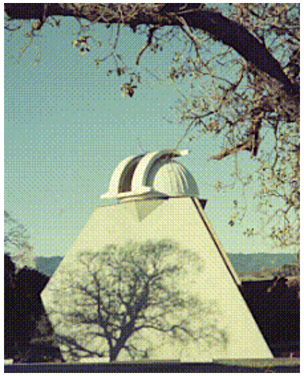
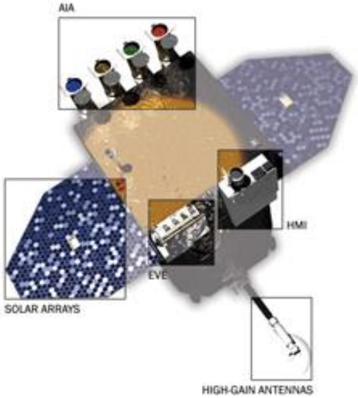


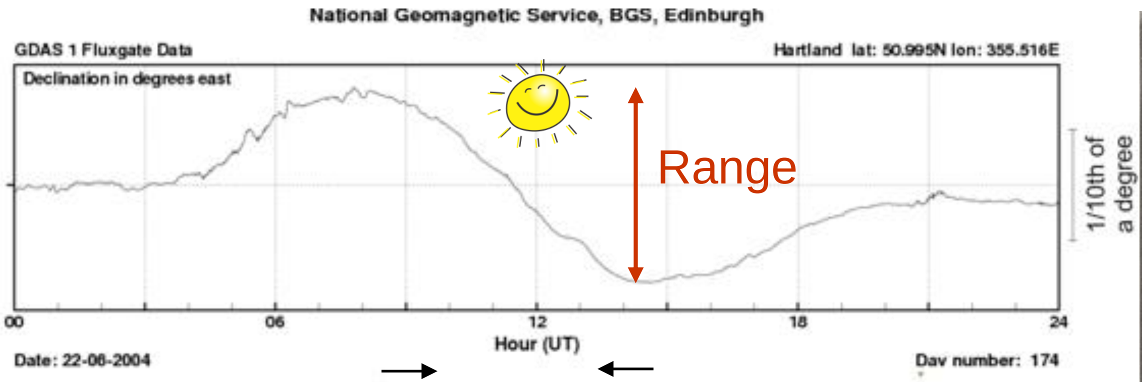


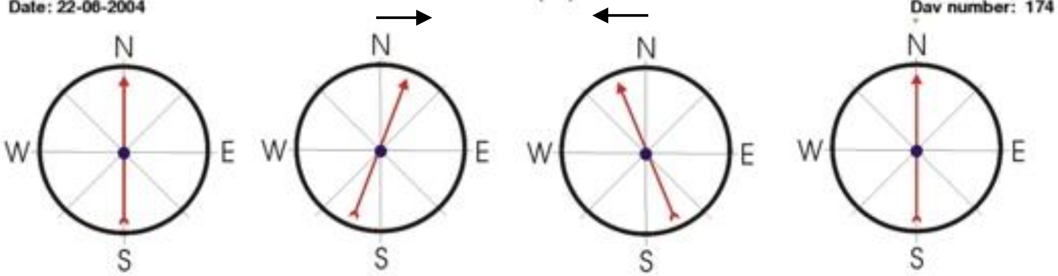
Radio, Ionosphere, Magnetism, and Sunspots

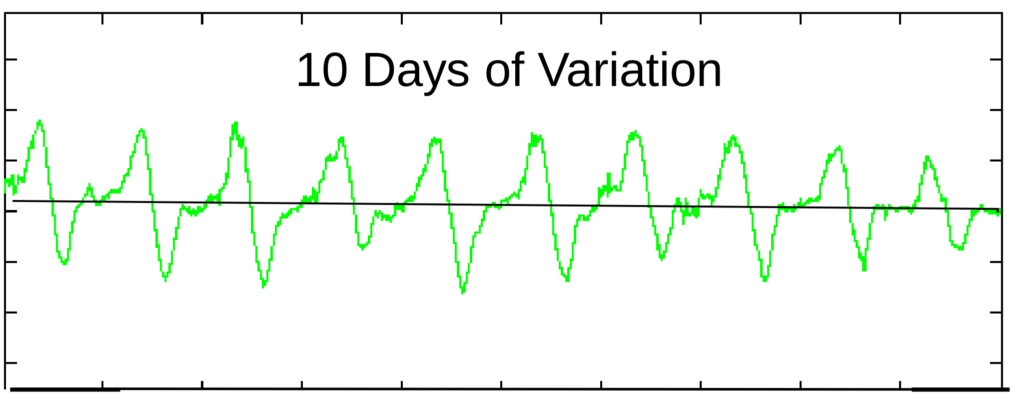
Leif Svalgaard
Stanford University

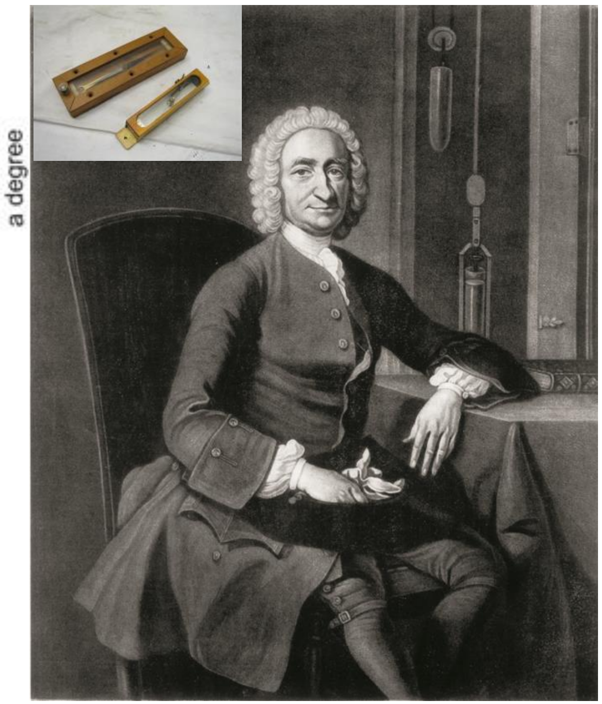
Stanford Amateur Radio Club, March 14, 2017 (π-day)

The Diurnal Variation of the Direction of the Magnetic Needle





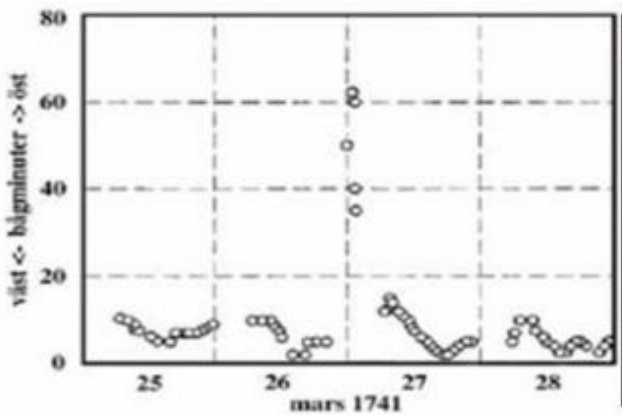


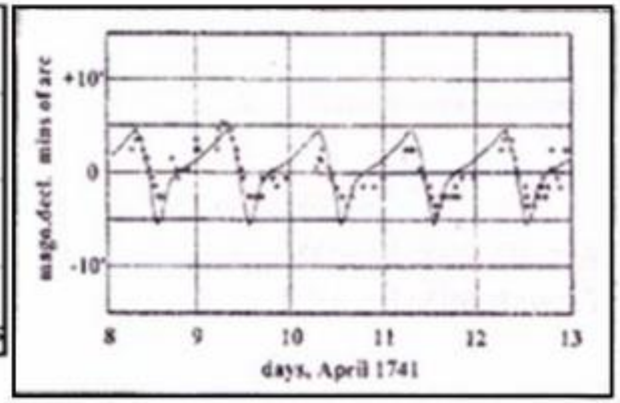


George Graham [London] discovered [1722] that the geomagnetic field varied during the day in a regular manner.

Observations in the 1740s

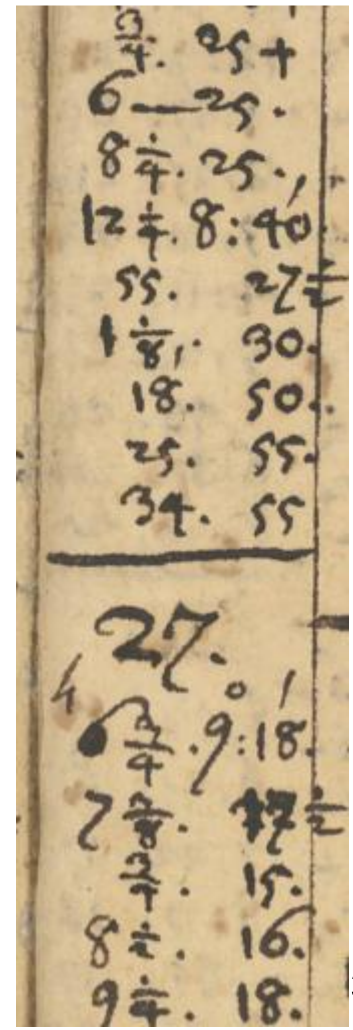
Olof Petrus Hjorter was married to Anders Celsius’ sister and made more than 10,000 observations of the magnetic declination in the 1740s.





Right: Hjorter’s measurements of the magnetic declination at Uppsala during April 8-12, 1741 (old style). The curve shows the average variation of the magnetic declination during April 1997 at nearby Lovö (Sweden).

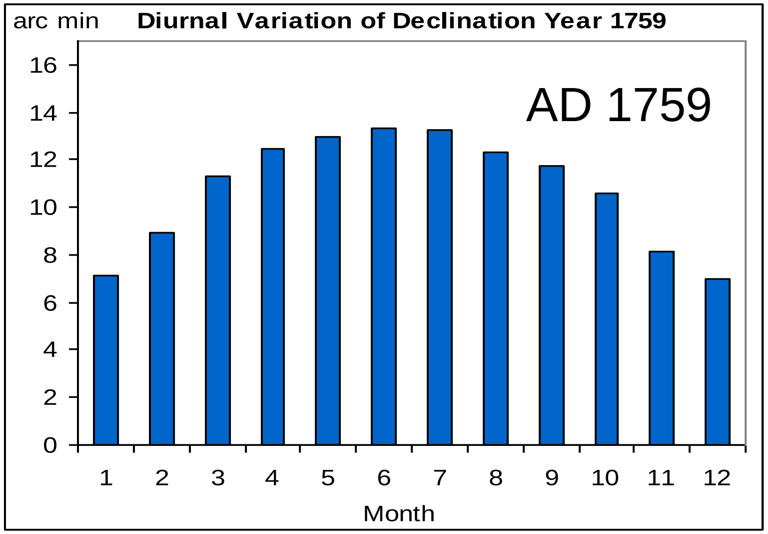
Left: Variation during strong Northern Light on March 27th. Also observed by Graham in London, showing that the aurorae and magnetic field are connected on a large scale and not just local meteorological phenomena.



This is from Hjorter’s original notebook for that day. Observations made with an instrument by Graham.

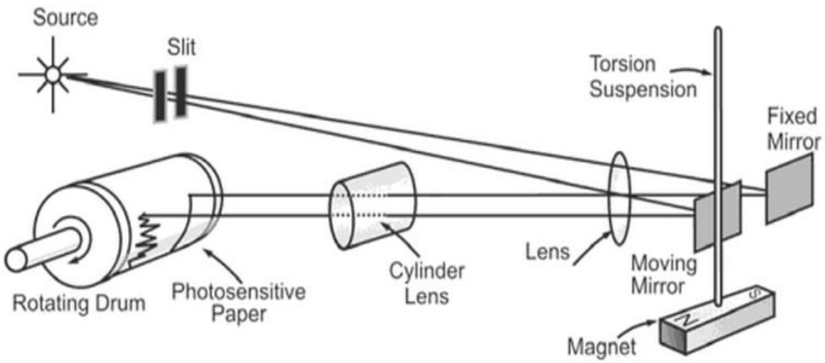
Even Rather Simple Instruments Could Readily Show the Variation

John Canton [1759] made more than 4000 observations of the Declination on 603 days in London

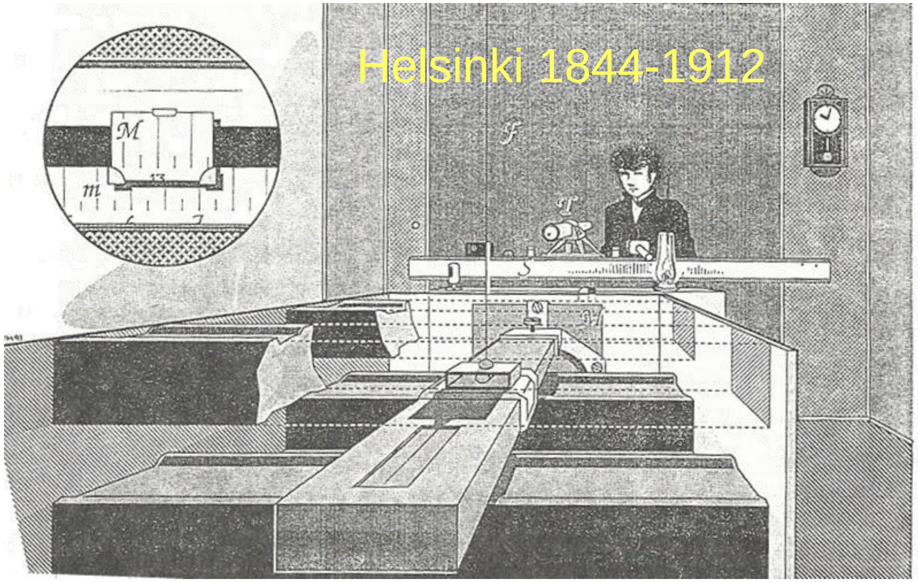


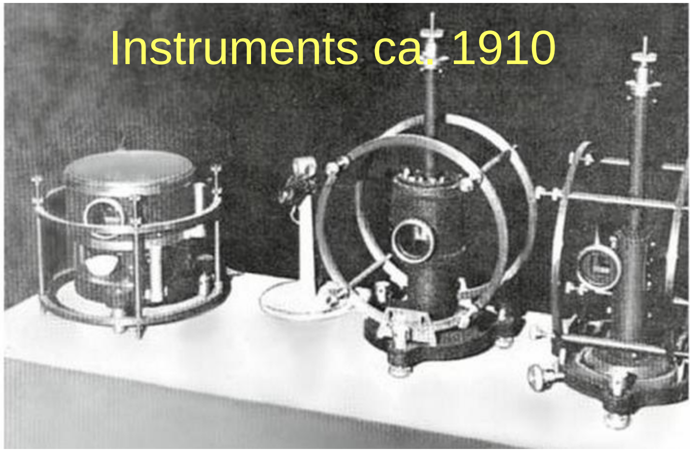
Canton's theory was that Temperature was controlling the magnet, and he thought that the daily and [predicted] seasonal variations were proof of that. Correct application of The Scientific Method, but nevertheless wrong.

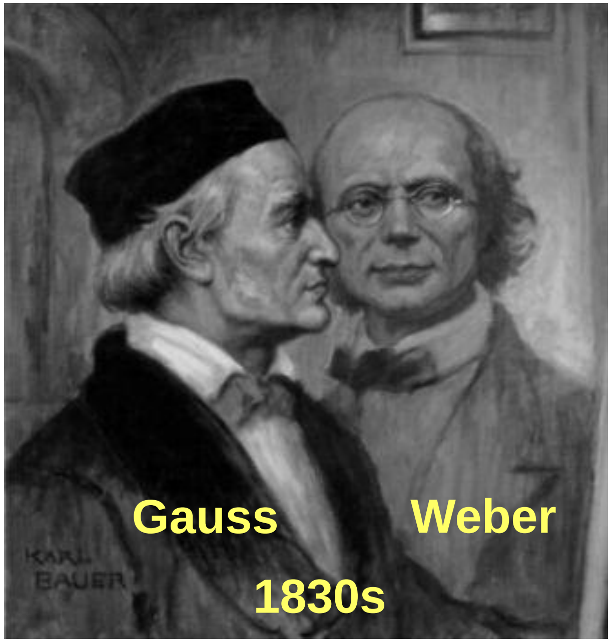
Magnetic Recording over Time



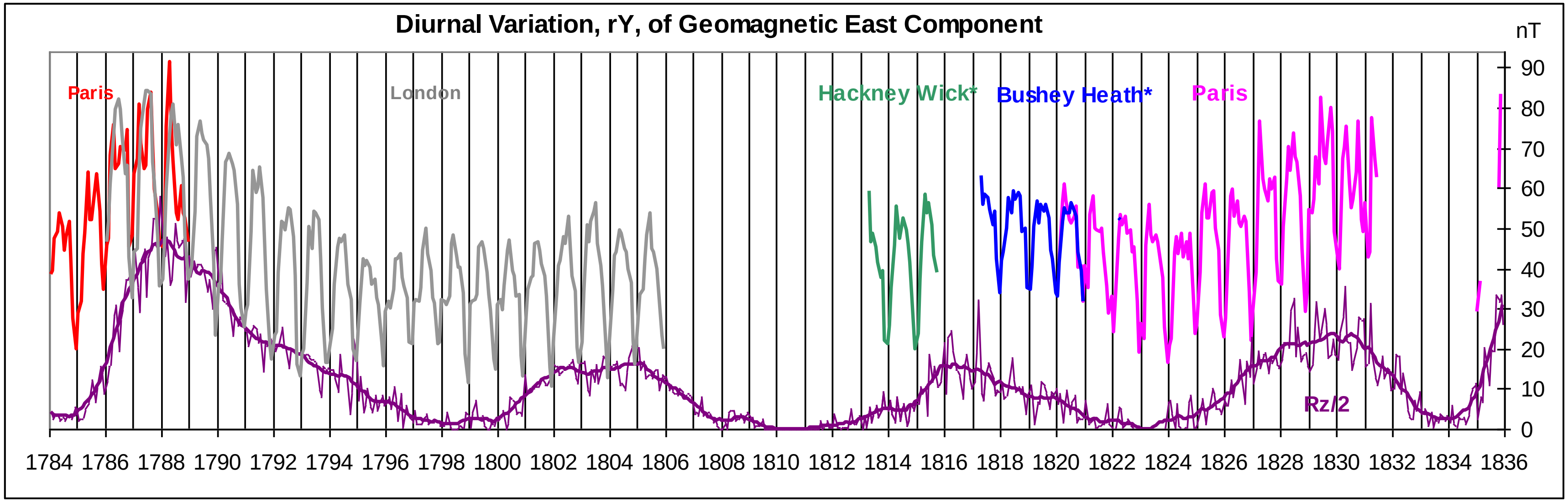
Classic Method since 1846

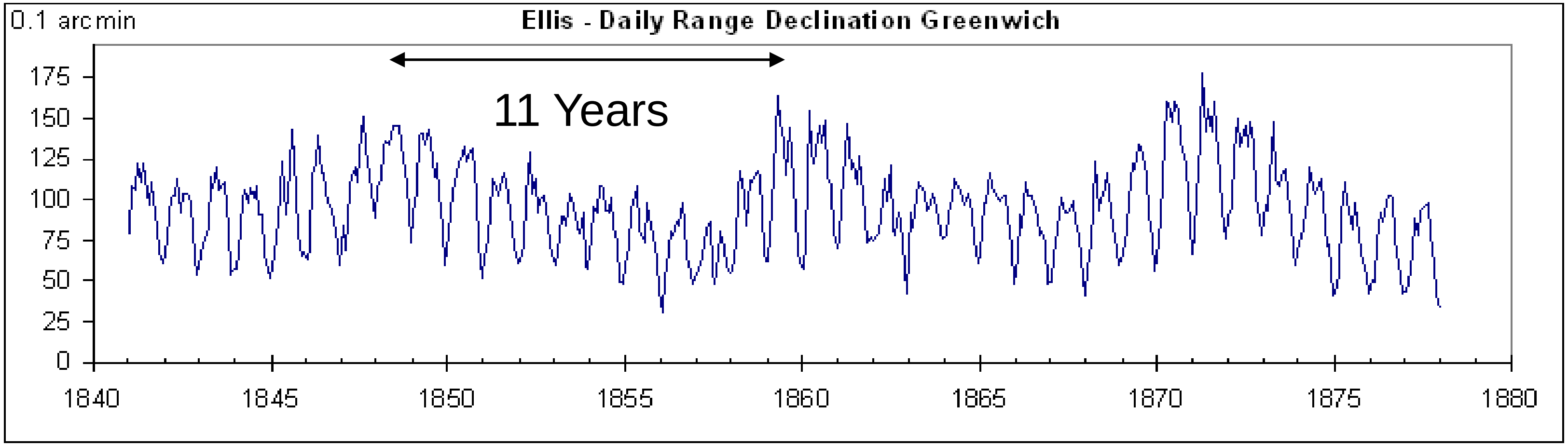




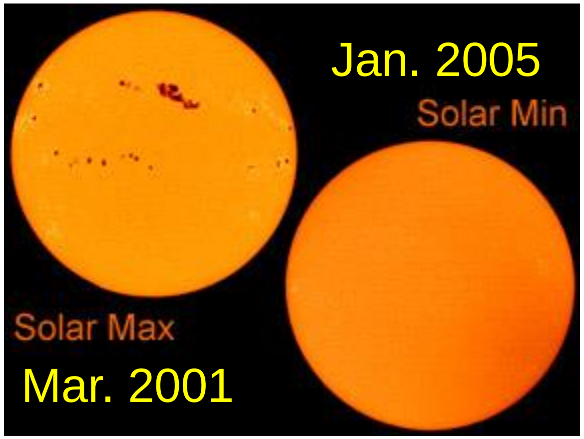


Zenith Angle and Sunspot Cycle Control

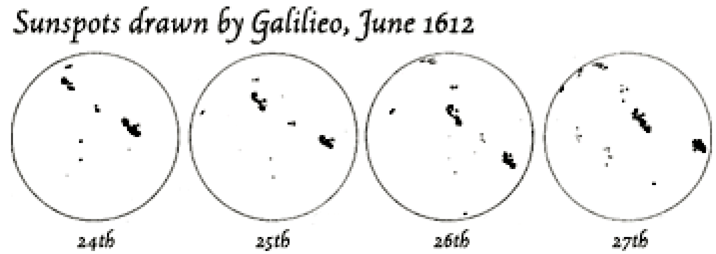


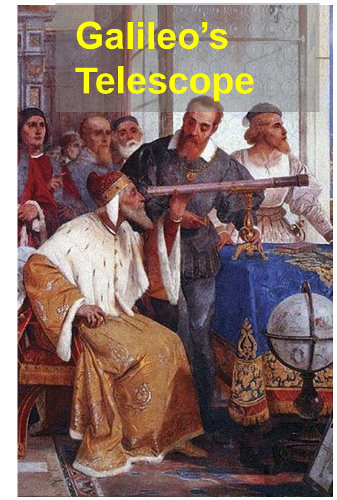


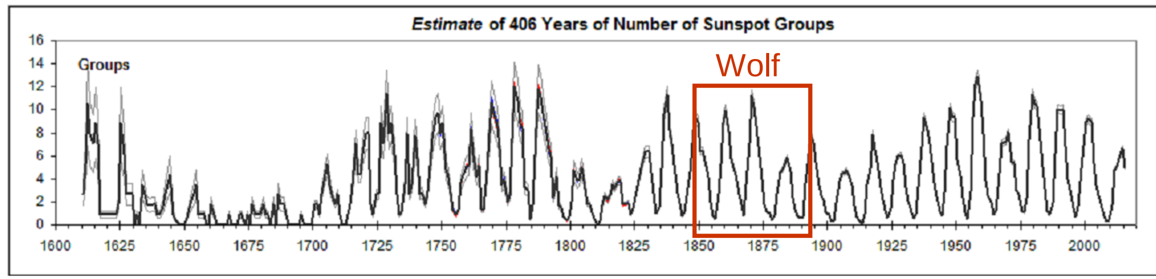
400-year Sunspot Cycle Record

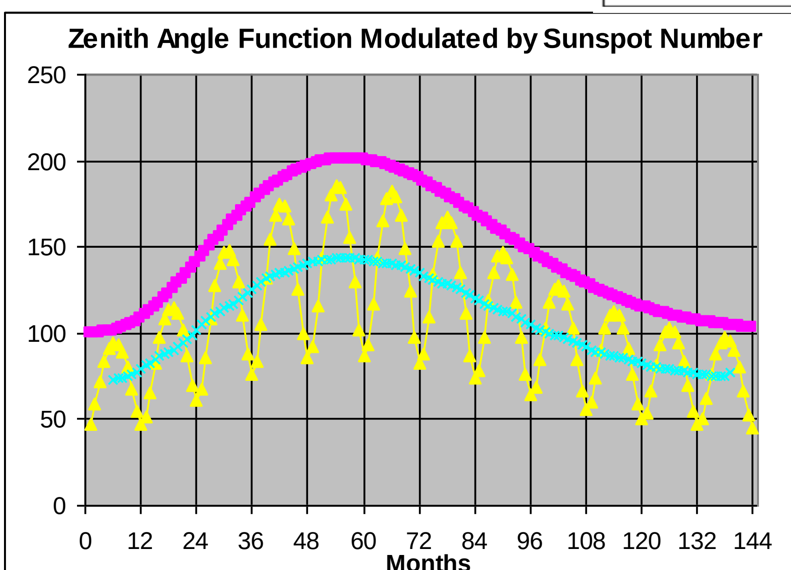


SOHO Spacecraft







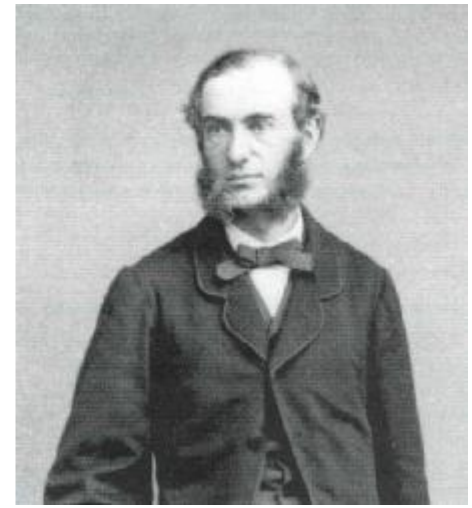


"Who would have thought just a few years ago that one could calculate a terrestrial phenomenon from observations of sunspots"

Rudolf Wolf, 1852

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

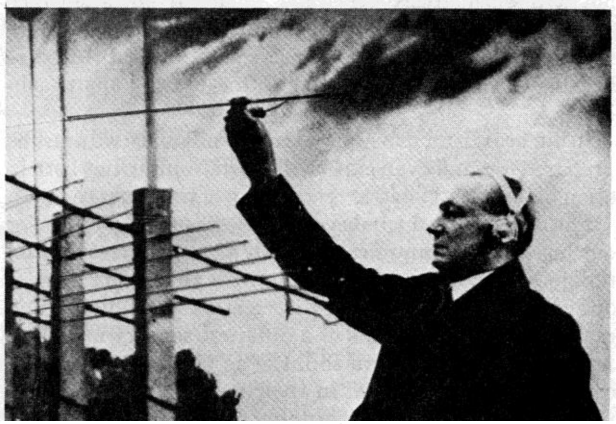
"The various speculations on the cause of these phenomena [daily variations of the geomagnetic field] have ranged over the whole field of likely explanations. (1) […], (2) It has been imagined that convection currents established by the sun's heating influence in the **upper regions of the atmosphere 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**…



Balfour Stewart
1828-1887

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

We all Know about Marconi's Long-Distance Radio Transmissions



Guglielmo Marconi sends message from England to Newfoundland

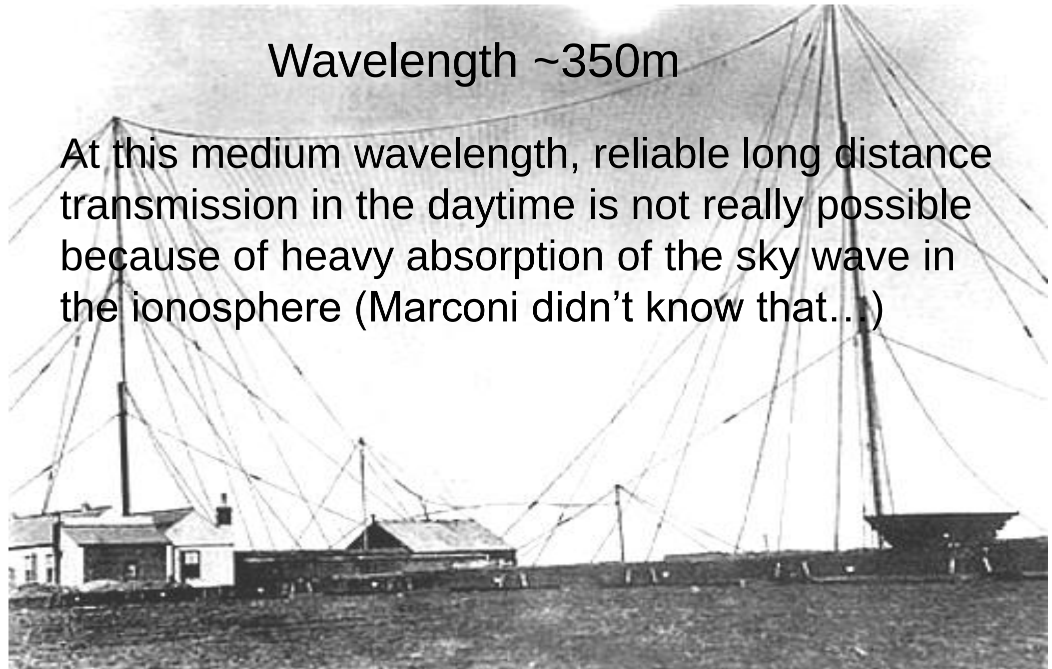
Dec 12. The Italian physicist Guglielmo Marconi, who sent wireless telegraphic messages across the English Channel from Dover, England, to Boulogne, France, on March 29, 1899, repeated his experiment today over the Atlantic Ocean, a distance of 2,232 miles.

