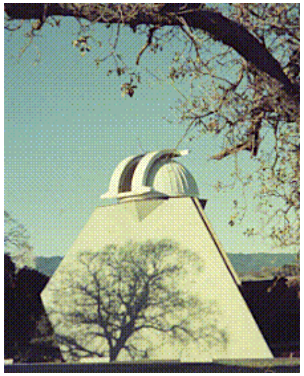


Geomagnetic Indicators of Solar Activity

Leif Svalgaard

Stanford University

19 Aug. 2019

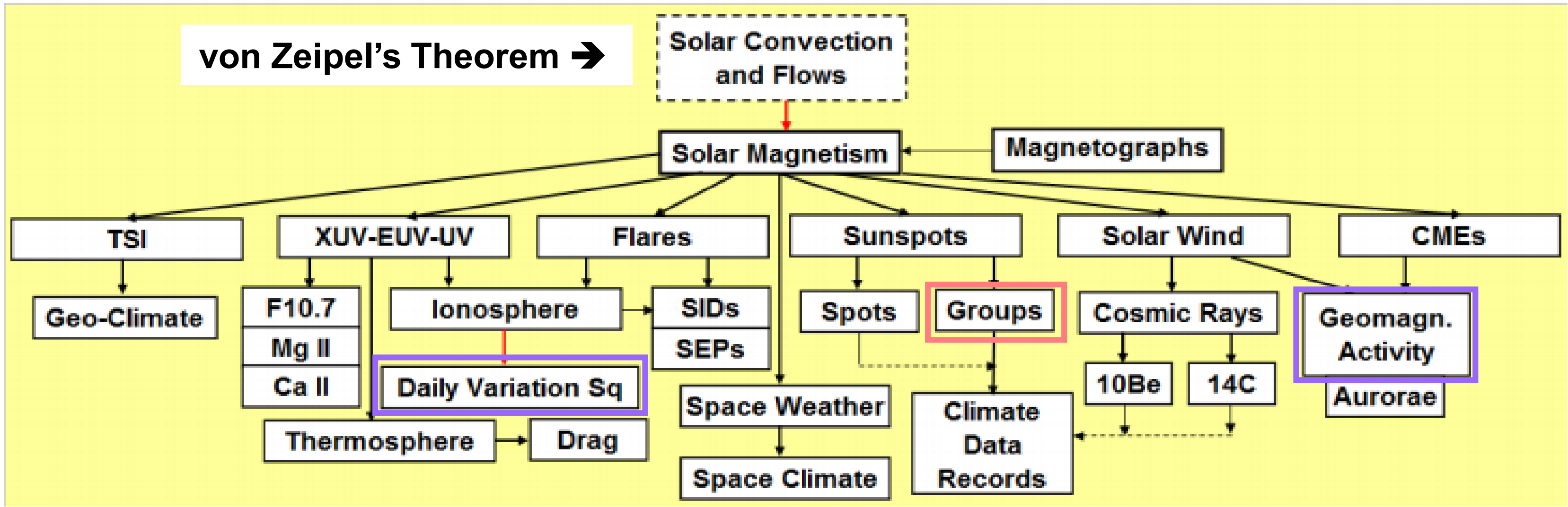
ISSI 417, Bern via Skype

https://arxiv.org/ftp/arxiv/papers/1506/1506.04408.pdf

https://arxiv.org/ftp/arxiv/papers/1002/1002.2934.pdf

We are Beginning to Understand the Complicated Physics of that ‘Great System’

A Systems Approach: Everything Must Fit



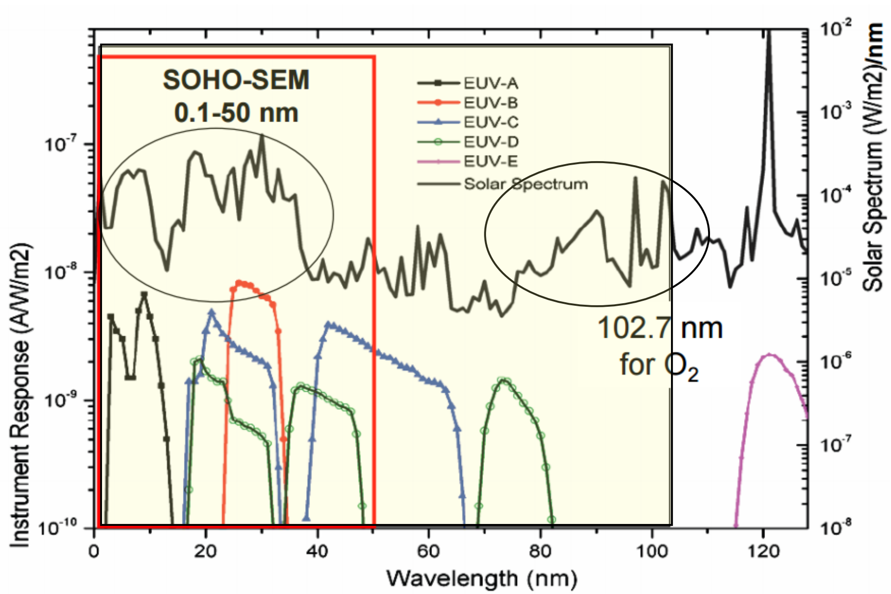
Faraday wrote to R. Wolf on 27th August, 1852: “I am greatly obliged and delighted by your kindness in speaking to me of your most remarkable enquiry, regarding the **relation existing between the condition of the Sun and the condition of the Earths magnetism**. The discovery of periods and the observation 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...

These are exciting times for Solar Physicists

Outline

- Observed EUV, Solar Microwave, and Magnetic flux records
- Deriving EUV [etc] from Geomagnetic Daily Variations
- Deriving Solar Wind Magnetic Field from Geomagnetism and Sunspots
- Comparing the Solar Flux(es) to the Sunspot (and Sunspot Group) Numbers

