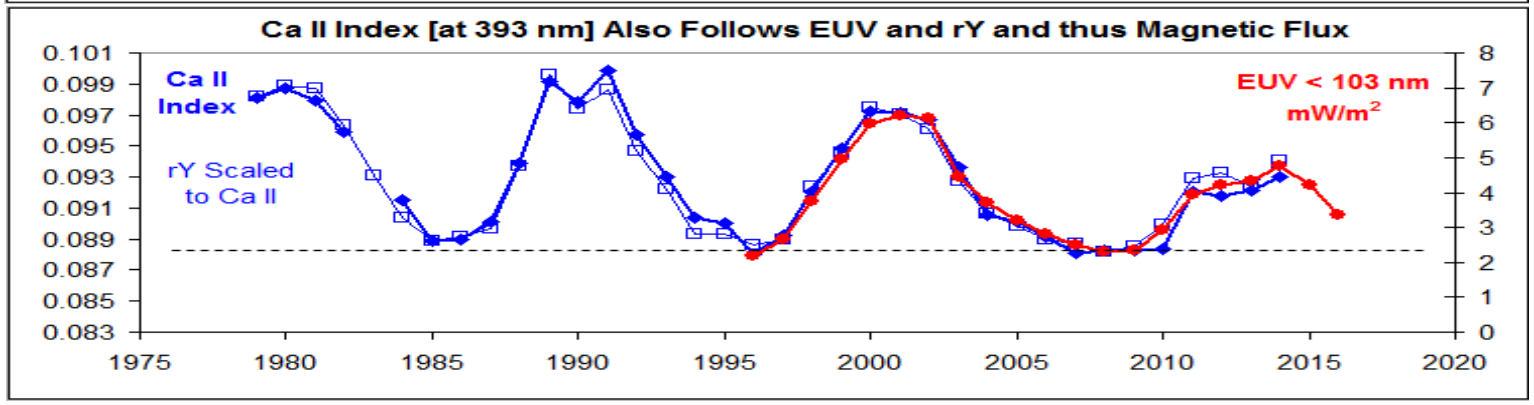


Note the constant basal level at *every* solar minimum

Lyman Alpha, Mg II, and Ca II also Follow the Magnetic Field and EUV

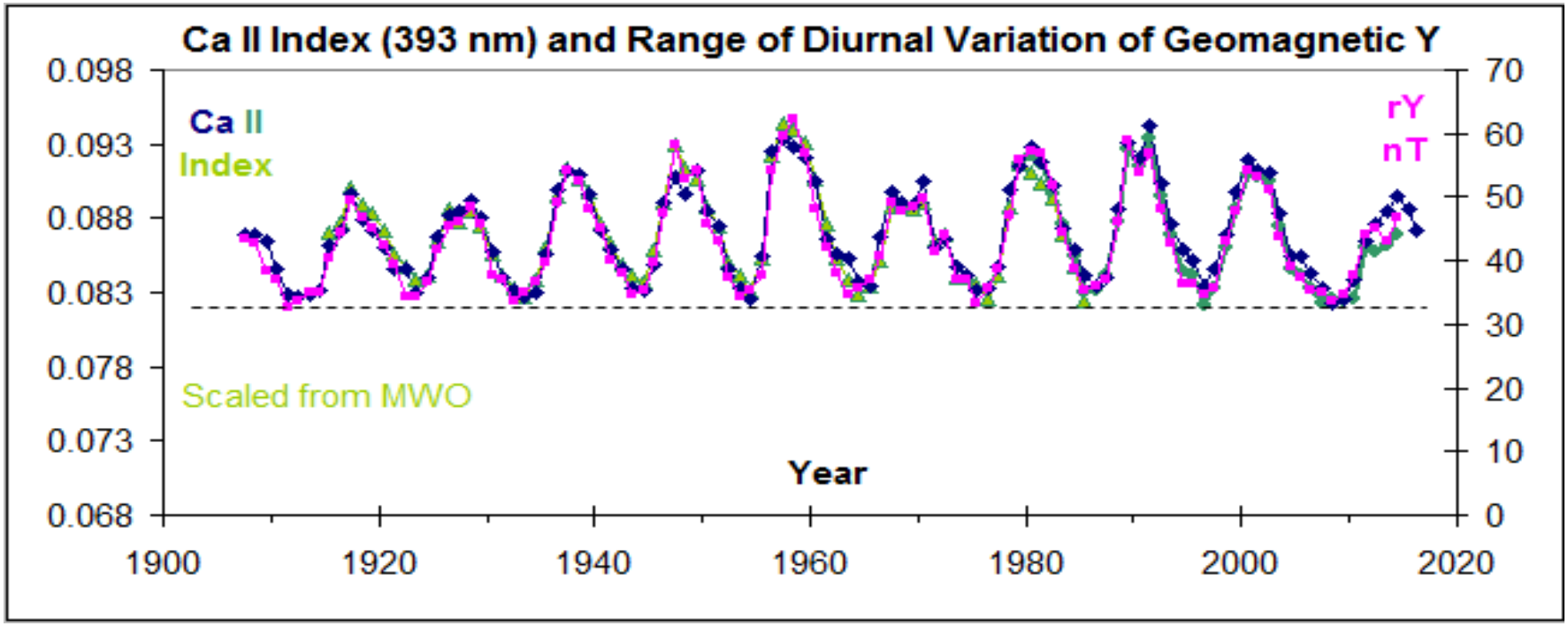






Same Basal Level at all Minima

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]

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

What do we have so far? #2

- The Regular Diurnal Variation of the Geomagnetic Field depends on the Solar Zenith angle and Solar Activity, e.g. as given by the Sunspot Number (Wolf, Gautier, 1852) and has been widely observed at many geomagnetic observatories since its discovery in 1722
- The Amplitude of the Diurnal Variation is strictly proportional to the Square Root of the EUV [and F10.7] Flux
- We can reconstruct EUV and F10.7 [and similar indices like Mg II & Ca II] back to the 1740s, and thus also the Total Magnetic Flux http://www.leif.org/research/Reconstruction-of-Solar-EUV-Flux-1740-2015.pdf
- All our solar indices show that solar activity [magnetic field] is nearly constant at every solar minimum [apart from tiny residuals] for the past 275 years
- The solar cycle variations ride on top of this constant background [as already Loomis knew in 1870]

Outline

- Recent EUV, Magnetic Flux, and Solar Microwave flux records
- Deriving EUV [etc] from Geomagnetic Variations
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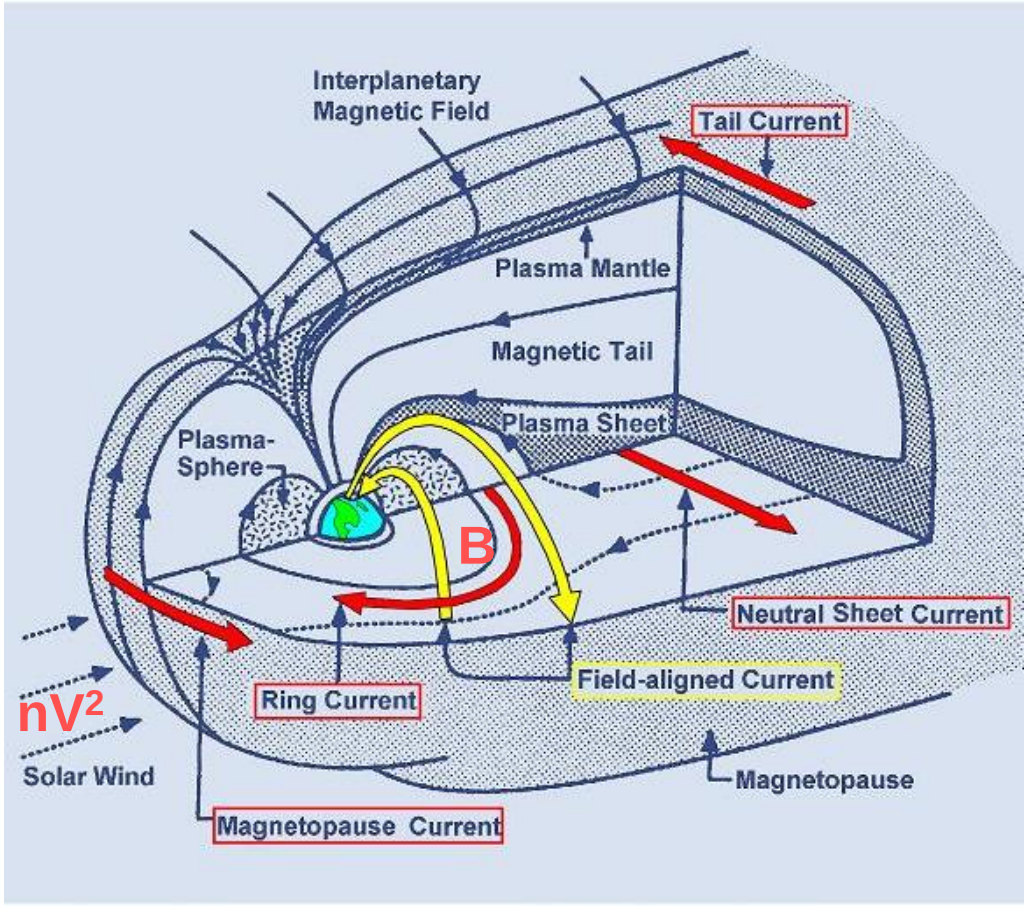
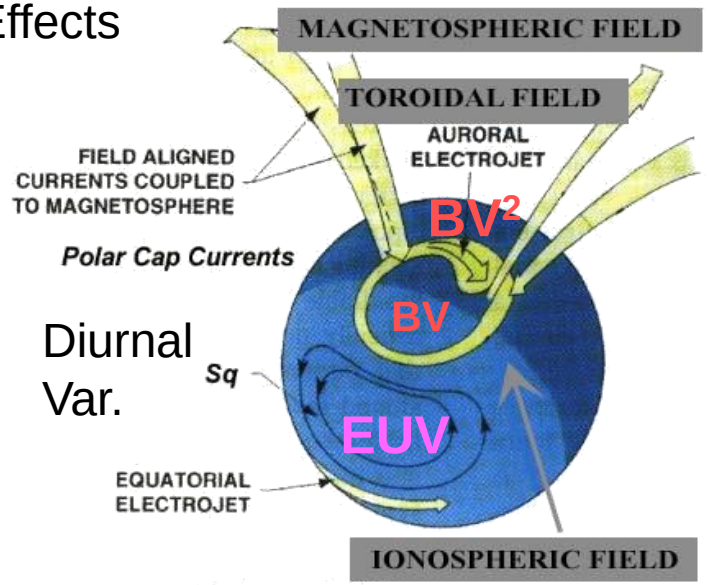
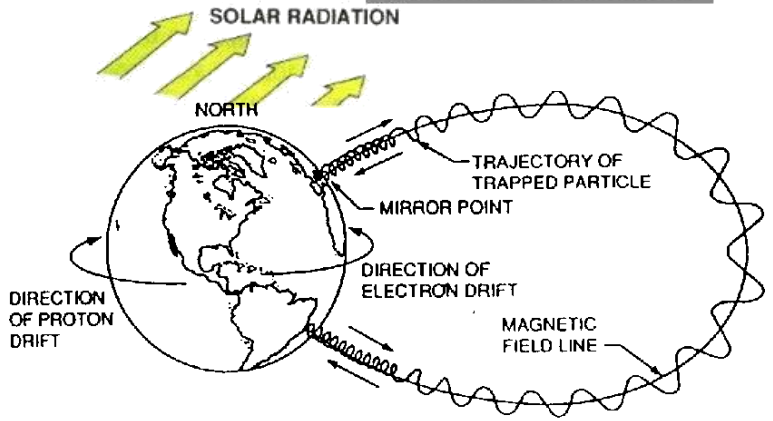
- Total Solar Irradiance, Magnetic Fields, and the Climate Data Record
- Calibration of TSI records

Electric Current Systems in Geospace

Different Current Systems ⇄ Different Magnetic Effects







We can now 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'.