In order to carry out this experiment, Marconi set up a 164-foot-high antenna in Poldhu, Cornwall, England. Then, he erected a receiver in St. John's, Newfoundland, Canada. In spite of the earth's curvature, he received a Morse signal corresponding to the letter "S" from the Poldhu station across the ocean.

When Marconi realized the importance of his first discoveries in 1895, he asked the Italian Minister of Telecommunication to help him. But the minister found that Marconi's experiments were too extravagant. That's why Marconi went to England, where he won the support of Sir William Peace, the Postmaster General, who immediately understood the significance of the young Marconi's work. Thanks to Peace's perspicacity and the help of Professor Adolf Slaby, Marconi could hit his target today (→ 2/22/03).

Guglielmo Marconi and his first wireless.

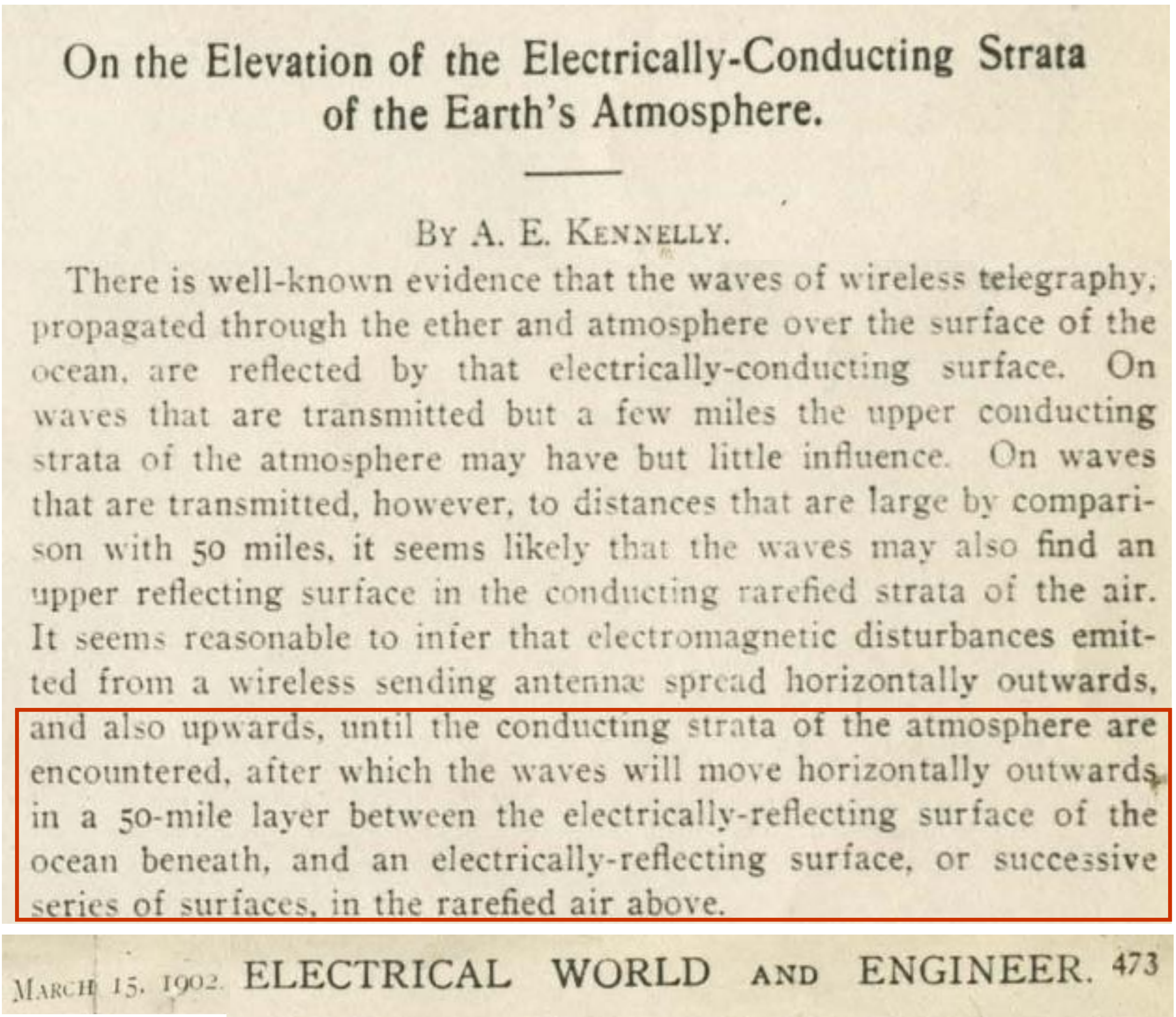
Dec. 12, 1901



Wavelength ~350m

At this medium wavelength, reliable long distance transmission in the daytime is not really possible because of heavy absorption of the sky wave in the ionosphere (Marconi didn't know that...)

Kennelly Suggested a Wave Guide



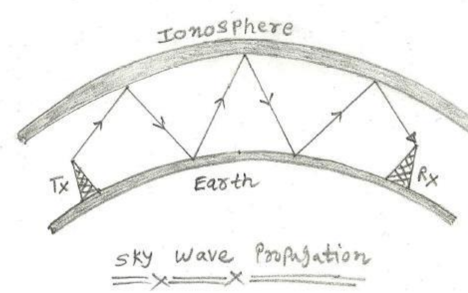
On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere.

By A. E. Kennelly.

There is well-known evidence that the waves of wireless telegraphy, propagated through the ether and atmosphere over the surface of the ocean, are reflected by that electrically-conducting surface. On waves that are transmitted but a few miles the upper conducting strata of the atmosphere may have but little influence. On waves that are transmitted, however, to distances that are large by comparison with 50 miles, it seems likely that the waves may also find an upper reflecting surface in the conducting rarefied strata of the air. It seems reasonable to infer that electromagnetic disturbances emitted from a wireless sending antennæ spread horizontally outwards, and also upwards, until the conducting strata of the atmosphere are encountered, after which the waves will move horizontally outwards in a 50-mile layer between the electrically-reflecting surface of the ocean beneath, and an electrically-reflecting surface, or successive series of surfaces, in the rarefied air above.

March 15, 1902. ELECTRICAL WORLD and ENGINEER. 473

Arthur E. Kennelly
1861-1939



Oliver Heaviside Got the Same Idea

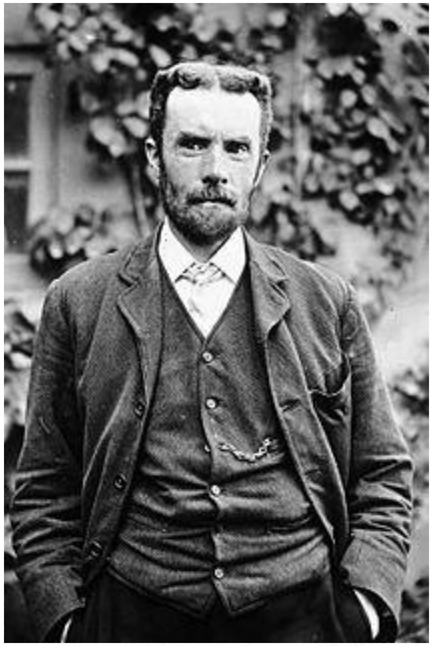
Marconi himself speculated that this might be the result of what he called the "diselectrification" of the antenna by daylight which prevented "the electrical oscillations [in the antenna] from acquiring so great an amplitude as they attain during darkness."

Heaviside proposed another possibility.

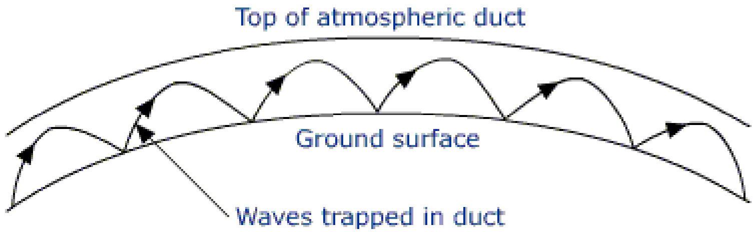
The actual correspondence is not available, but an account[56] has been given by Eccles[57]:

> In the spring of 1902 I was writing from time to time on wireless telegraphy in the pages of *The Electrician*, and one day Mr. Tremlett Carter, the editor, showed me a letter from Mr. Oliver Heaviside which, while discussing other things, asked if the recent success of Mr. Marconi in telegraphing from Cornwall to Newfoundland might not be due to the presence of a permanently conducting upper layer in the atmosphere. I believe this letter was shown to various friends of the editor, but I think it was not published [indeed, it was not].

Whatever the reason for the rejection of this letter for publication (I have been unable to find any reference to it in the surviving Heaviside editorial correspondence[58] with *The Electrician*), it merely made Oliver look for an alternative outlet. He found this outlet in the form of an invited contribution[59] to the new (10th) edition of the *Encyclopedia Britannica*.



And then comes the *most* famous part of the article. "There is another consideration. There may possibly be a sufficiently conducting layer in the upper air. If so, the waves will, so to speak, catch on to it more or less. Then the guidance will be by the sea on one side and the upper layer on the other."



It Took These Gentlemen to Convincingly Establish the Ionosphere in the 1920s

Edward V. Appleton
1892-1965

Merle Anthony Tuve
1901-1982

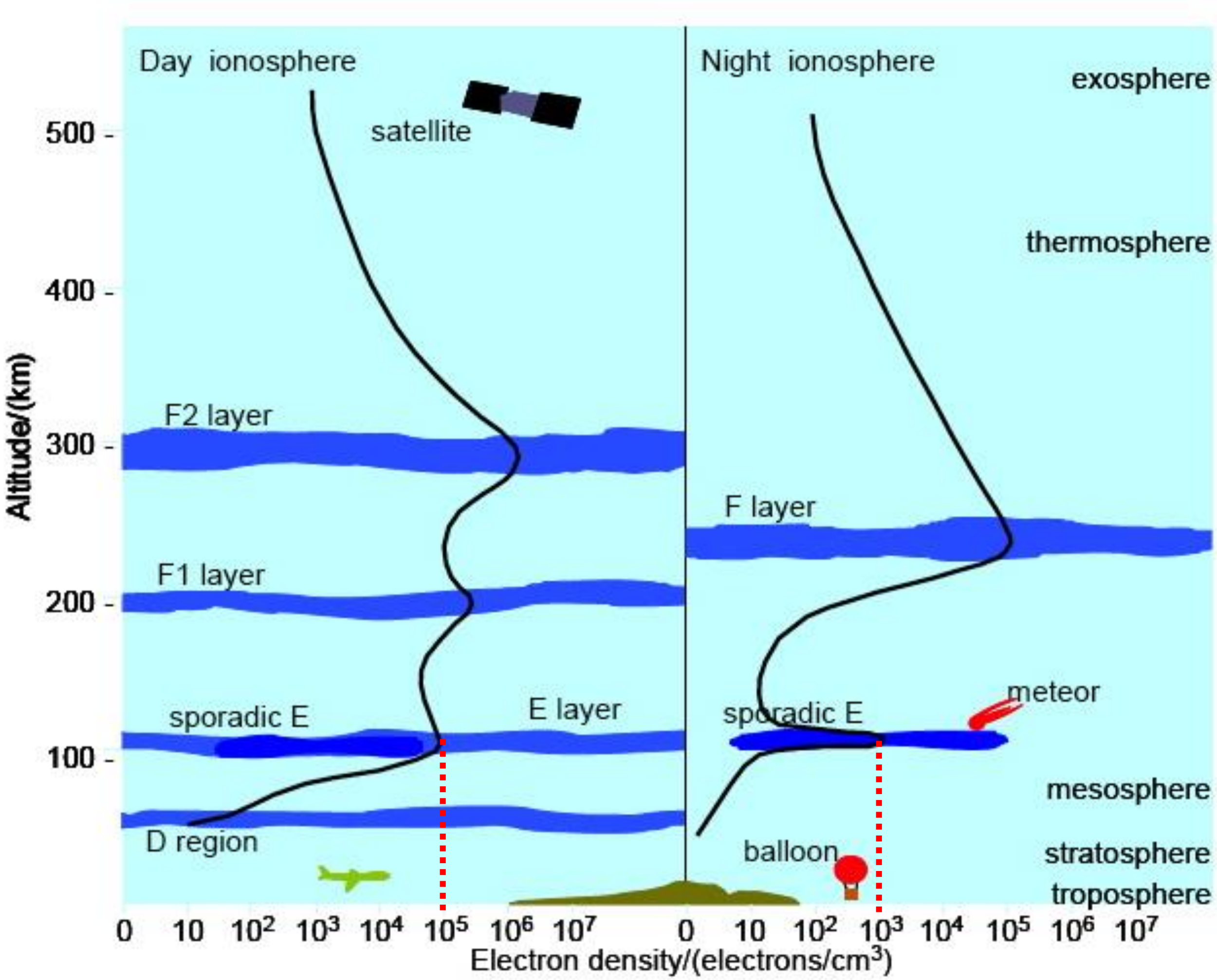
Grigory Breit
1899-1981

Discovered the F-layer higher up

Used pulsed radio transmissions to determine the height of the ionosphere from timing the echoes

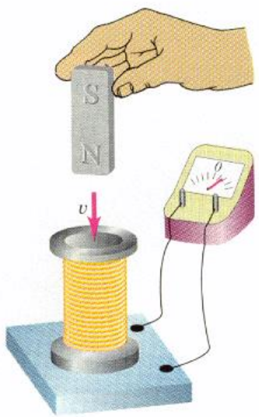
Nobel Prize 1947

Ionospheric Conducting Layers



We need 1) something to produce the charges and 2) something to move them across the magnetic field

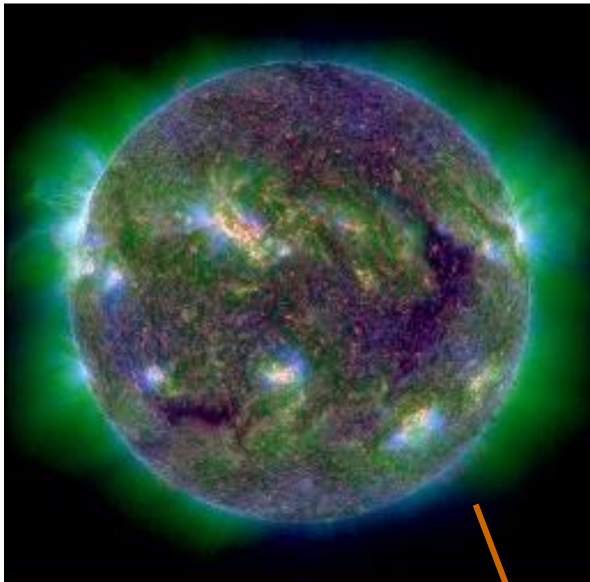
Dynamo

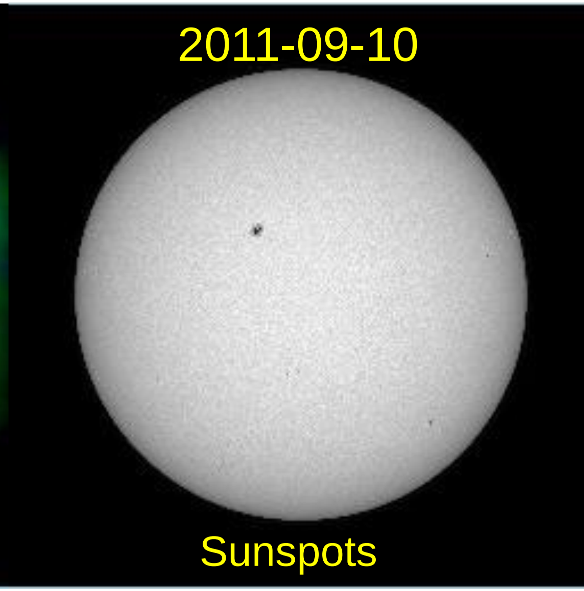


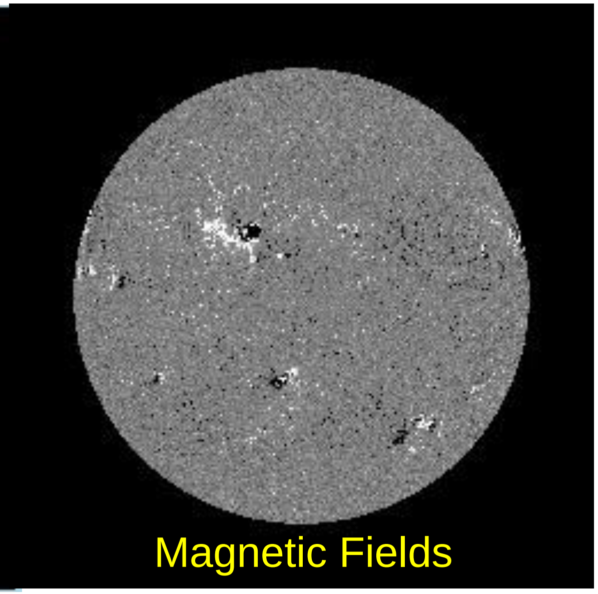
An effective dynamo process takes place in the dayside E-layer where the density, both of the neutral atmosphere and of the electrons are high enough.

We thus expect a geomagnetic response due to electric currents induced in the E-layer.

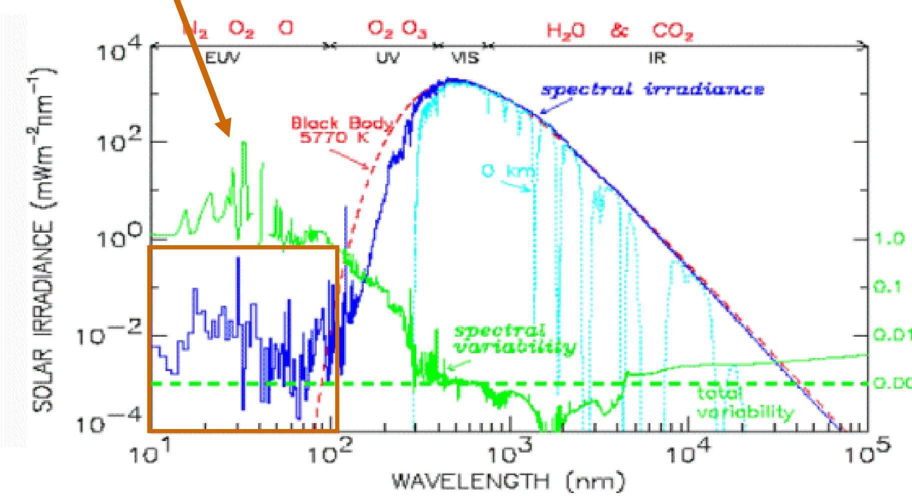
The Source of the Ionization

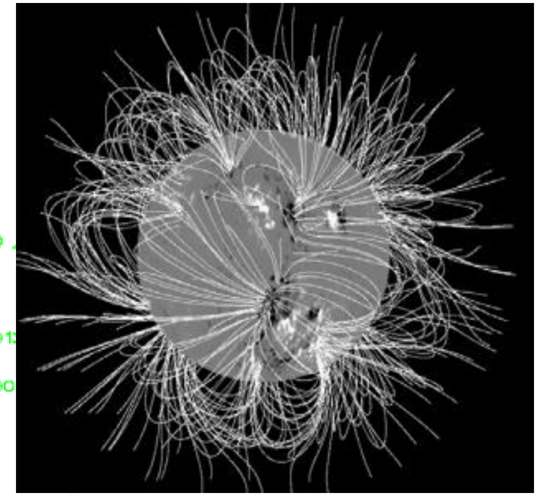






Extreme Ultraviolet (EUV), wavelengths 17.1-21.1-30.4 nm from chromosphere and corona with temperatures from 50,000 K to 2 million K





Electron Density due to EUV

< 102.7 nm

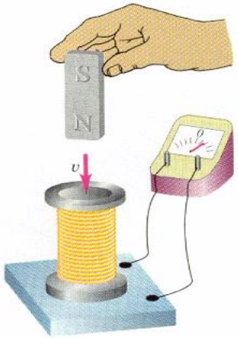
$$O_2 + h\nu \xrightarrow{J} O_2^+ + e^-$$

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

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.

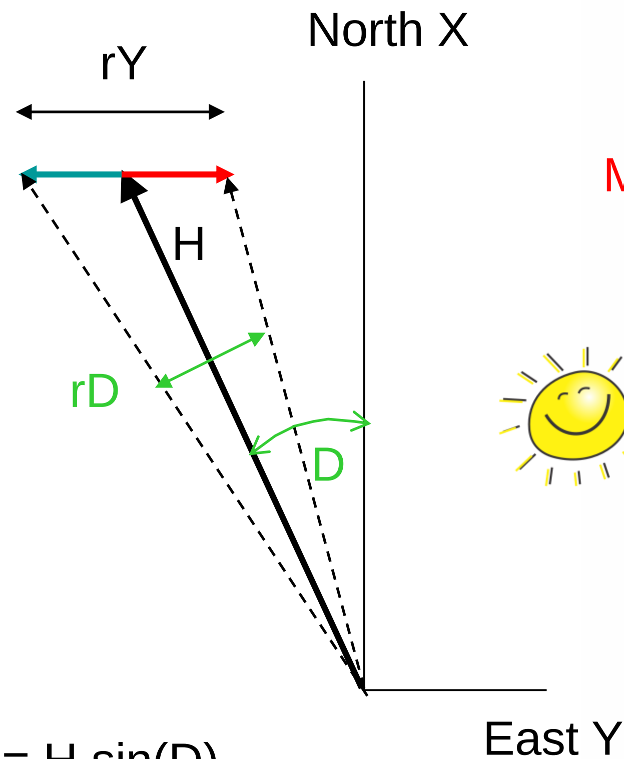
Because the process is slow (the Zenith angle χ changes slowly) we have a quasi steady-state, in which there is no net electric charge, so $N_i = N_e = N$. In a steady-state $dN/dt = J \cos(\chi) - \alpha N^2 = 0$ and so $N = \sqrt{(J \cos(\chi) / \alpha)}$

Since the effective 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.