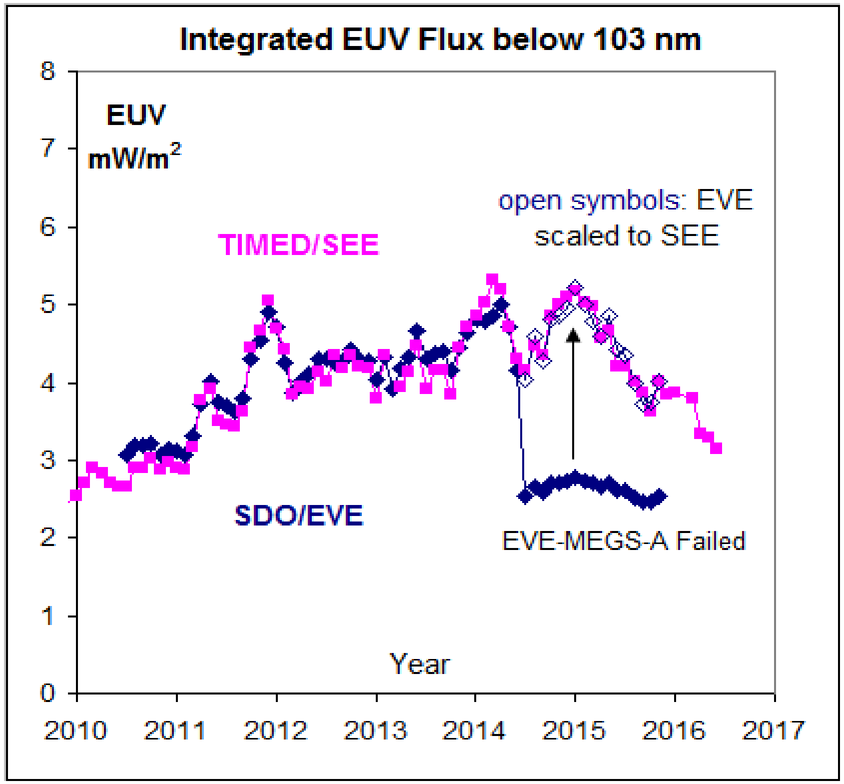
Sources of EUV Data: SEM, SEE, EVE



≤102.7 nm to ionize molecular Oxygen

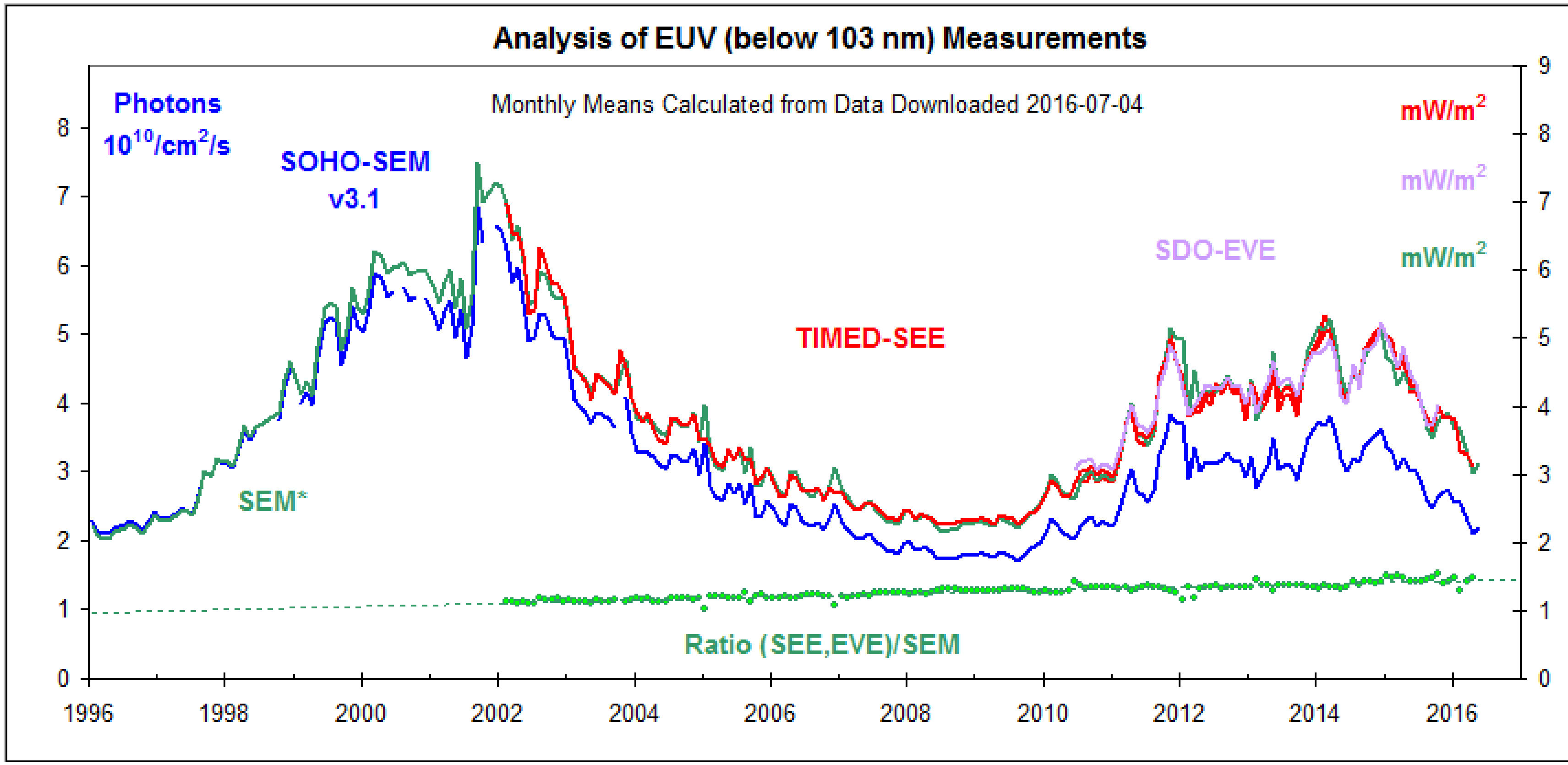
$$O_2 + h\nu \rightarrow O_2^+ + e^-$$

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



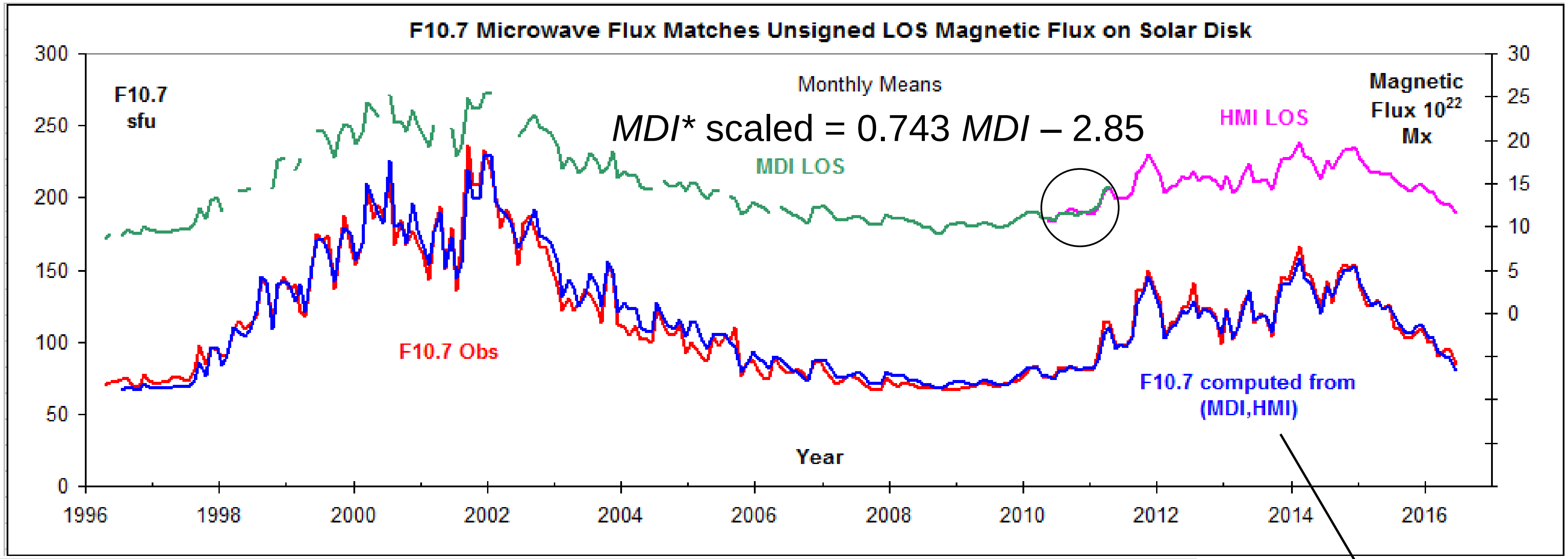
The detectors on the TIMED and SDO satellites agree well until the failure of the high-energy detector on EVE in 2014. We can still scale to earlier levels [open symbols]. 2016 not yet corrected.

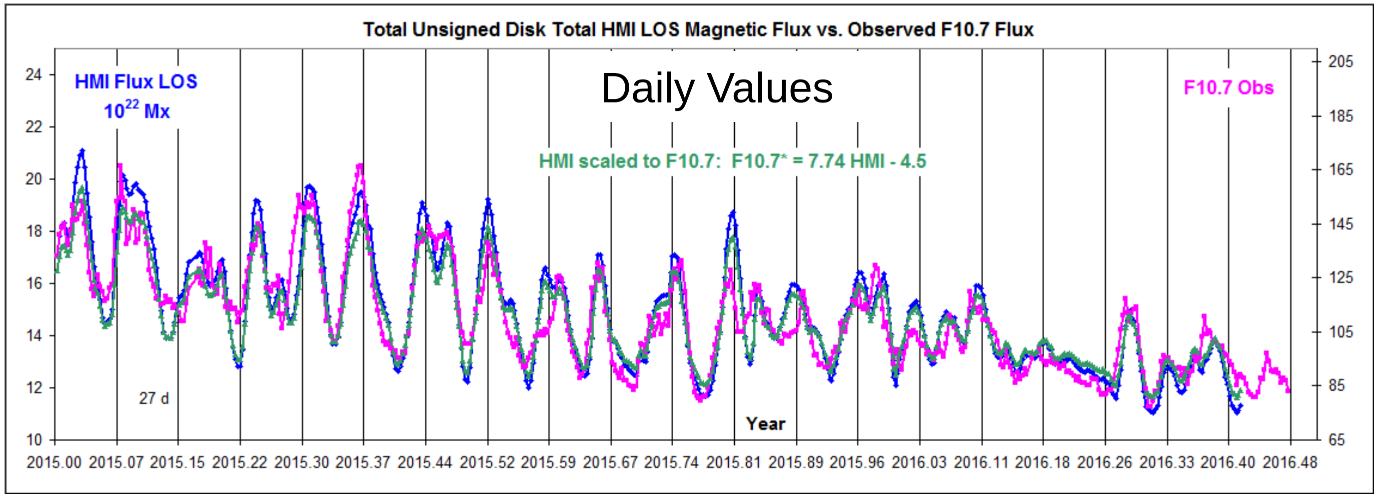
Creating an EUV (<103 nm) Composite

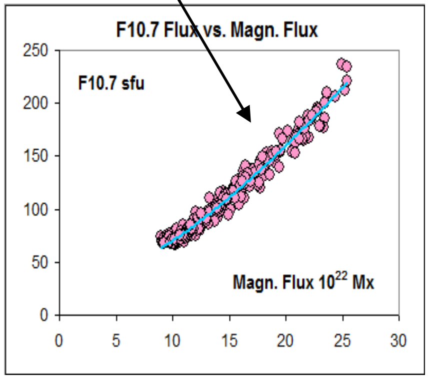


SEE and EVE agree nicely and we can form a composite (SEE,EVE) of them. SEM is on a different scale, but we can convert that scale to the scale of (SEE,EVE). The scale factor [green line] shows what to scale SEM with to match (SEE,EVE) [SEM*, upper green curve], to get a **composite** of all three (SEM*,SEE,EVE)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

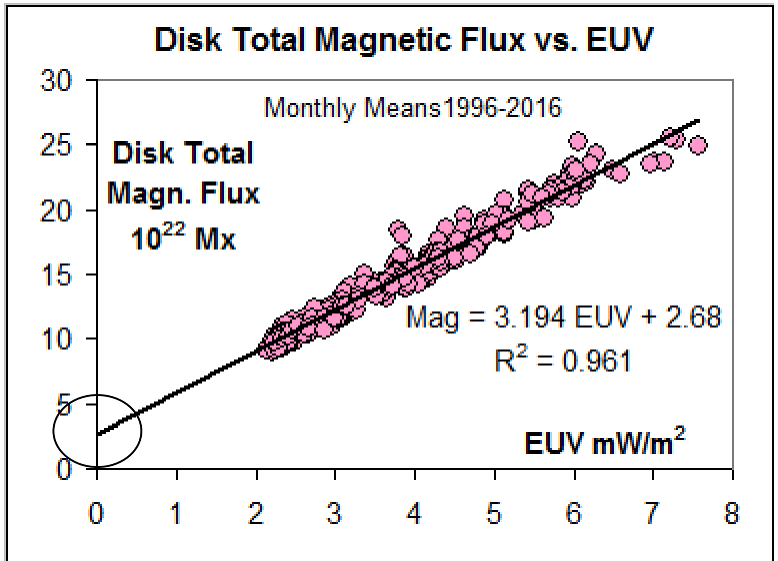
Magnetic Flux from MDI and HMI Match F10.7 Microwave Flux

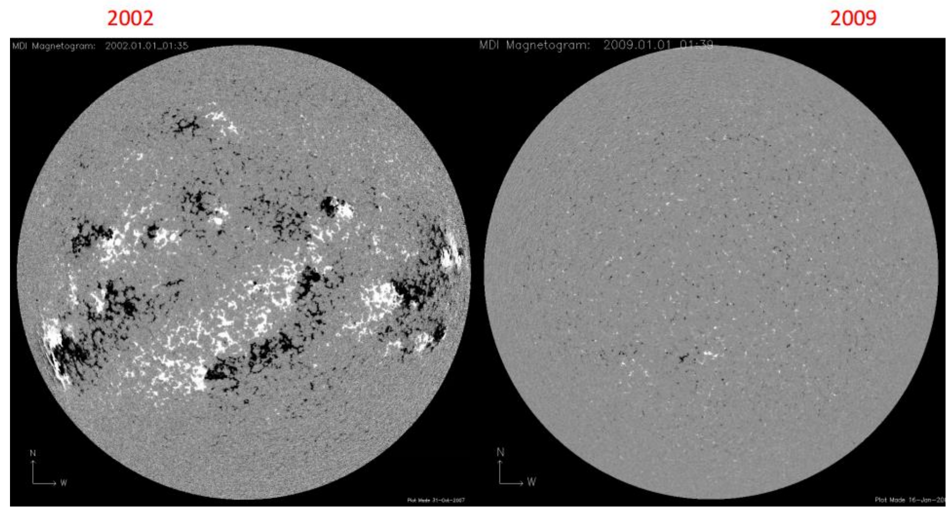




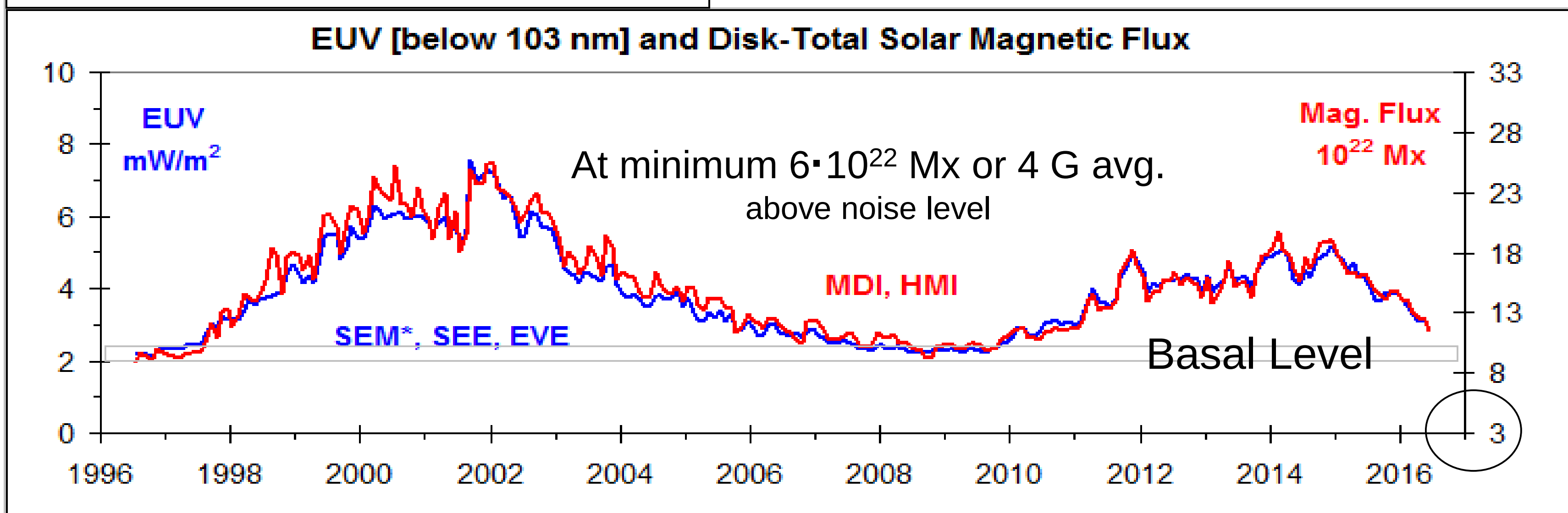


EUV Follows Total Unsigned Magnetic Flux



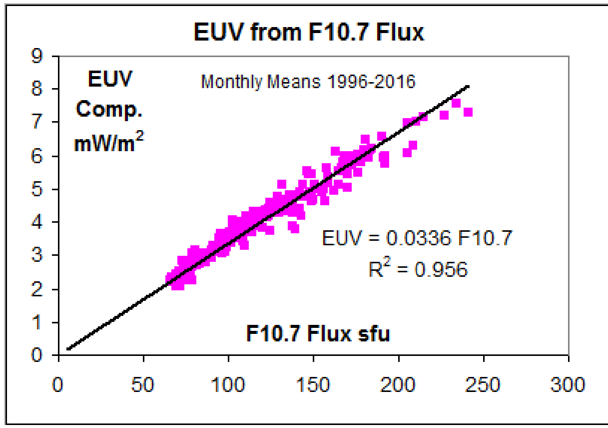


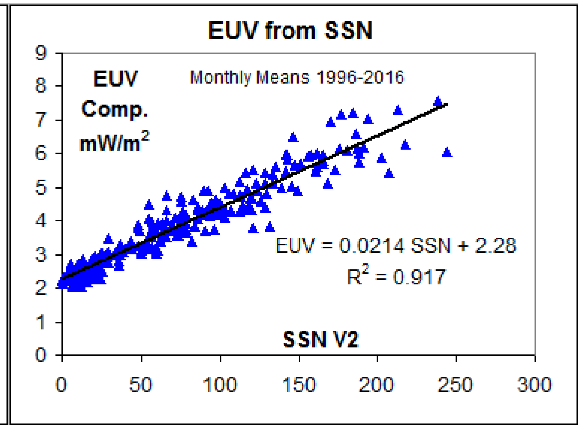
Offset interpreted as Noise Level ≈ 3·10^{22} Mx