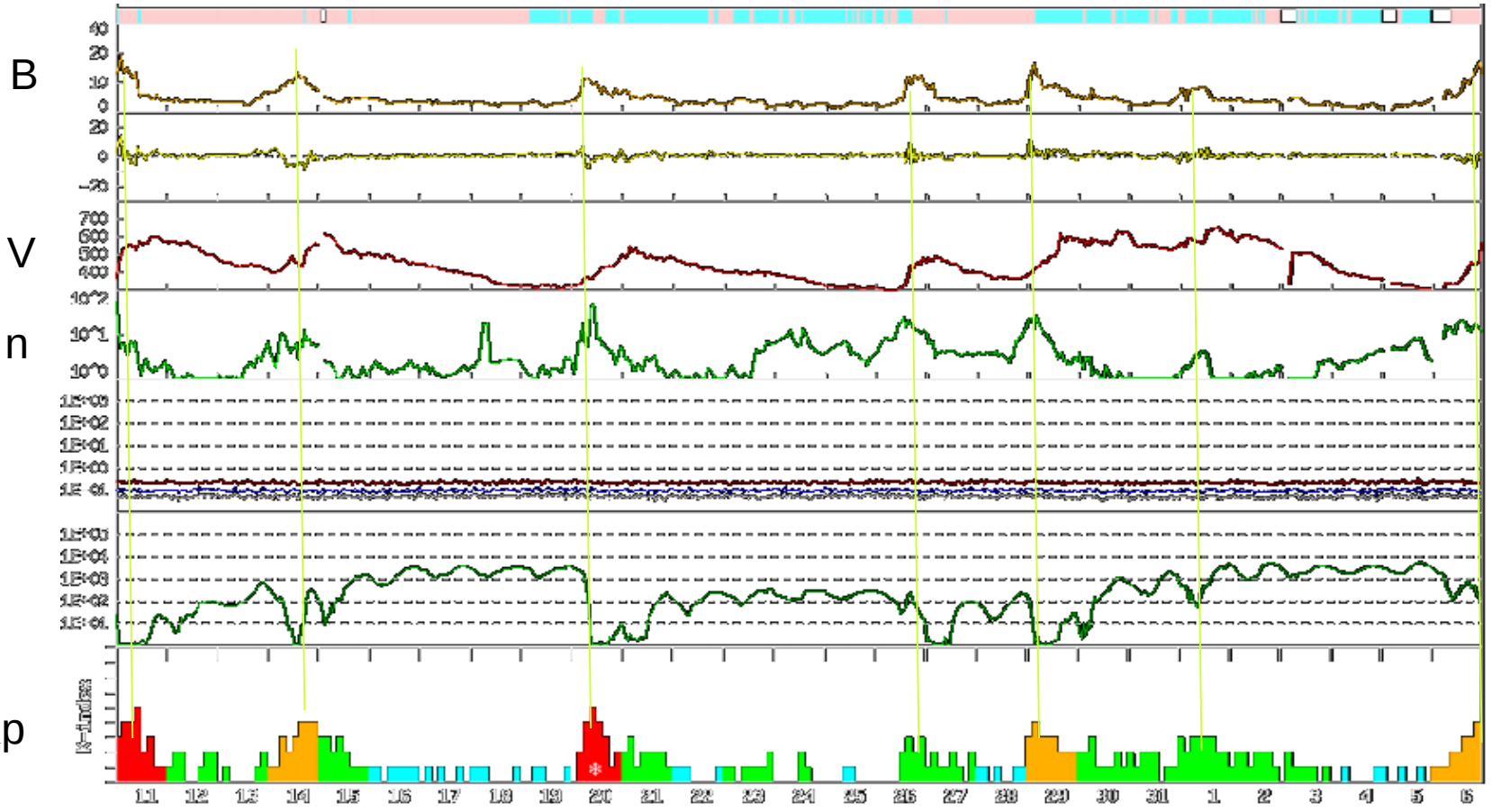
‘Different Strokes for Different Folks’

- The key to using geomagnetism to say something about the sun is the realization that geomagnetic ‘indices’ can be constructed that respond differently to different solar and solar wind parameters, so can be used to disentangle the various causes and effects
- In the last decade of research this insight (e.g. Svalgaard et al. 2003) has been put to extensive use and a consensus has emerged

The IDV Geomagnetic Index

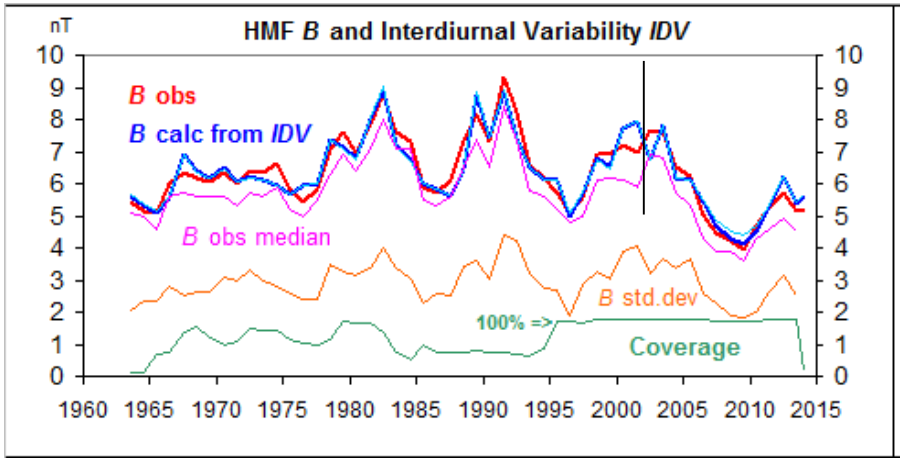
- Since the daily variation is fairly regular from day to day we can eliminate it by considering the difference between the fields on consecutive days
- Further suppression of the daily variation can be achieved by working only with the field during night hours or the average over a whole day
- That led to the definition of the Interdiurnal Variability Index [IDV] as the unsigned difference between a geomagnetic field component on consecutive local nights
- IDV [from several stations] is a Global index
- IDV is a modern version of the *u*-measure (Bartels)

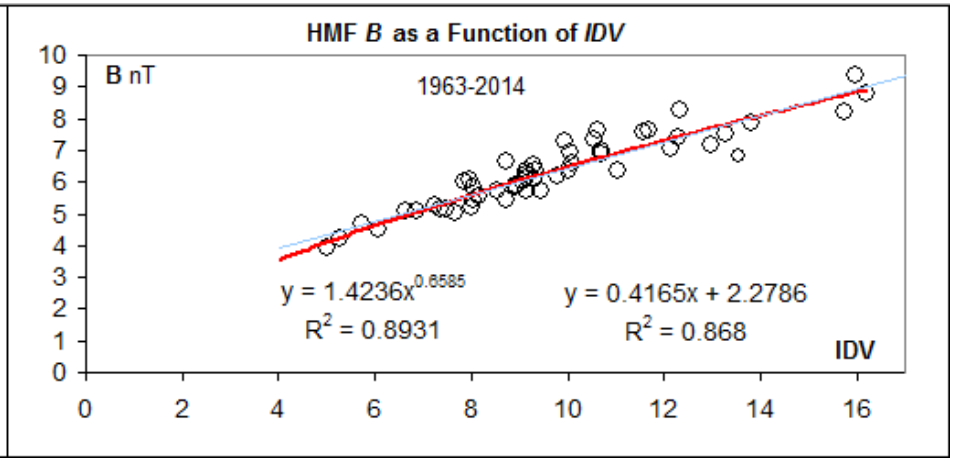
Examples of High Solar Wind B and Geomagnetic Activity A