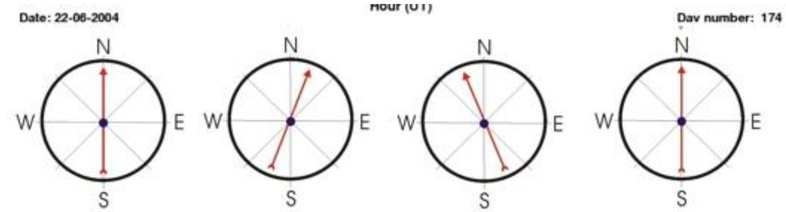
Dynamo

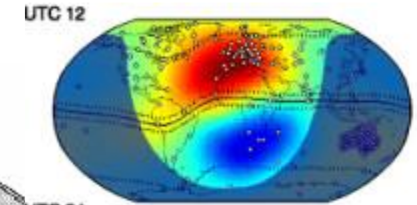
The E-layer Electric Current System

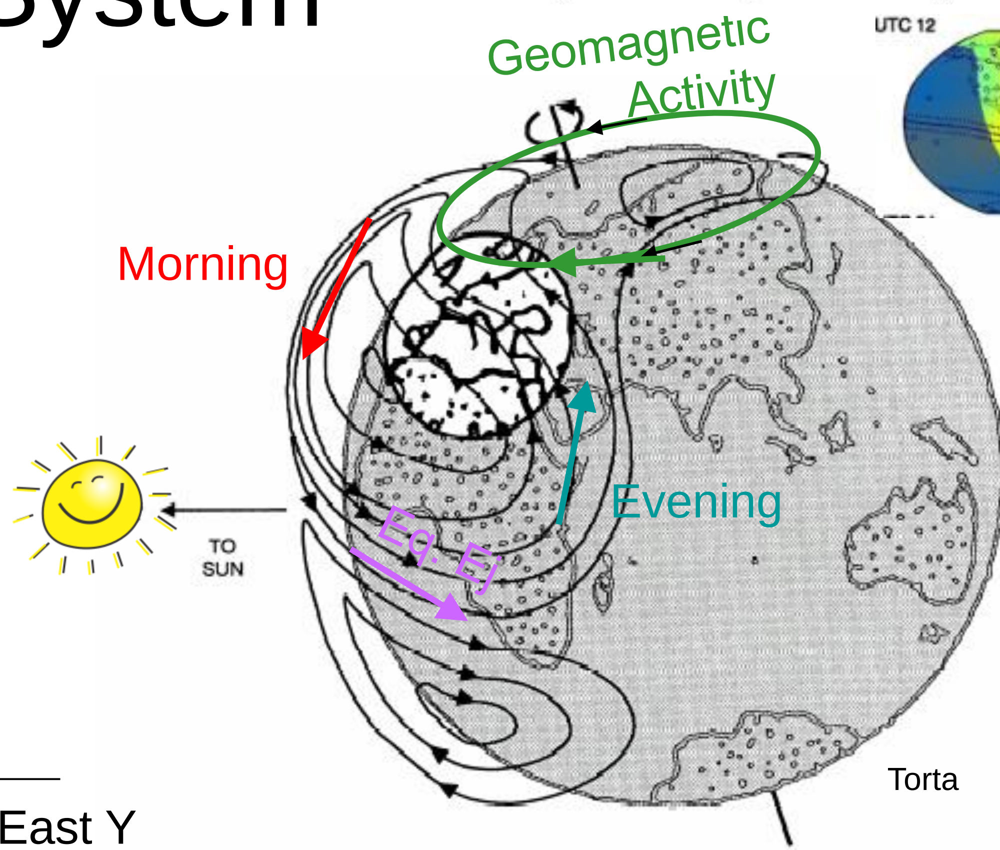


$Y = H \sin(D)$

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





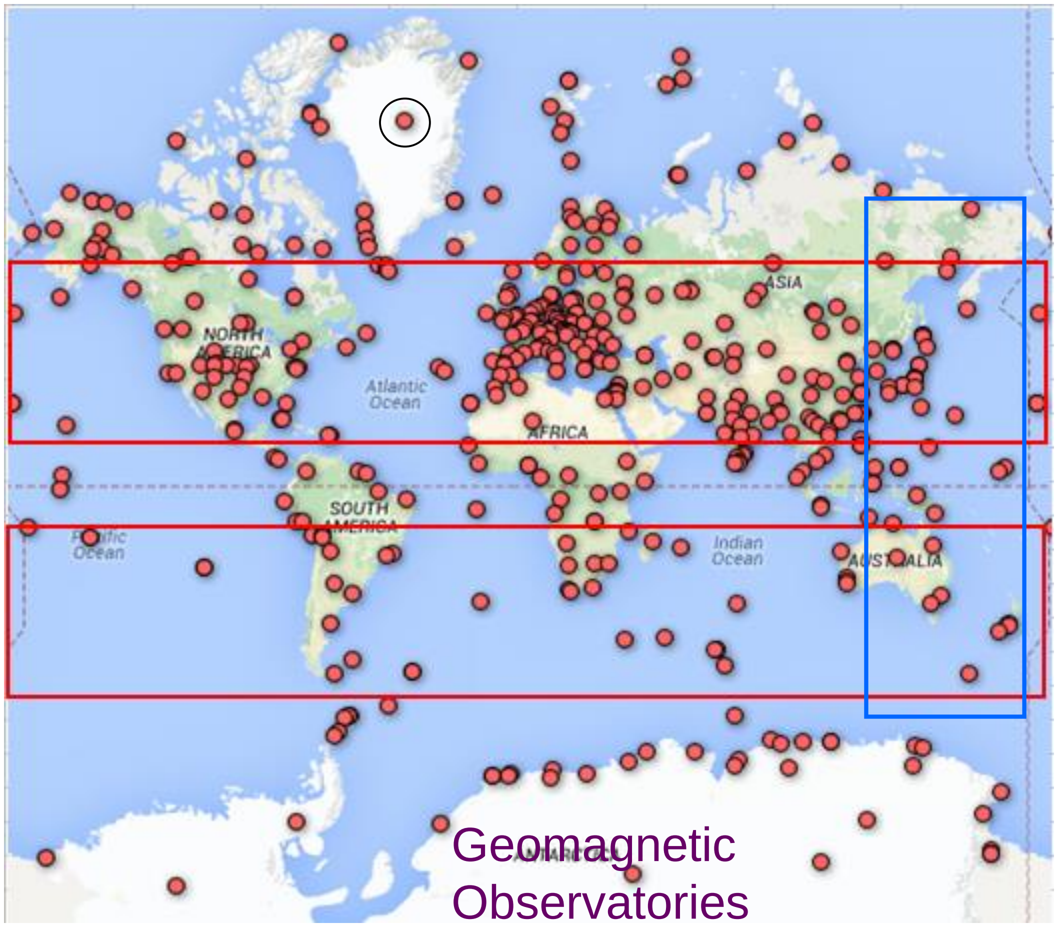


Torta

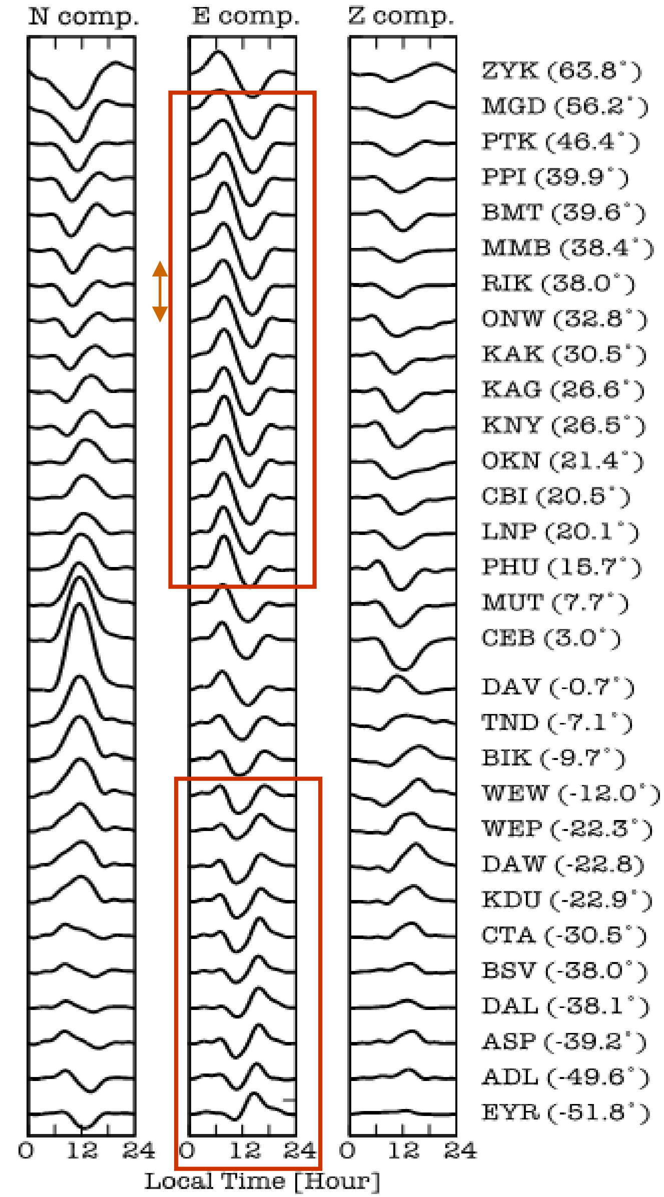
A current system in the ionosphere is created and maintained by solar EUV radiation

The magnetic effect of this system was what George Graham discovered

The Magnetic Signal at Mid-latitudes

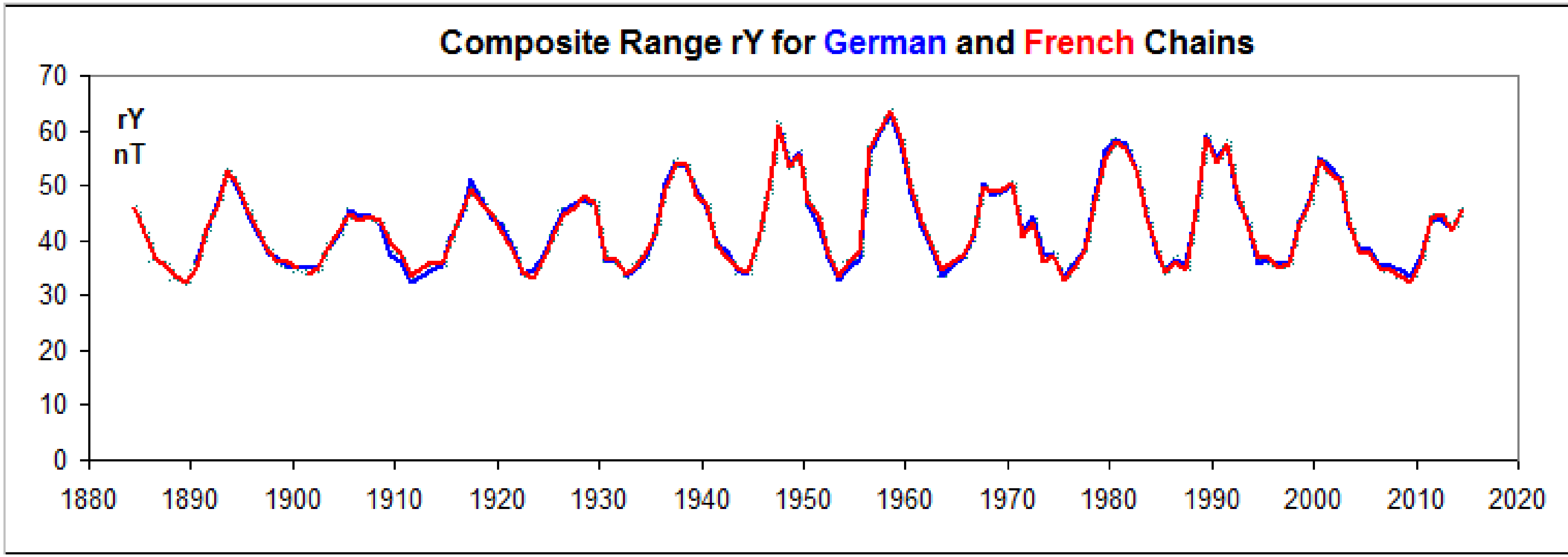


Geomagnetic Observatories



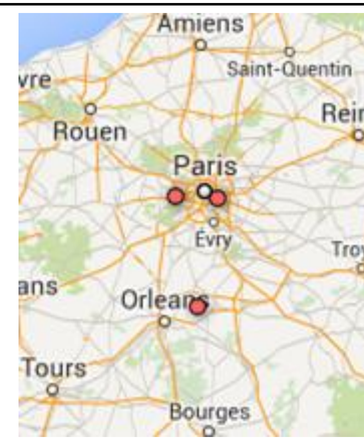
The effect in the Y-component is rather uniform for latitudes between 20º and 60º

PSM-POT-VLJ-SED-CLF-NGK



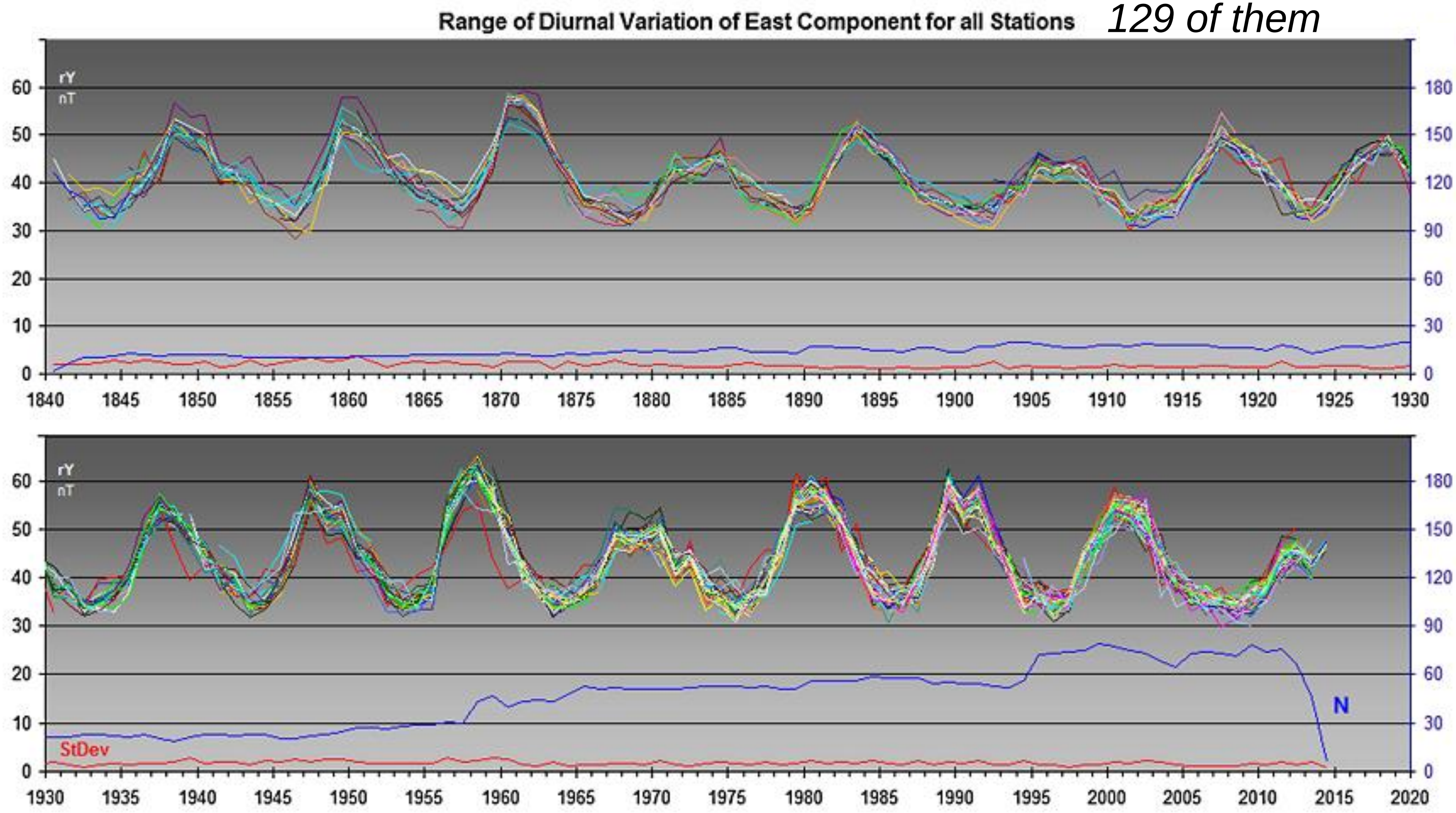
A 'Master' record can now be build by averaging the German and French chains.

We can add all other mid-latitude stations to this record and extend it further back in time.



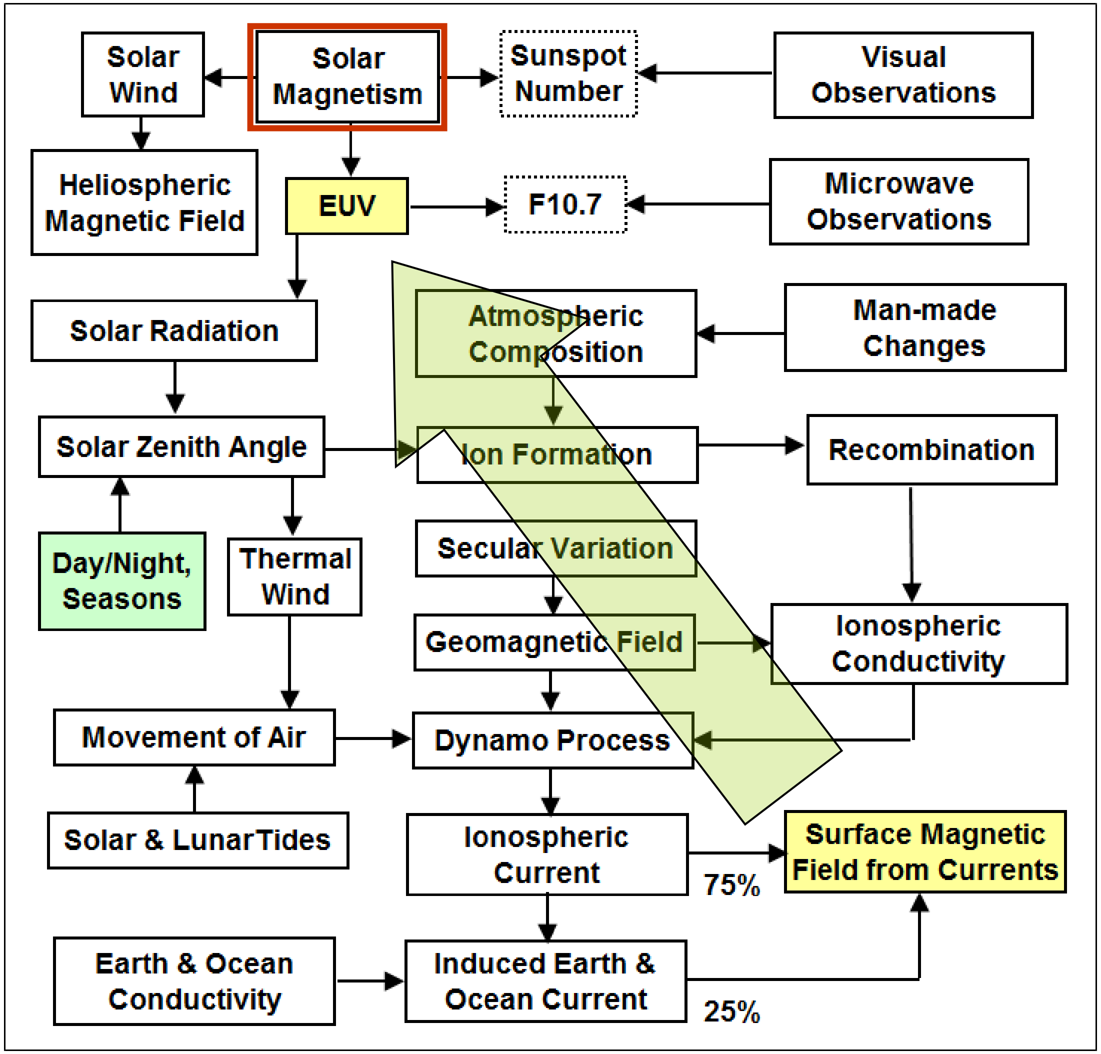
Observed Diurnal Ranges of the Geomagnetic East Component since 1840

129 of them



We plot the yearly average range to remove the effect of changing solar zenith angle through the seasons. What remains is the solar cycle modulation.
The blue curve shows the number of stations

The Effect of Solar EUV



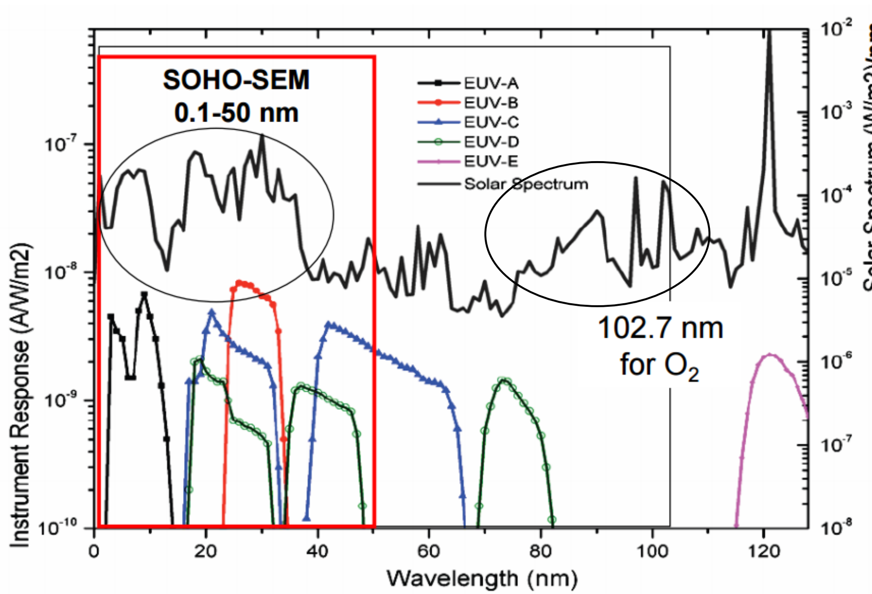
The EUV causes an observable variation of the geomagnetic field at the surface through a complex chain of physical connections.

The physics of each link in the chain is well-understood in quantitative detail and can be successfully modeled.

We use this chain in reverse to deduce the EUV flux from the geomagnetic variation.

SOHO TIMED SDO

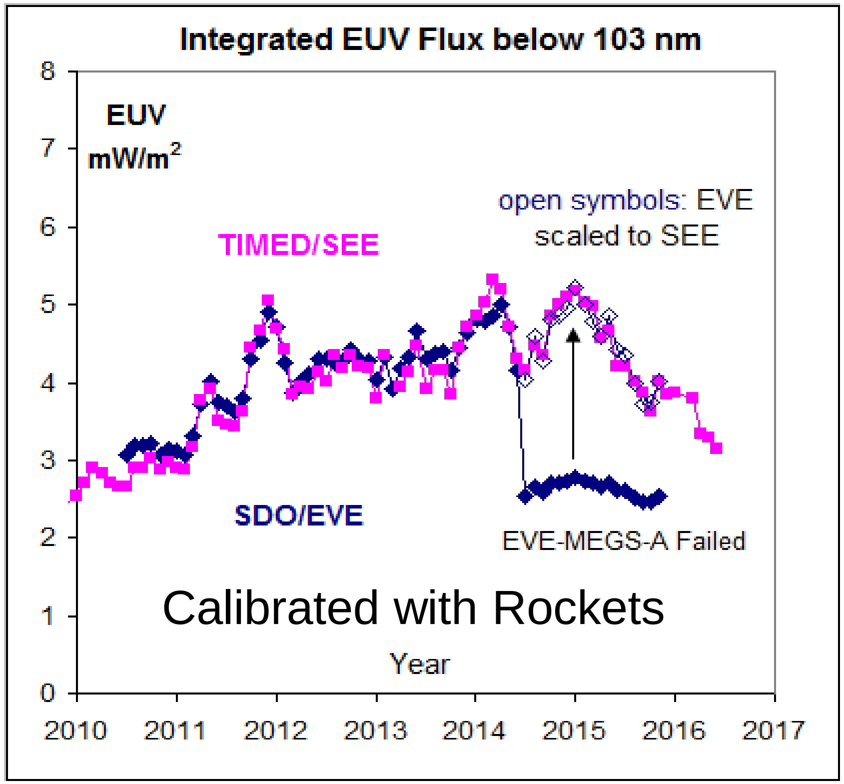
Sources of EUV Data: SEM, SEE, EVE



≤102.7 nm to ionize molecular Oxygen

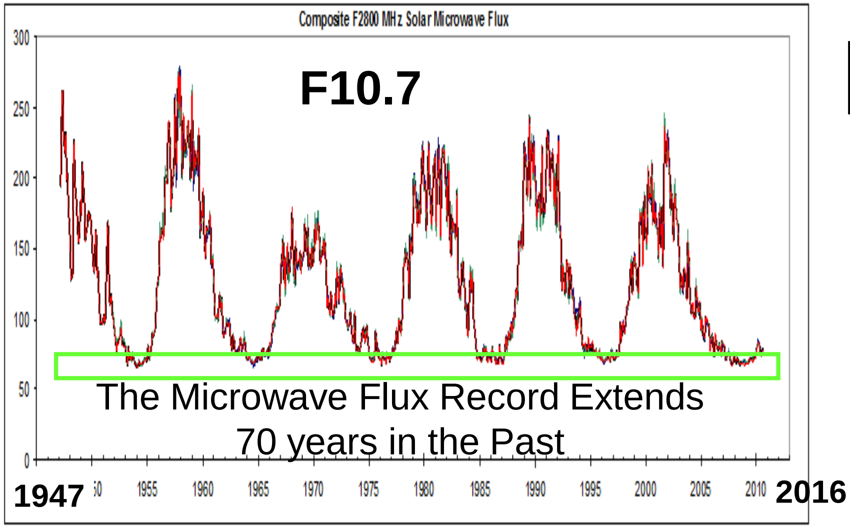
$$O_2 + h\nu \rightarrow O_2^+ + e^-$$

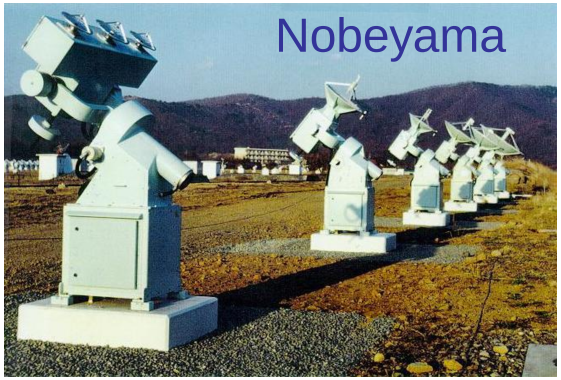
This reaction creates and maintains the conducting E-region of the Ionosphere (at ~105 km altitude)

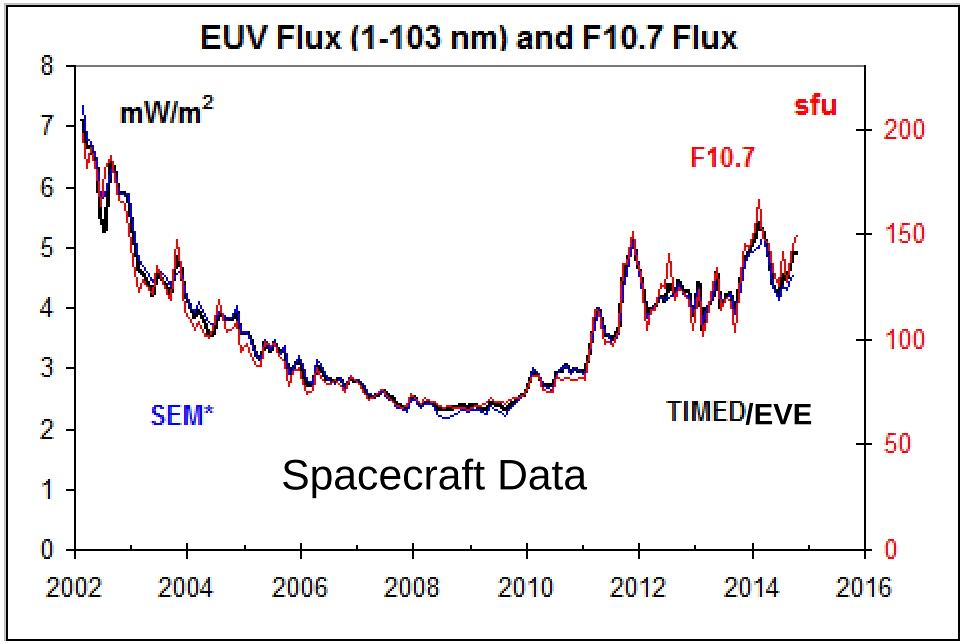


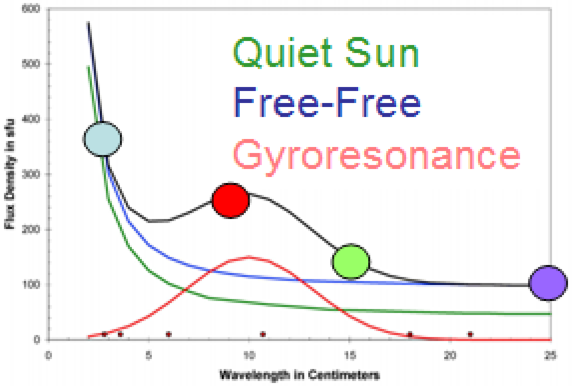
The detectors on the TIMED and SDO satellites agree well until the failure of the high-energy detector on EVE in 2014. We can still scale to earlier levels [open symbols].