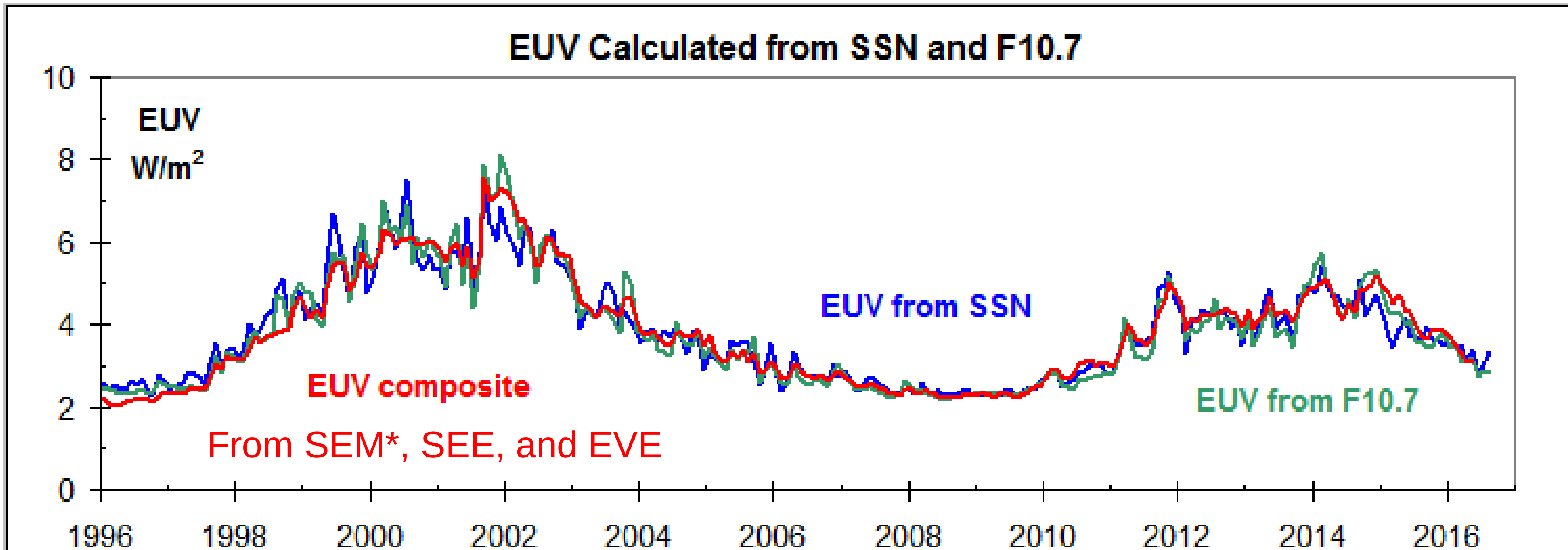
There is a ‘basal’ level at solar minima. Is this the case at every minimum?

EUV Composite Matches F10.7 and Sunspot Numbers

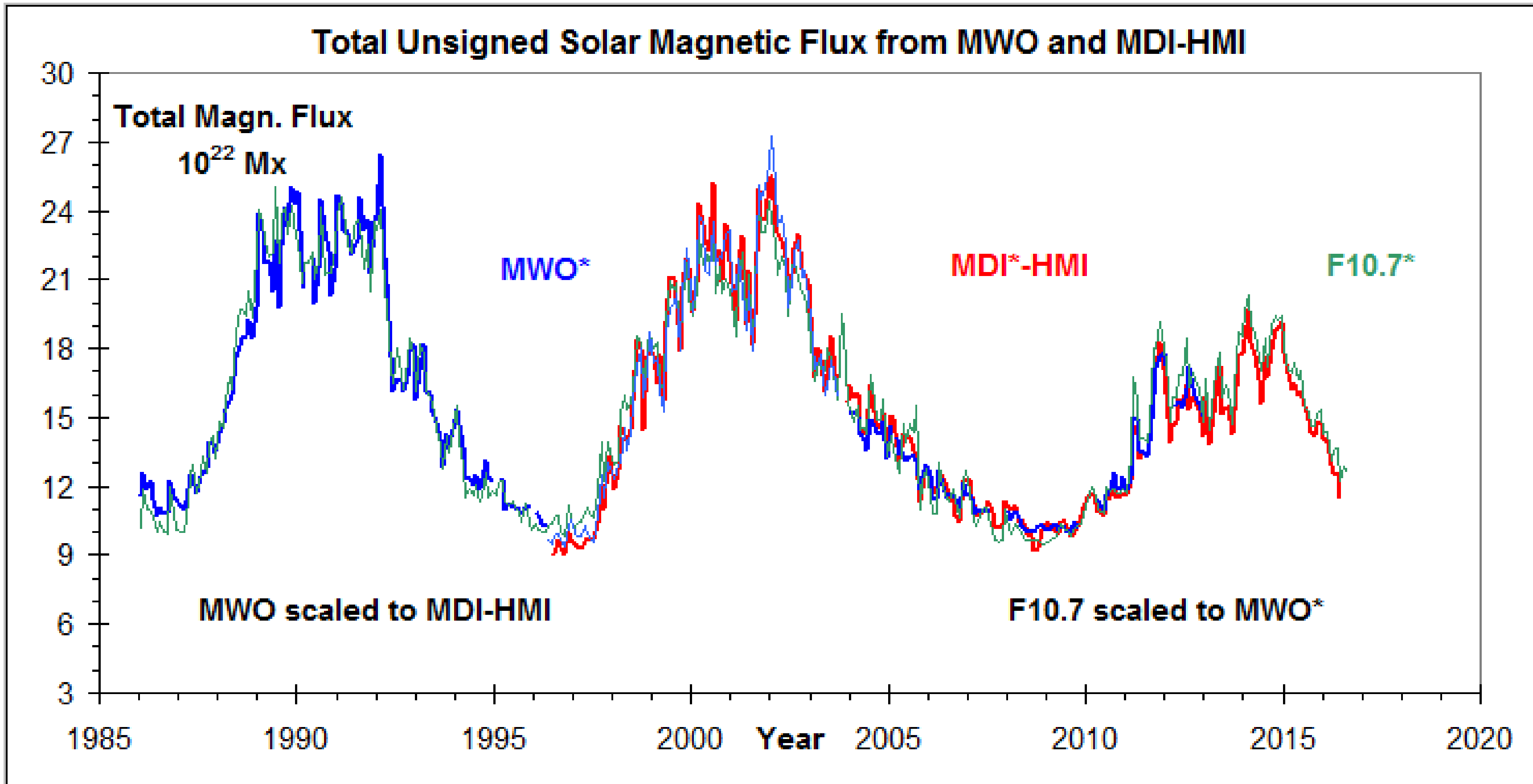




So, we can calculate the EUV flux both from the Sunspot Number and from the F10.7 flux which then is a good proxy for EUV [as is well-known].

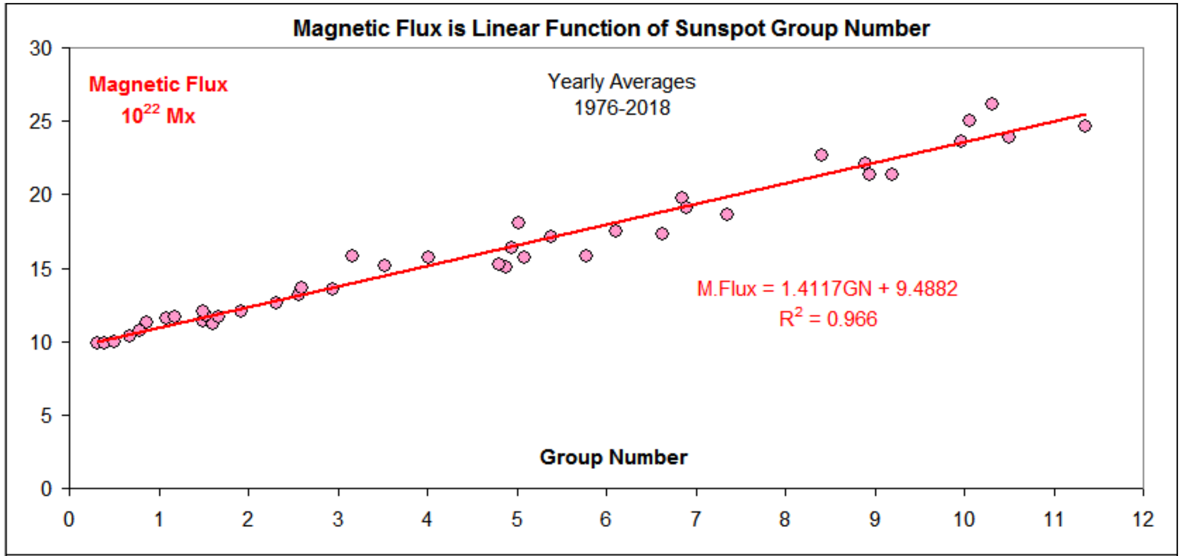


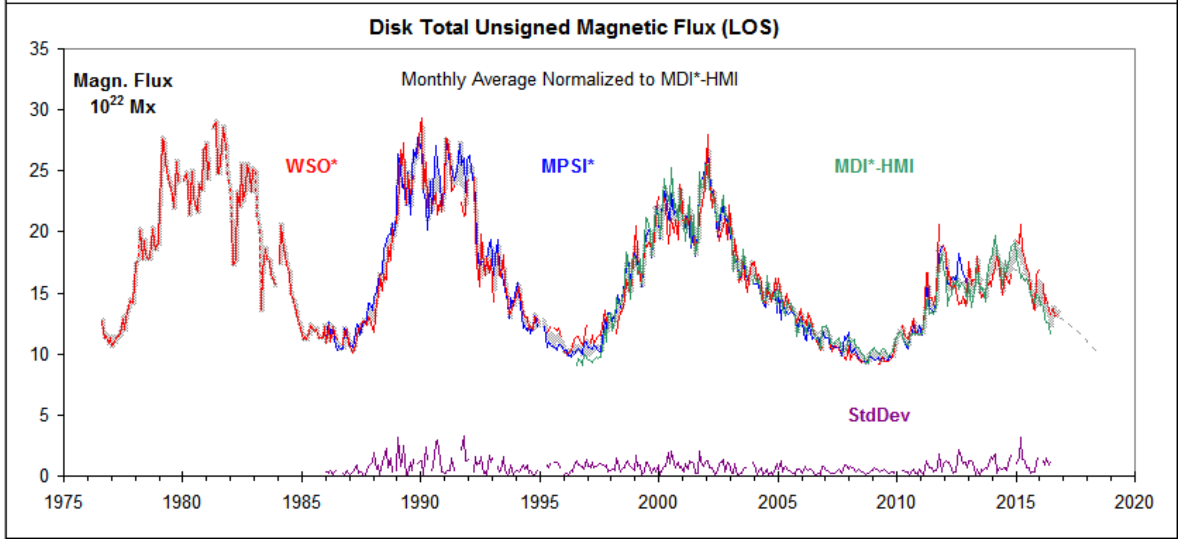
Magnetic Flux from MWO Tracks MDI-HMI and the F10.7 Flux



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 and the Sunspot Group Number (SS16)





Scaling MWO to MDI-HMI and WSO to the result yields a good measure of the LOS unsigned full disk magnetic flux which turns out to be a linear function of the Sunspot Group Number (S&S 2016).

Even at the limit of zero Groups there is still a significant amount of solar magnetic flux as needed to explain the interplanetary flux.