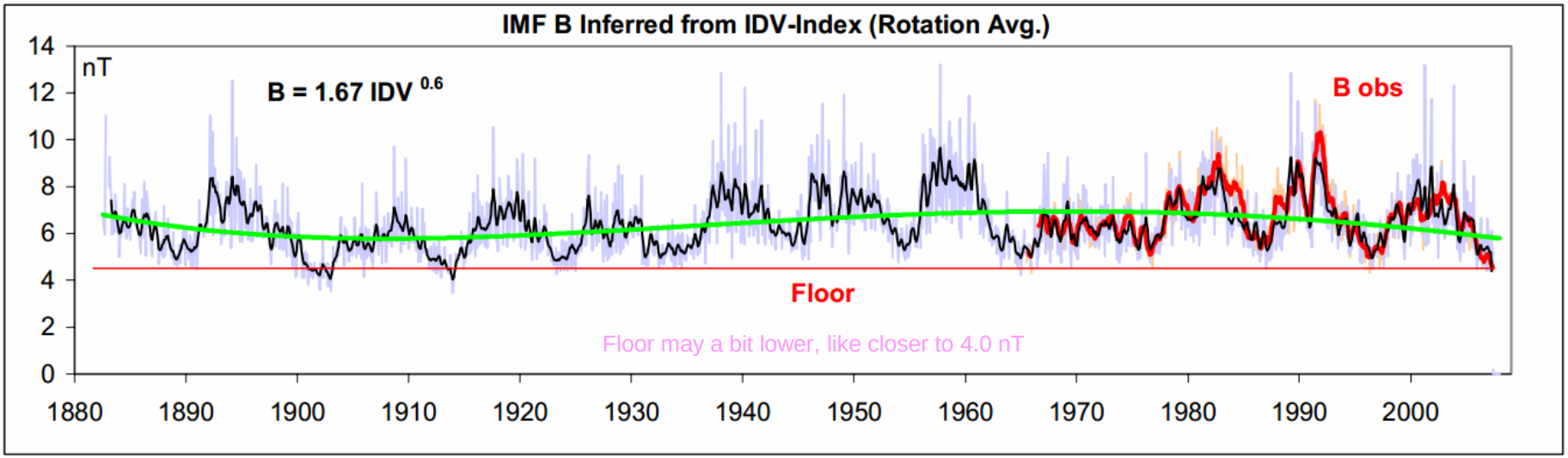


$$A = k\, q(a,f)\, (B\, V)\, (n\, V^2)^{1/3} \sim B\, V^2$$

Relationship between HMF *B* and *IDV*

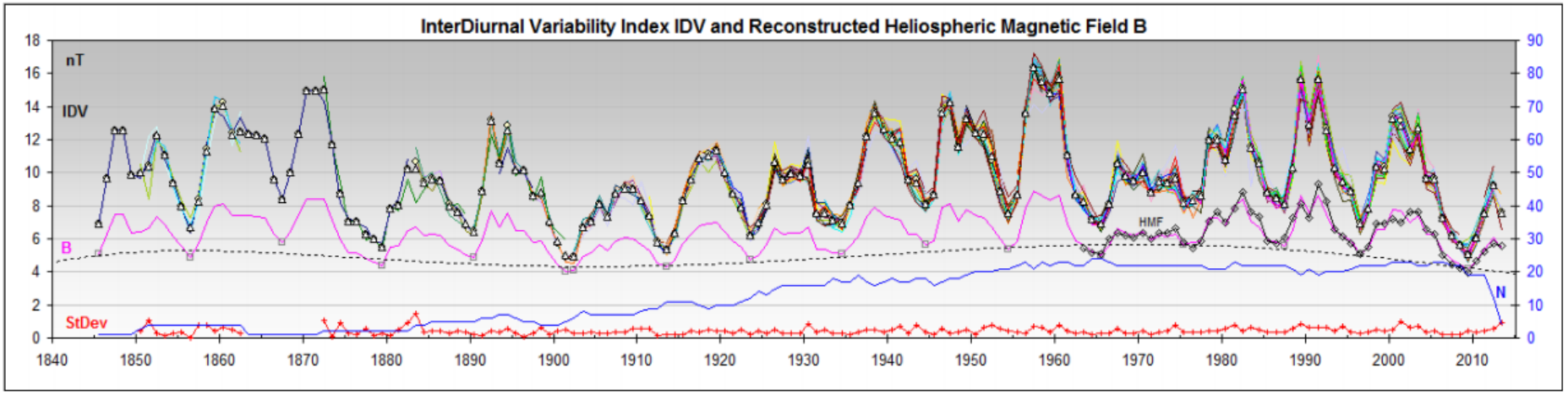


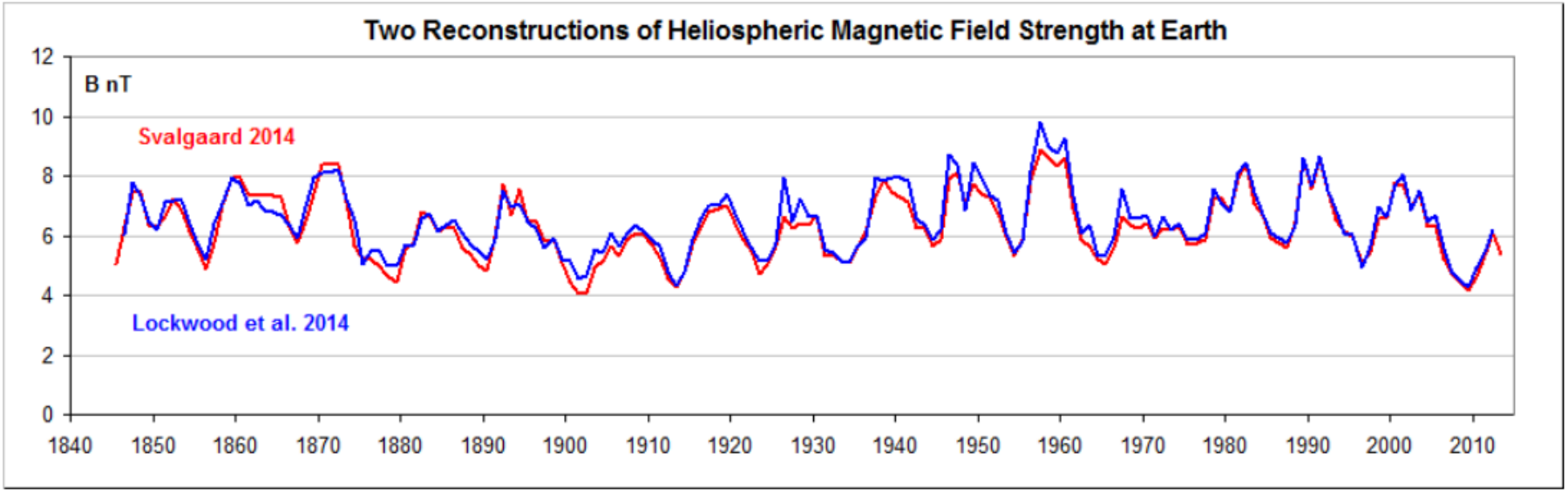




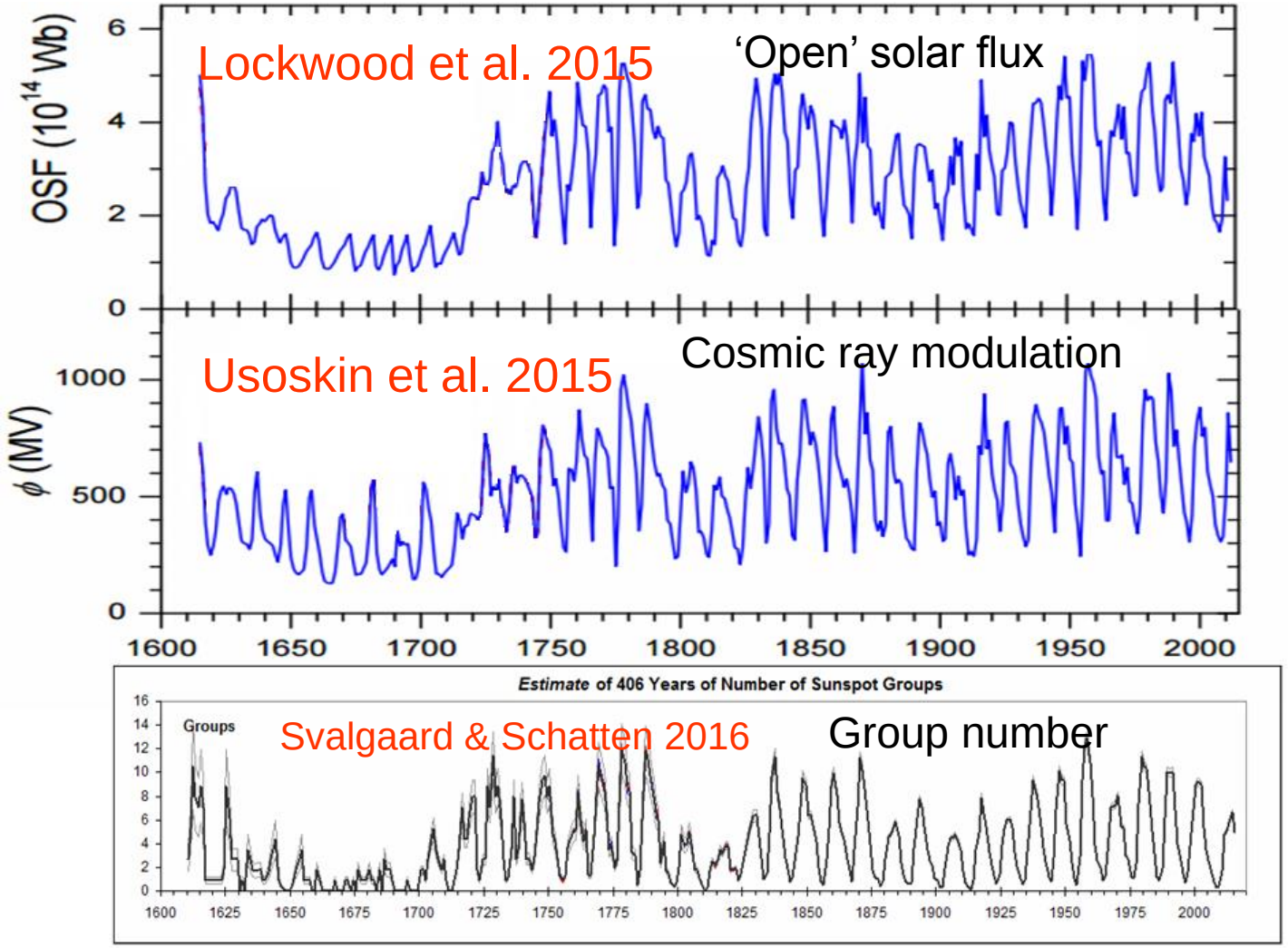
Also holds on timescales shorter than one year

Applying the relationship we can reconstruct HMF magnetic field B with Confidence:





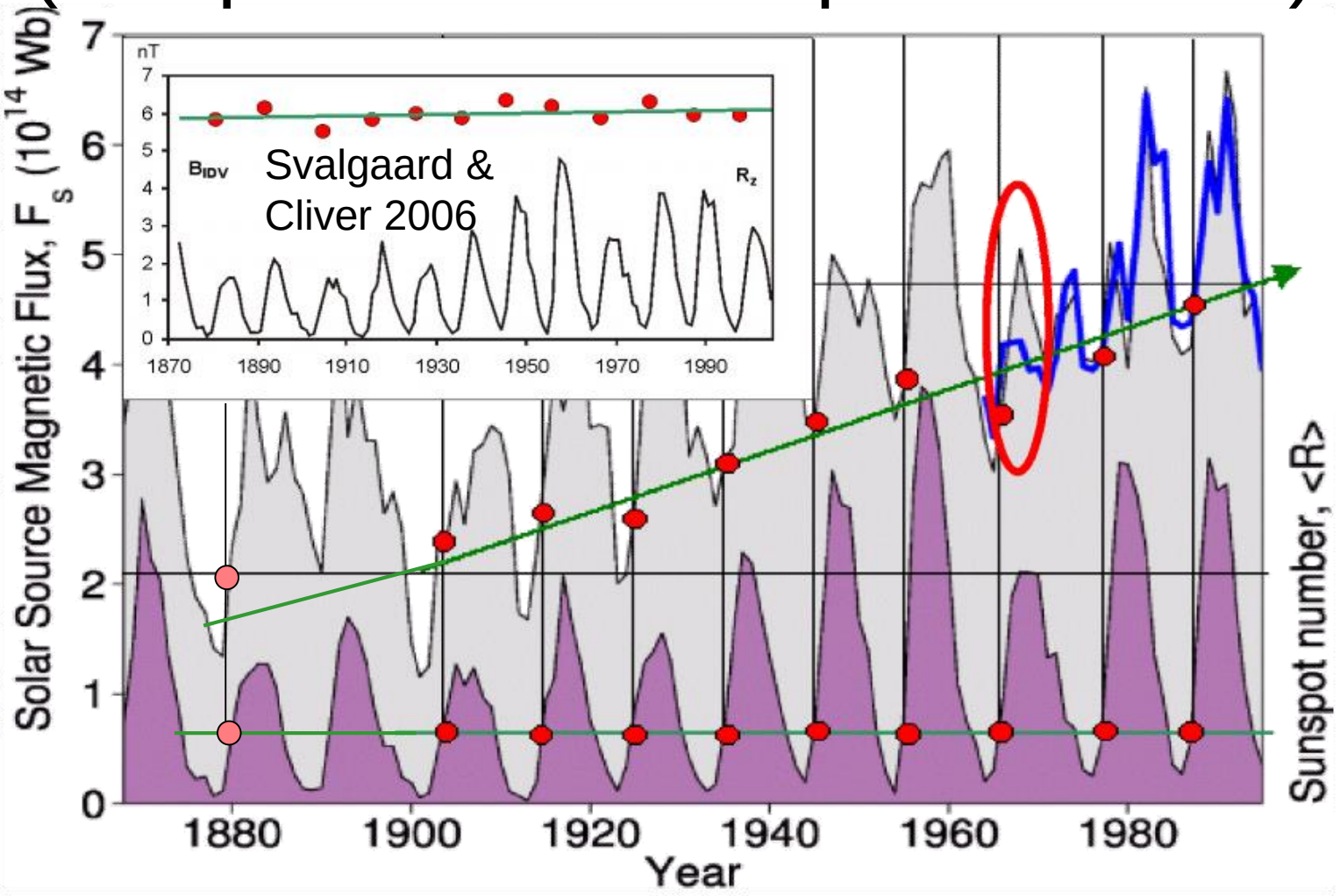
Putting it All Together (Real Progress!)



Very good agreement between different reconstructions.

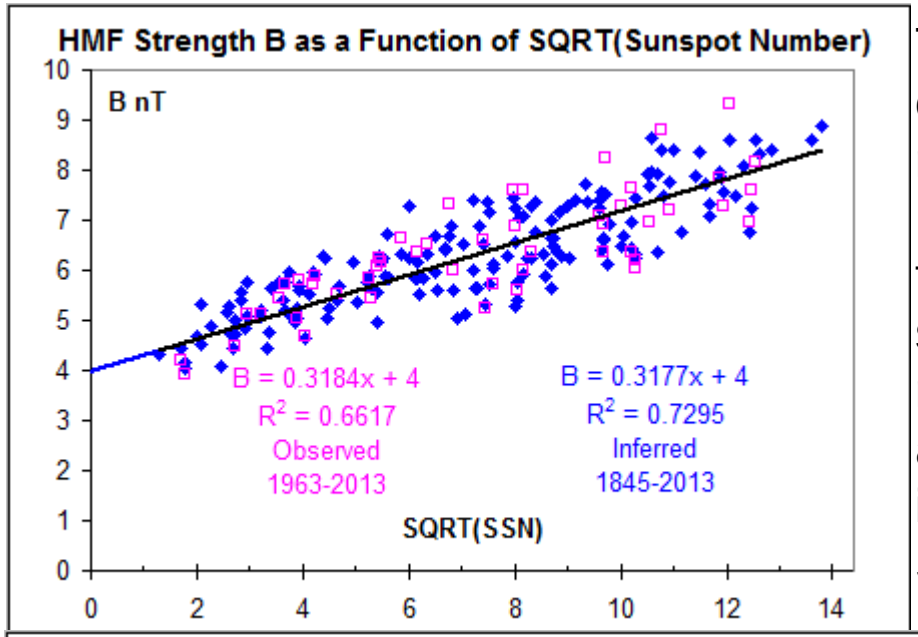
Full Disclosure: There is still a rear-guard debate about the early record

The Debate about ‘Doubling’ (independent of sunspot number?)

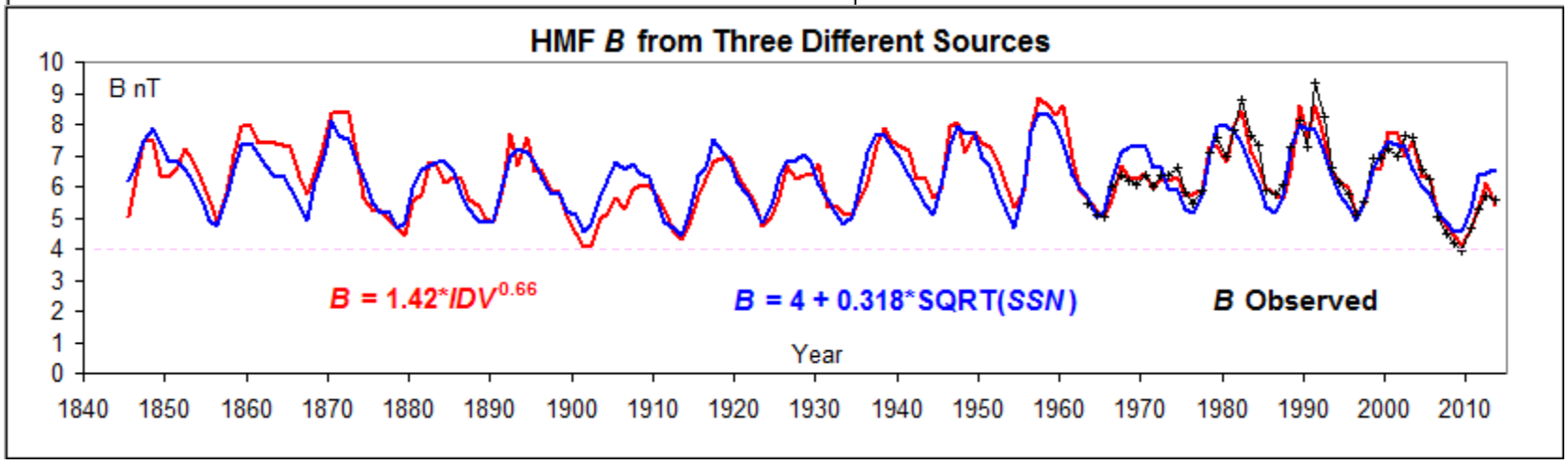


Lockwood, M., R. Stamper, and M. N. Wild (1999), A **doubling of the Sun’s coronal magnetic field** during the past 100 years, Nature, 399(6735), 437, doi:10.1038/20867

HMF *B* related to Sunspot Number

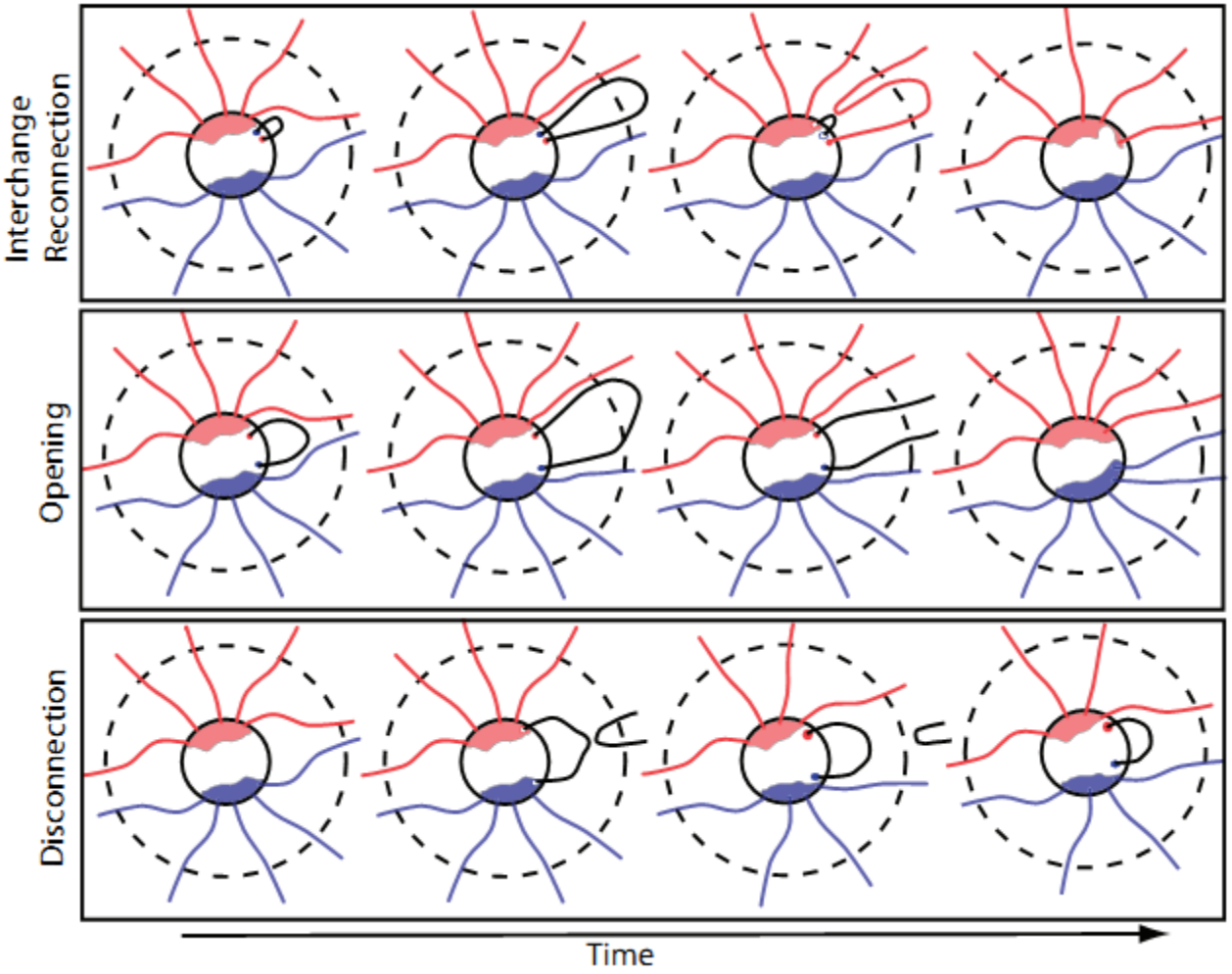


The main sources of the equatorial components of the Sun's large-scale magnetic field are large active regions. If these emerge at random longitudes, their net equatorial dipole moment will scale as the square root of their number. Thus their contribution to the average HMF strength will tend to increase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