EUV and its proxy: F10.7 Microwave Flux





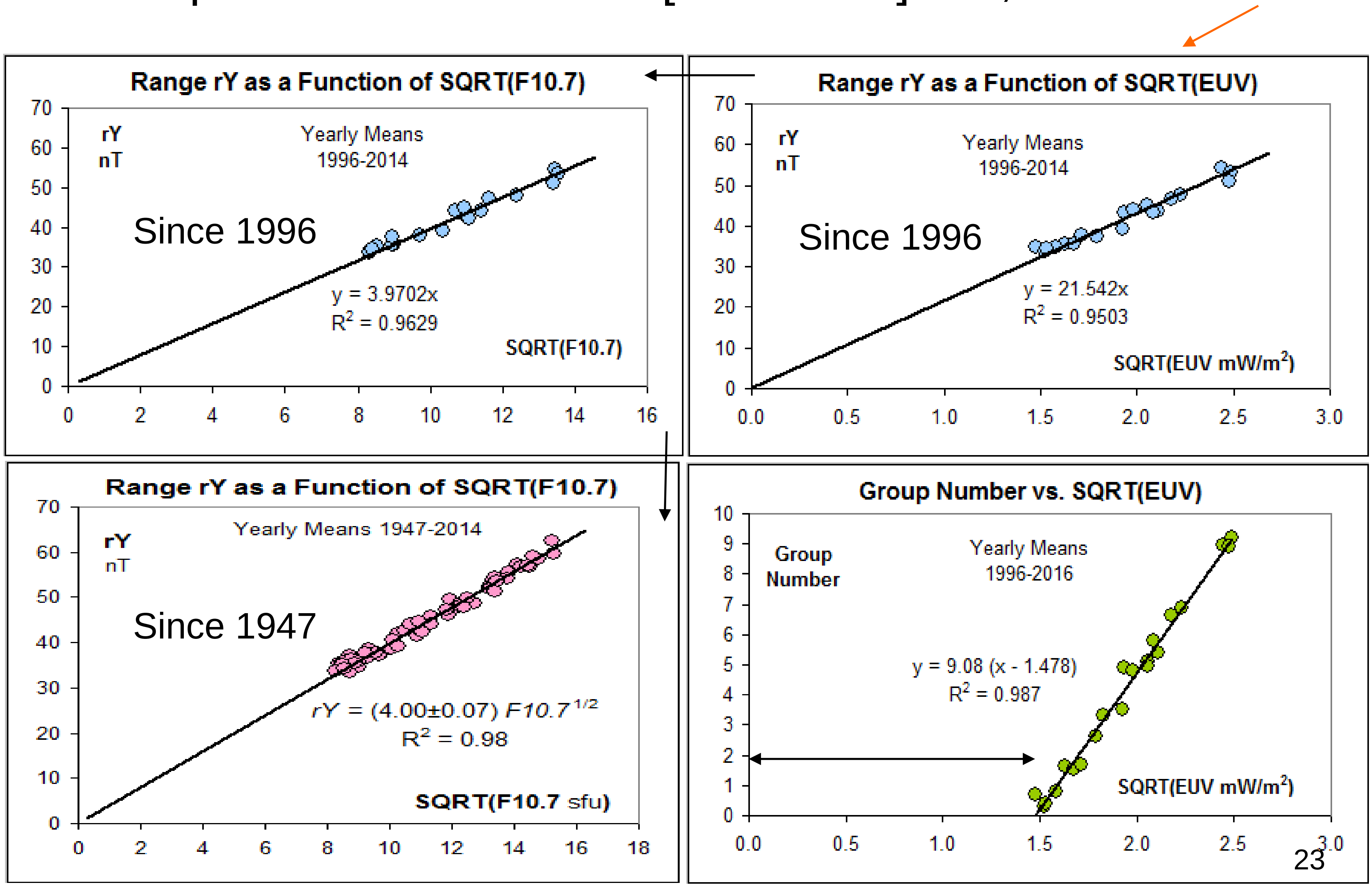




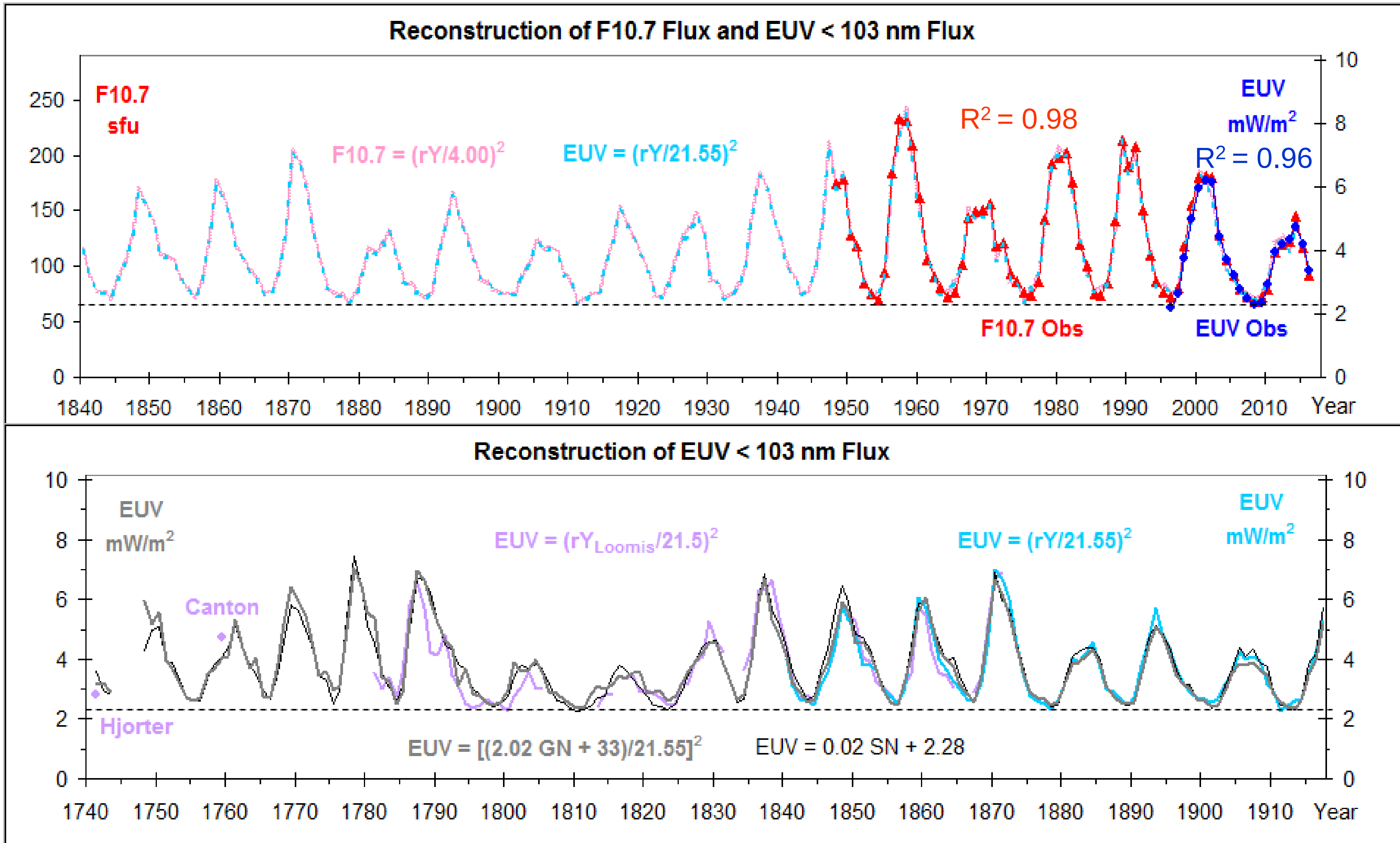
Space is a harsh environment:
Compensate for Sensor Degradation

10.7 cm= 2800 MHz

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:

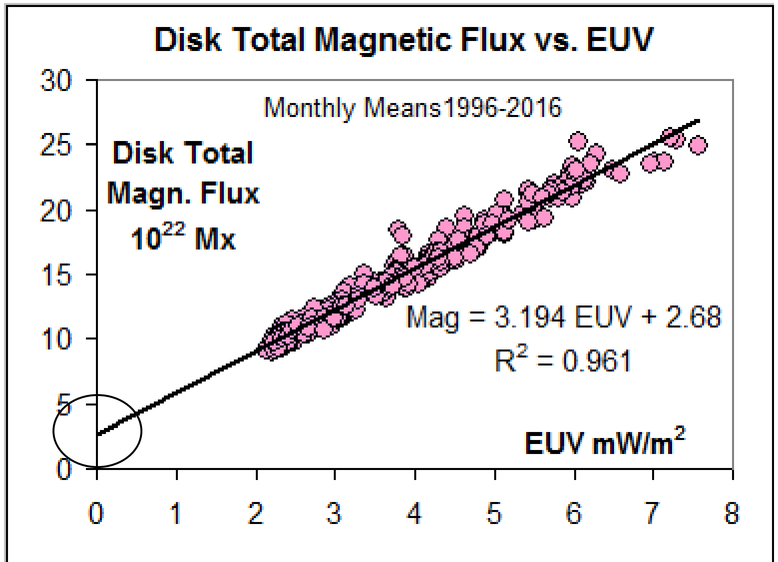


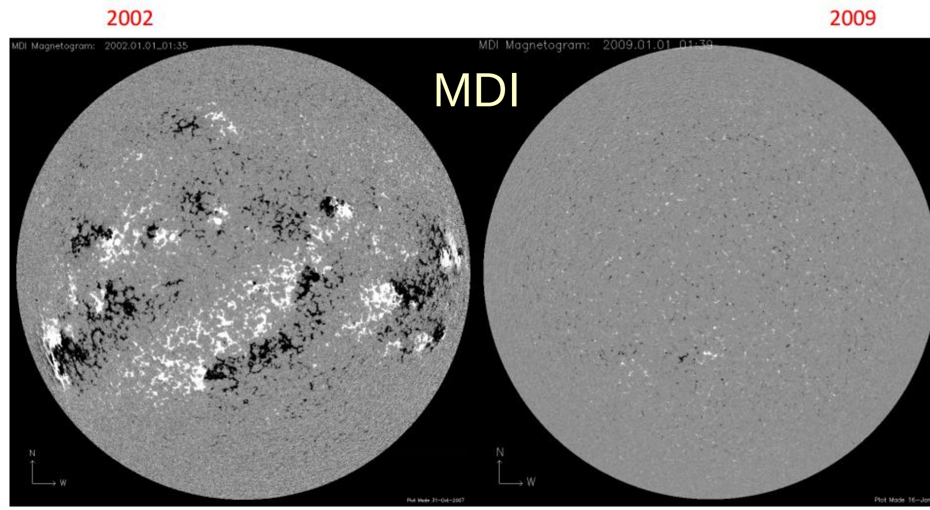
Reconstructions of EUV and F10.7



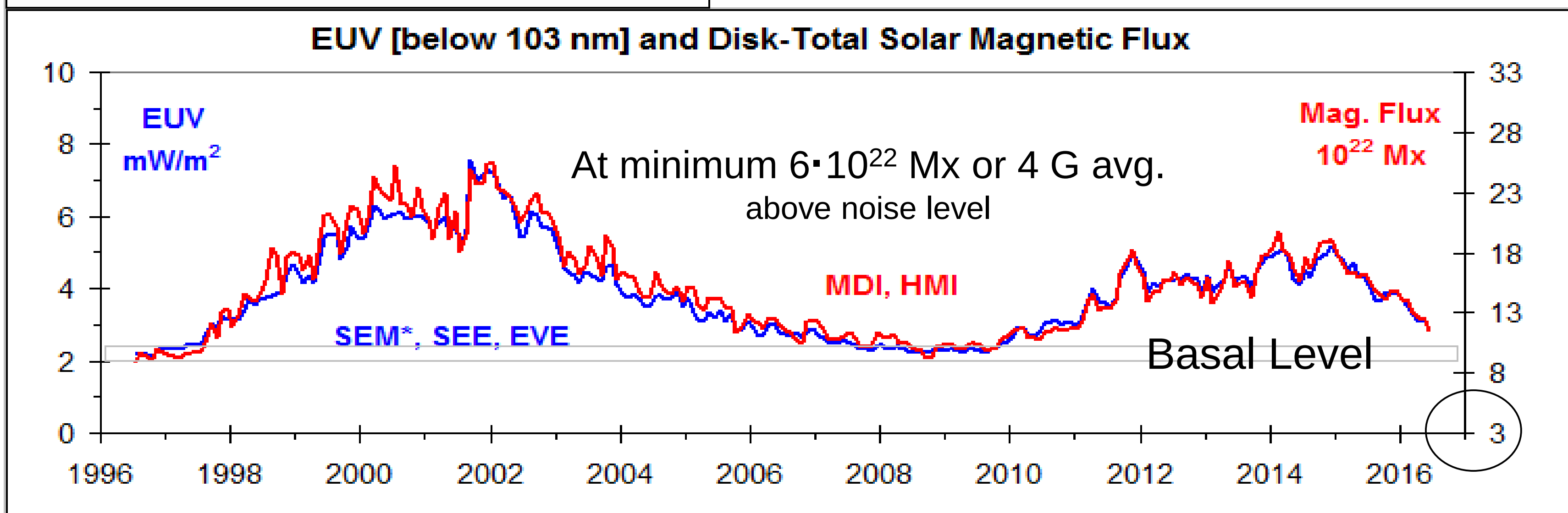
Note the constant basal level at *every* solar minimum

EUV Follows Total Unsigned Magnetic Flux



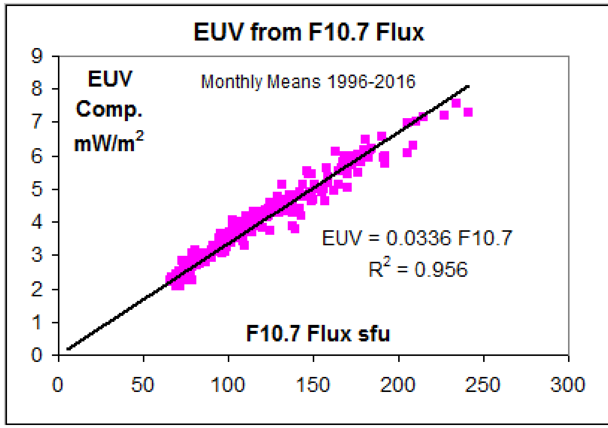


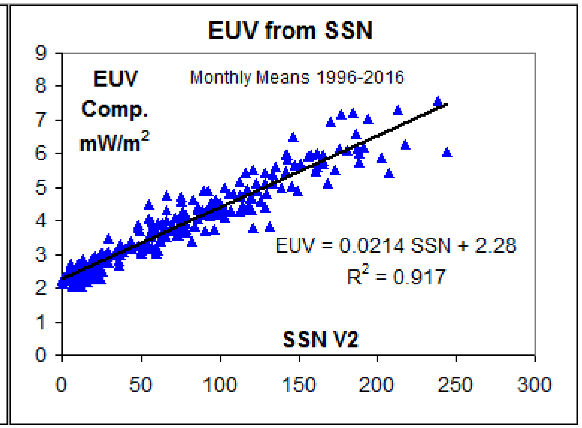
Offset interpreted as Noise Level ≈ $3 \cdot 10^{22}$ Mx



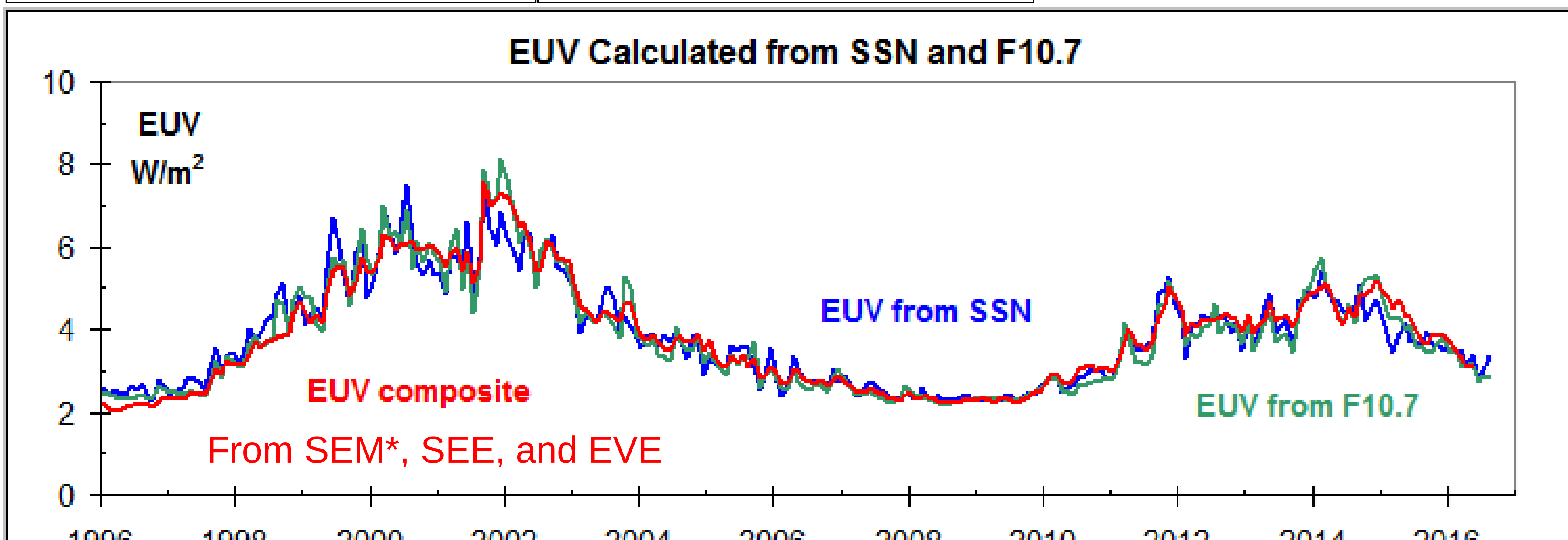
There is a 'basal' level at solar minima. Is this the case at every minimum?

EUV Composite Matches F10.7 and Sunspot Numbers

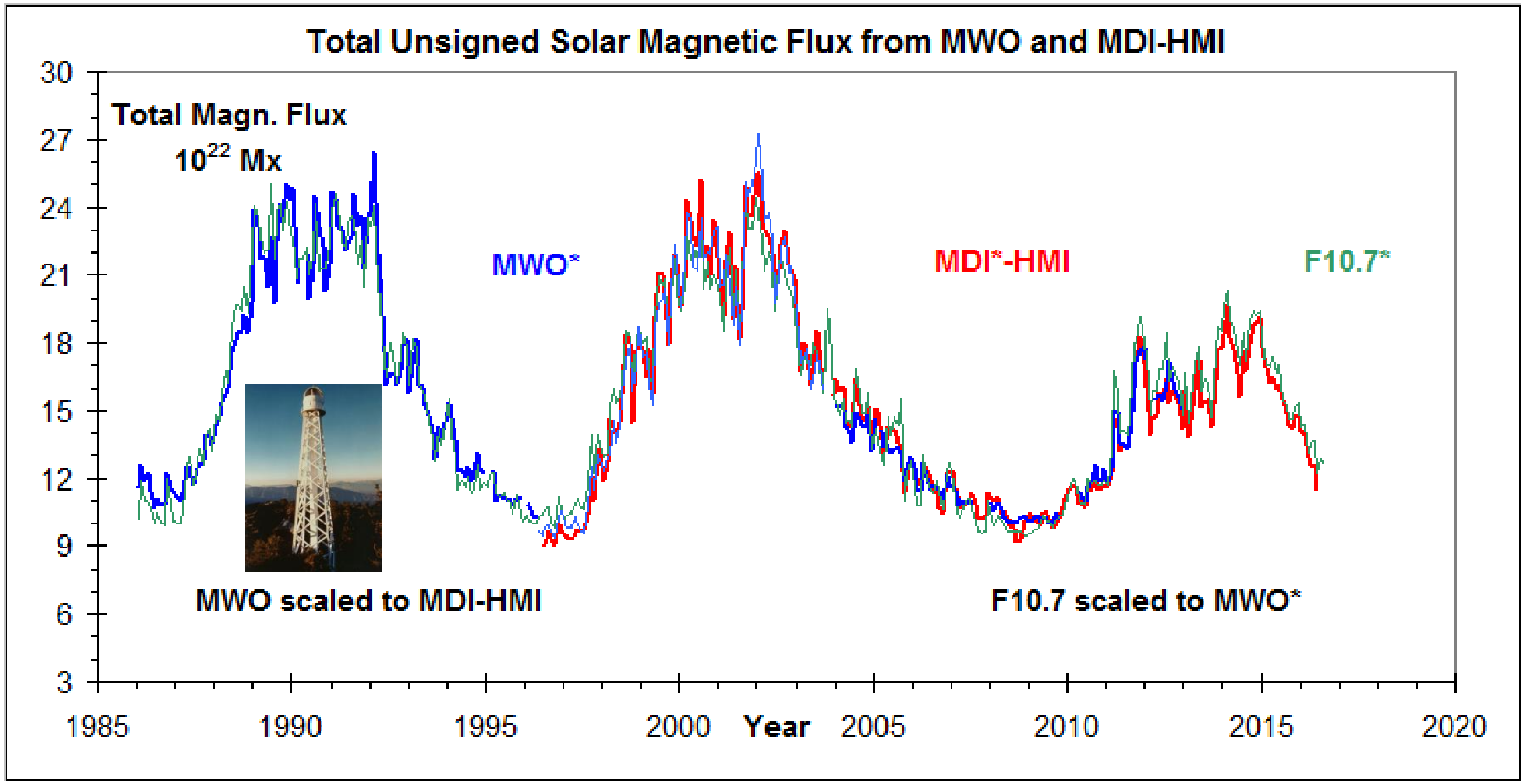




So, we can calculate the EUV flux both from the Sunspot Number and from the F10.7 flux which then is a good proxy for EUV [as is well-known].