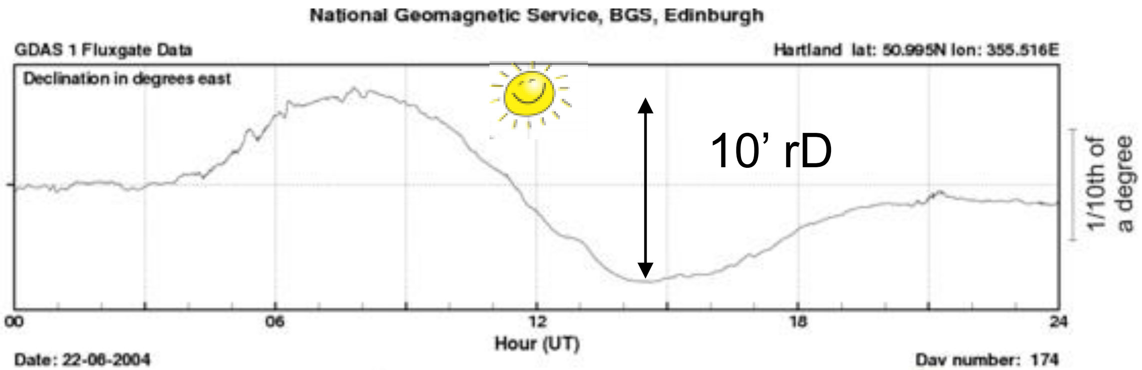
What do we have so far? #1

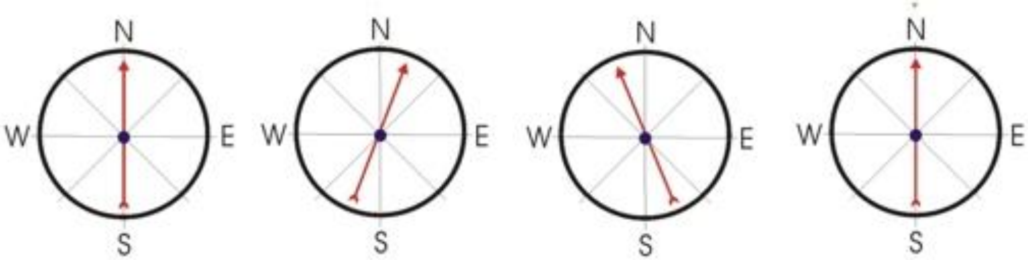
- We can construct an observed EUV composite back to 1996
- We can construct an observed Magnetic Flux composite back to 1976
- The EUV matches the Magnetic Flux
- The Microwave Flux [1-10 GHz] matches the EUV, Magnetic Flux, and Sunspot Number
- The magnetic flux matches the Sunspot Group Number linearly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

Outline

- Recent EUV, Solar Microwave, and Magnetic flux records
- Deriving EUV [etc] from Geomagnetic Daily Variations
- Deriving Solar Wind Magnetic Field from Geomagnetism and Sunspots
- Comparing the Solar Flux(es) to the Sunspot (and Sunspot Group) Numbers

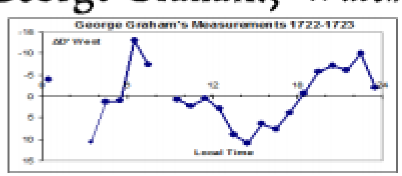
The Diurnal Variation of the Direction of the Magnetic Needle





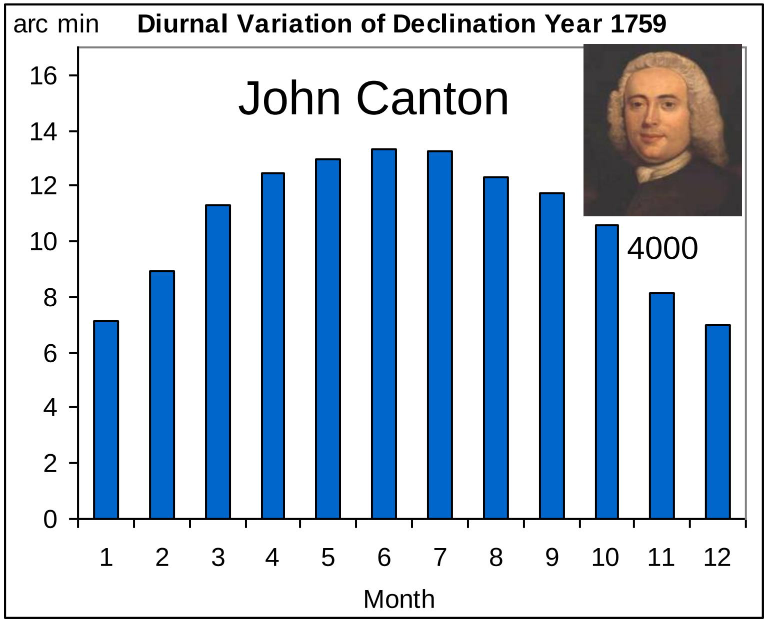
IV. *An Account of Observations made of the Variation of the Horizontal Needle at* London, *in the latter Part of the Year* 1722, *and beginning of* 1723. *By Mr.* George Graham, *Watchmaker, F. R. S.*

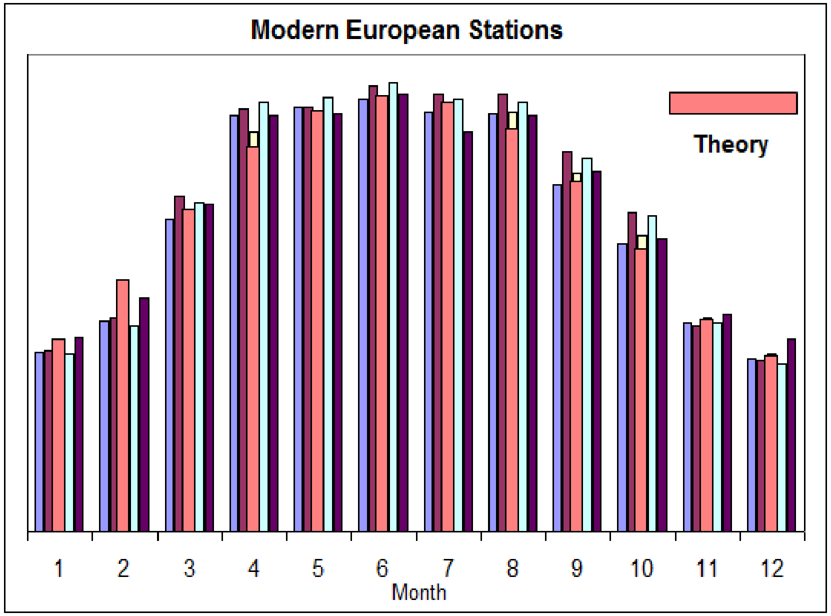
Made ~1000 observations

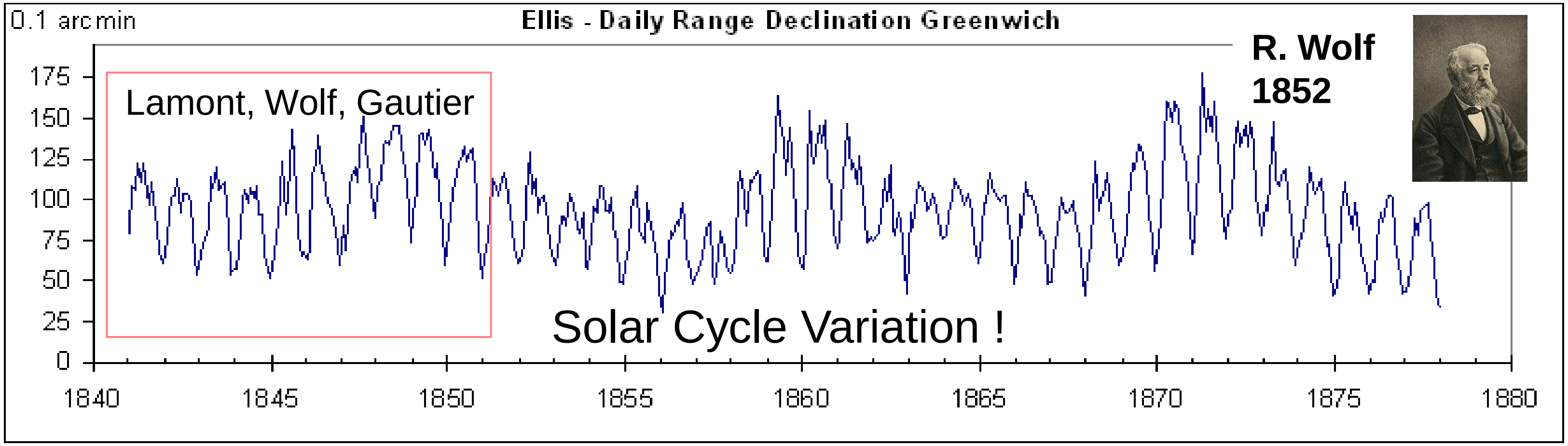


George Graham [London] discovered [1722] that the geomagnetic field varied during the day in a regular manner.