Magnetic Flux Balance in the Heliosphere

Schwadron et al. ApJ 722, L132, 2010



Closed loop CMEs connecting with polar flux reduces the latter, moving it to lower latitudes

CMEs eject loops that open up and increase the HMF flux and increase polar holes

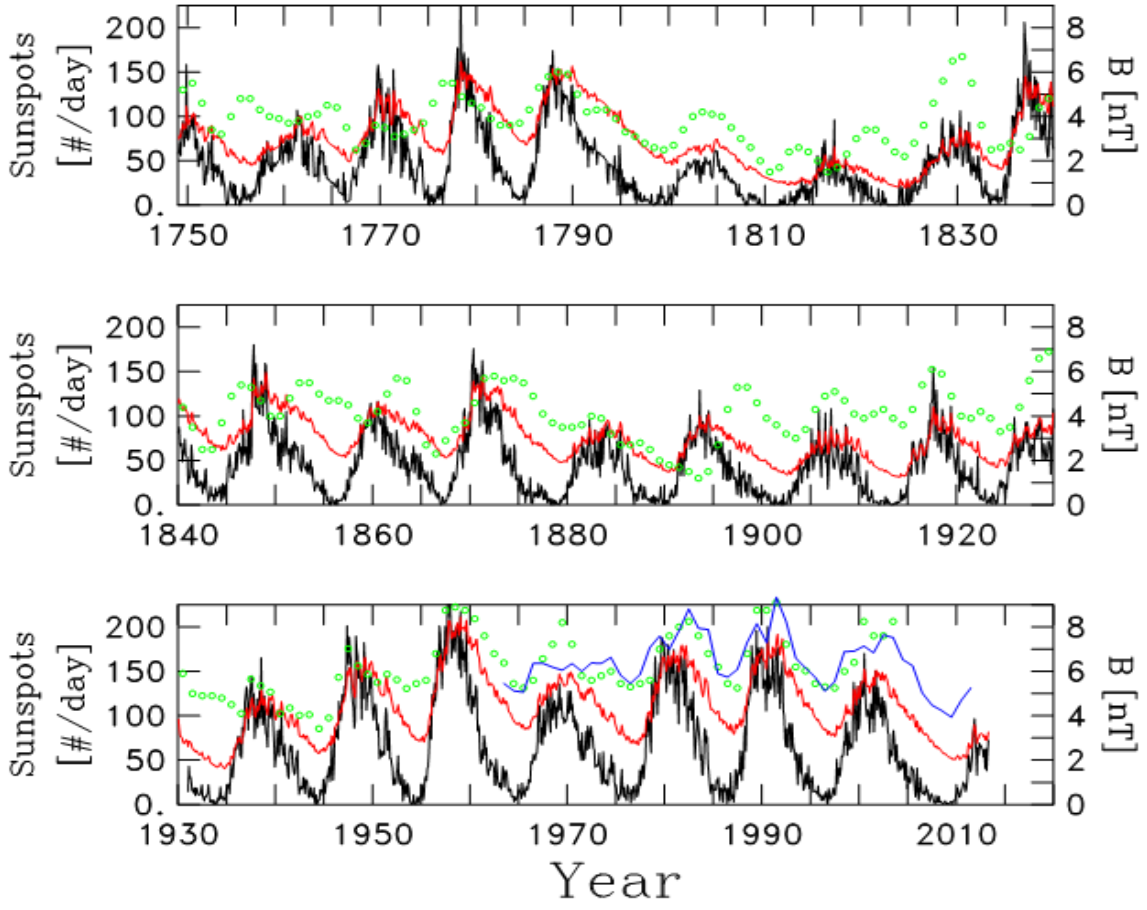
Disconnection leads to removal of HMF flux and shrinkage of polar holes

A set of parameters describe the time scales and magnetic fluxes involved

Comparing Theory with Observations

The theory posits two components of the HMF: the CME associated magnetic flux ϕ_{CME} from the ejecta and the open magnetic flux Φ_0 of the steady solar wind. The time derivative of the CME-associated flux Φ_{ej} is written as

$$\frac{d\Phi_{ej}}{dt} = f(1-D)\phi_{CME} - \Phi_{ej}\left(\frac{1}{\tau_{ic}} + \frac{1}{\tau_d} + \frac{1}{\tau_o}\right)$$

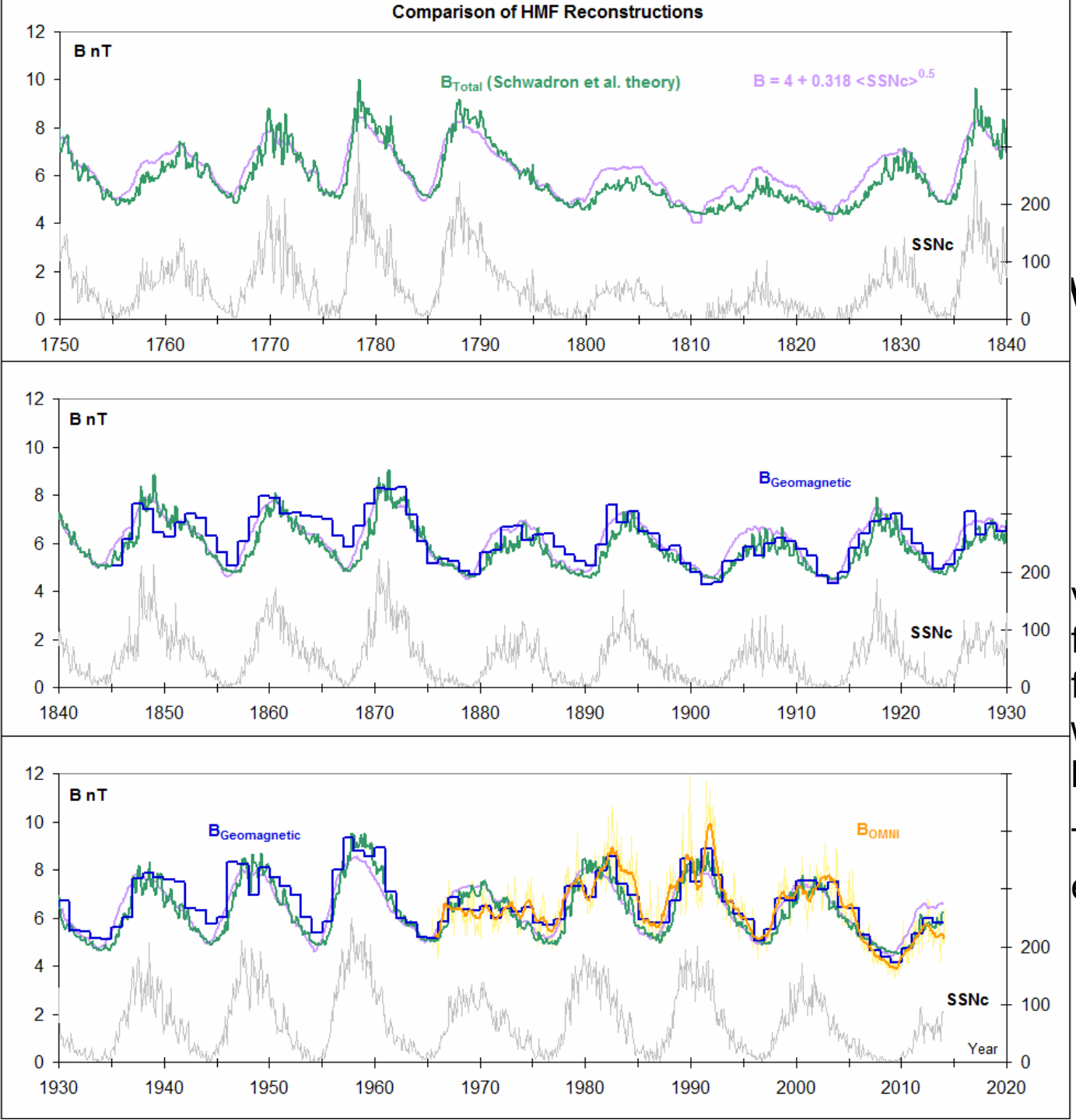


Black is Official Sunspot Number *SSN* from SIDC

Red is *B* calculated from their theory. Green is *B* deduced from ^{10}Be data by McCracken 2007

Blue is B taken from the spacecraft-based OMNI dataset

At first blush the correspondences don't look too good…



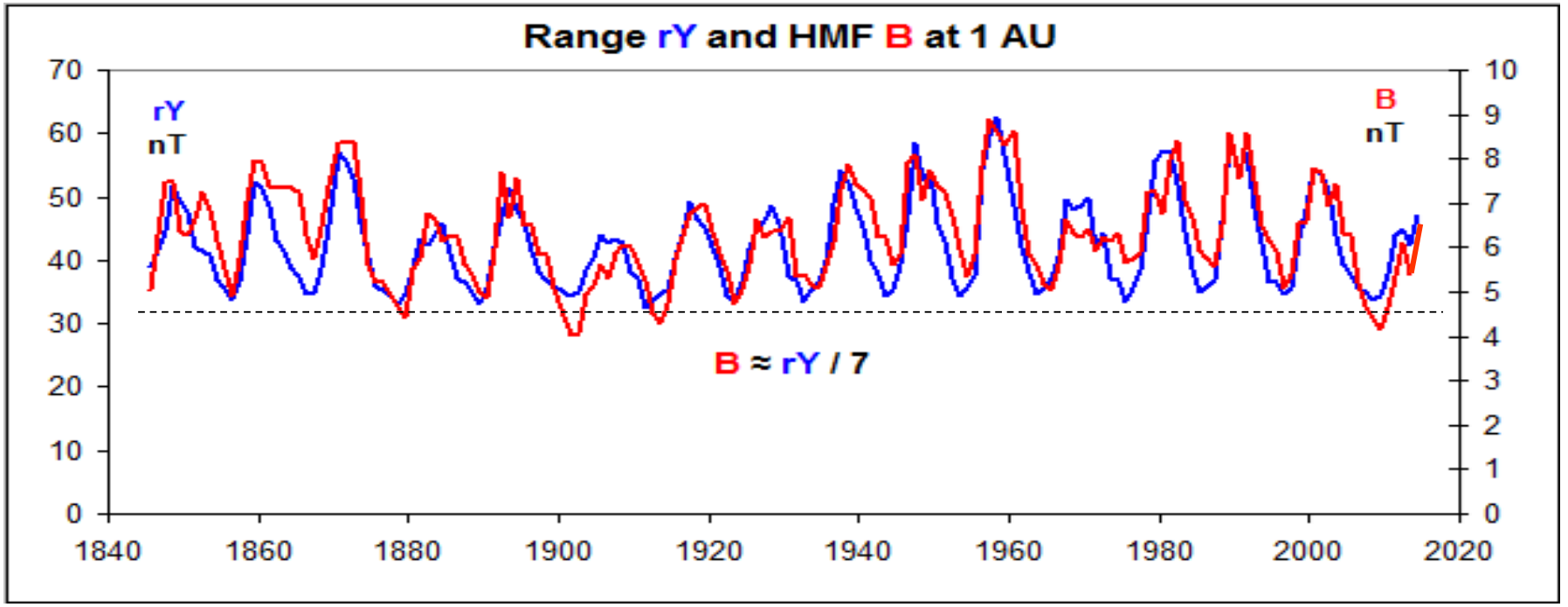
Schwadron et al. HMF B Model (2010) with my set of parameters: good fit back to 1750

von Neumann: “with four parameters I can fit an elephant, and with five I can make him wiggle his trunk”

This model has about eight parameters…

http://www.leif.org/research/Goelzer-Paper-2014.pdf

Network 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 network 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.

