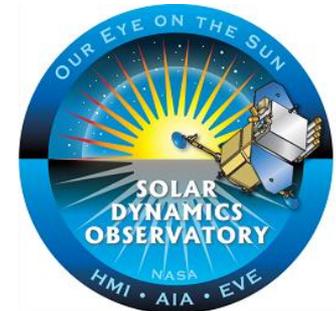


Radio, Ionosphere, Magnetism, and Sunspots

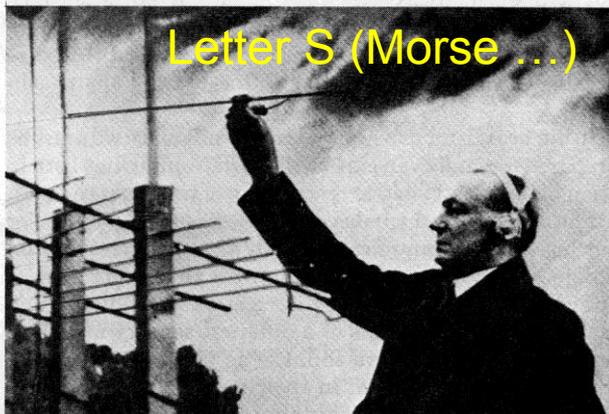


Leif Svalgaard
Stanford University



January 9, 2019

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-



Guglielmo Marconi and his first wireless.

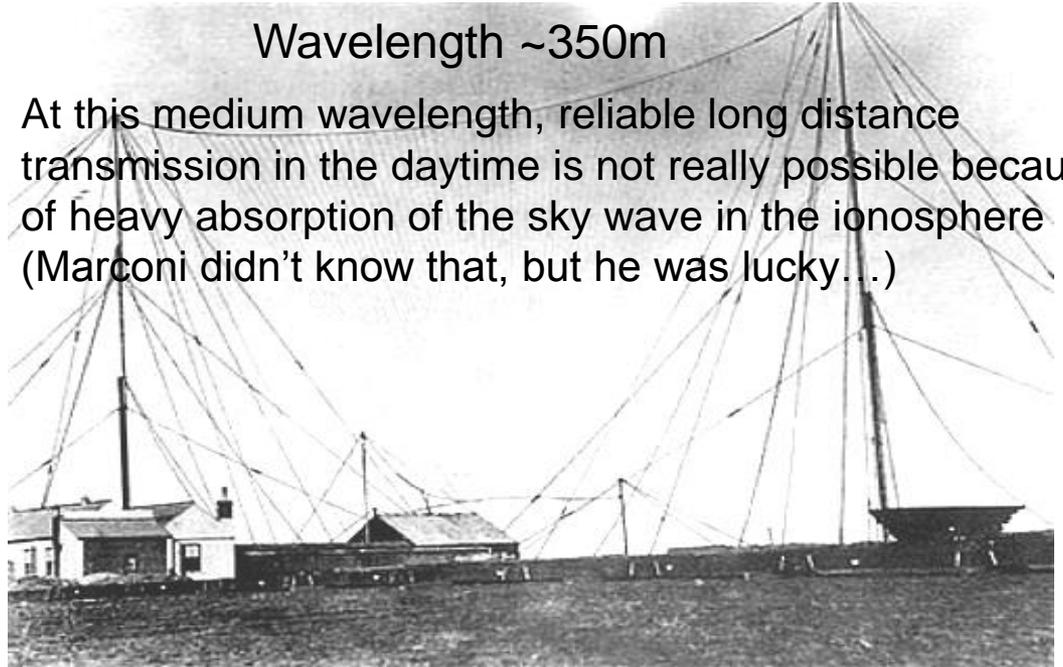
high antenna in Poldhu, Cornwall, England. Then, he erected a receiver in St. John's, Newfoundland, Canada. In spite of the earth's curvature, he received a Morse signal corresponding to the letter "S" from the Poldhu station across the ocean.

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).

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, but he was lucky...)