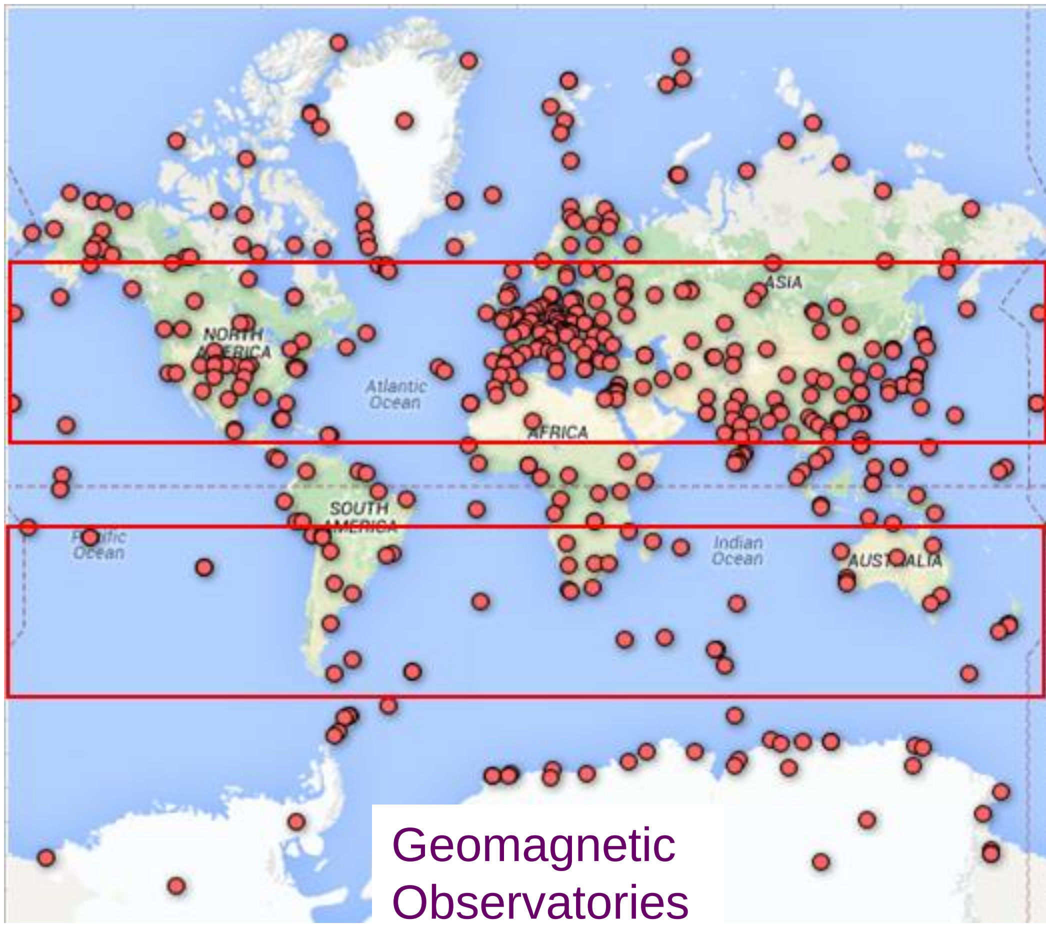
Zenith Angle Dependence Discovered

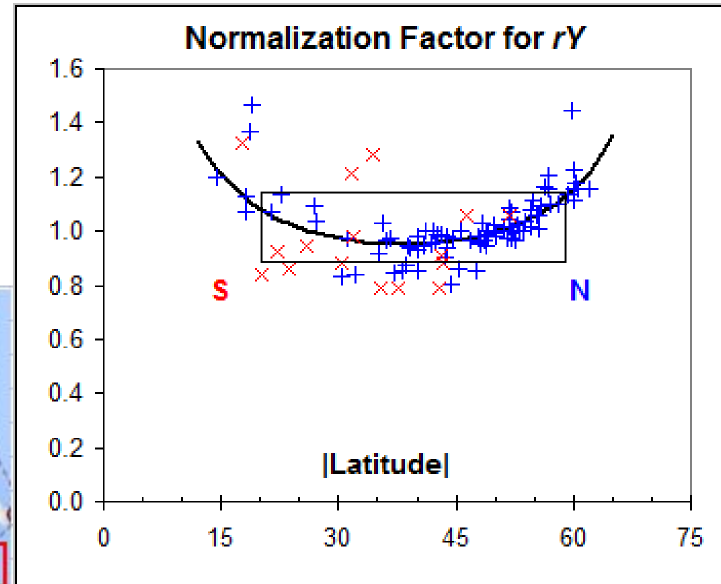


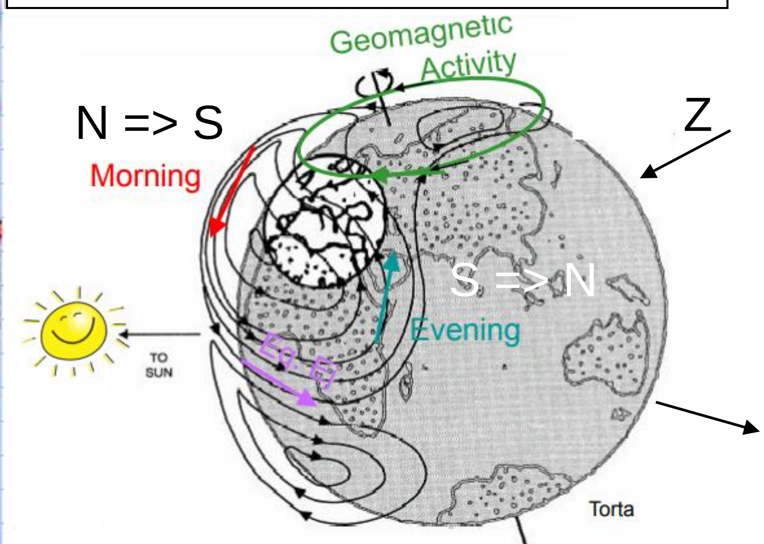




The Magnetic Signal at Midlatitudes



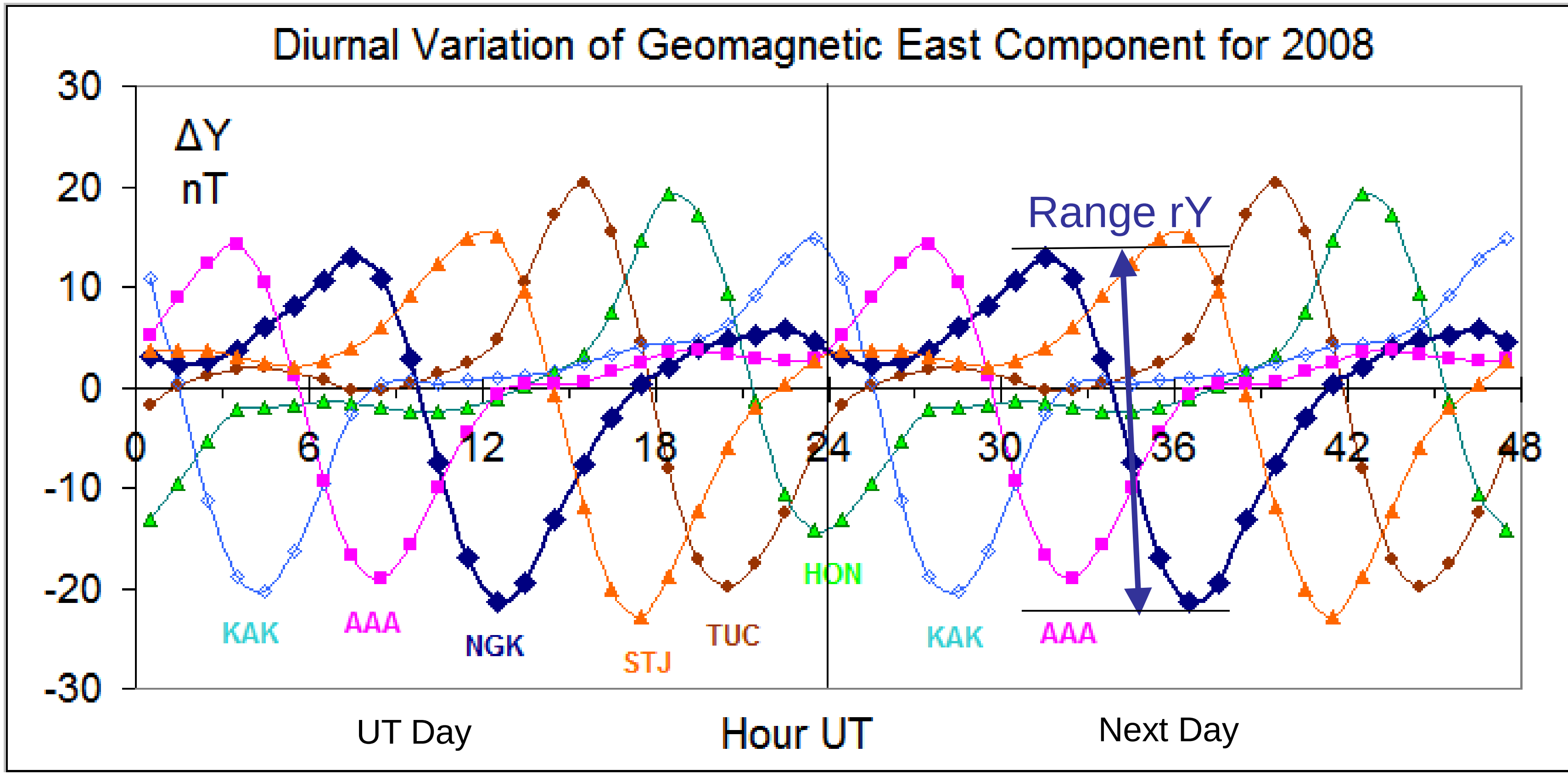




A current system in the ionosphere is created and maintained by solar EUV radiation

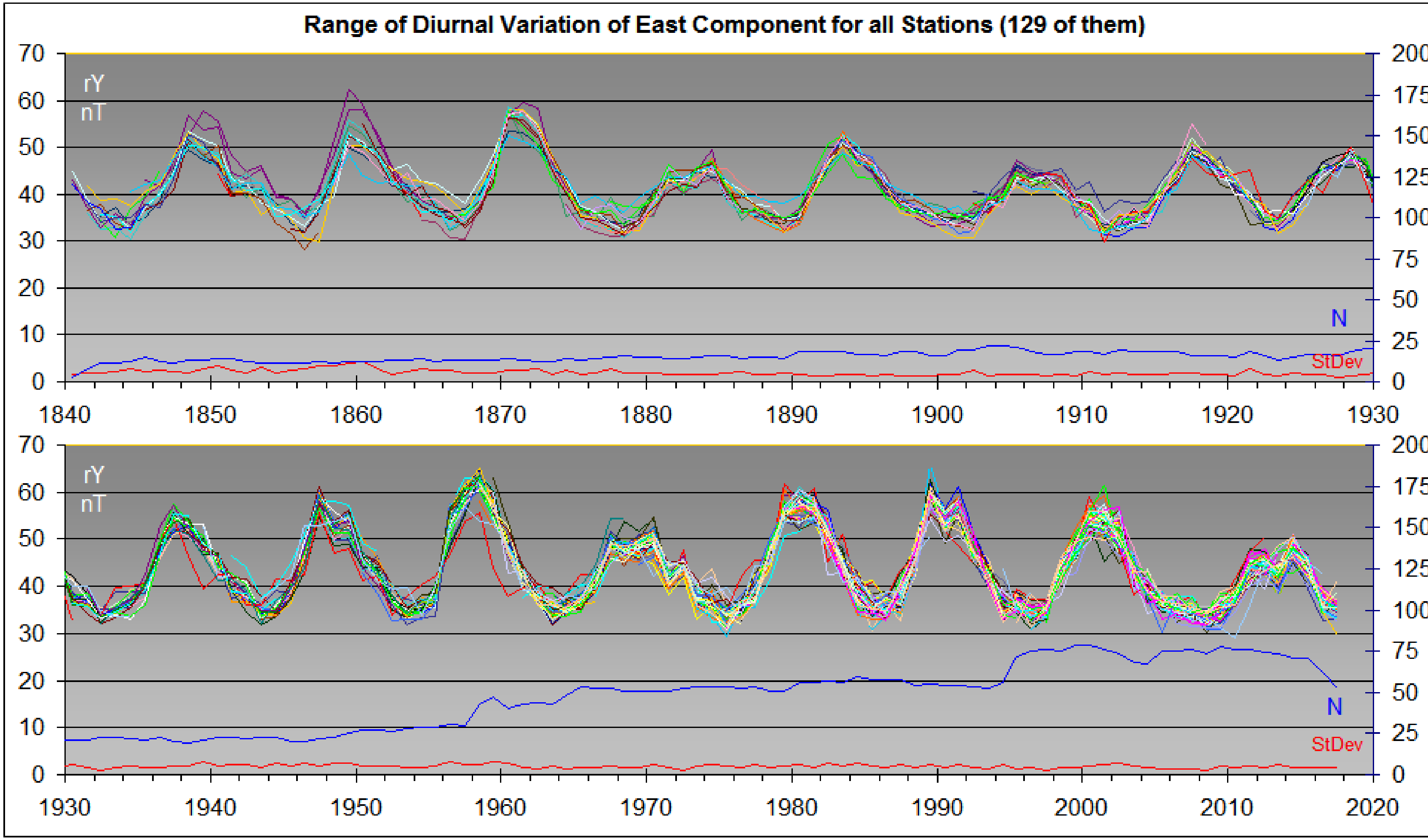
The effect in the Y-component is rather uniform for latitudes between 20º and 60º

The Shape of the Magnetic Signature is Remarkably Stable



Here we walk around the Globe to show that the variation [deviation from the mean] is the same from station to station, only differing slightly in amplitude, thus lending itself to straightforward normalization [e.g. to Niemegk, NGK].

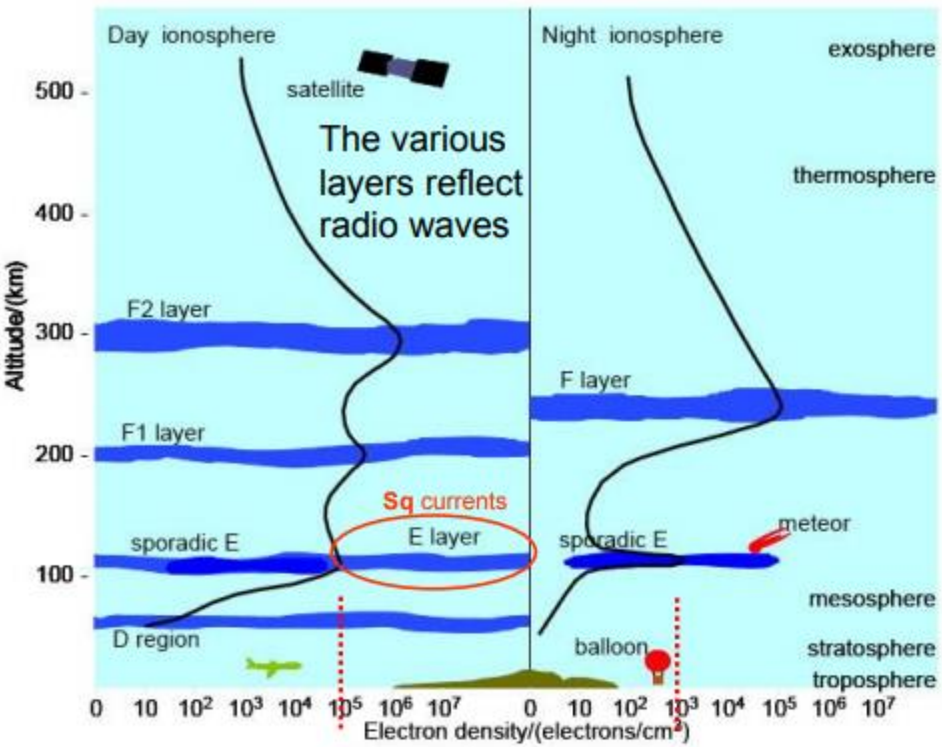
Normalized Observed Diurnal Ranges of the Geomagnetic East Component since 1840



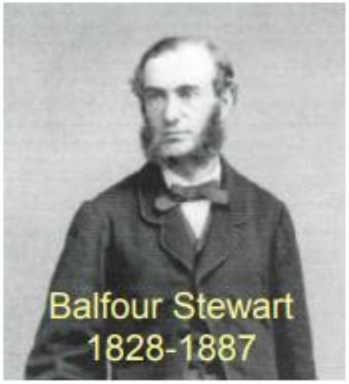
We plot the yearly average range to remove the effect of changing solar zenith angle through the seasons. A slight normalization for latitude and underground conductivity has been performed. Data used comprise 48 million hourly values.[17]

The Physics of the Daily Variation

Ionospheric Conducting Layers



Winds moving the charges across the magnetic field creates a dynamo current, whose magnetic effect we can observe at the surface as Graham discovered