Red Flash => 'Burning Prairie' => Network Magnetism

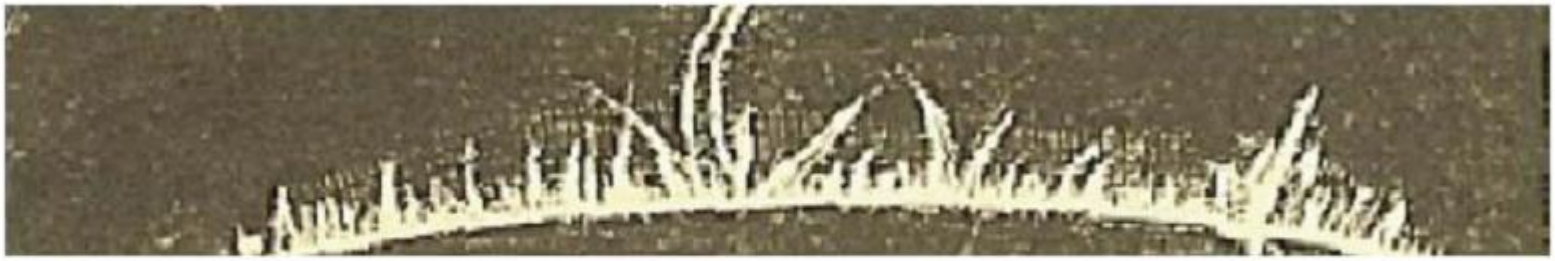


Figure 1 An early drawing of the "burning prairie" appearance of the Sun's limb made by C.A. Young, on 25 July 1872. All but the few longest individual radial structures are spicules.

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

What do we have so far? #3

- Consensus reconstruction of Heliospheric magnetic field B for centuries past
- HMF B also has a ‘floor’ at every solar minimum, probably including the Maunder Minimum, and certainly the Dalton and modern Minima.
- The solar cycle variation of B above the floor is probably controlled by the CME rate [varying with Square Root of the sunspot number]
- There is a good relationship between HMF B and the Network Magnetic Field [EUV from diurnal geomagnetic variation, rY]
- In particular, there is no clear secular increase in solar activity the past 300 years

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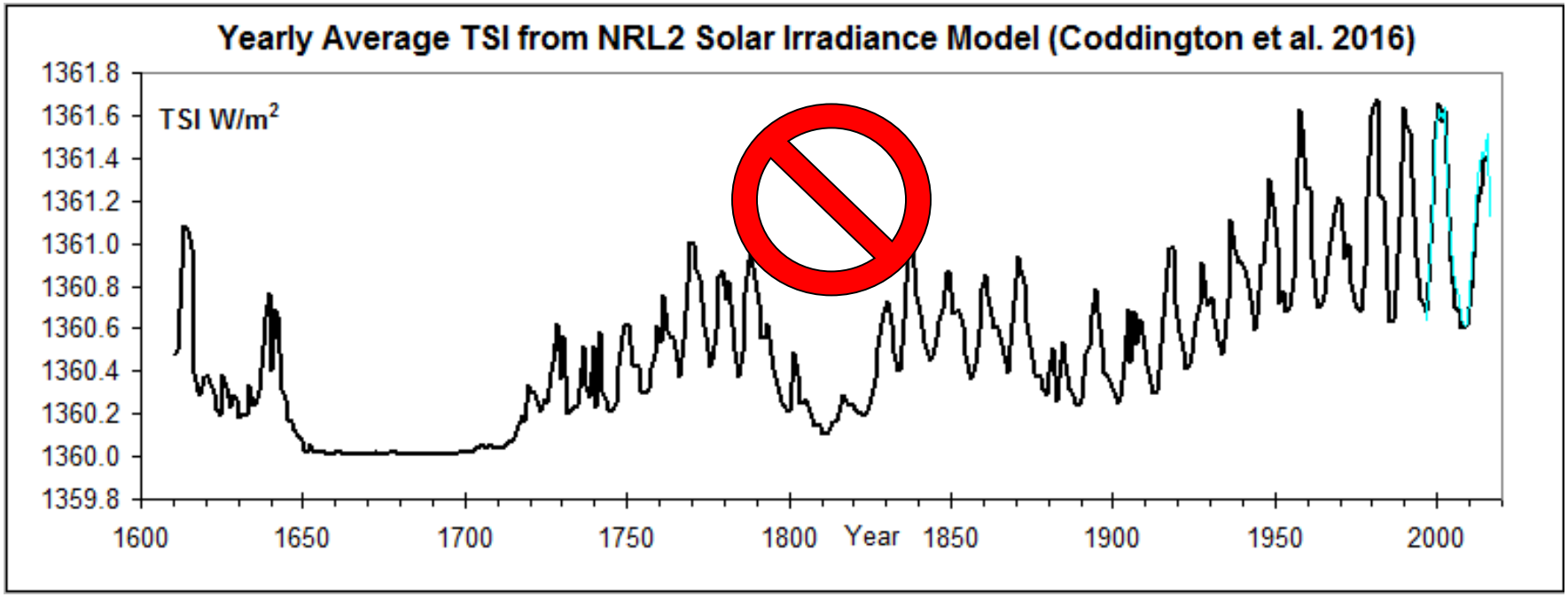
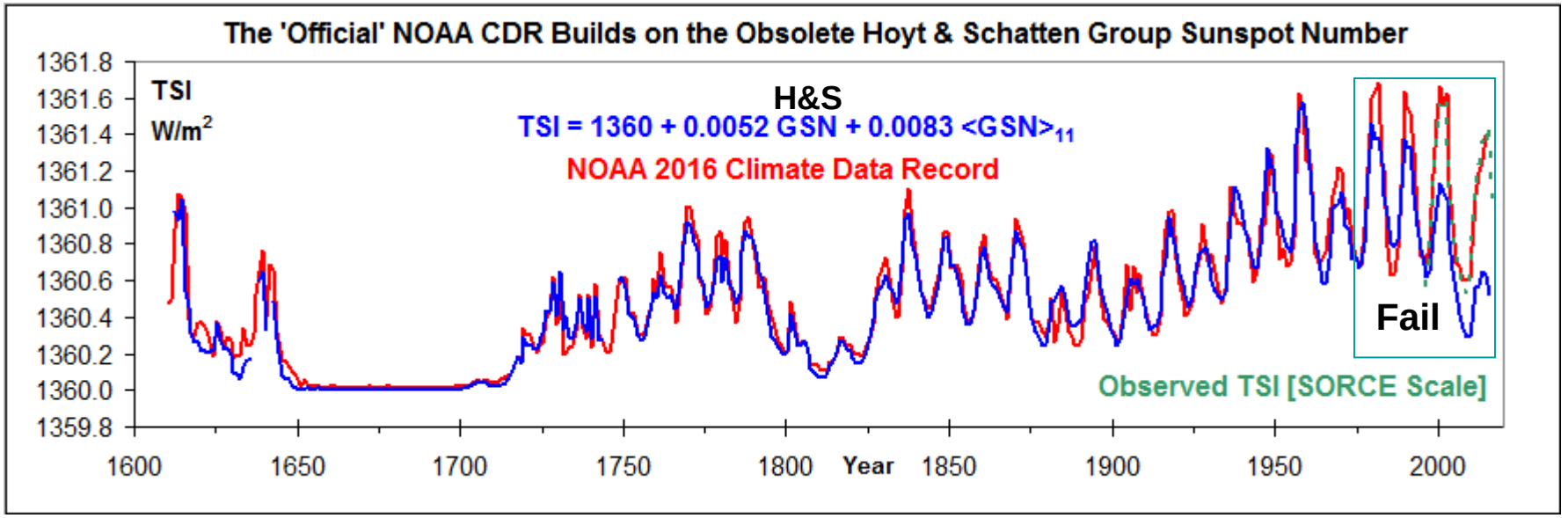
- Calibration of TSI records

The Official TSI Climate Data Record (CDR)



"The data record, which is part of the National Oceanic and Atmospheric Administration's (NOAA) Climate Data Record (CDR) program, provides a **robust, sustainable, and scientifically defensible** record of solar irradiance that is of sufficient length, consistency, and continuity for use in studies of climate variability and climate change on multiple time scales and for user groups spanning climate modeling, remote sensing, and natural resource and renewable energy industries." [LASP, NRL: http://dx.doi.org/10.1175/BAMS-D-14-00265.1]

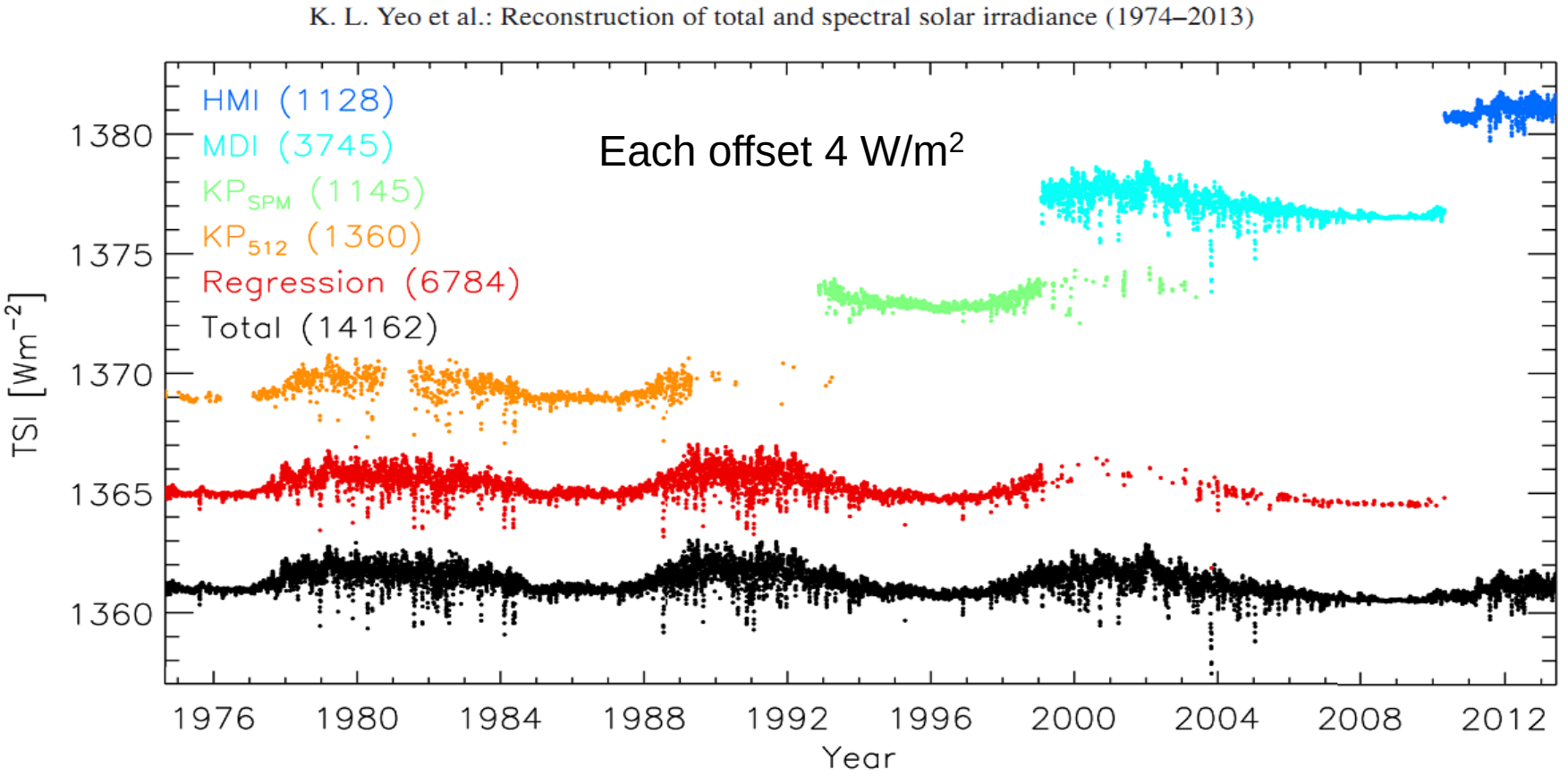
Shaky Justification for Using a ‘Background’ Component in TSI



“A third component of irradiance variability is an **assumed** long-term facular contribution that is **speculated** (Solanki et al. 2013) to produce the **secular** irradiance change *underlying* the solar activity cycle on historical time scales (**Obsolete H&S** prior to 1978). According to **simulations** from a magnetic flux transport **model** (with **variable** meridional flow) of eruption, transport, and accumulation of magnetic flux on the sun’s surface since 1617, a small accumulation of total magnetic flux and **possibly** the rate of emergence of small bipolar magnetic regions on the quiet sun (called ephemeral regions) produce a net increase in facular brightness.”