Later he managed to send a message from US president Theodore Roosevelt to the King of the UK via his Glace Bay station in Nova Scotia, Canada, across the Atlantic on 18 January 1903.

Kennelly Suggested a Wave Guide

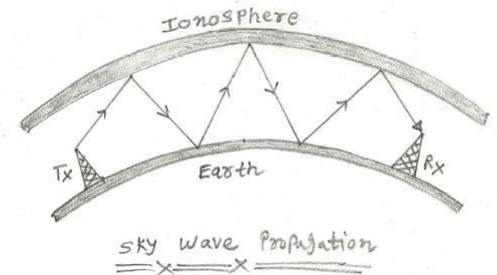
On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere.

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.



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.”

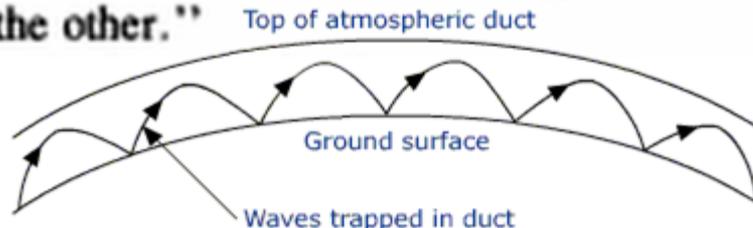
Heaviside proposed another possibility.

The actual correspondence is not available, but an account⁵⁶ has been given by Eccles⁵⁷:

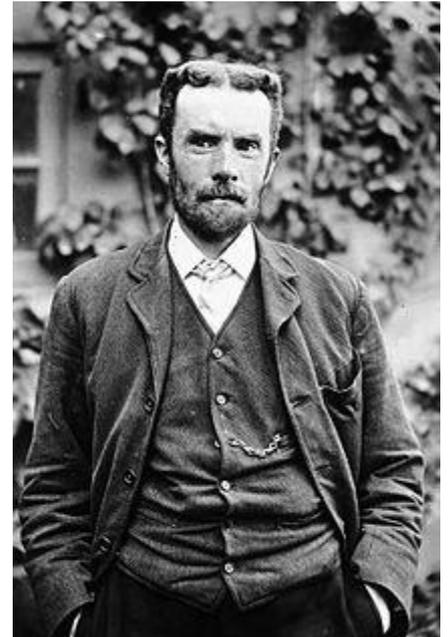
In the spring of 1902 I was writing from time to time on wireless **telegraphy** in the pages of *The Electrician*, and one day Mr. Tremlett Carter, the editor, showed me a letter from Mr. Oliver **Heaviside** which, while discussing other things, asked if the recent success of Mr. Marconi in telegraphing 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 correspondence⁵⁸ with *The Electrician*), it merely made Oliver look for an alternative outlet. He found this outlet in the form of an invited contribution⁵⁹ to the new (10th) edition of the *Encyclopedia Britannica*.