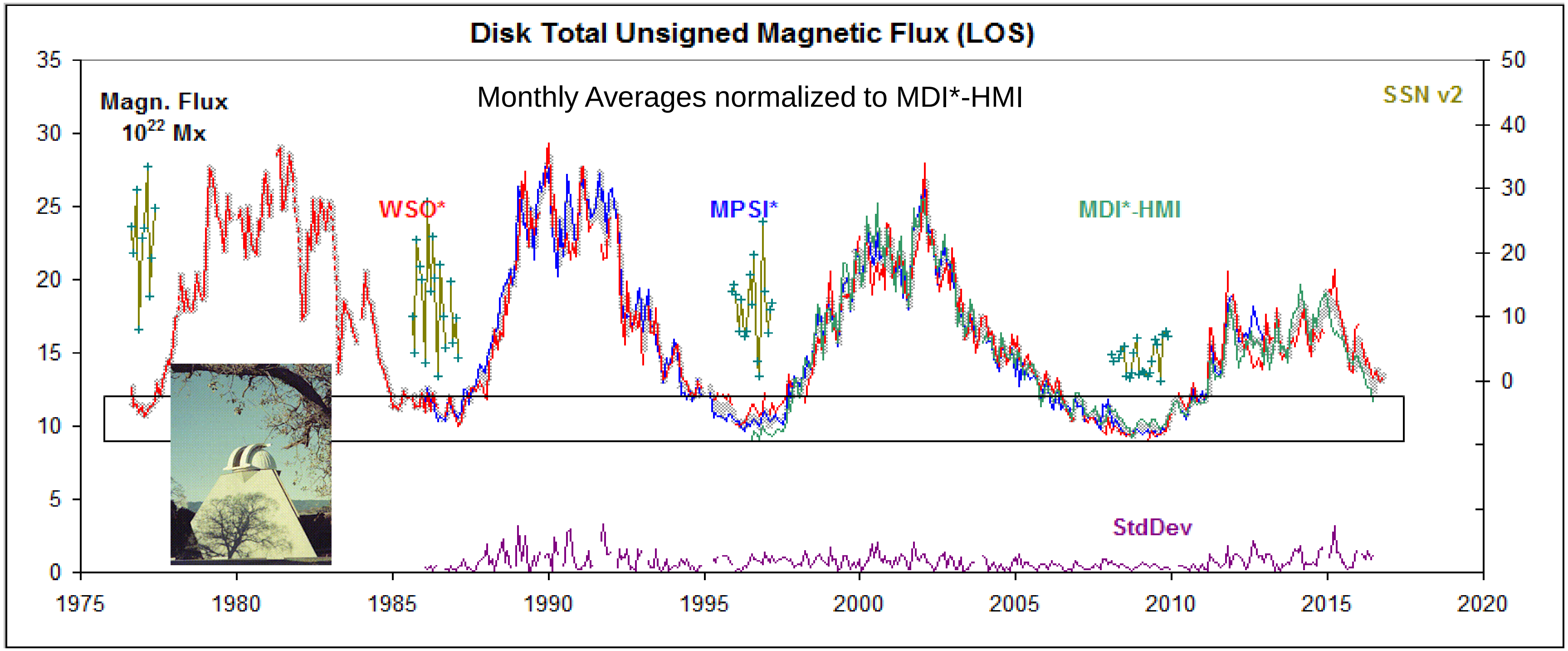


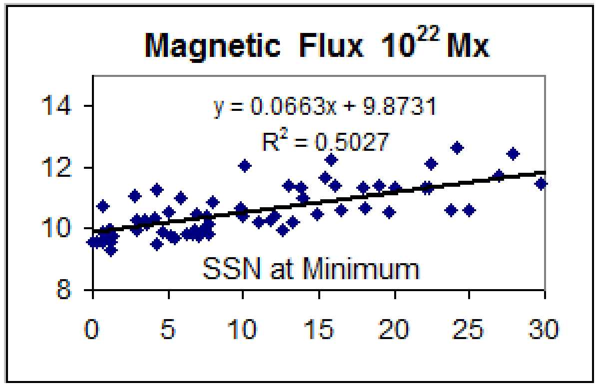
Magnetic Flux from MWO Tracks MDI-HMI and the F10.7 Flux



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.

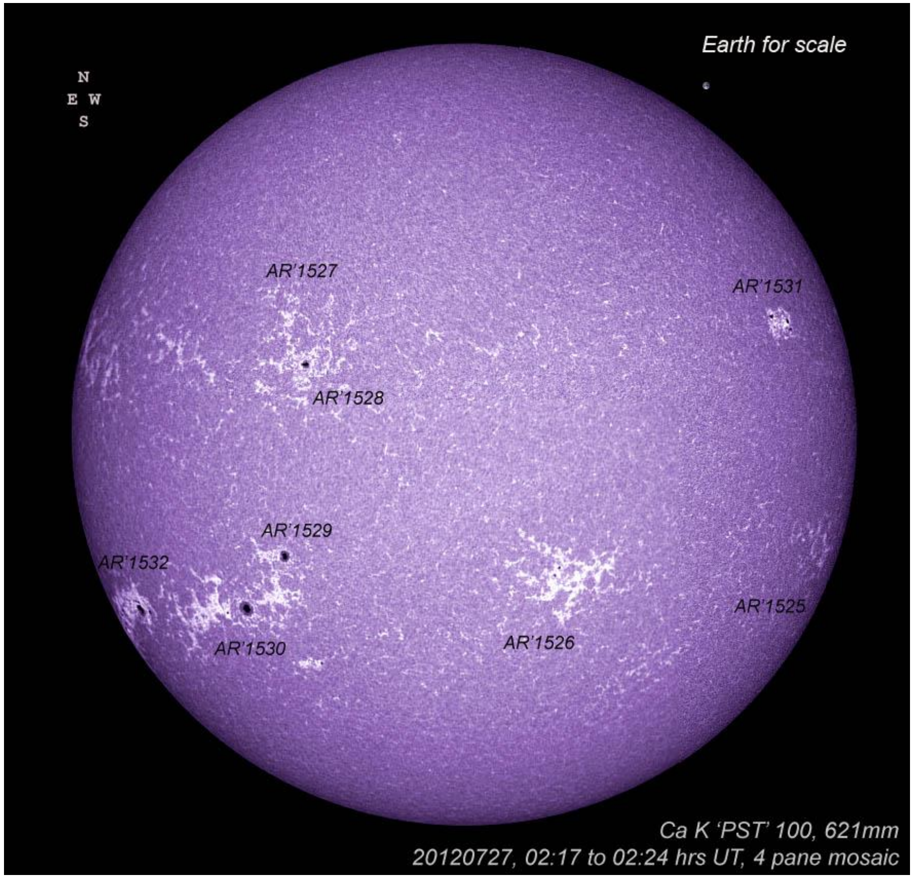
Magnetic Flux back to 1976





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]

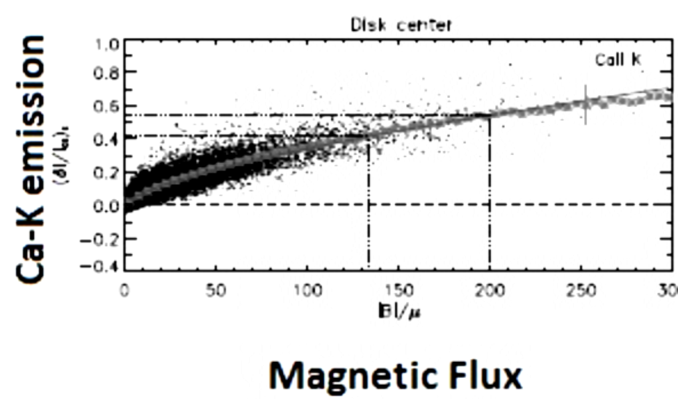
Emission in Light from Calcium



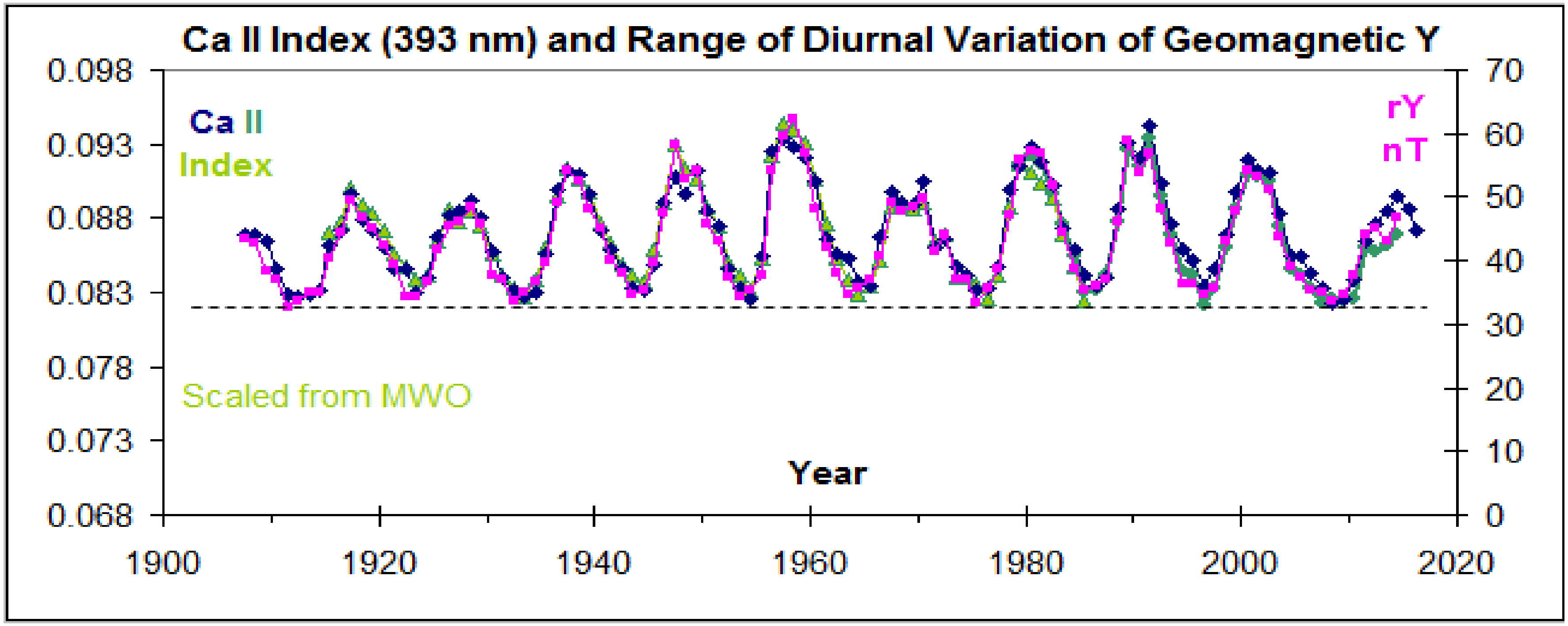
The emission of Calcium at 393 nm is an indicator of the magnetic flux

FIG. 2—Low-Level Calcium, Flocculi. Slit set on H_1

Mount Wilson, Nov. 18, 1905, Ionized Calcium [Ca II] at wavelength 393 nm



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

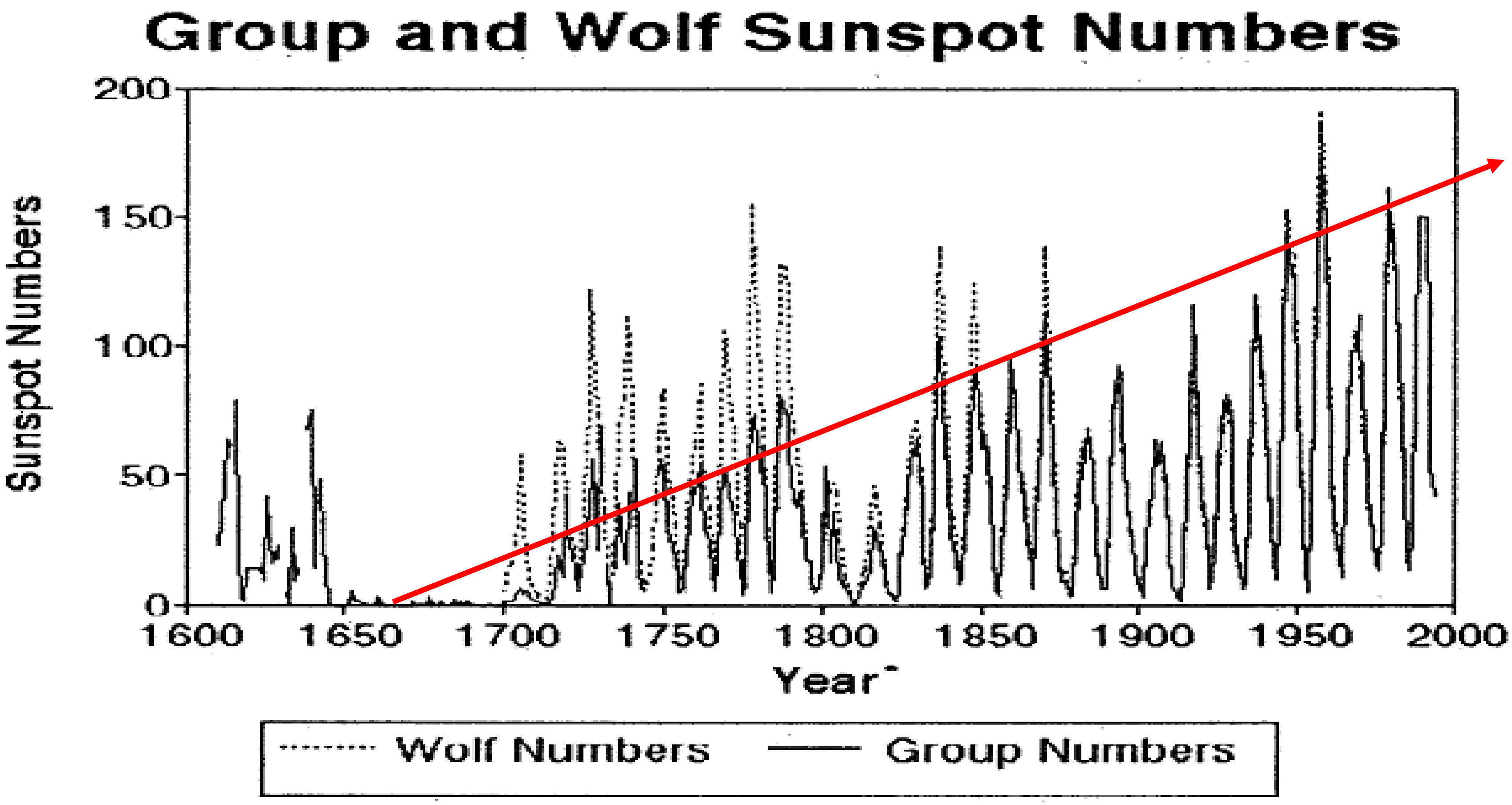


The long-term **Ca** II Index is constructed from Kodaikanal, Sacramento Peak, and SOLIS/ISS data [Luca Bertello, NSO]. Data from Mount Wilson [**Green**] has been scaled to the Kodaikanal series. Calibration of the old spectroheliograms is a difficult and on-going task.

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

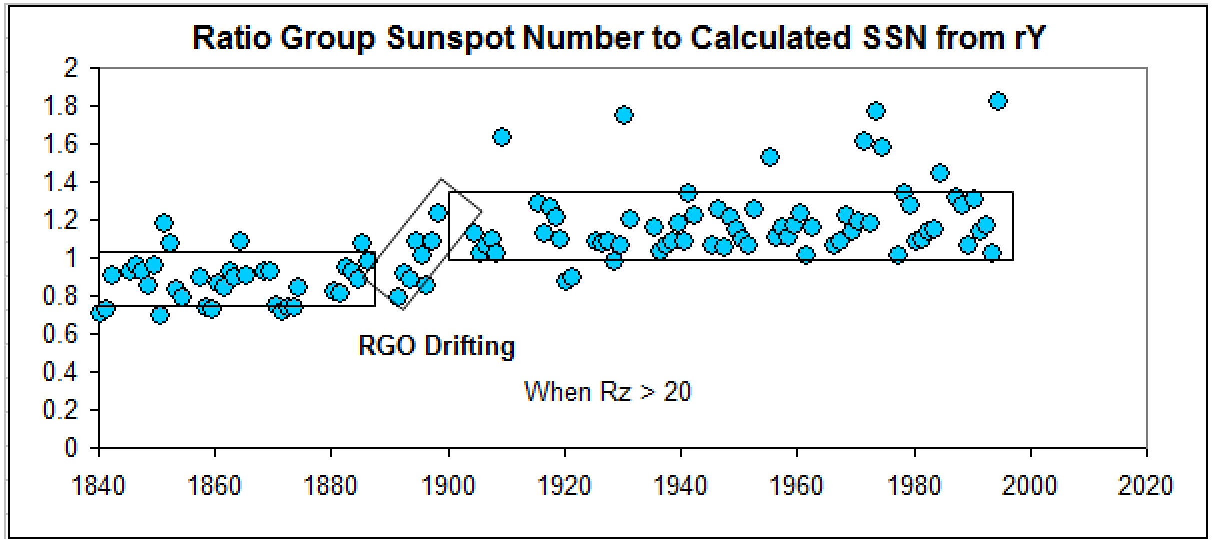
A Problem: Discordant Sunspot Numbers

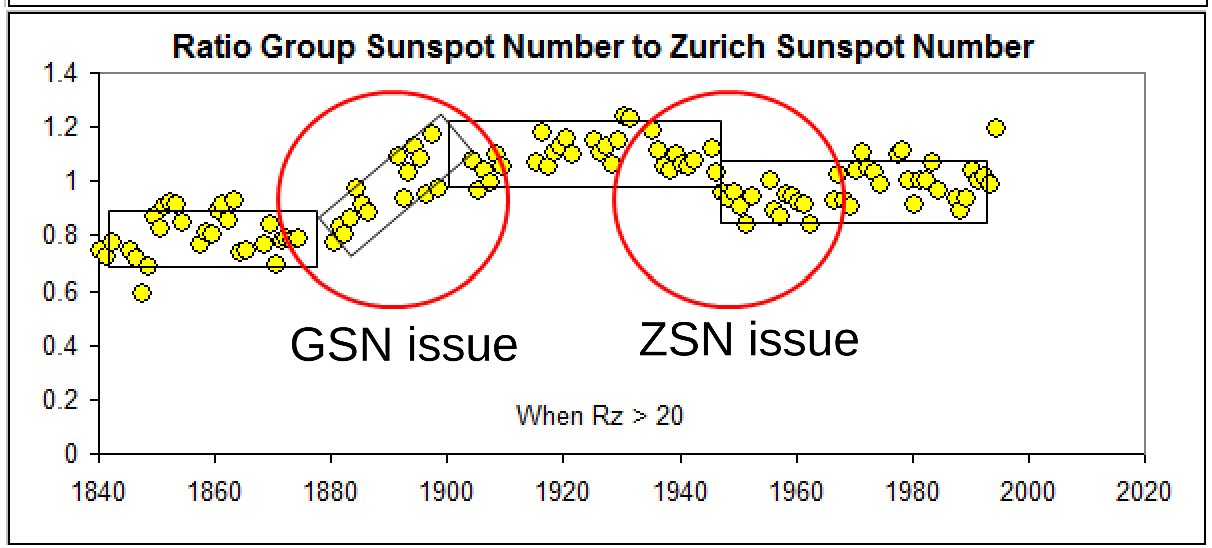
GSN = 12 GN WSN = 0.6(10 * GN + SN)



Hoyt & Schatten, GRL *21*, 1994

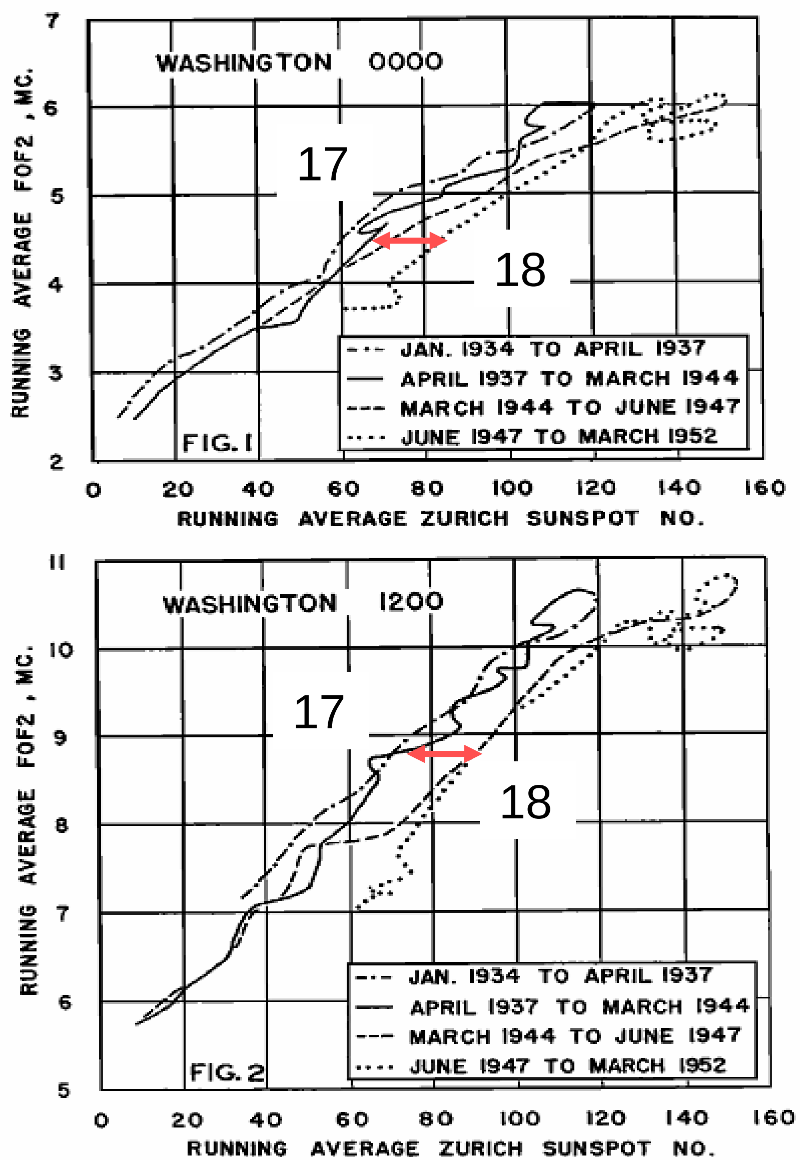
Compare with the Sunspot Records





The main issue with the GSN is a change relative to the ZSN during 1880-1900. This is mainly caused by a drift in the reference count of the standard (Royal Greenwich Observatory)

The ratio between the Group Sunspot Number reveals two major problem areas. We can now identify the cause of each



FIGS. 1 AND 2—PLOT OF 12-MONTH RUNNING AVERAGE OF MONTHLY MEDIAN f^oF2 AGAINST 12-MONTH RUNNING AVERAGE OF MONTHLY ZURICH SUNSPOT NUMBER, LOCAL TIME

foF2

F2-layer critical frequency. This is the maximum radio frequency that can be reflected by the F2-region of the ionosphere at vertical incidence (that is, when the signal is transmitted straight up into the ionosphere). And has been found to have a profound solar cycle dependence.

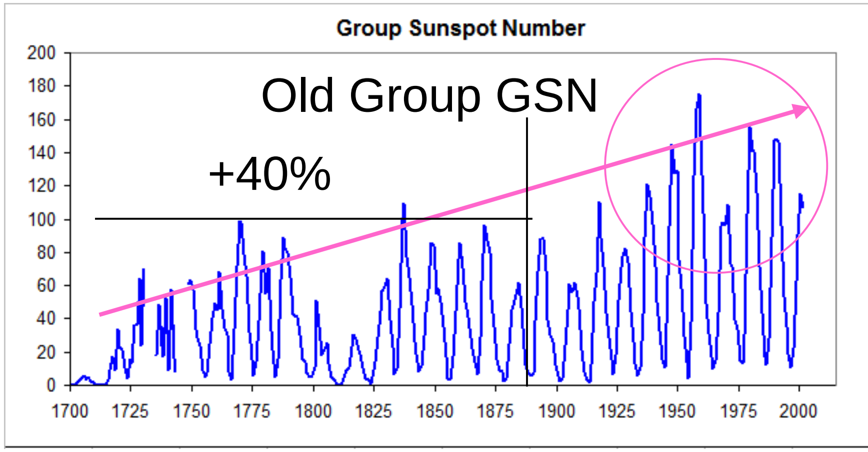
The curves for cycle 18 [1945-] and cycle 17 [-1944] are displaced.

The shift in SSN to bring the curves to overlap is ~20%

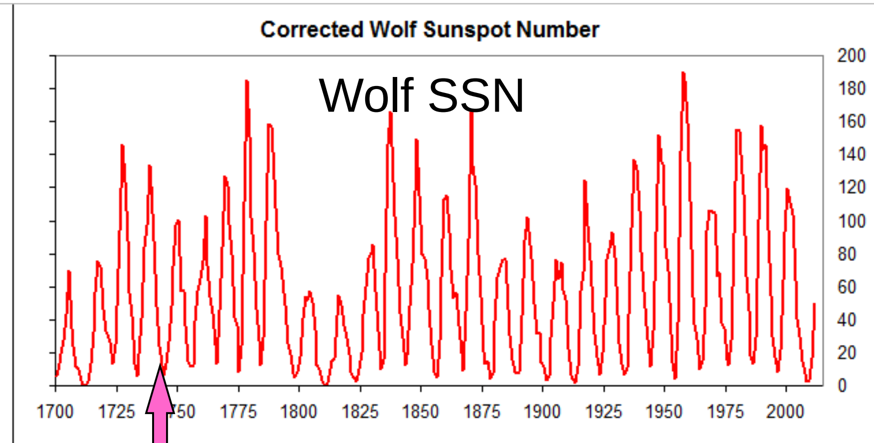
The evidence for the Waldmeier Jump begins to be mind-numbing..

The Tale of Two Sunspot Numbers

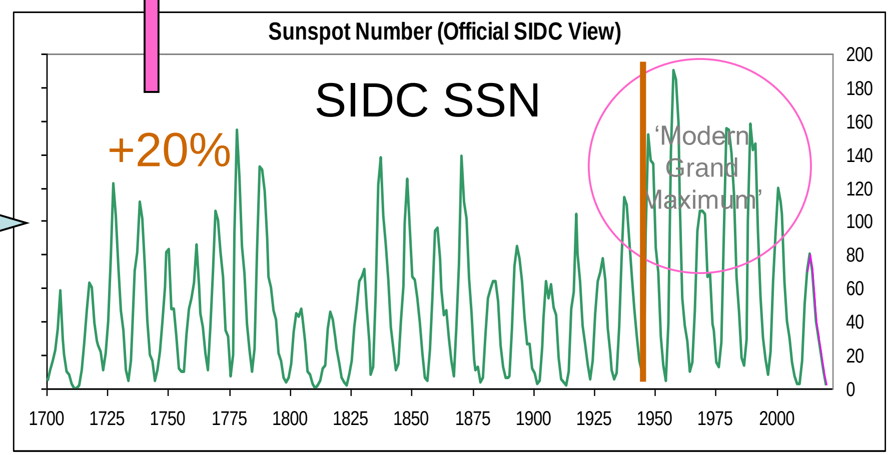
GSN = 12 * Groups



WSN = 10 * Groups + Spots



The old 'official' sunspot number [maintained by SIDC in Brussels] showed a clear 'Modern Maximum' in the last half of the 20th century.