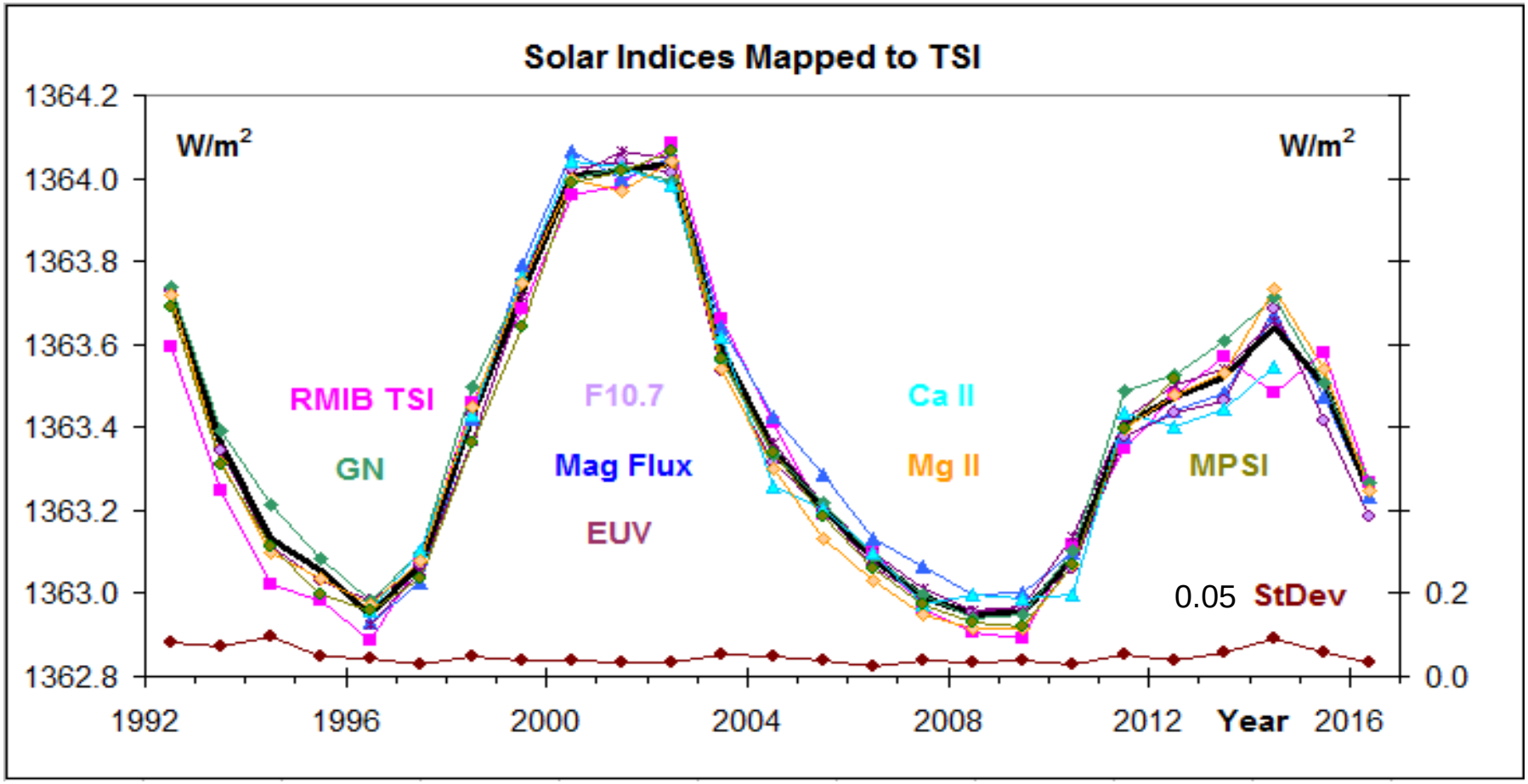
It seems to me that all that advanced [?] physics and sophisticated [?] modeling only added a bit of noise to a simple linear combination of H&S’s GSN and $\langle GSN \rangle_{11}$, even failing for modeling the recent instrumental spacecraft record.

Variation of the Photospheric Magnetic Field Causes the Variation of TSI [Total Solar Irradiance]



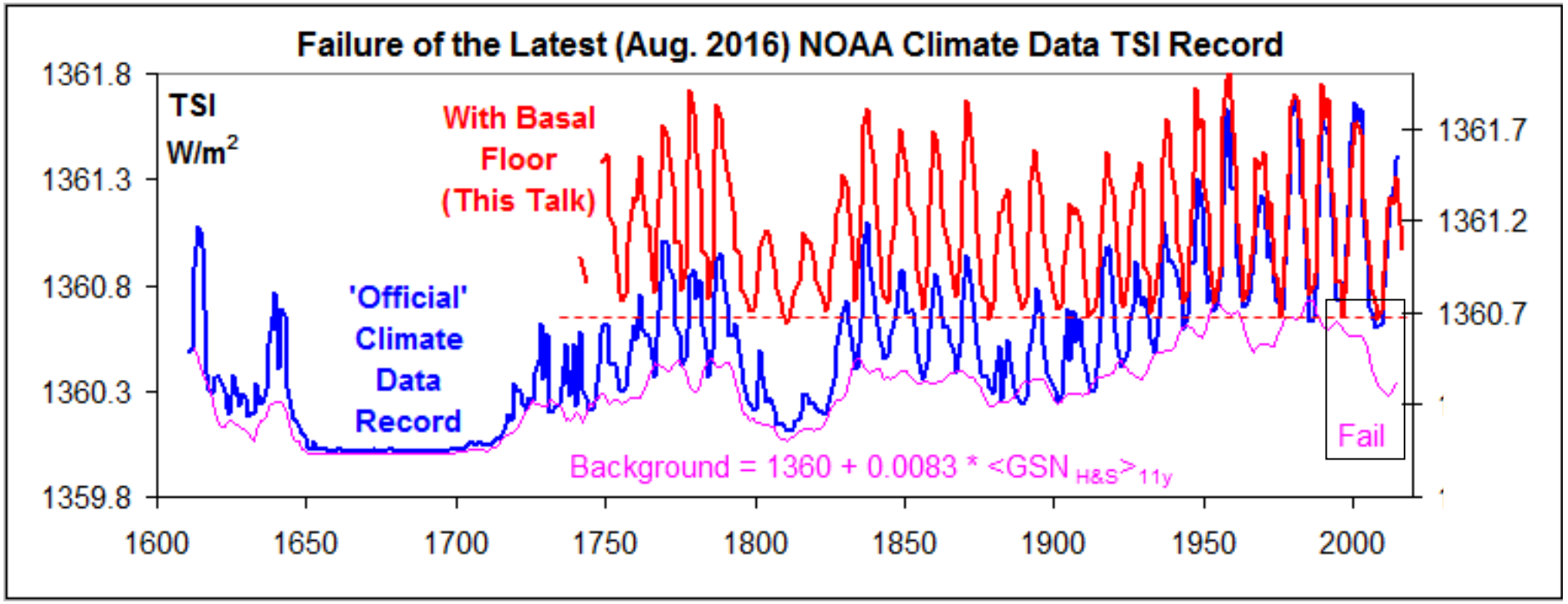
"The results of this work strengthen support for the hypothesis that variation in solar irradiance on timescales greater than a day is driven by **photospheric** magnetic activity". Yeo et al., A&A **570**, A85 (2014)

Solar Indices Mapped Linearly to TSI



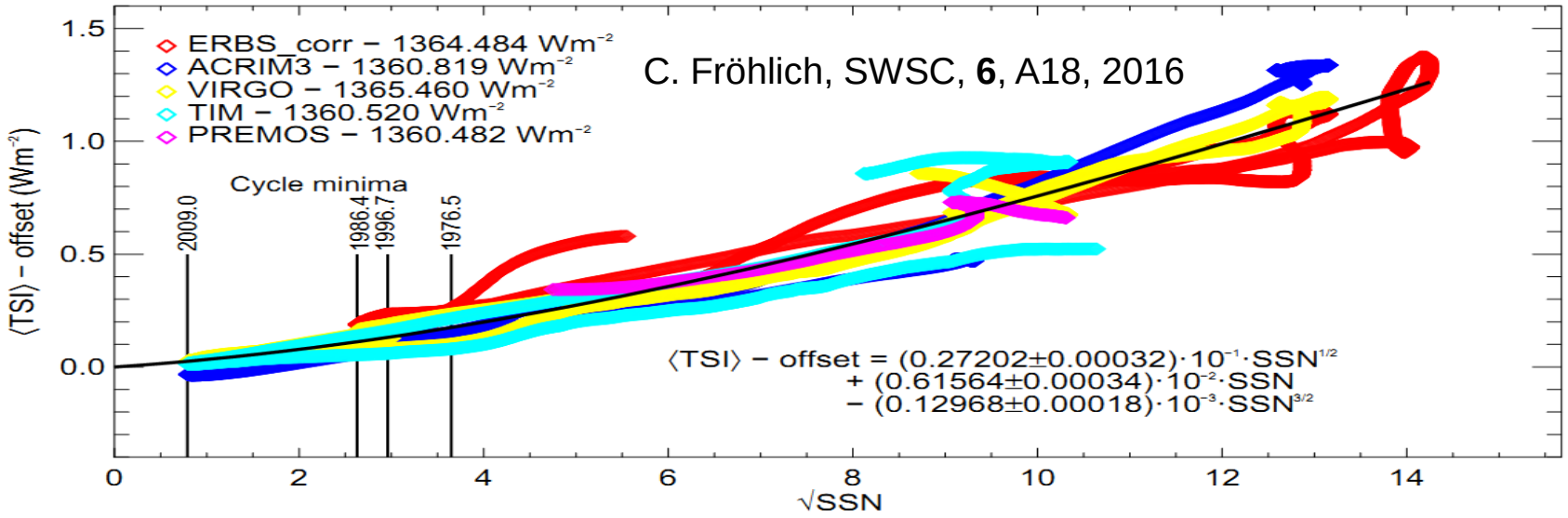
The TSI record is that by the Belgian Meteorological Institute [RMIB]

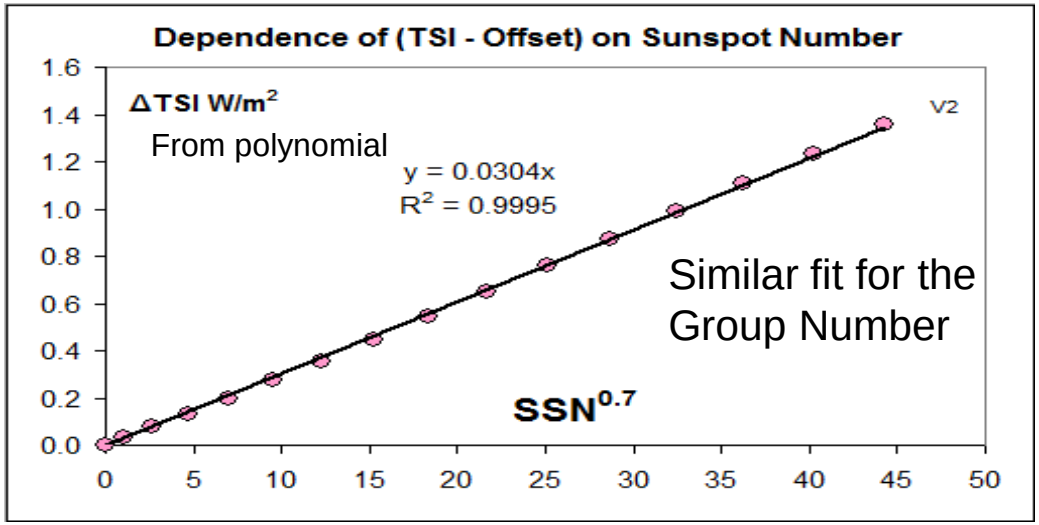
The Basal EUV and Magnetic Flux Records Do Not Support the NOAA Climate Data Record, CDR



1: **One can fit EUV to the instrumental part of NOAA's Climate Data Record**
2: There is no support for a variable 'Background' (pink curve) and surely not
3: if constructed from the obsolete Hoyt & Schatten Group Sunspot Number
4: which the CDR didn't even use during the 'instrumental era'

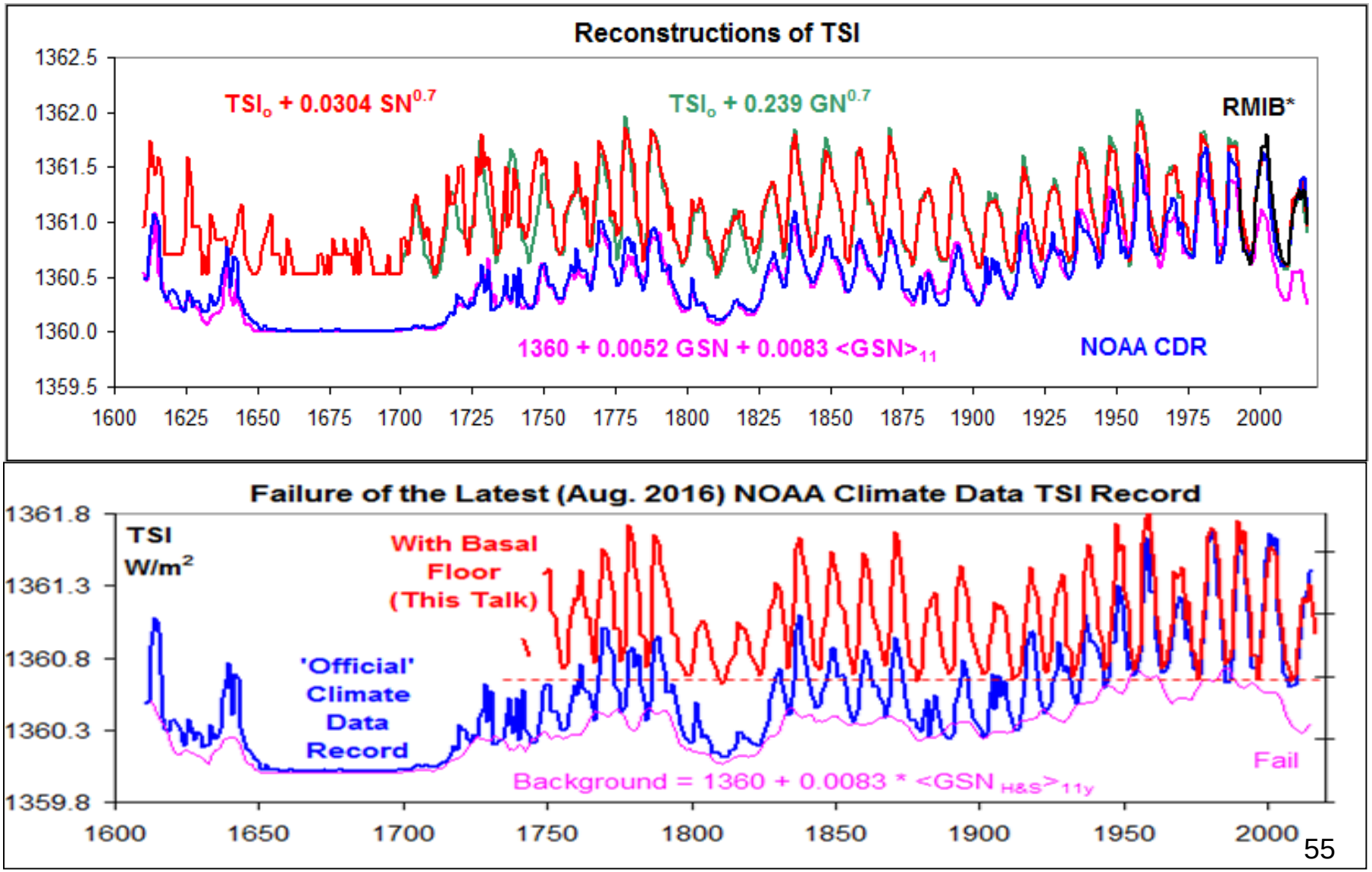
Claus Fröhlich Lined up TSIs as a Function of the Square Root of the Sunspot Number