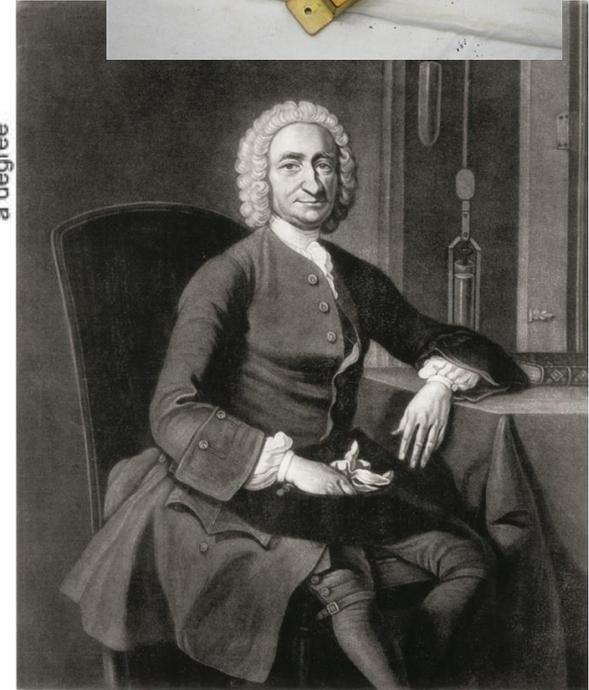
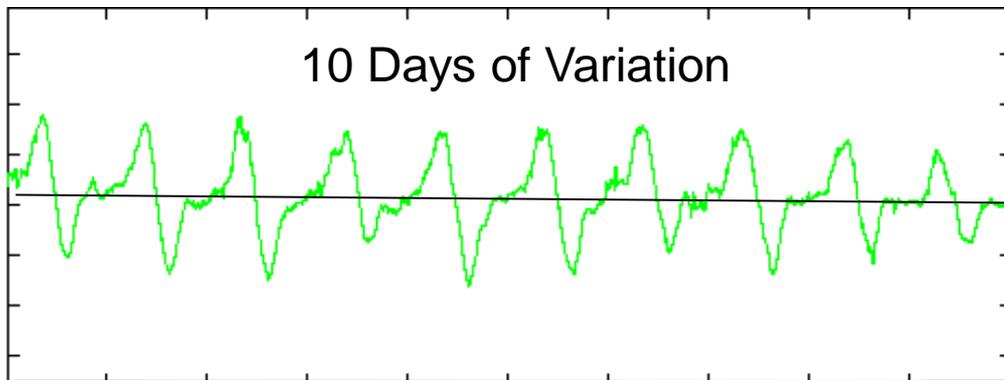
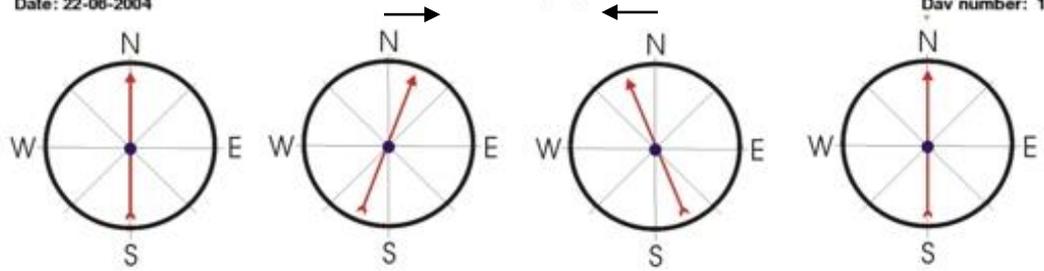
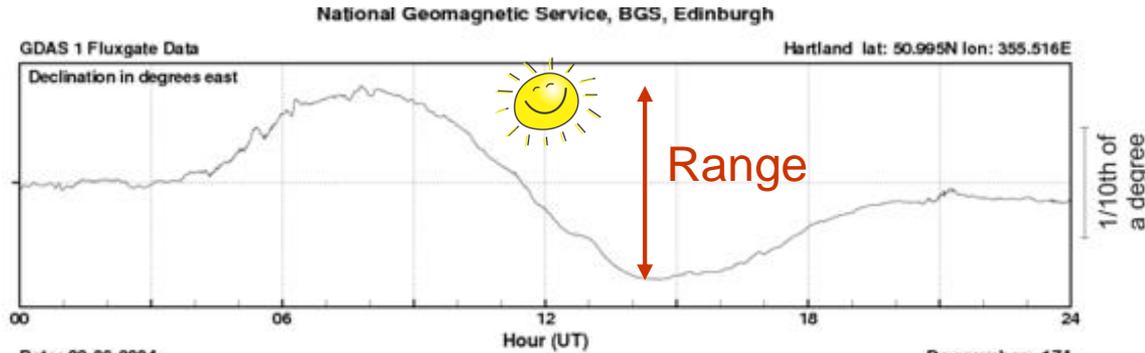
And then comes the *most* famous part of the article. “There is another consideration. There may possibly be a sufficiently conducting layer in the upper air. If so, the waves will, so to speak, catch on to it more or less. Then the guidance will be by the sea on one side and the upper layer on the other.”