Correct GSN by +40% before ~1885
Correct WSN by -20% after 1946, because of weighting of the count introduced then (the Waldmeier Jump)

The new SSN series suggest that there likely was no Modern Grand Maximum

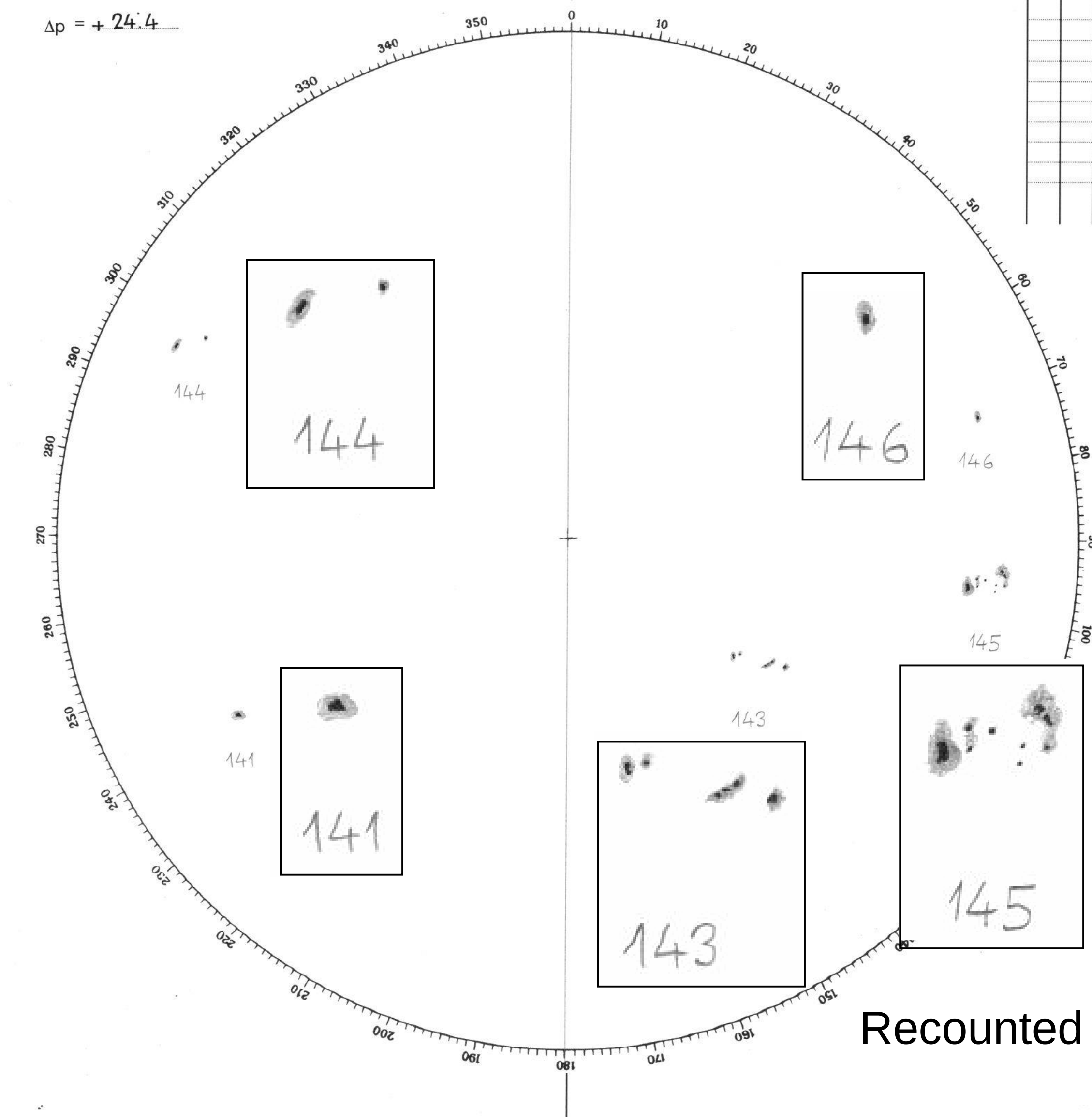
Counting with Weighting

No. 76
2014.IV.29.344
08:15 T.U.
Osservatore: S. Cortesi
Immagini: 3 (SIDC: 3)
$\Delta p = +24.4$

SPECOLA SOLARE TICINESE
LOCARNO MONTI

$L_o = 69.7$
$B_o = -4.4$
$p_o = -24.4$

g	f	t	B
141	3	J	-23
143	15	D	-18
144	6	G	+20
145	17	D	-7
146	3	J	+12
5	44		



g	f	No weighting
141	3	**1**
143	15	**6**
144	6	**2**
145	17	**9**
146	3	**1**
5	44	**19**

5x10+44=94 5x10+19=69

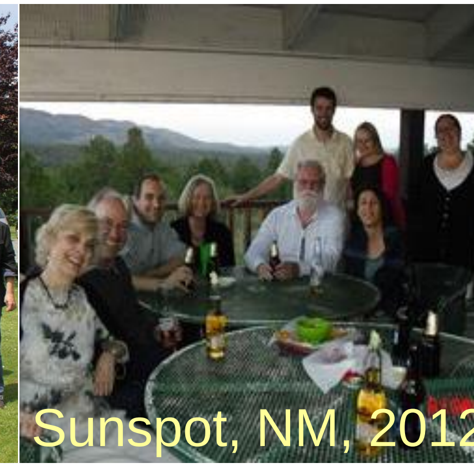
94/69 = 1.36

Recounted 2003-2014: ~55,000 spots

The SSN Workshops. The Work and Thoughts of Many People


Sunspot, NM, 2011


Brussels, BE, 2012


Sunspot, NM, 2012


Tucson, AZ, 2013


Locarno, CH, 2014


Brussels, BE, 2015

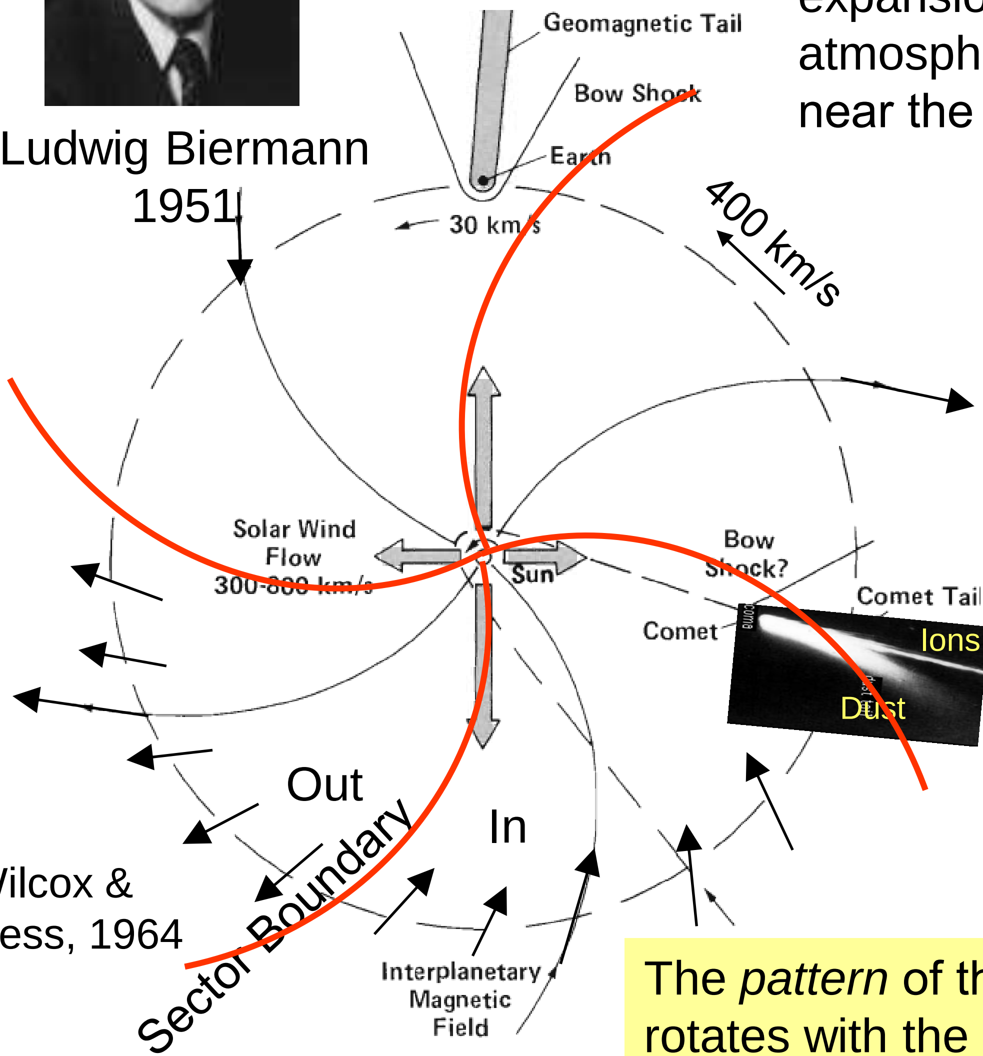
A revised Sunspot Number was announced at IAU Assembly in August, 2015

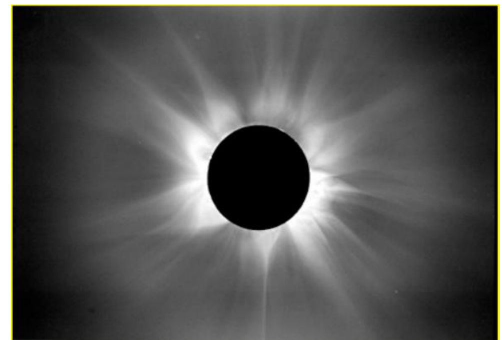
The Solar Wind

Ludwig Biermann
1951

“Blows” all the time and is the expansion of the extremely hot atmosphere into space, visible near the Sun as the ‘Corona’:

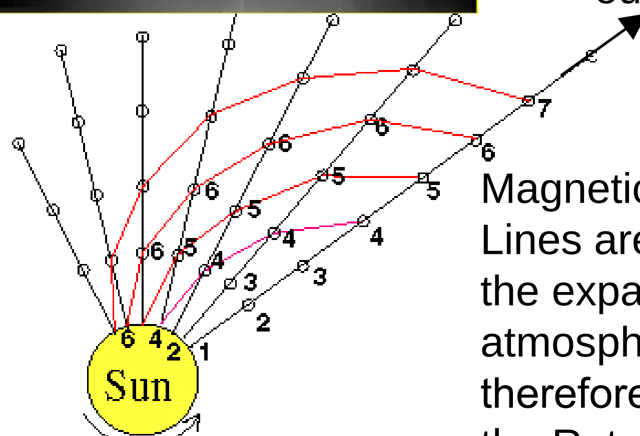
Gene Parker
1958





Wilcox &
Ness, 1964

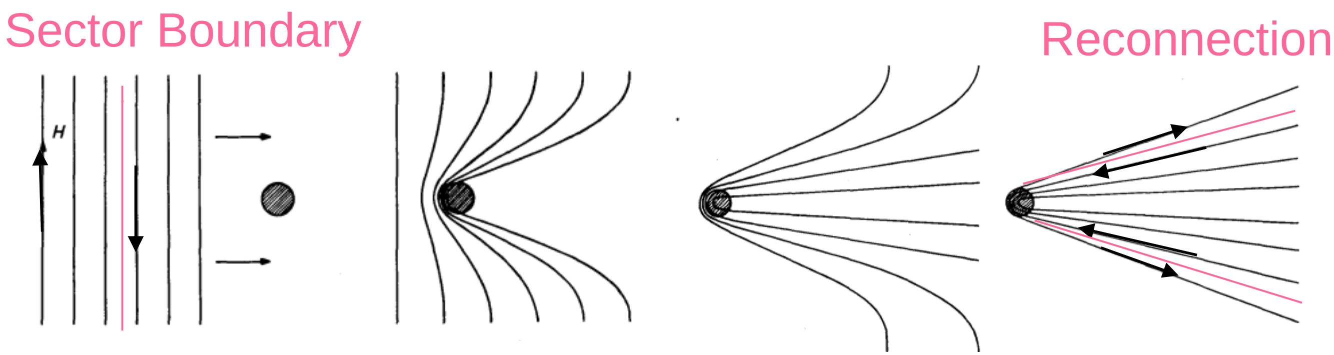
Expansion is radially outwards



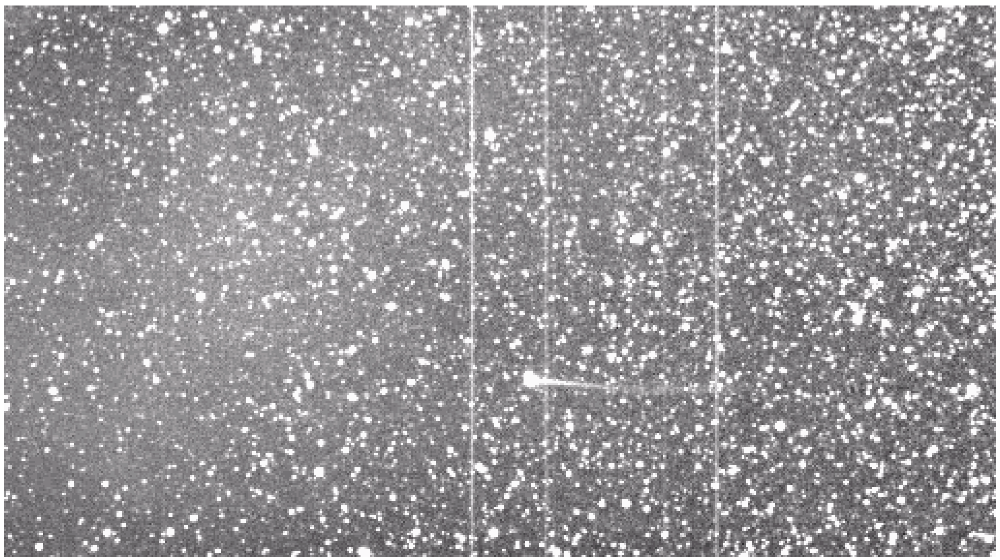
Magnetic Field Lines are tied to the expanding atmosphere and therefore ‘rooted’ in the Rotating Sun

The *pattern* of the magnetic ‘spiral’ rotates with the Sun once in 25 days

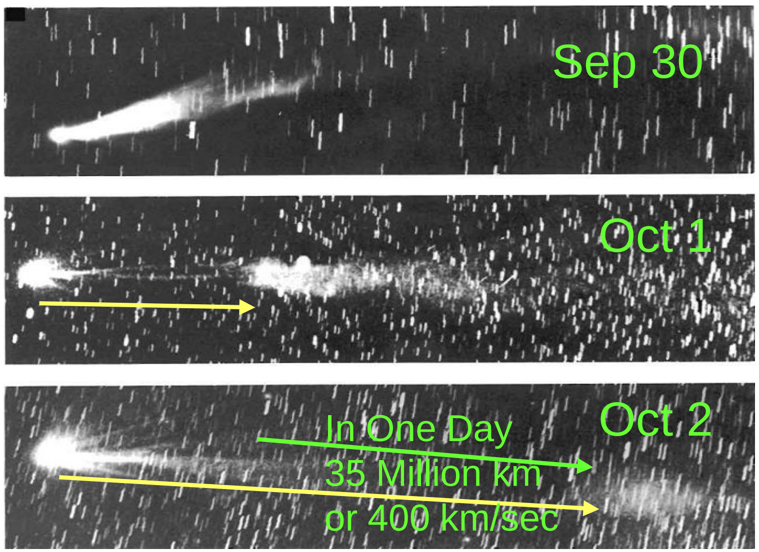
Solar Wind Stealing a Comet Tail



Fragile: Comet ion tail inside



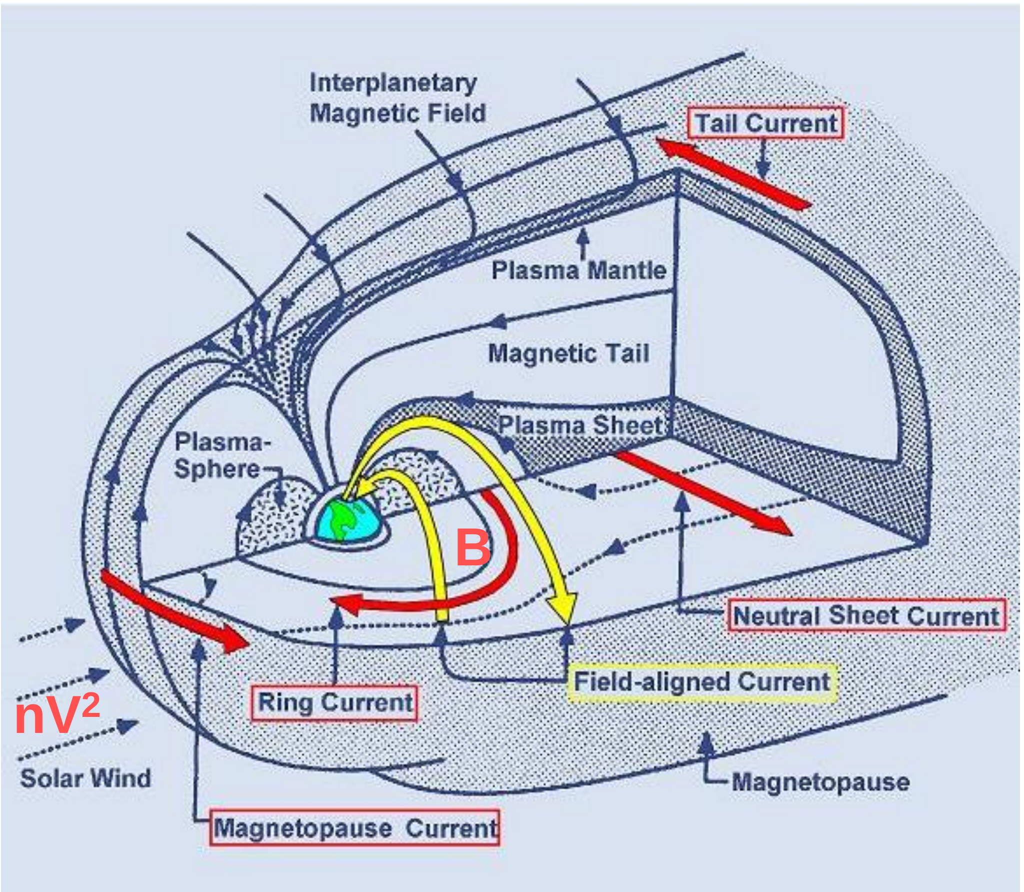
Comet Encke, 2007/04/20

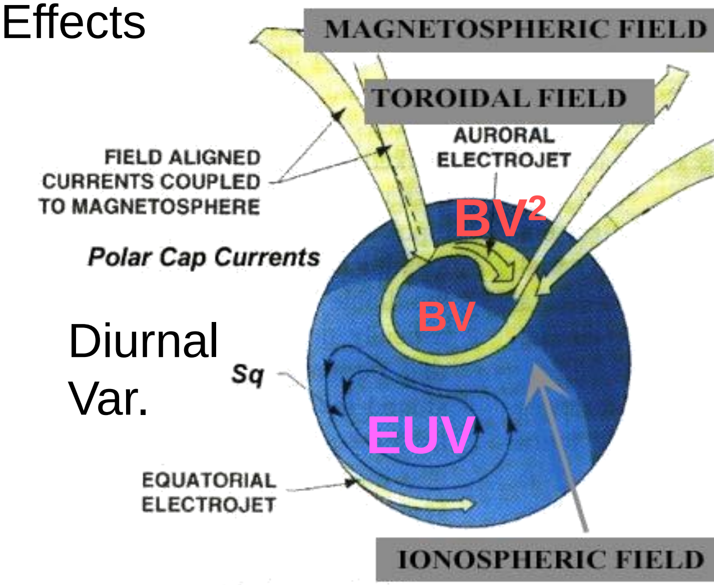


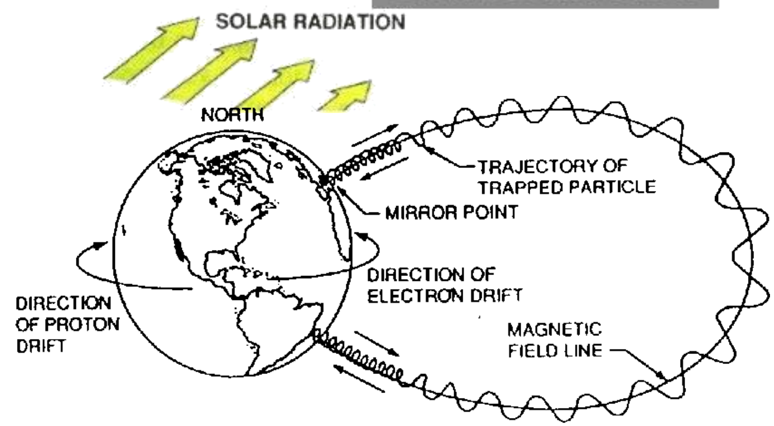
Comet Morehouse, 1908

Electric Current Systems in Geospace

Different Current Systems ⇄ Different Magnetic Effects



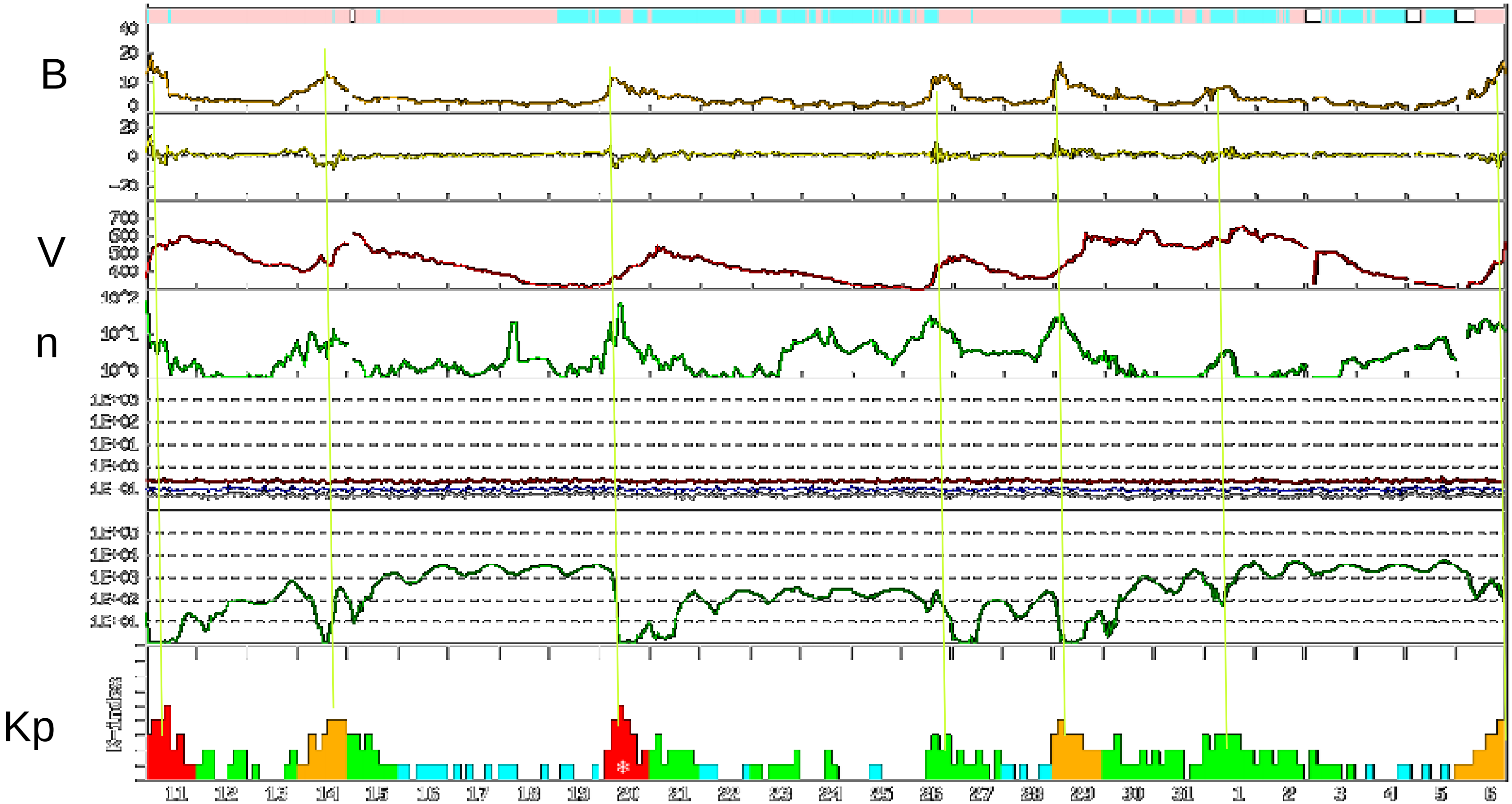




We can now invert the Solar Wind – Magnetosphere relationships…

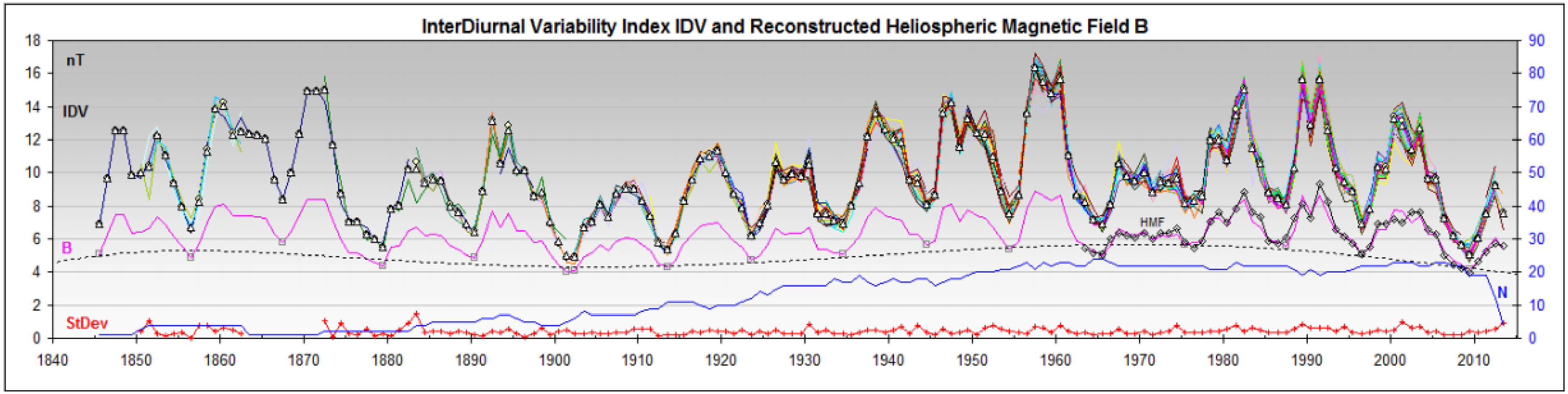
Oppositely charged particles trapped in the Van Allen Belts drift in opposite directions giving rise to a net westward ‘Ring Current’.