The relationship is not quite linear in $SSN^{0.5}$, but rather in $SSN^{0.7}$ which is a very close [and much simpler] fit to Fröhlich's polynomial

Using Fröhlich's Relationship



What do we have so far? #4

- There is no support for a variable TSI ‘Background’
- The current Climate Data Record [CDR] is not helpful to Climate Research
- The CDR should not be based on obsolete solar activity data
- I expect strong ‘push-back’ from entrenched ‘settled science’, but urge [at least] the solar community to be honest about the issue

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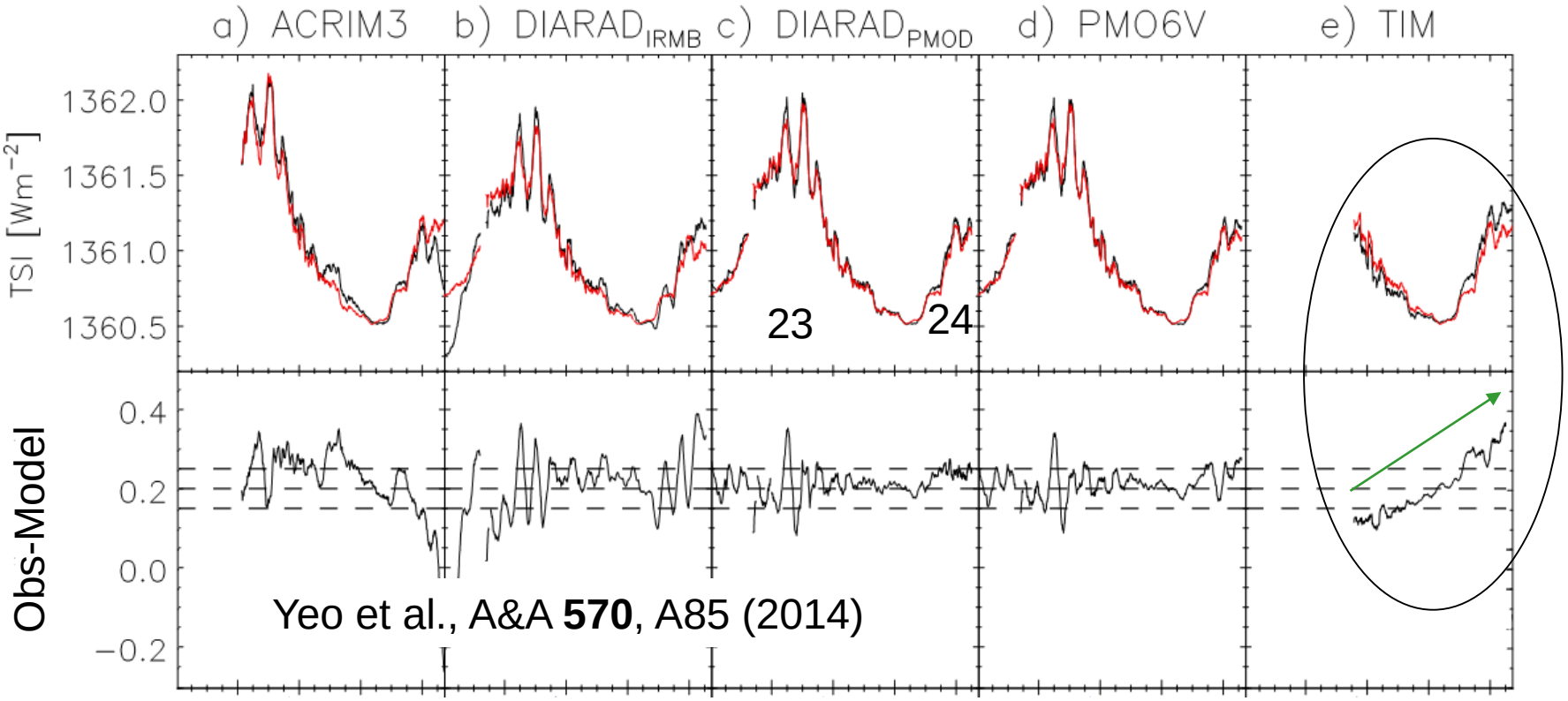
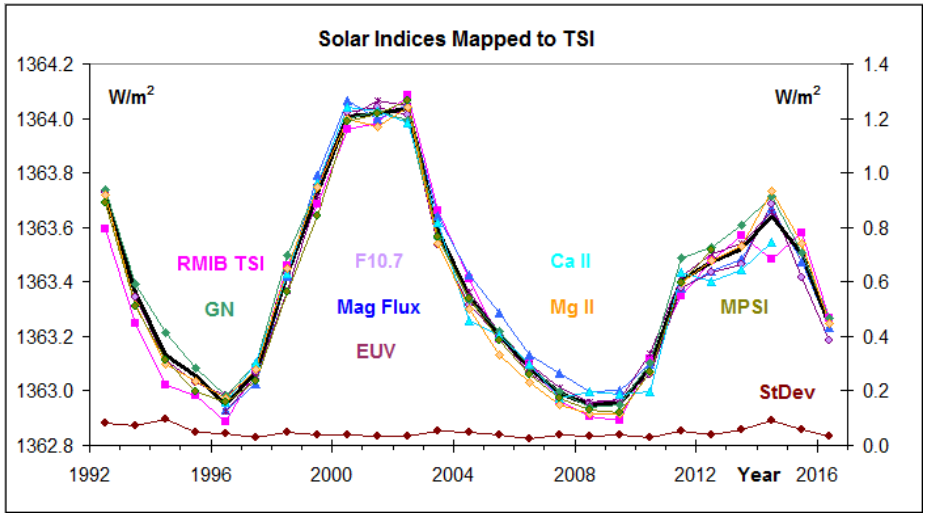
- Problematic Calibration of TSI records

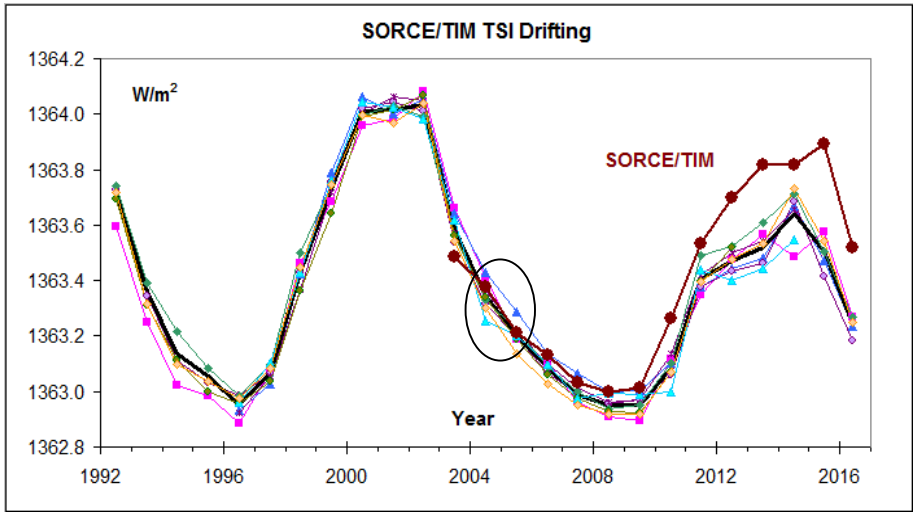
The Yeo Model et al. (2014) Compared to Observations

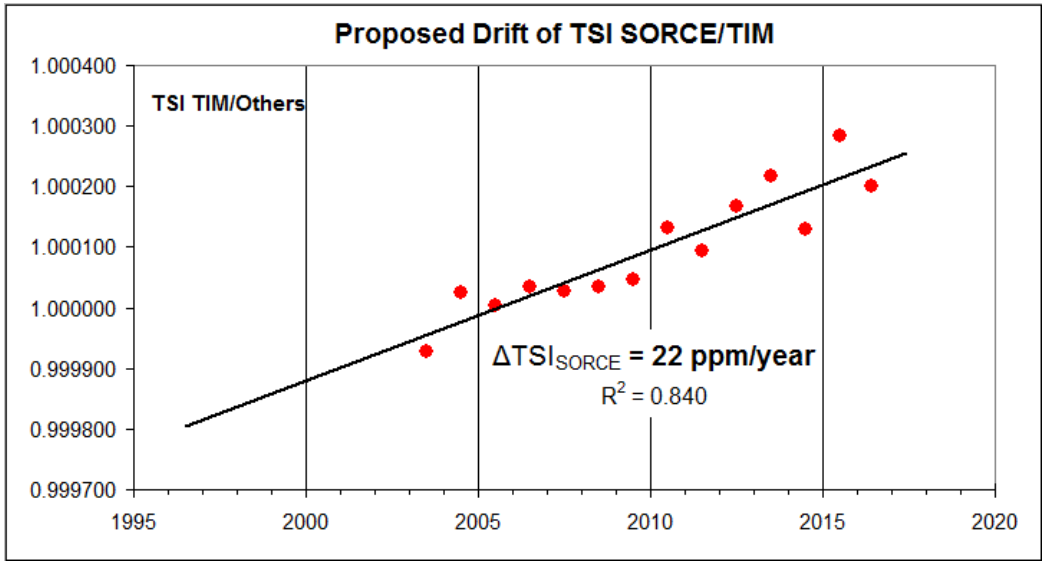


The Yeo et al. model reconstructs TSI (red curves) from MDI and HMI magnetograms. TIM has the least noise but seems to be drifting (upwards)

SORCE TIM Compared to Our Other Solar Indicators







I adjust the TIM data to match the reconstructed TSI composite during 2004-2005.

Perhaps TIM values are drifting [upwards]. Overcompensation for sensor degradation?