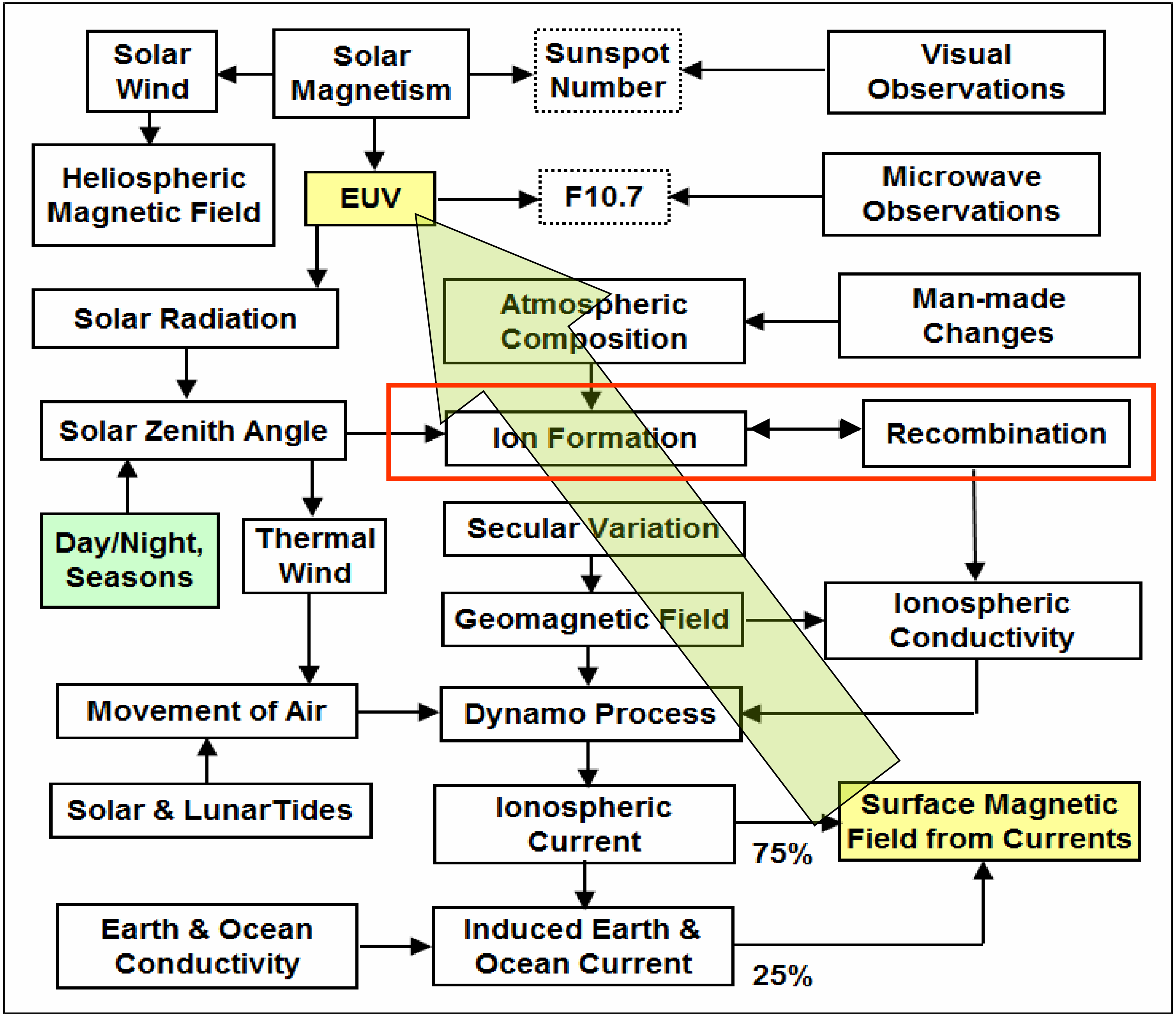
1882, Encyclopedia Britannica, 9th Ed.:

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

But why?

Dynamo

An effective dynamo process takes place in the dayside E-layer where the density, both of the neutral atmosphere and of the electrons are high enough.



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 can determine the EUV from the magnetic effects

Electron Density due to EUV

< 102.7 nm

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

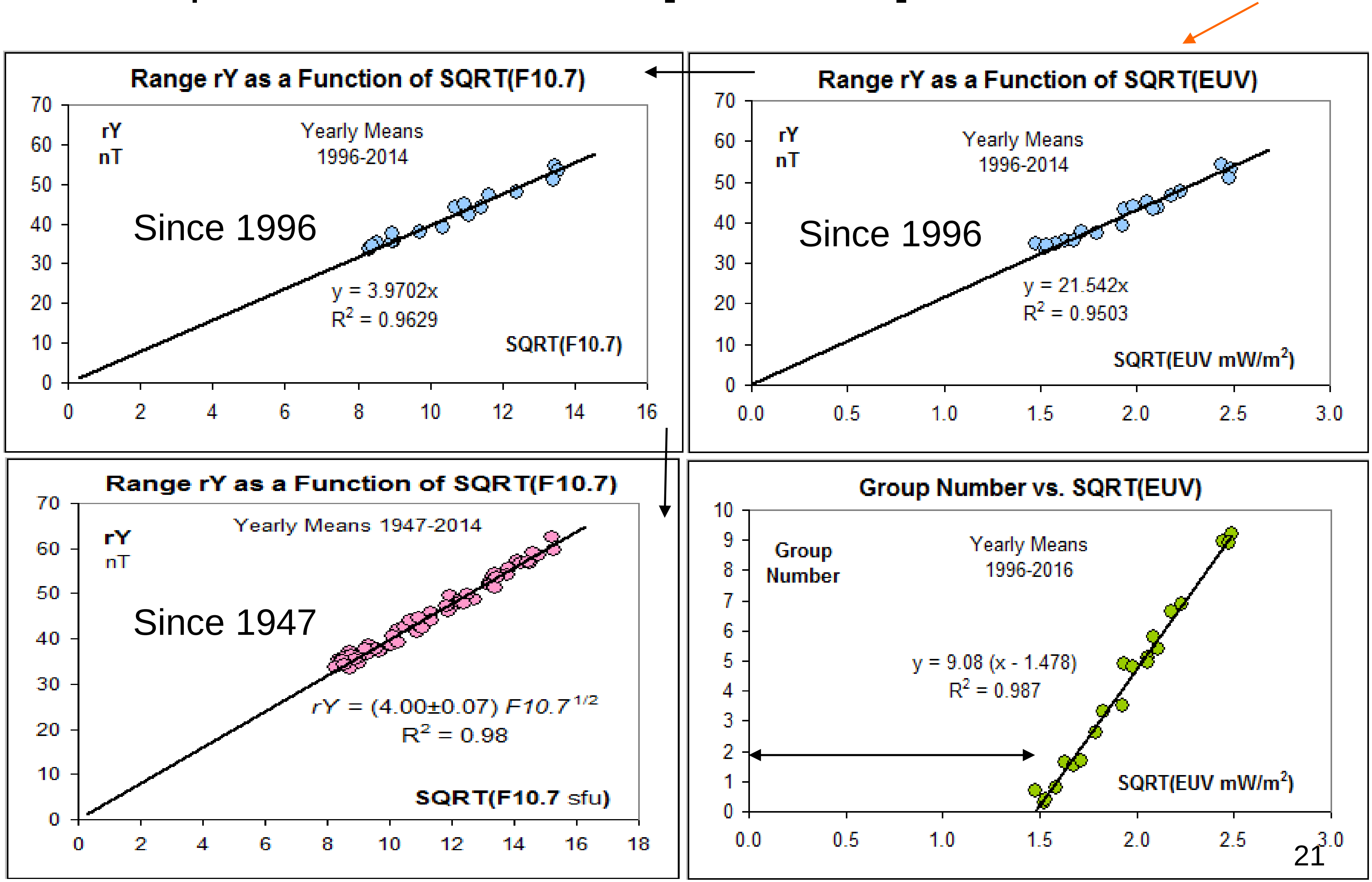
$$O_2^+ + e^- \xrightarrow{\alpha} O + O$$

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.

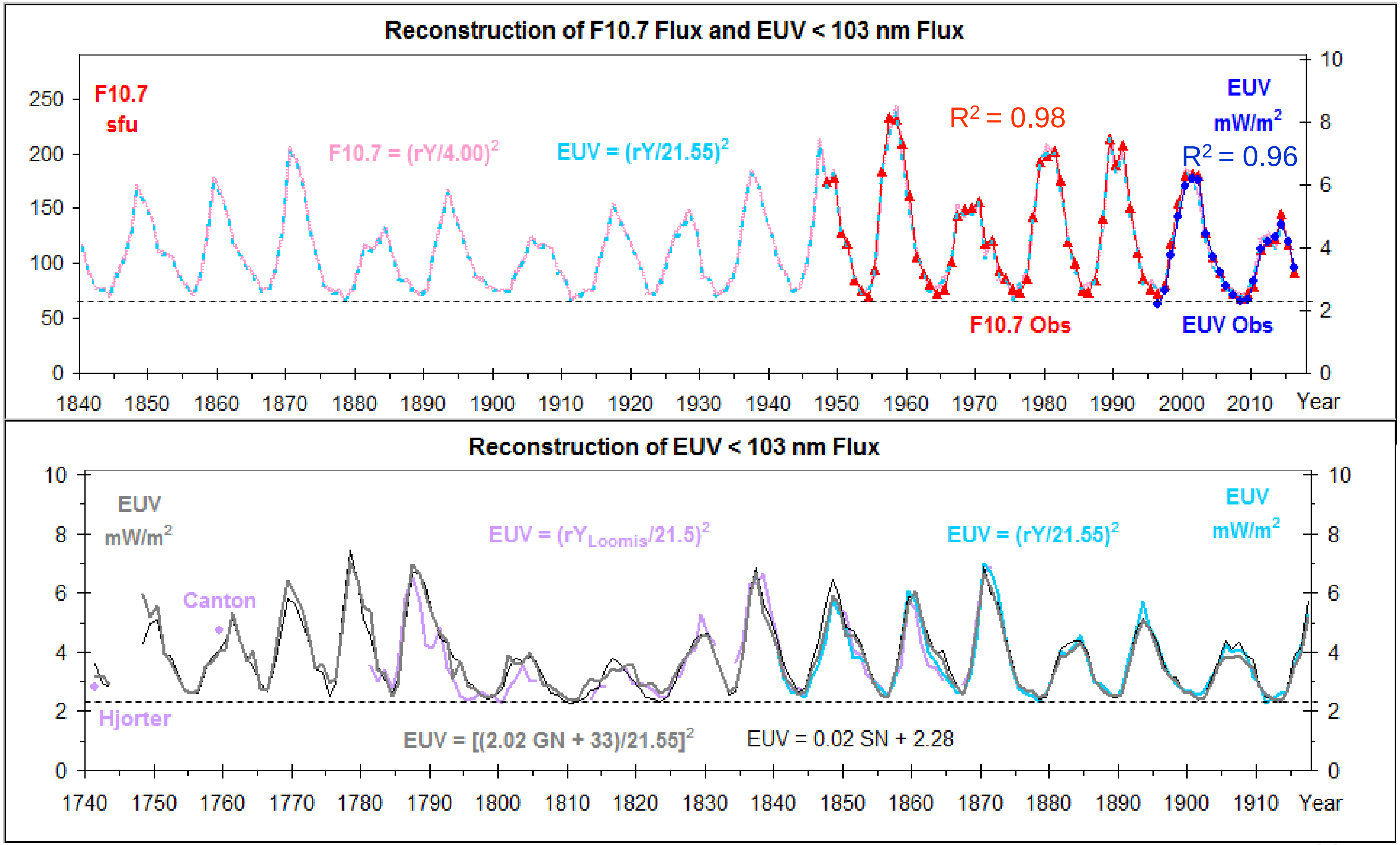
The rate of change of the number of ions N_i, dN_i/dt and in the number of electrons N_e, dN_e/dt are given by $dN_i/dt = J \cos(\chi) - \alpha N_i N_e$ and $dN_e/dt = J \cos(\chi) - \alpha N_e N_i$. Because the Zenith angle χ changes slowly we have a quasi steady-state, in which there is no net electric 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 $\lambda < 102.7$ 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



The Observational **Facts** are 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.