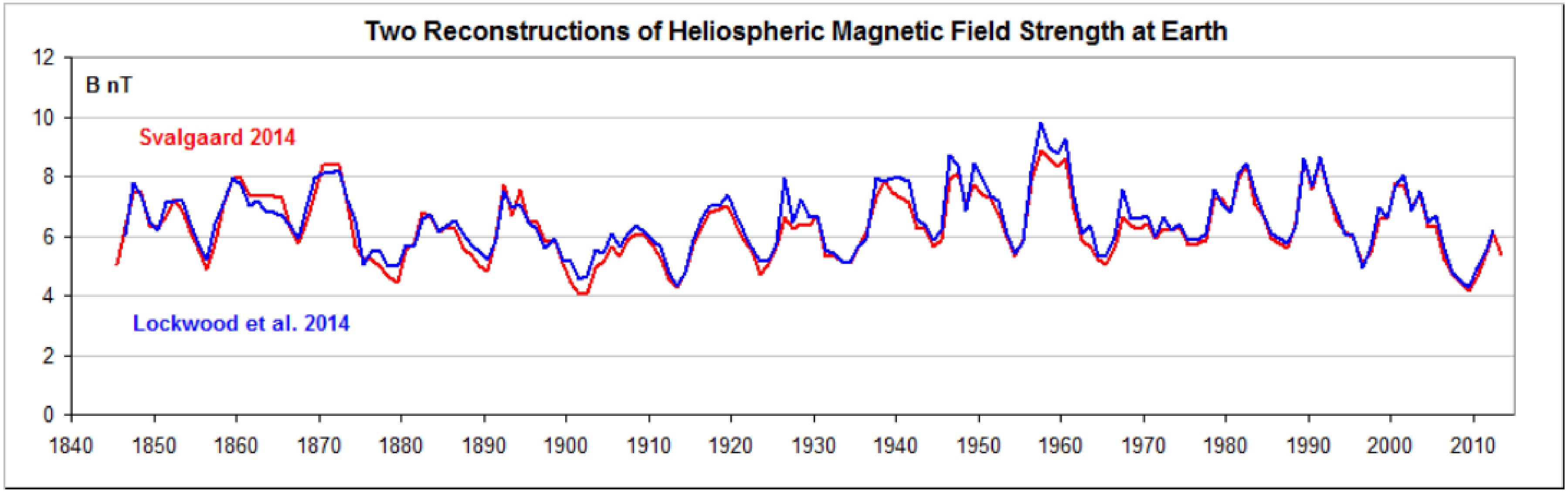
Examples of High Solar Wind B and Geomagnetic Activity A



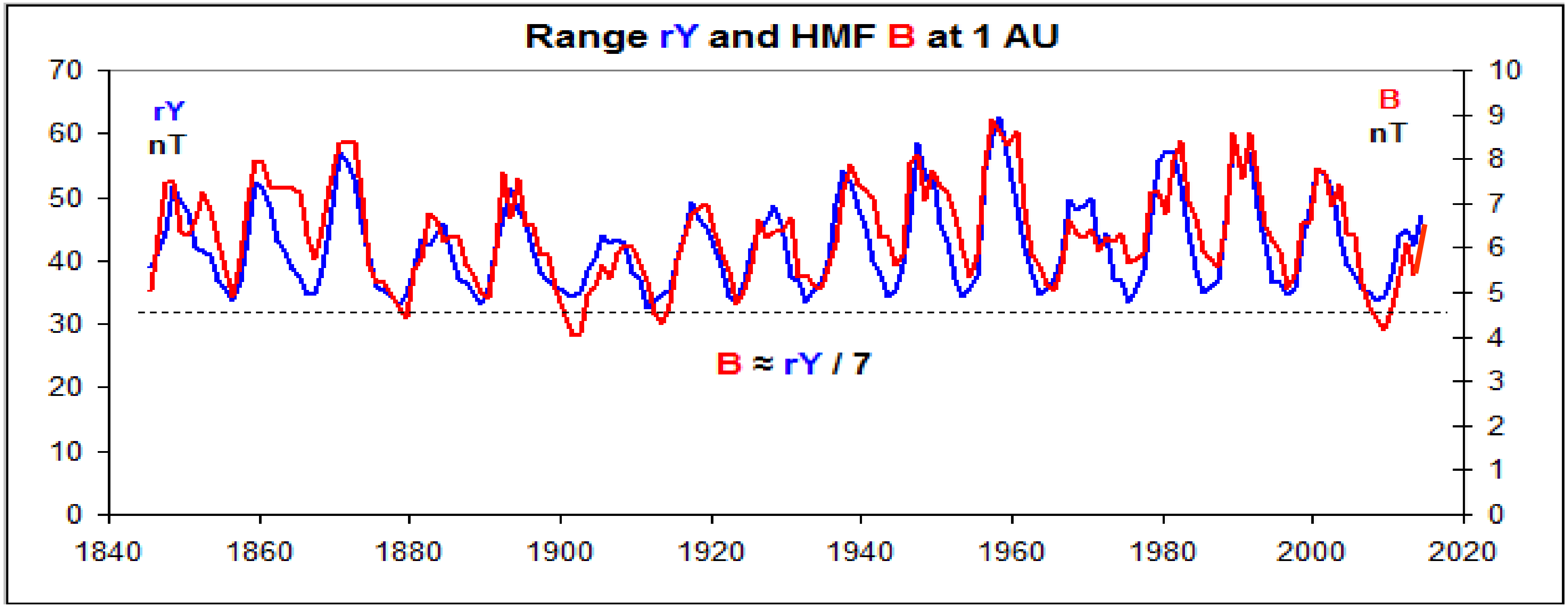
$$A = k\, q(a,f)\, (B\, V)\, (n\, V^2)^{1/3} \sim B\, V^2$$

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



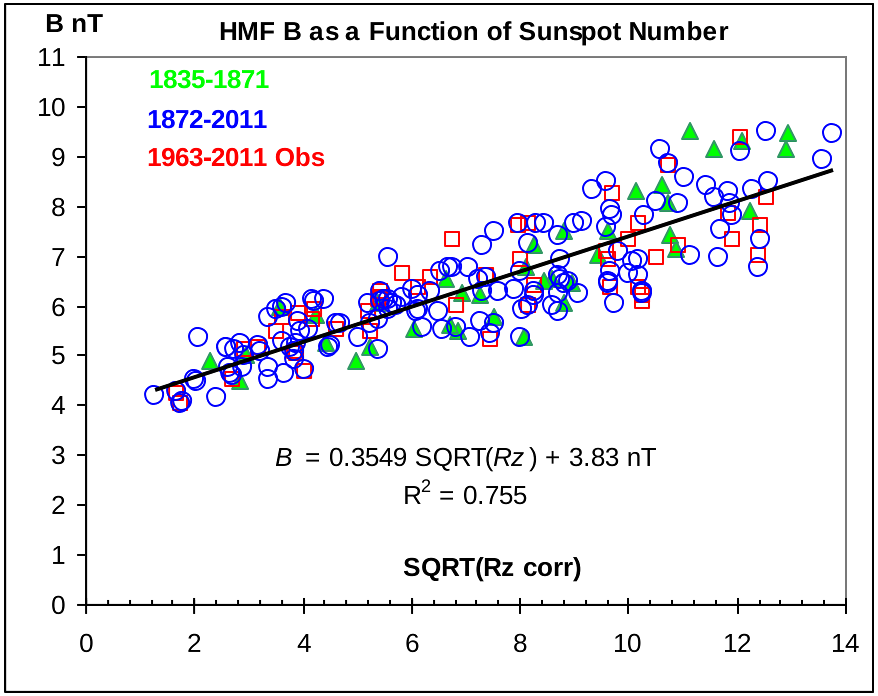


Network Field and Solar Wind Field



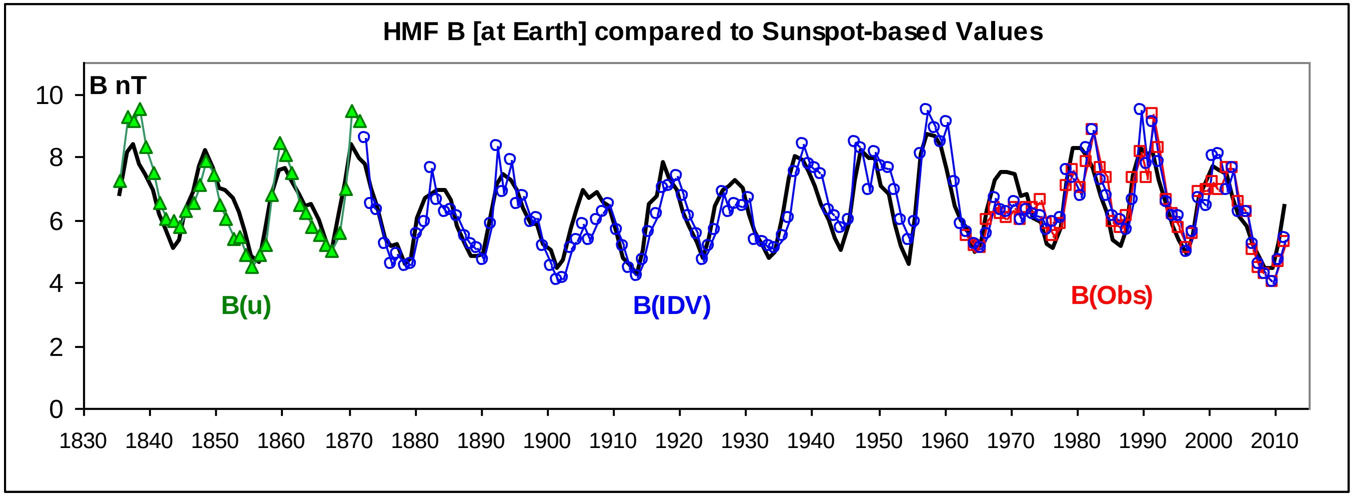
The magnetic field in the solar wind (the Heliosphere) ultimately arises from the magnetic field on the solar surface filtered through the corona, and one would expect an **approximate** relationship between the network field (EUV and rY) and the Heliospheric field, as observed.

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.



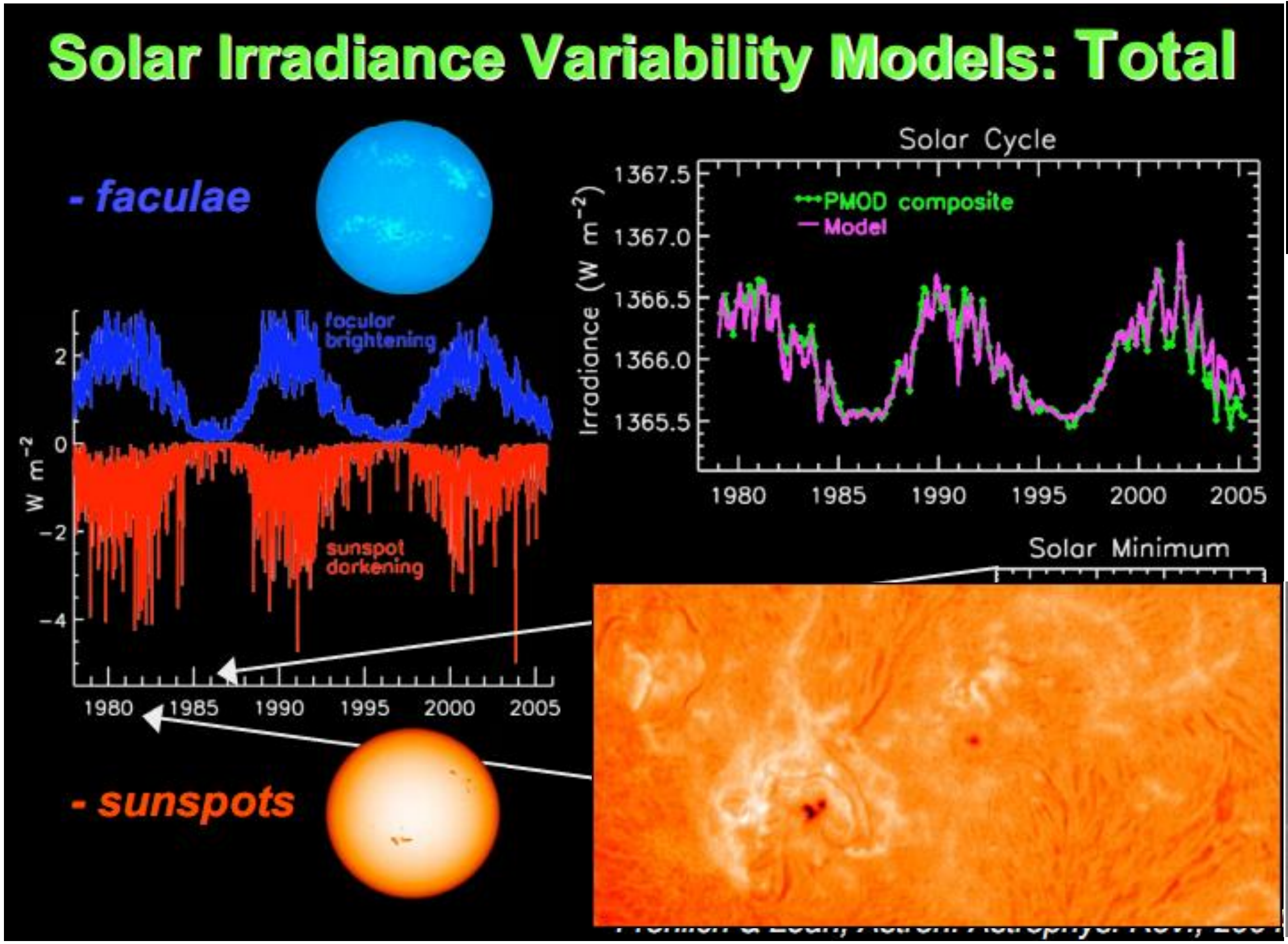
HMF *B* and Sunspot Number

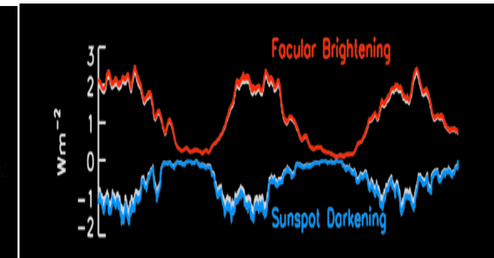
The main sources of low-latitude large-scale solar magnetic field are large active regions. If these emerge at random longitudes, their net equatorial dipole moment will scale as the square root of their number. Their contribution to the HMF strength should then vary as $Rz^{1/2}$ (Wang and Sheeley, 2003)



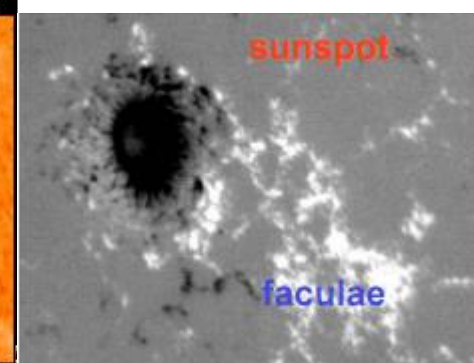
Again, there does not seem to be evidence that the last 50 years were any more active than 150 years ago

TSI is the combined effect of sunspot dimming and facular brightening (2x)

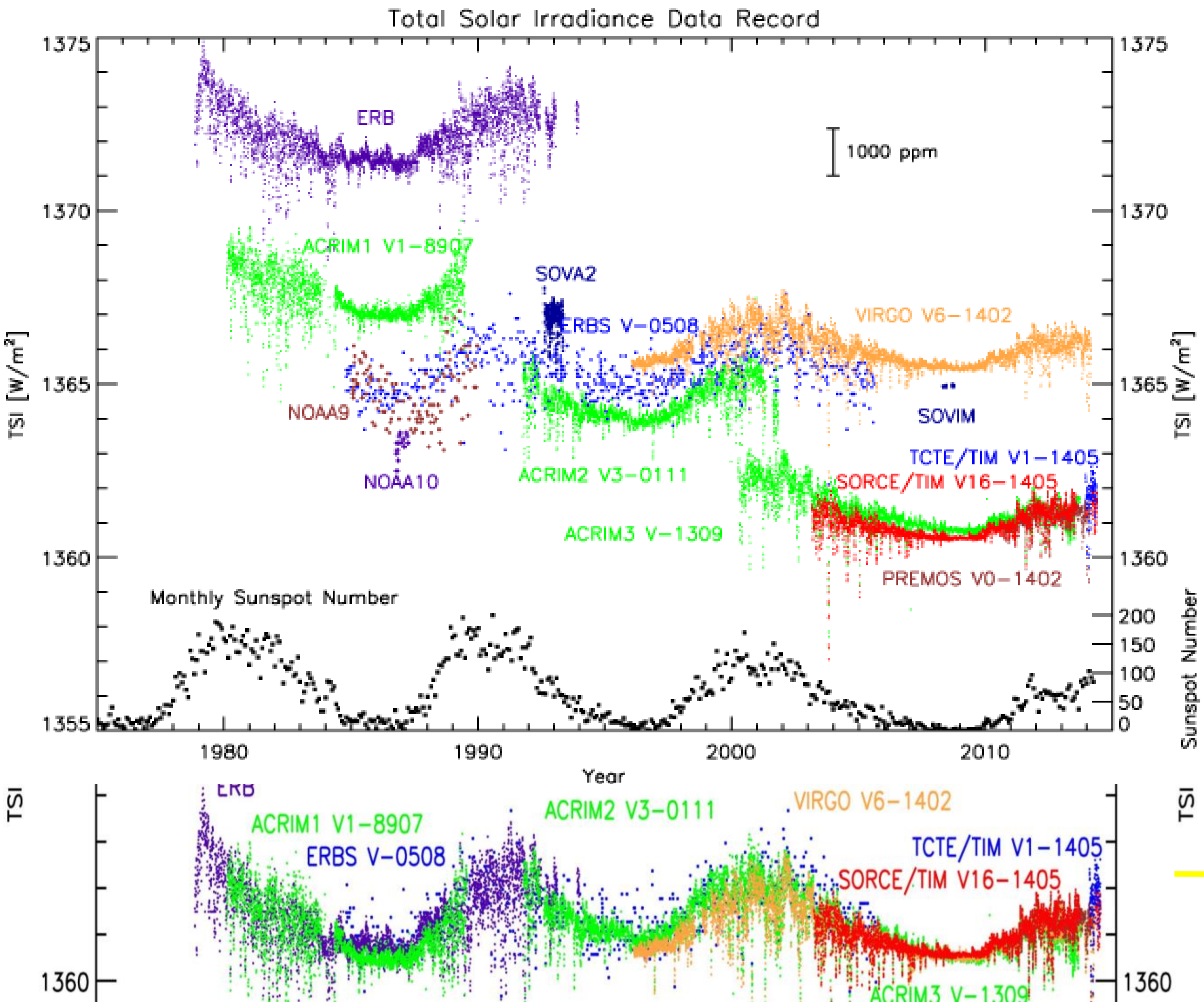




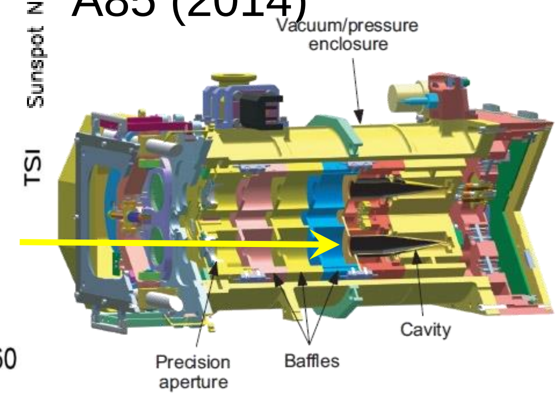
Faculae are areas with significant magnetic fields near sunspots



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



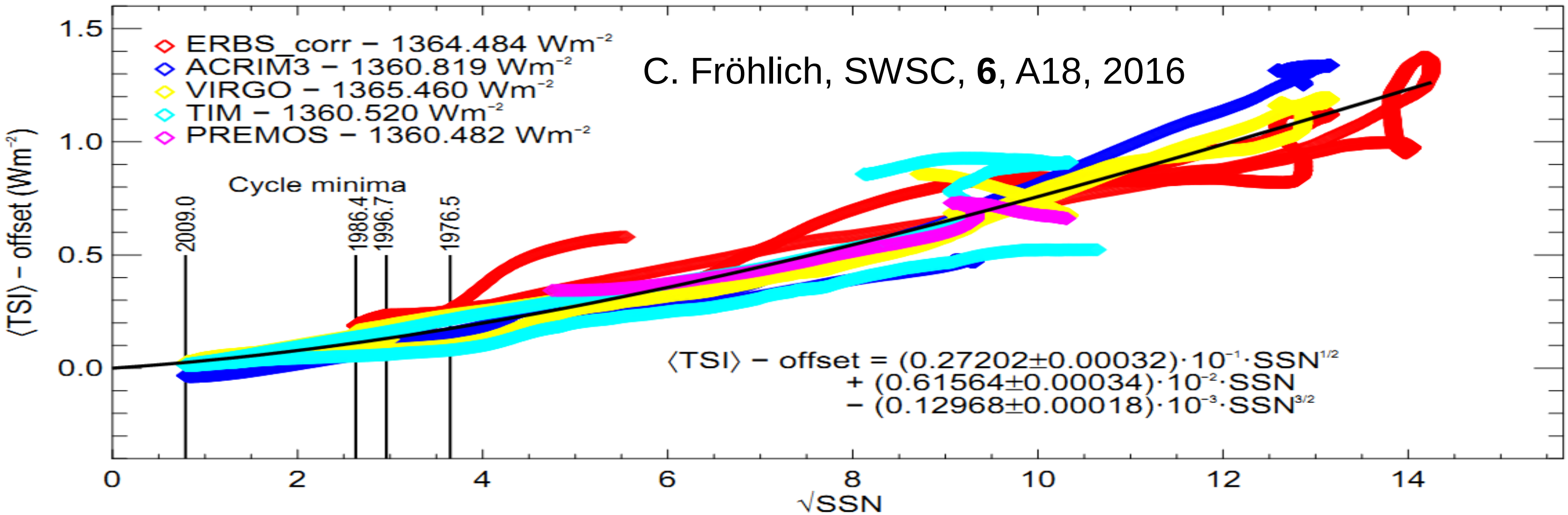
"The results of this work strengthen support for the hypothesis that variation in solar irradiance on timescales greater than a day is driven by **photospheric** magnetic activity". Yeo et al., A&A **570**, A85 (2014)

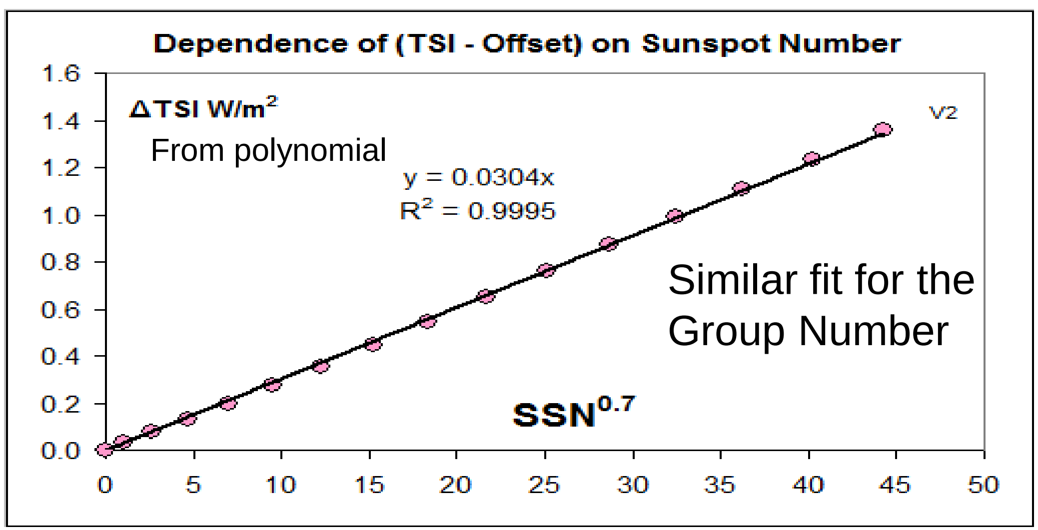


Radiometer

Building a Composite from Different Spacecraft Datasets

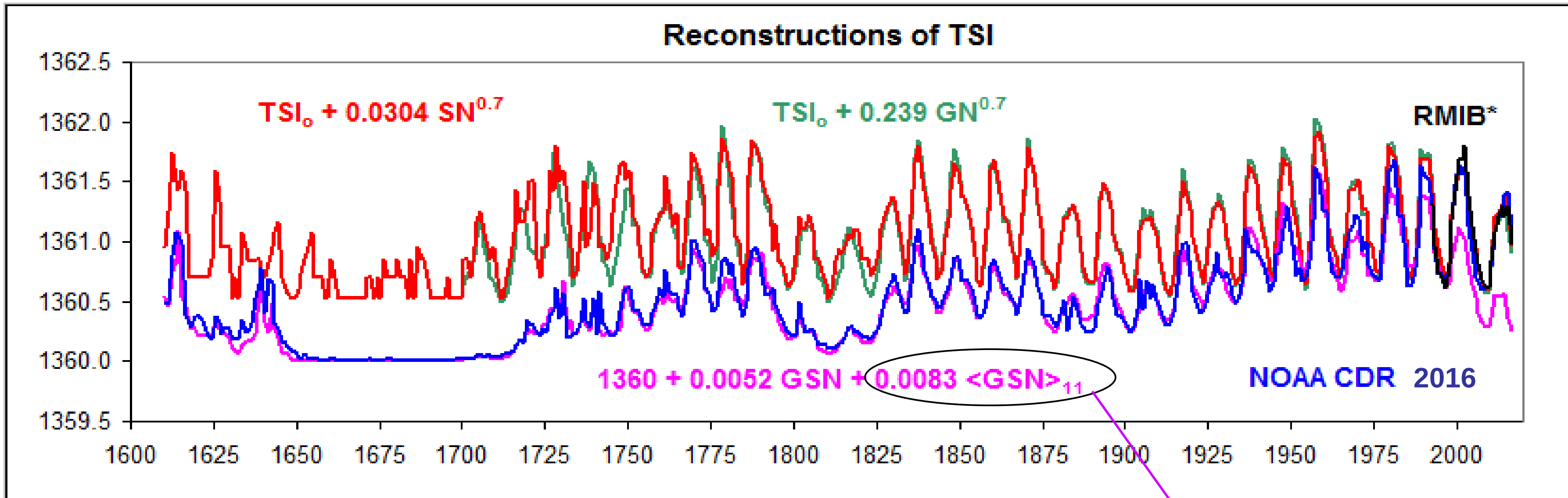
Claus Fröhlich Lined up TSIs as a Function of the Square Root of the Sunspot Number