DeWitte and Nevens suggest a Similar Drift of SORCE/TIM

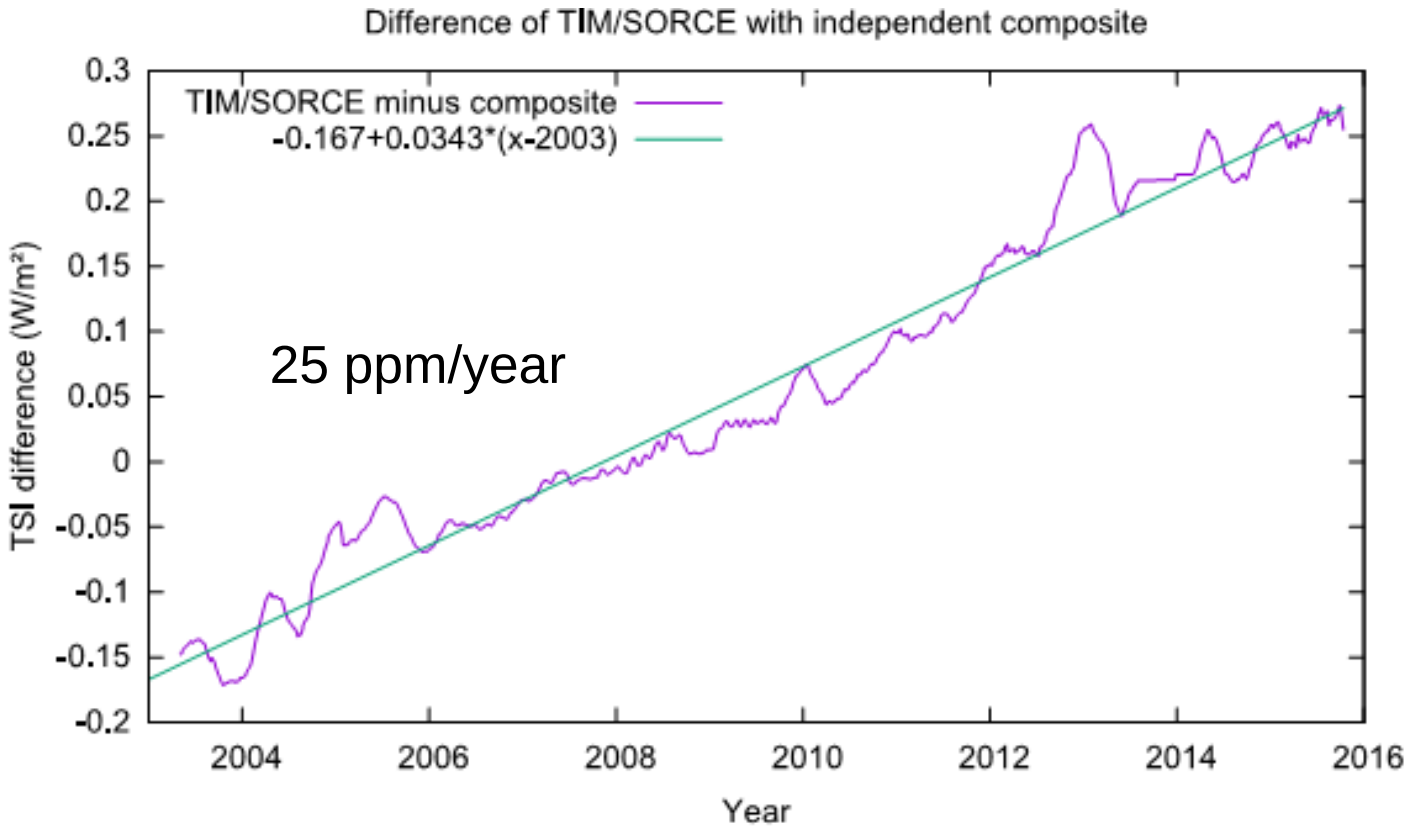
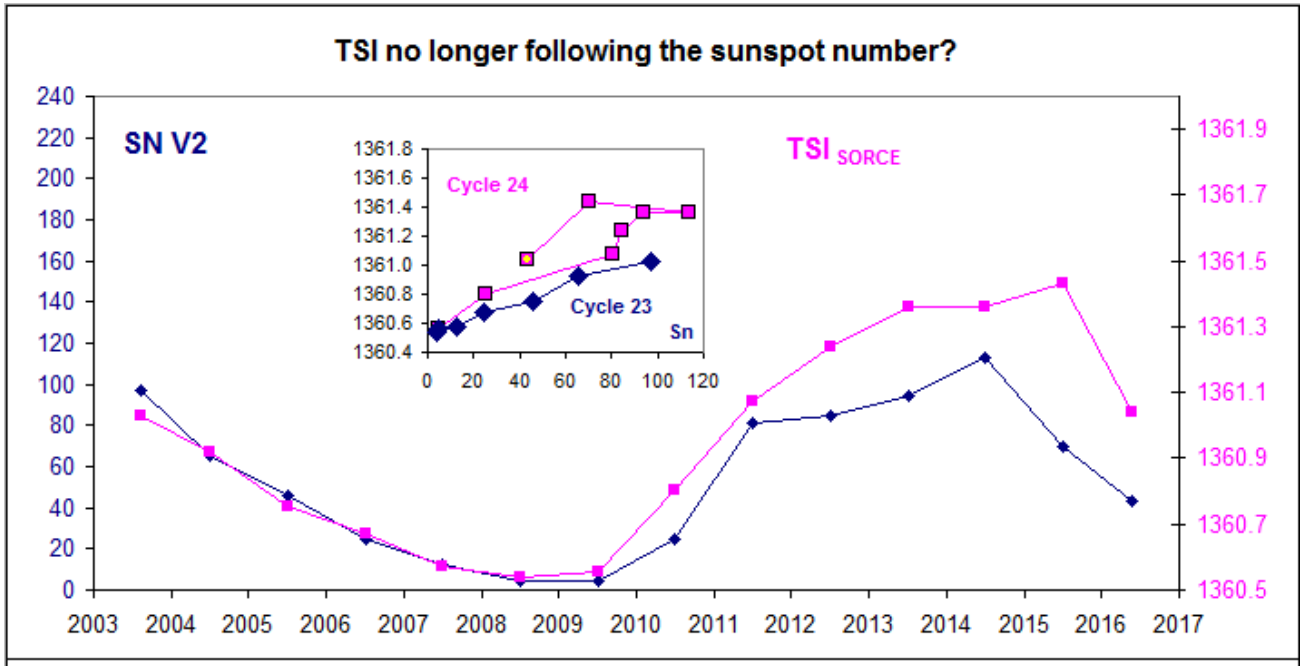
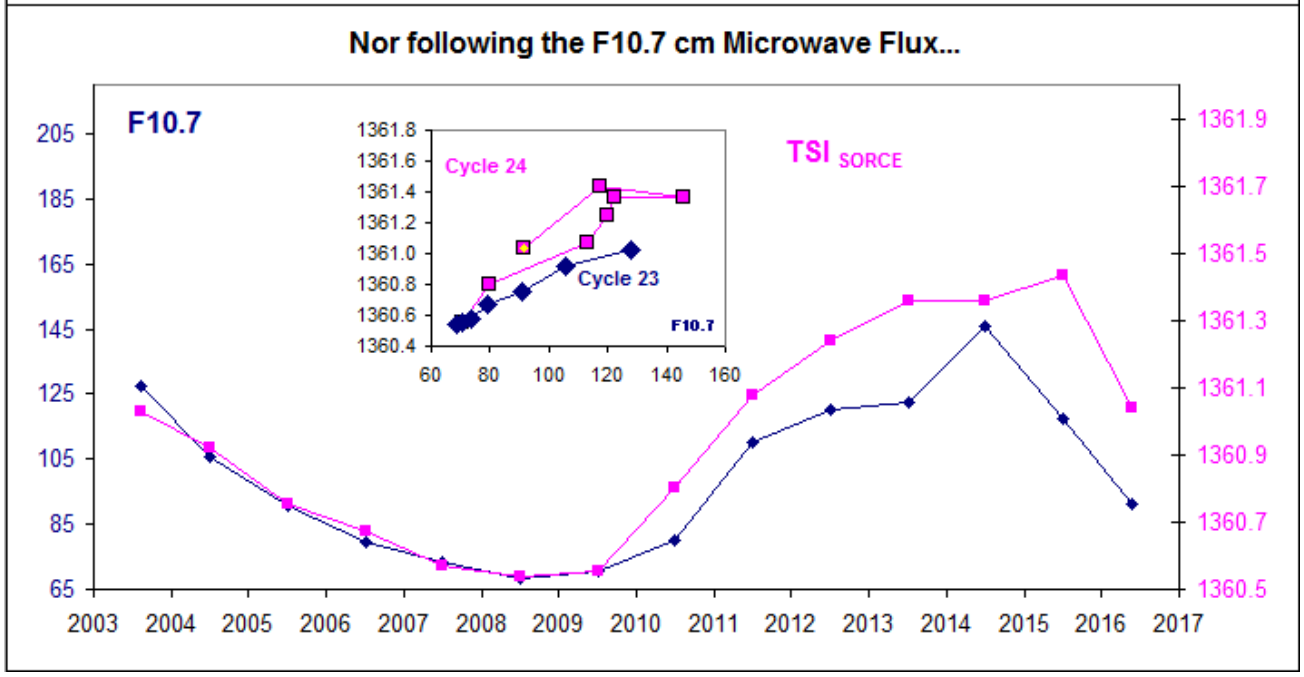


Figure 3. Difference of TIM/SORCE to independent composite (average) of DIARAD/VIRGO, PMO6B/VIRGO, and ACRIM3, and linear fit to this difference.

DeWitte, S. & Nevens, S.: ApJ, **830**, 25 (2016)

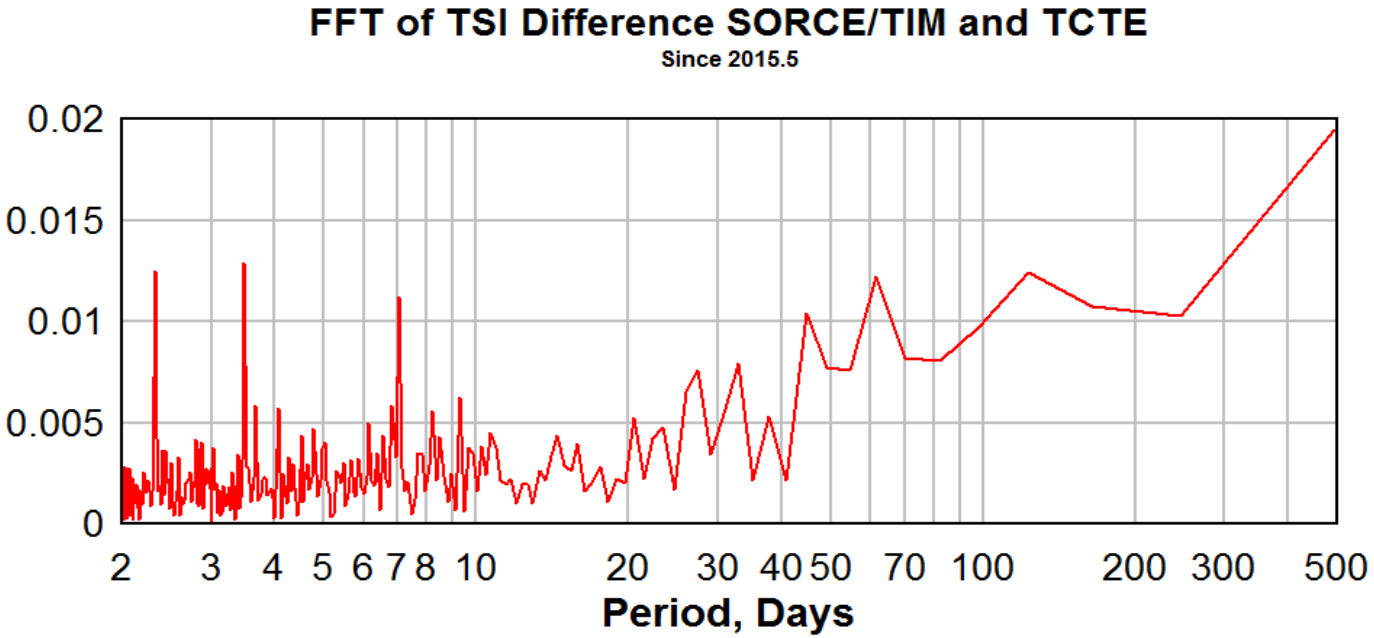


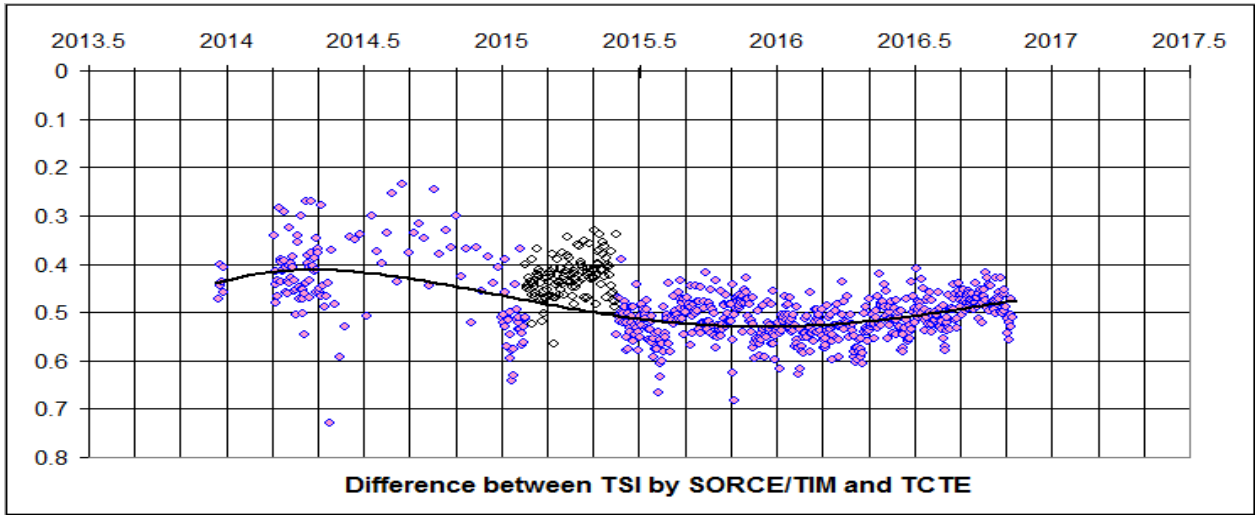


TSI (SORCE/ TIM) no longer following Sunspot Numbers nor F10.7 Flux

I have been following this for some time and am puzzled by this behavior of my 'Gold Standard'

How Stable are the TSI Measurements?





Sharp peaks at 1 week (7.00 days) and ½ and ⅓ week. Averaging to daily data with uneven distribution over the week?

The 'Thursday Effect' in TIM we found earlier?

TSI measurements perhaps not as stable as thought

Conclusion(s)

- We can reconstruct with some confidence the EUV flux [and its proxy F10.7] back to the 1740s
- The fluxes follow the total magnetic flux over the solar disk, which means that the latter can also be derived since then
- The solar wind magnetic flux can also be inferred and matches well the solar surface magnetic flux
- There is no ‘Background’ variation of TSI and the current NOAA [and NASA] Climate Data Records are not correct
- Possible problems with the calibration of TSI records

The End

Abstract

A composite record of the total unsigned magnetic (line-of-sight) flux over the solar disk can be constructed from spacecraft measurements by SOHO-MDI and SDO-HMI complemented by ground-based measurements by SOLIS covering the period 1996-2016, covering the two solar mimina in 1996 and 2009 and the two solar maxima in 2001 and 2014. A composite record of solar EUV from SOHO-SEM, TIMED-SEE, and SDO-EVE covering the same period is very well correlated with the magnetic record (R2=0.96), both for monthly means. The magnetic flux and EUV [and the sunspot number] are extremely well correlated with the F10.7 microwave flux, even on a daily basis. The tight correlations extend to other solar indices (Mg II, Ca II) reaching further back in time. Solar EUV creates and maintains the ionosphere. The conducting E-region [at ~105 km altitude] supports an electric current by a dynamo process due to thermal winds moving the conducting region across the Earth's magnetic field. The resulting current has an easily observable magnetic effect at ground level, maintaining a diurnal variation of the geomagnetic field [discovered by Graham in 1722]. Data on this variation go back to the 1740s [with good coverage back to 1840] and permit reconstruction of EUV [and proxies, e.g. F10.7] back that far. We confirm that the EUV [and hence the solar magnetic field] relaxes to the same [apart from tiny residuals] level at every solar minimum. Since the variation of Total Solar Irradiance [TSI] is controlled by the magnetic field, the reconstruction of EUV does not support a varying 'background' on which the solar cycle variation of TSI rides, strongly suggesting that the Climate Data Records advocated by NOAA and NASA are not correct before the space age. Similarly, the reconstruction does not support the constancy of the calibration of the SORCE/TIM TSI-record since 2003, but rather indicates an upward drift, suggesting an over-correction for sensor degradations.