Amateur radio operators (HAMs) began to use this effect in the 1920s at 200 meters

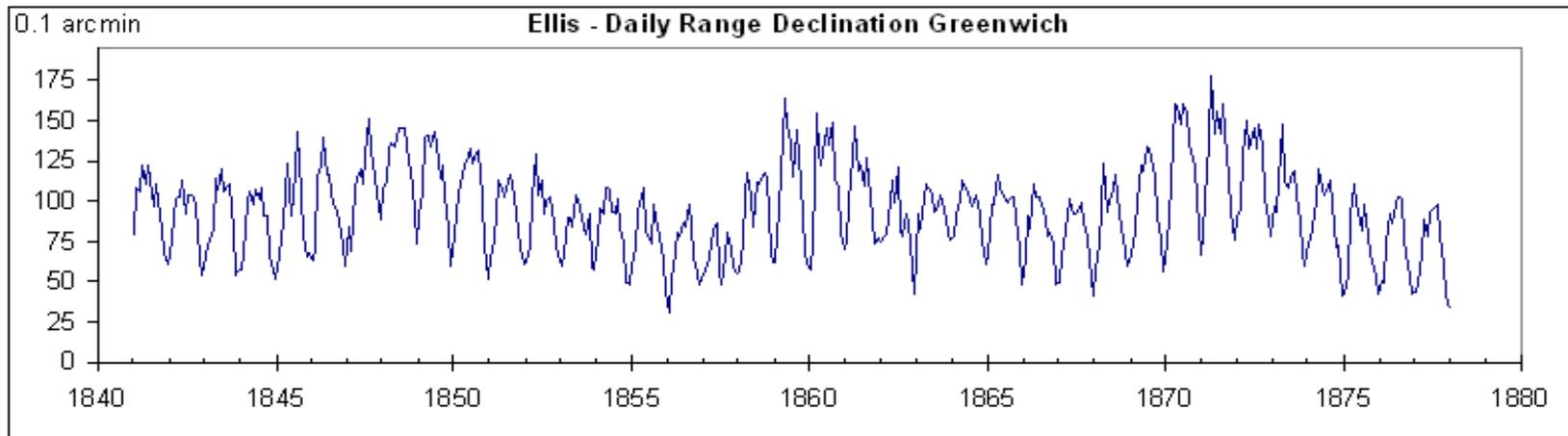
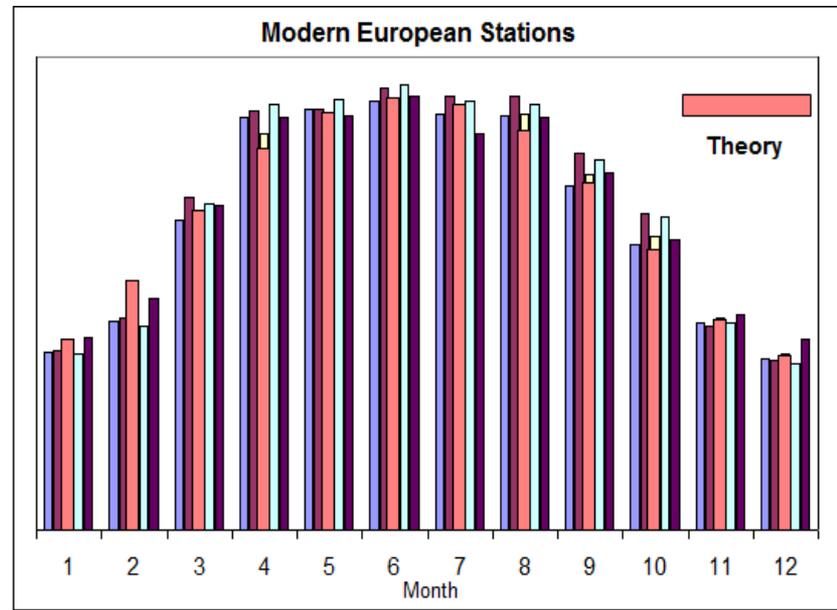
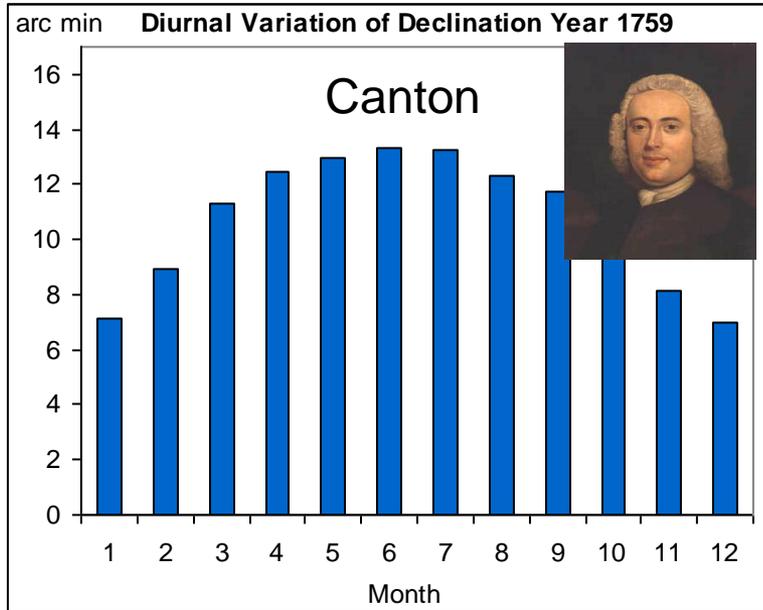