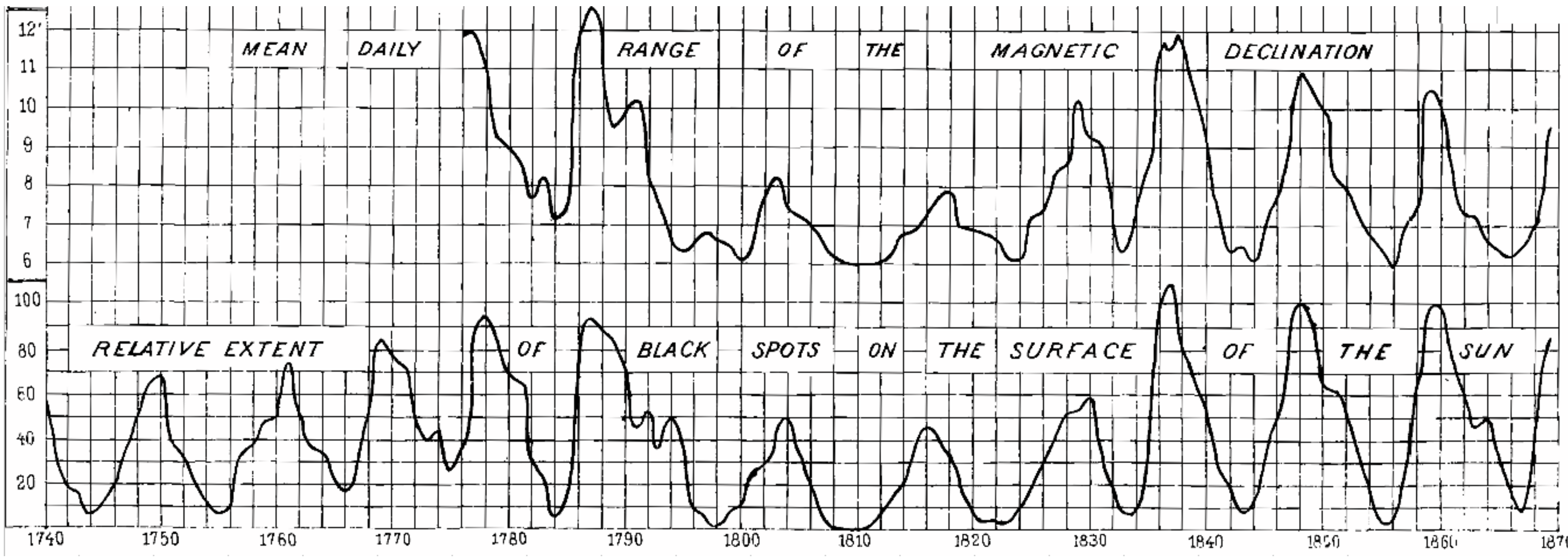
This comparison seems to warrant the following propositions:

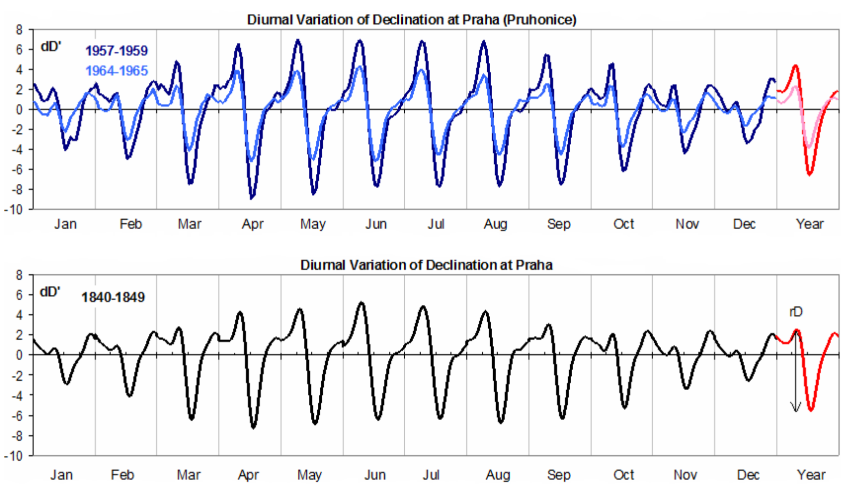
1. A diurnal inequality of the magnetic declination, amounting at Prague to about six minutes, is independent of the changes in the sun's surface from year to year.

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.

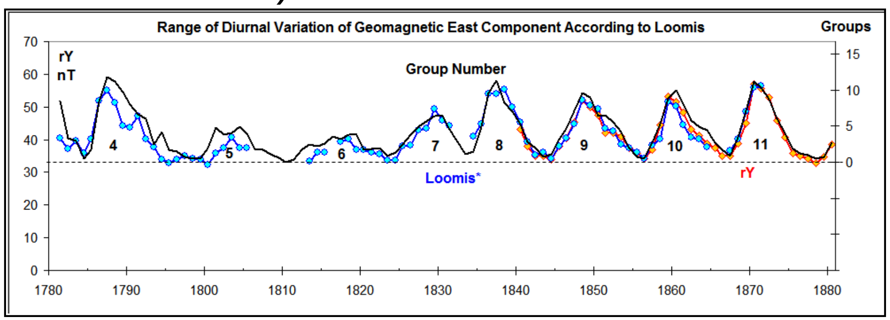
19th century 'Inequality' = deviation from [i.e. 'not equal to'] the mean

Loomis' Evidence for his Proposition





Comparison of the variation in the 1840s with modern data (1950-1960s) shows that the old data are good (even small 'wiggles' are the same)



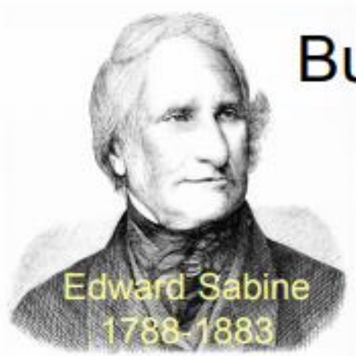
What do we have so far? #2

- 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

Outline

- Observed EUV, Solar Microwave, and Magnetic flux records
- Deriving EUV [etc] from Geomagnetic Daily Variations
- Deriving Solar Wind Magnetic Field from Geomagnetism and Sunspots
- Comparing the Solar Flux(es) to the Sunspot (and Sunspot Group) Numbers

Geomagnetic Storms Caused by Sun



But the Aurorae are Due to that "Other Cause" (The Solar Atmosphere)

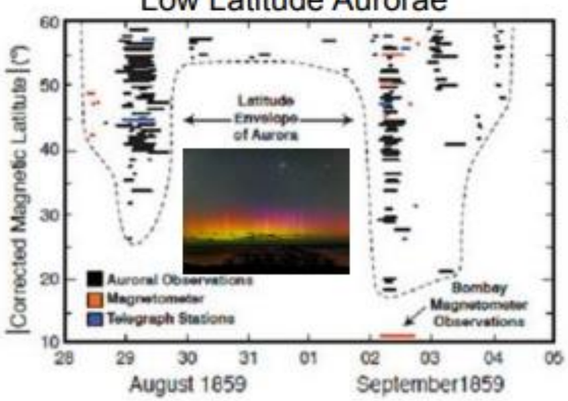
As are also the great magnetic disturbances associated with them.

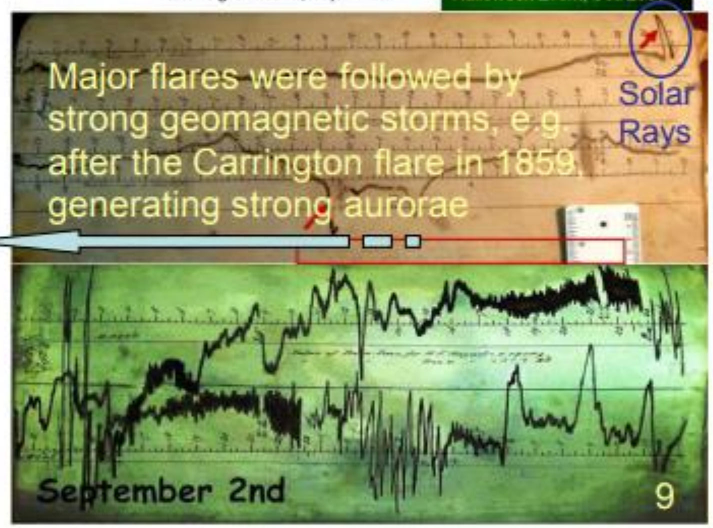
Sabine (1852) noted that magnetic perturbations superimposed on the daily variation also varied in phase with the newly discovered Sunspot Cycle.

Solar Observations of Flares

Carrington Event, Sept. 1859

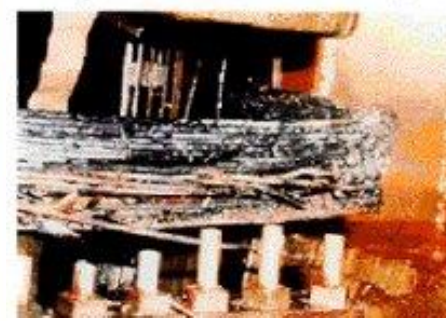
Low Latitude Aurorae





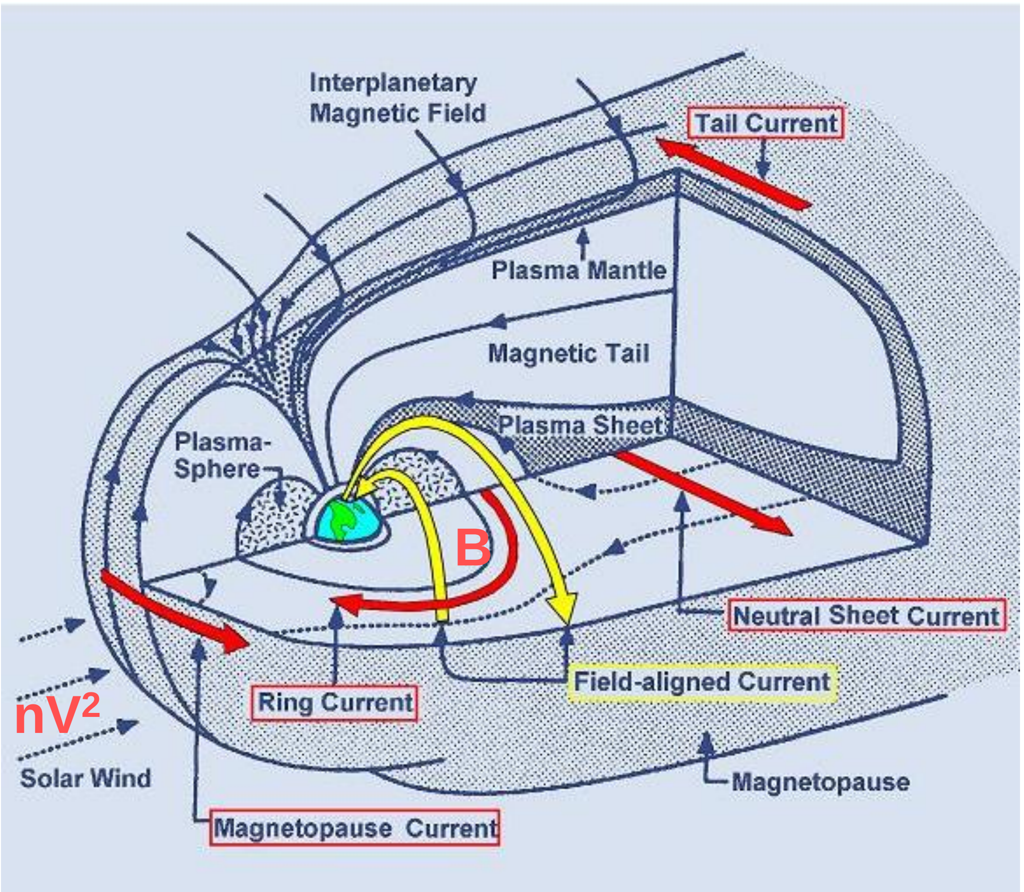
PJM Public Service Step Up Transformer

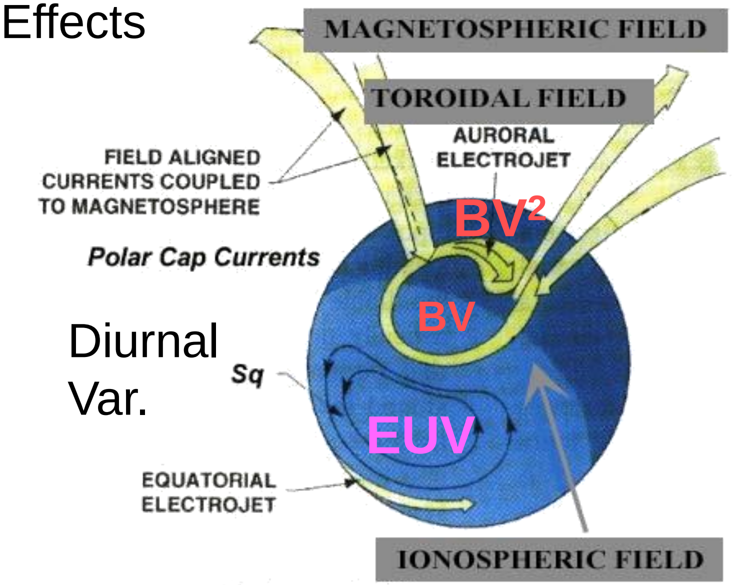
Severe internal damage caused by the space storm of 13 March, 1989

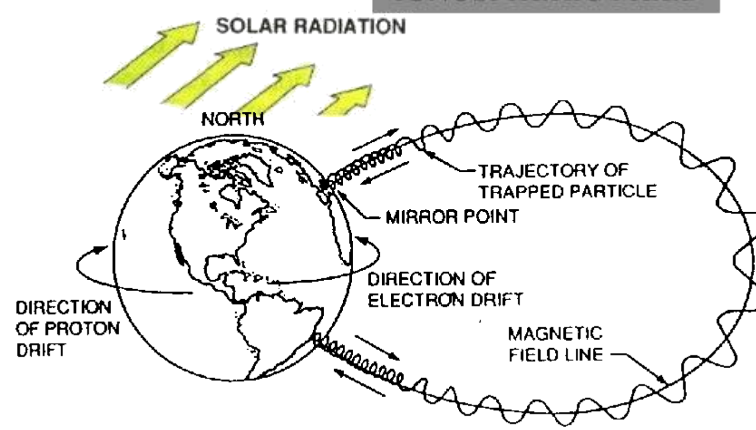


Electric Current Systems in Geospace

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'.