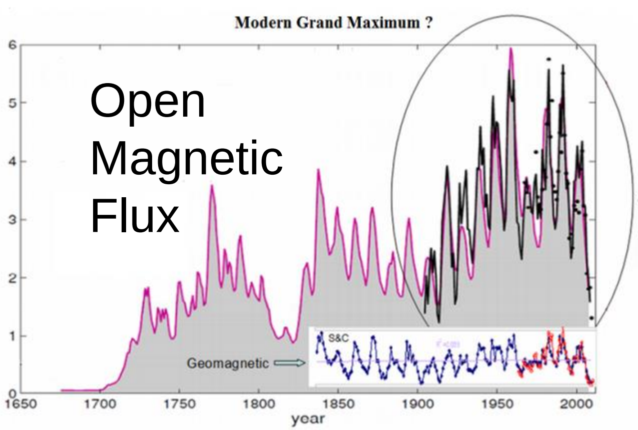


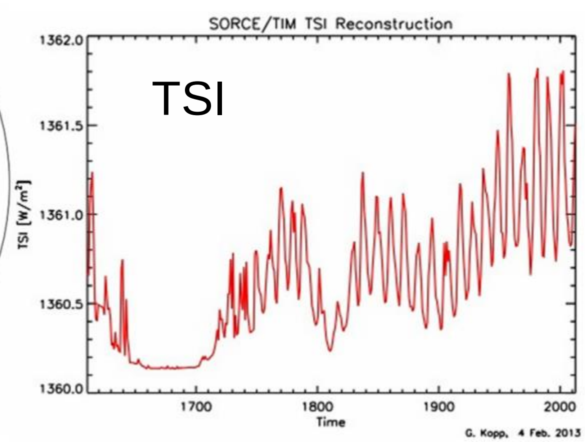


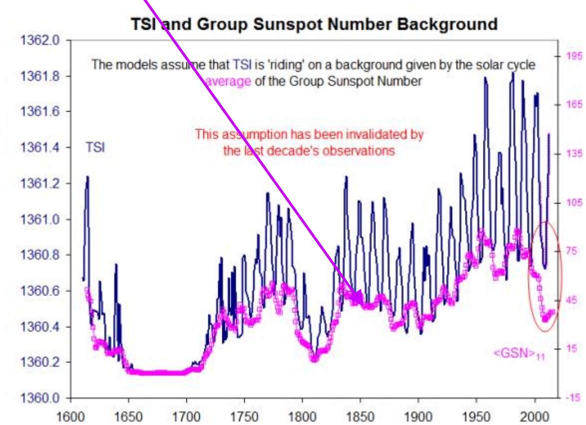
The relationship is not quite linear in $SSN^{0.5}$, but rather in $SSN^{0.7}$ which is a very close [and much simpler] fit to Fröhlich's polynomial

Using Fröhlich's Relationship



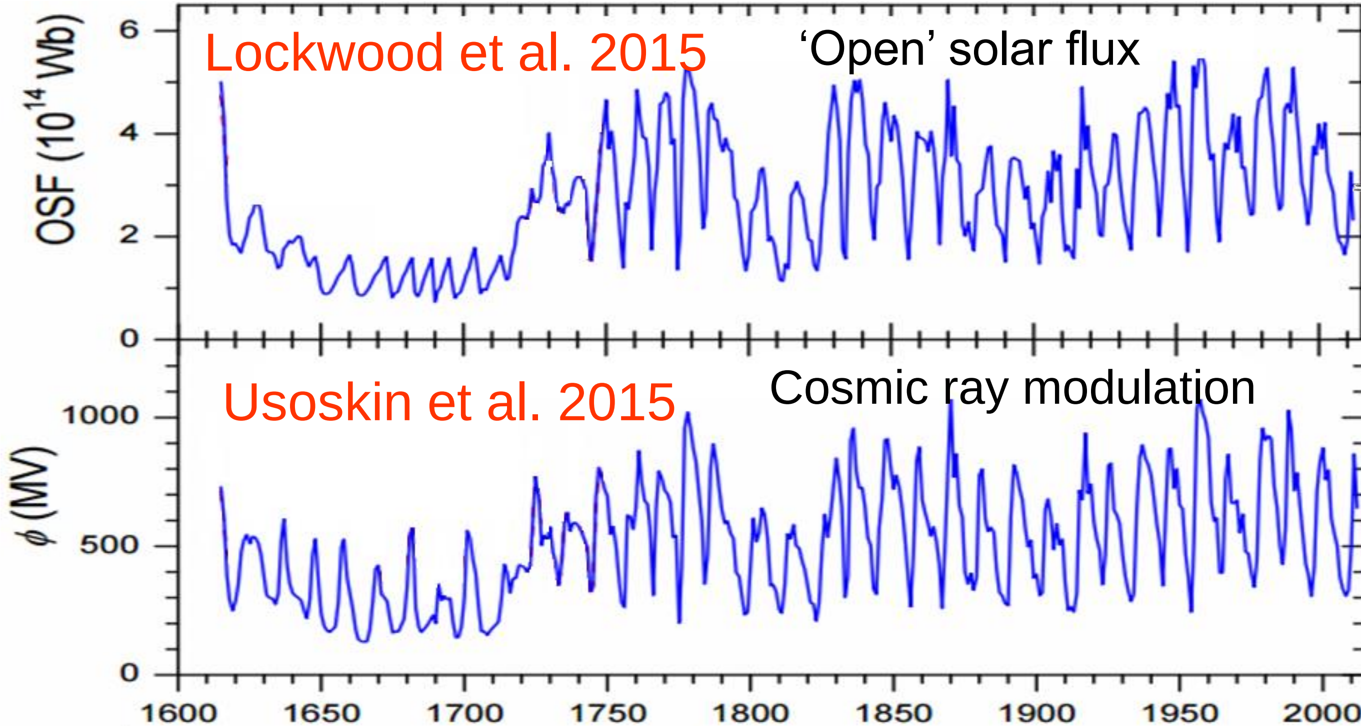




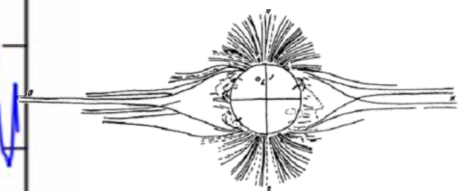


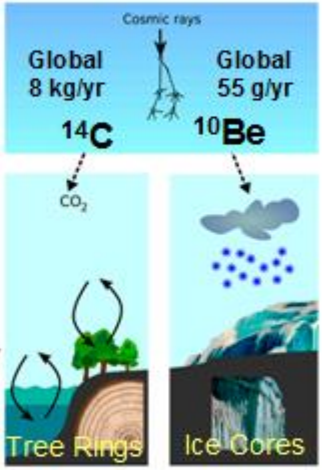
But there is no slowly varying Background acting as Climate Forcing.

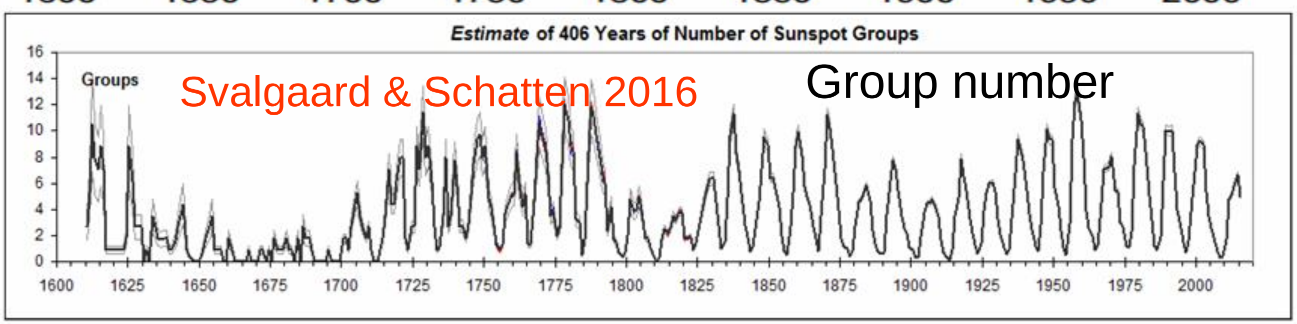
Putting it All Together (Real Progress!)



Solar Eclipse 1954



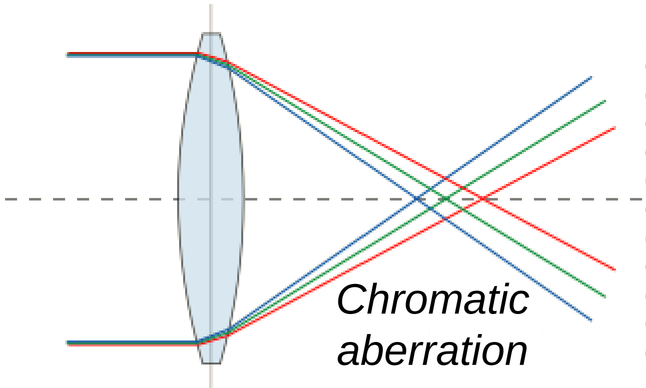


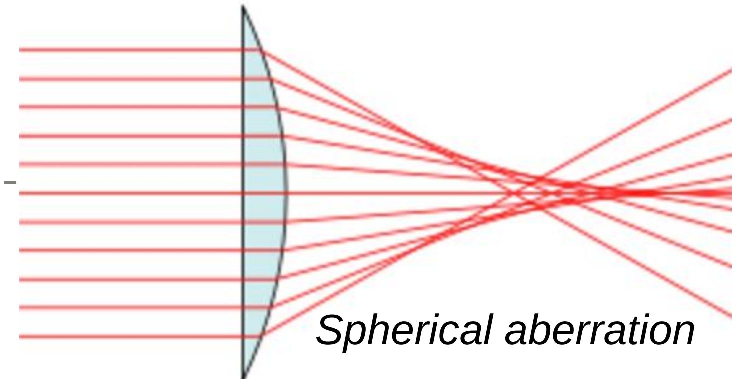


Very good agreement between different reconstructions.

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

18th Century Amateur Telescopes had Lenses with Aberrations





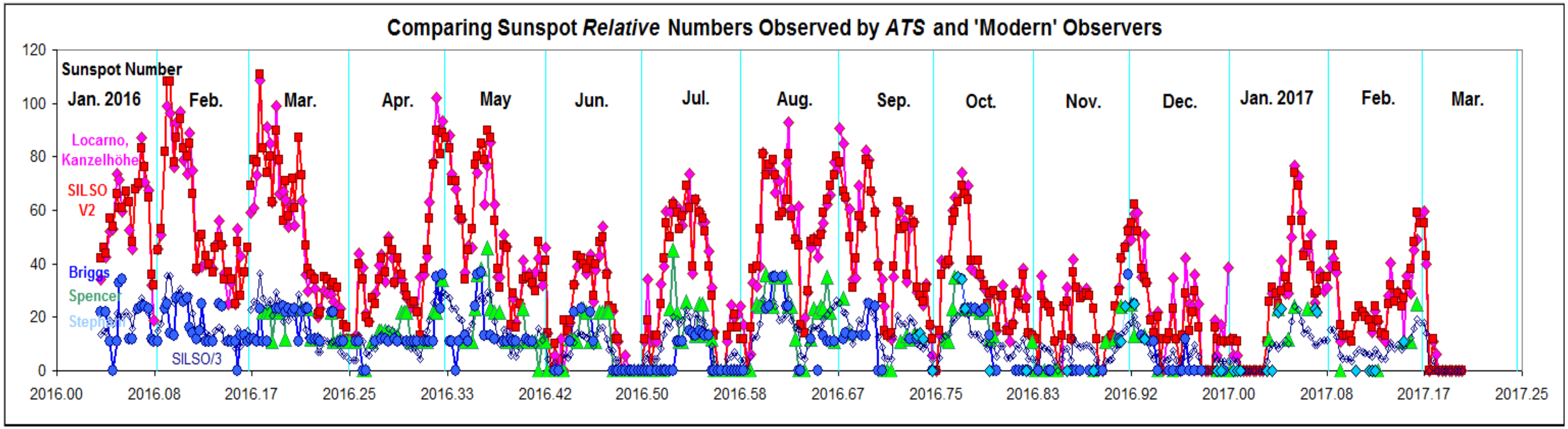
To estimate the effect of those imperfections we built replicas with the same flaws…

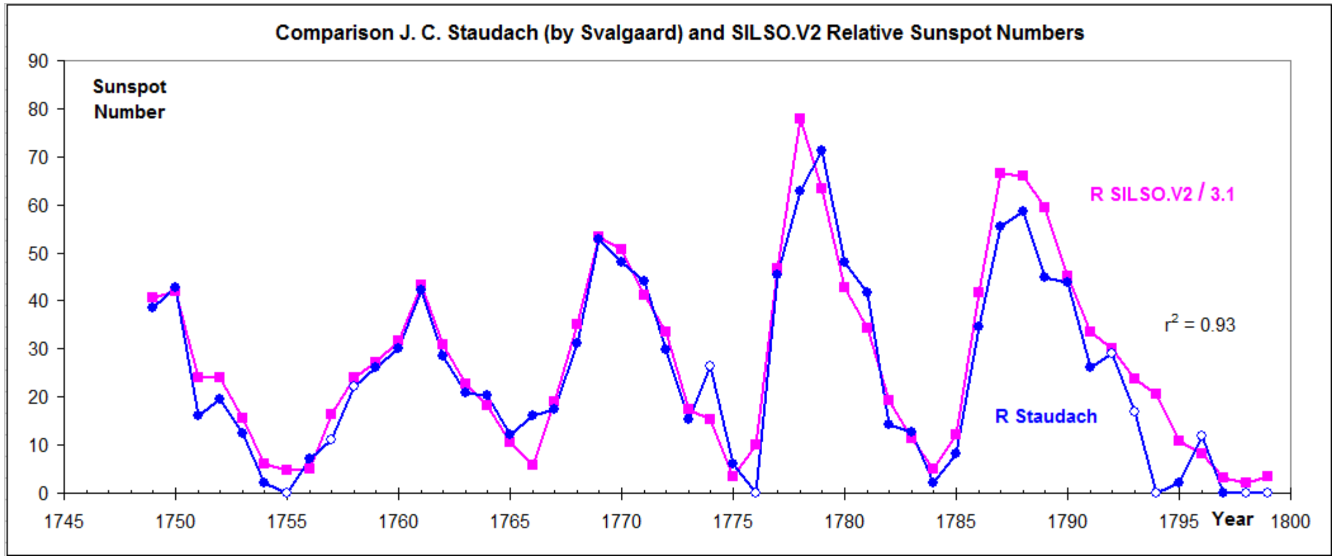
the Antique Telescope Society

Telescopes from the mid-1700s

Stephani, Germany

We Find that the Replicas show only a Third of the Spots that Modern Observers See

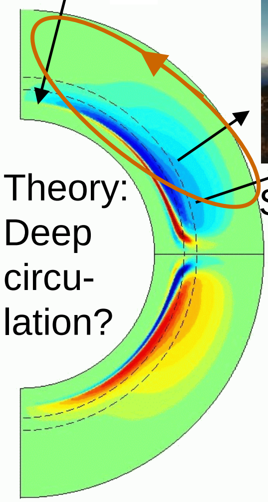




This verifies [or at least makes plausible] the calibration factors we had determined from the sunspot records themselves

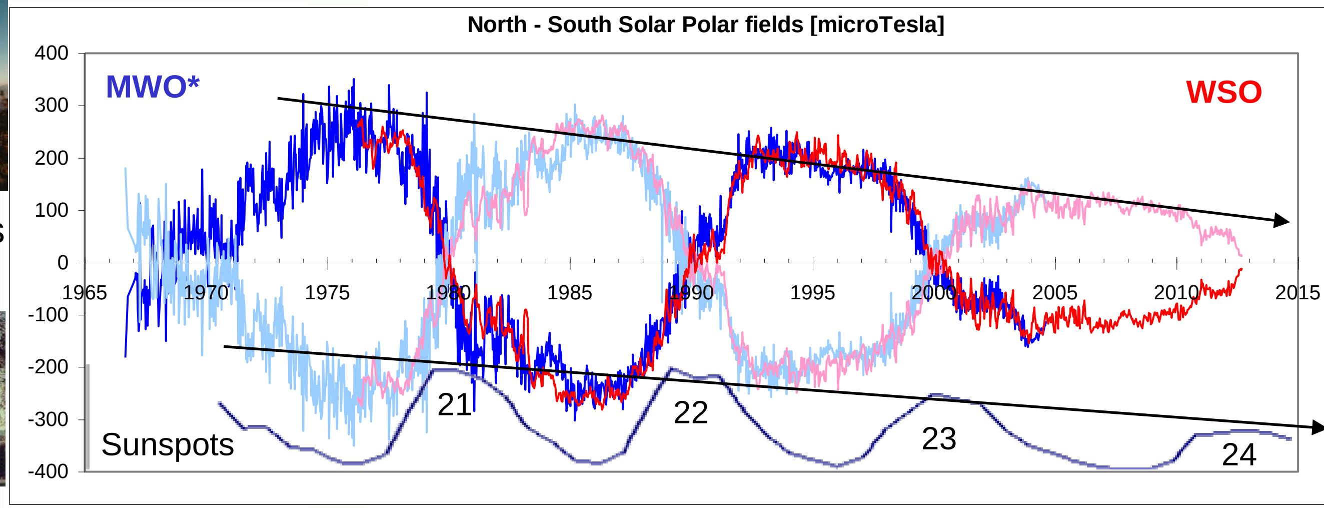
So, what will Solar Activity be in the Future? Can we predict Solar Activity?

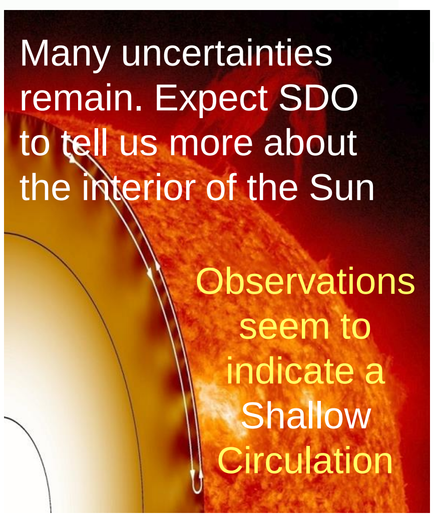
Polar Fields

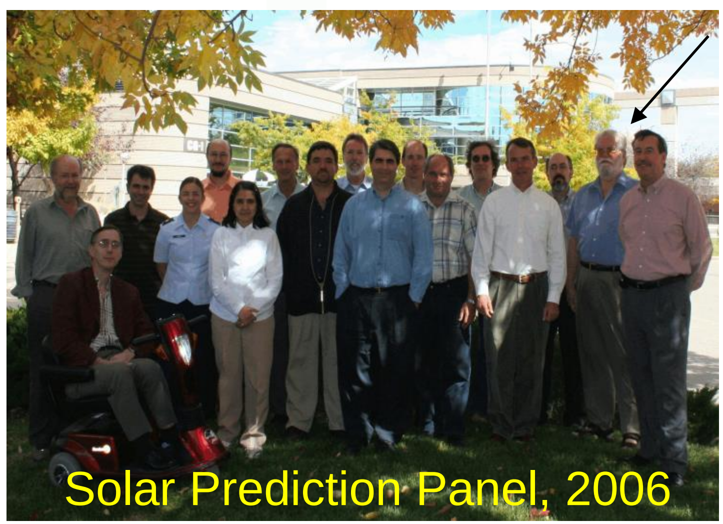


Theory: Deep circu- lation?

Sunspots







Solar Prediction Panel, 2006

Observations and theory suggest that the magnetic field at the poles of the Sun at solar minimum is a good predictor of the next solar cycle.

The low polar fields at the recent minimum predicted a small cycle 24

Polar Fields Predict Sunspot Cycle

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

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

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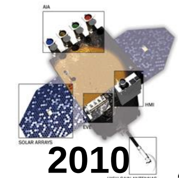
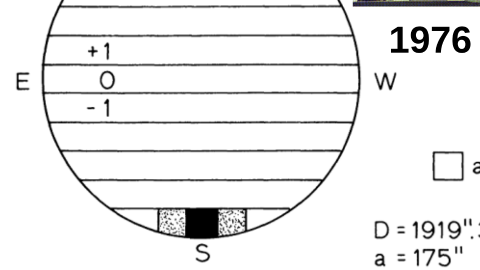
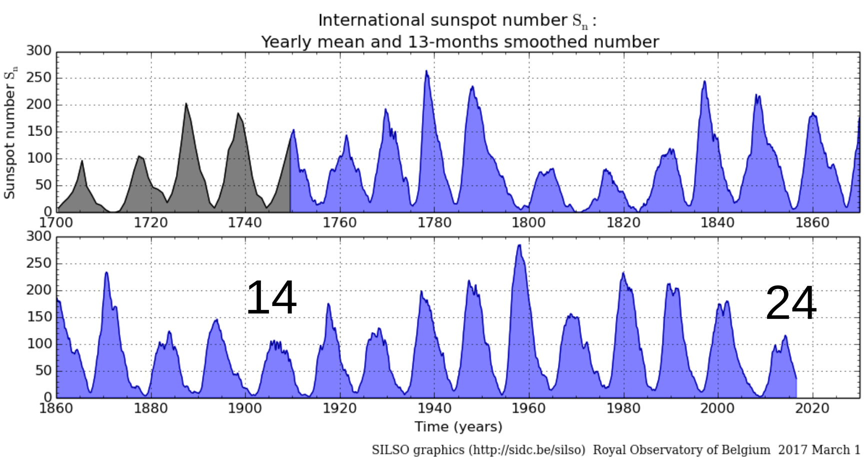
Abstract. On physical grounds it is suggested that the sun's polar field strength near a solar minimum is closely related to the following cycle's solar activity.

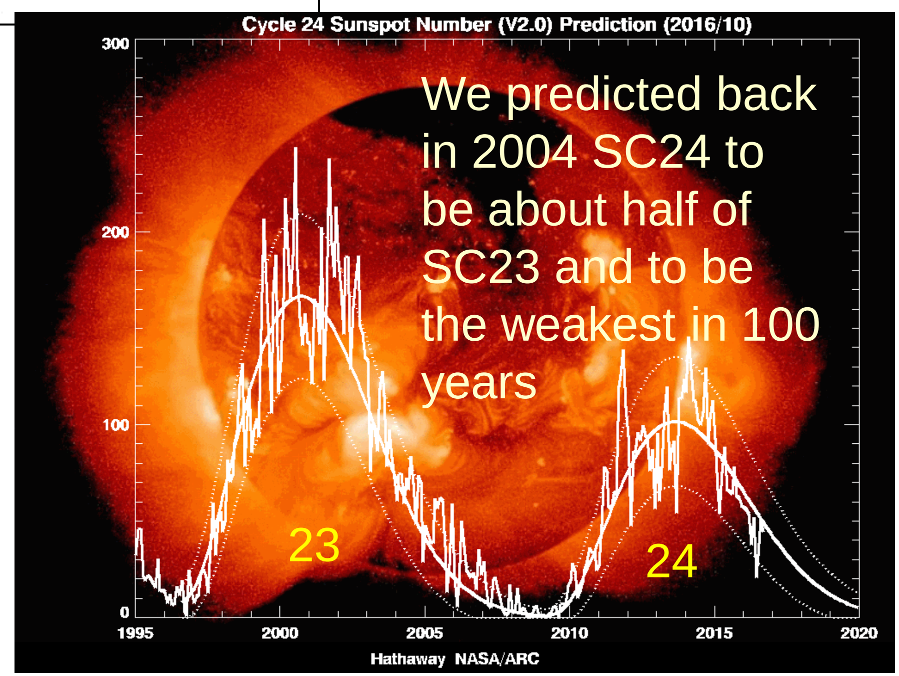




1976



Currently, the polar fields are at least as strong as before cycle 24, so cycle 25 will be at least as strong as 24.



Abstract

When Marconi in 1902 demonstrated that radio communication across the Atlantic Ocean at a distance of 2000 miles it became clear that an electric 'mirror' existed high in the atmosphere to guide the radio waves around the curvature of the Earth. Kennelly and Heaviside independently suggested that a layer of ionized gas, the 'ionosphere' at an altitude of 60-100 miles was responsible for the effect, but it was only more than two decades later that the existence of such a layer was firmly established by the British scientist Appelton for which he received the 1947 Nobel Prize in Physics. Physicists long resisted the idea of the reflecting layer because it would require total internal reflection, which in turn would require that the speed of light in the ionosphere would be greater than in the atmosphere below it. It was an example of where the more physics you knew, the surer you were that it couldn't happen. However, there are two velocities of light to consider: the phase velocity and the group velocity. The phase velocity for radio waves in the ionosphere is indeed greater than the Special Relativity speed limit making total internal reflection possible, enabling the ionosphere to reflect radio waves. Within a conducting layer electric currents can flow. The existence of such currents was postulated as early as 1882 by Balfour Stewart to explain the diurnal variation [discovered in 1722] of the Earth's magnetic field as due to the magnetic effect of electric currents flowing in the high atmosphere; such currents arising from electromotive forces generated by periodic (daily) movements of an electrically conducting layer across the Earth’s permanent magnetic field. Today, we know that solar Extreme Ultraviolet radiation is responsible for ionizing the air and that therefore the ionospheric conductivity varies with the solar cycle [e.g. as expressed by the number of sunspots]; so, observations of the Sun are vital in monitoring and predicting radio communications for Amateurs and Professional alike. Conversely, centuries-long monitoring of variations of the Earth's magnetic field can be used to determine long-term variations of solar activity. The talk weaves these various threads from multiple scientific and engineering disciplines together to show the unity of scientific endeavor and its importance for our technological civilization.