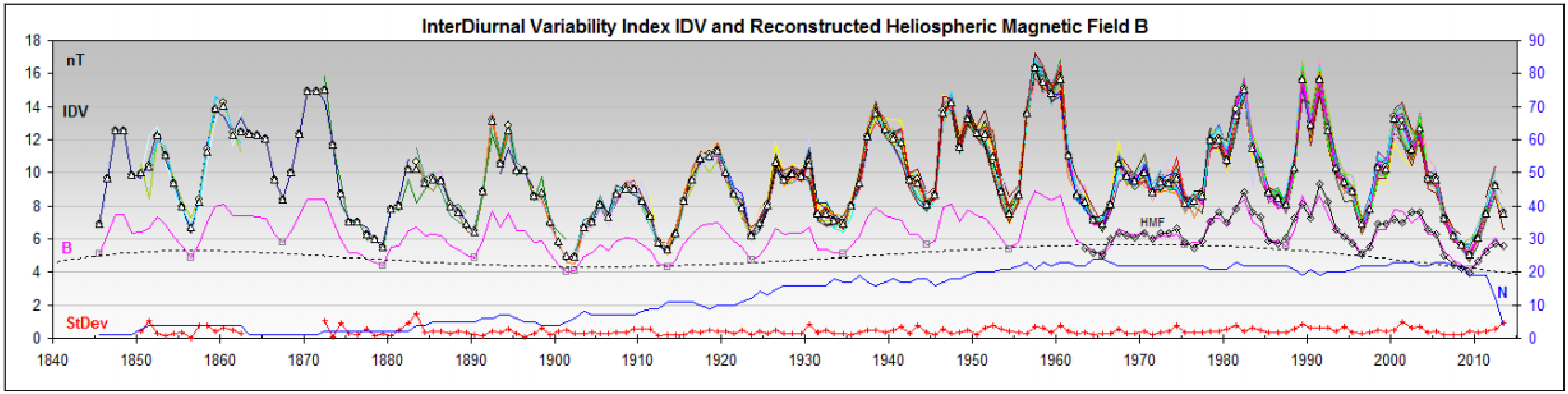
‘Different Strokes for Different Folks’

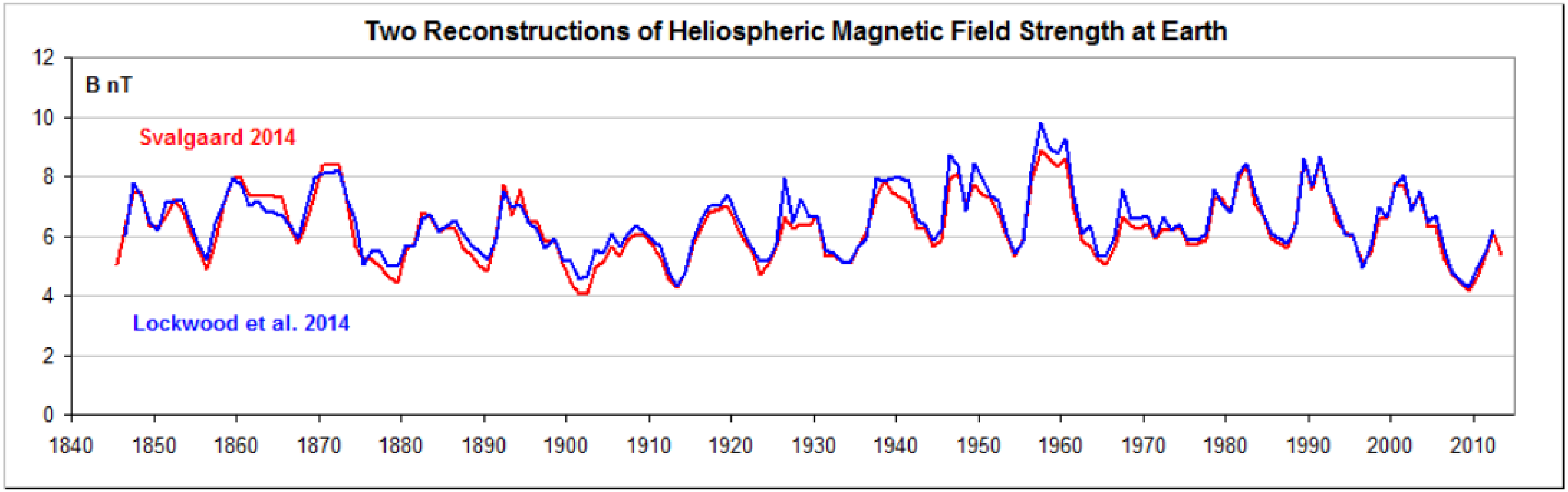
- The key to using geomagnetism to say something about the sun is the realization that geomagnetic ‘indices’ can be constructed that respond differently to different solar and solar wind parameters, so can be used to disentangle the various causes and effects
- In the last decade of research this insight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

The IDV Geomagnetic Index

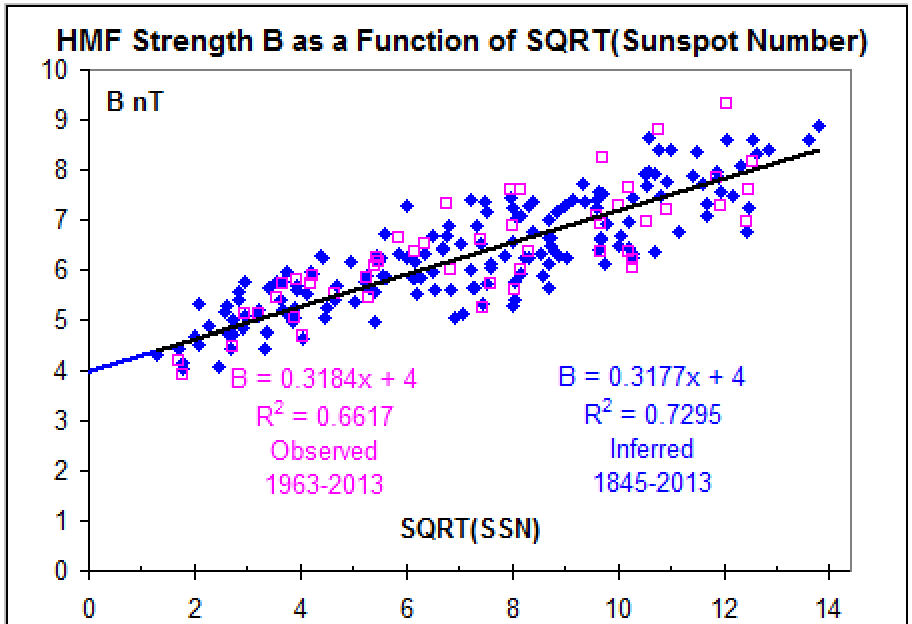
- Since the daily variation is fairly regular from day to day we can eliminate it by considering the difference between the fields on consecutive days
- Further suppression of the daily variation can be achieved by working only with the field during night hours or the average over a whole day
- That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

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

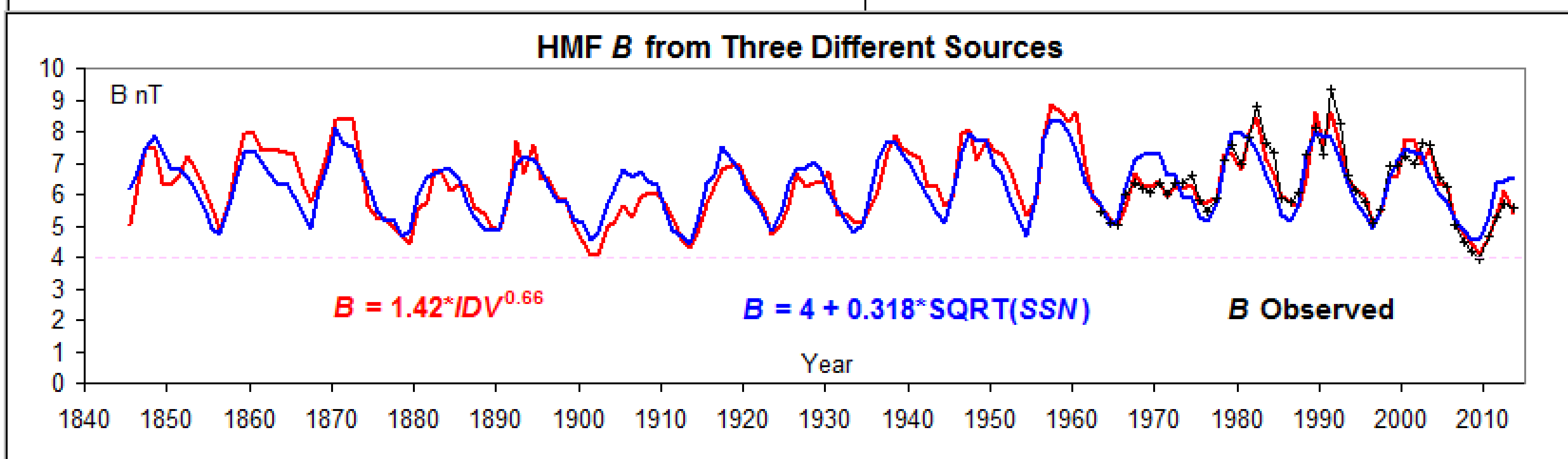




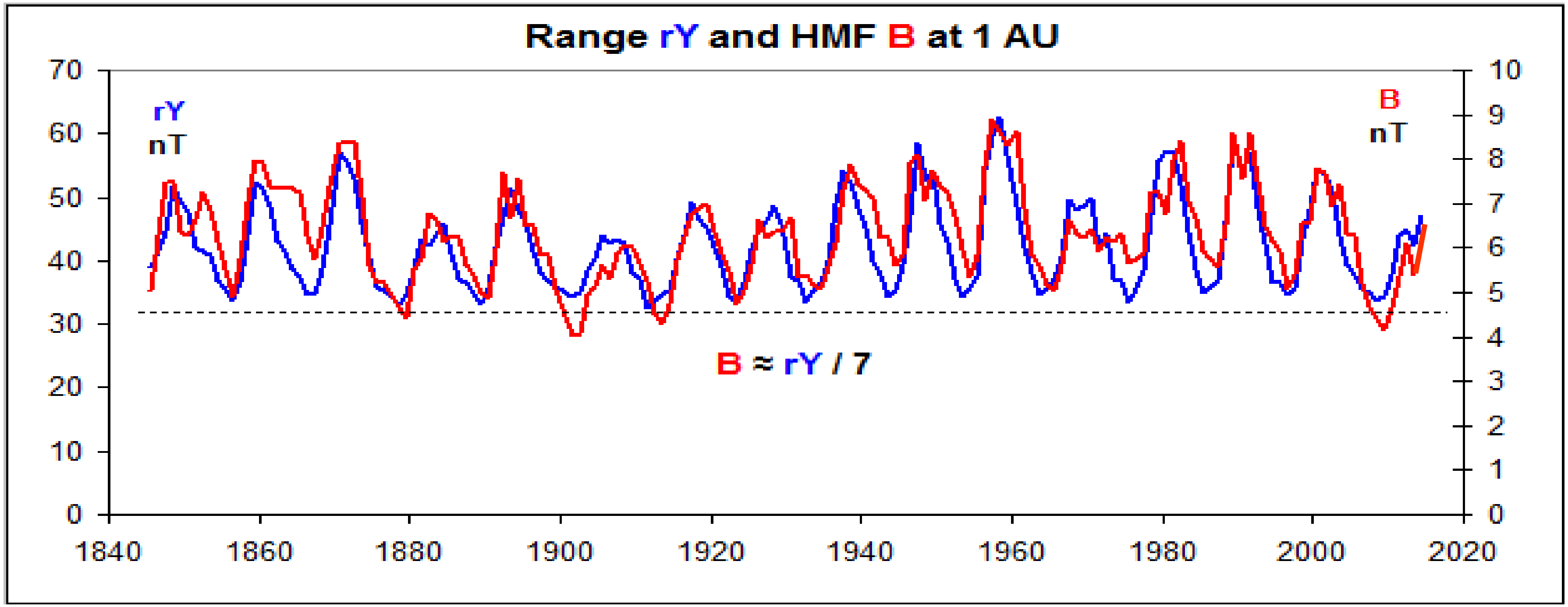
HMF *B* related to Sunspot Number



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]).



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.

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

Outline

- Observed EUV, Solar Microwave, and Magnetic flux records
- Deriving EUV [etc] from Geomagnetic Daily Variations
- Deriving Solar Wind Magnetic Field from Geomagnetism and Sunspots
- Comparing the Solar Flux(es) to the Sunspot (and Sunspot Group) Numbers. This is for my talk tomorrow.

Conclusion(s)

- We can reconstruct with confidence the EUV flux [and its proxy F10.7] back to the 1740s
- The recent 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 reasonably well the scaled solar surface magnetic flux
- These reconstructions validate the SNv2 and the GNv2 revisions of solar activity (see tomorrow’s talk)

The End