The Diurnal Variation of the Direction of the Magnetic Needle

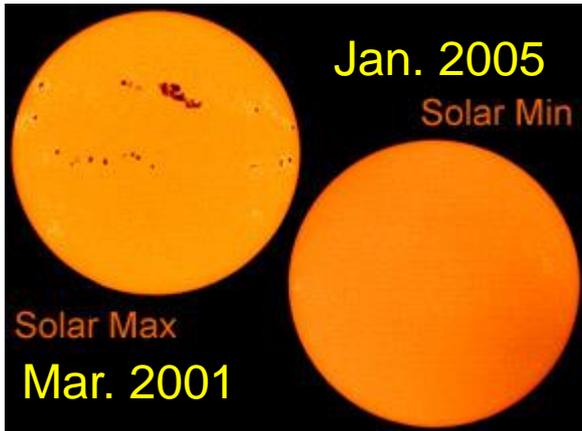
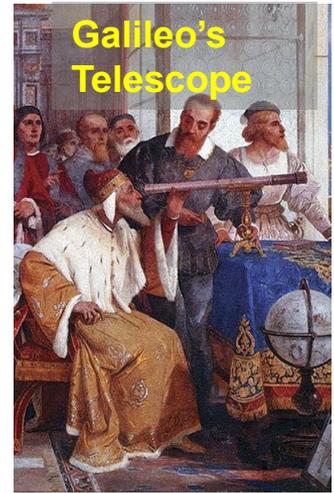


George Graham [London] discovered [1722] that the geomagnetic field varied during the day in a regular manner.

Zenith Angle Dependence Confirmed

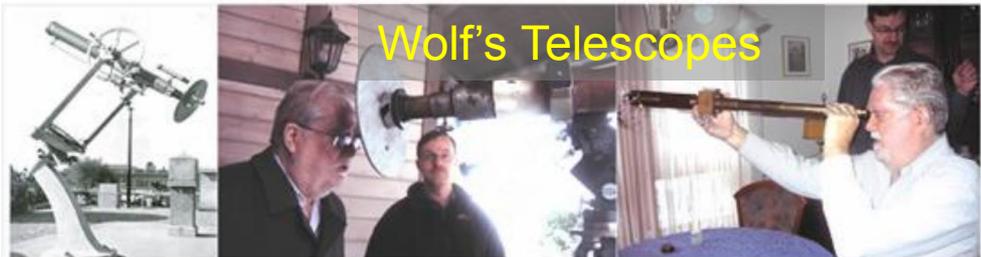
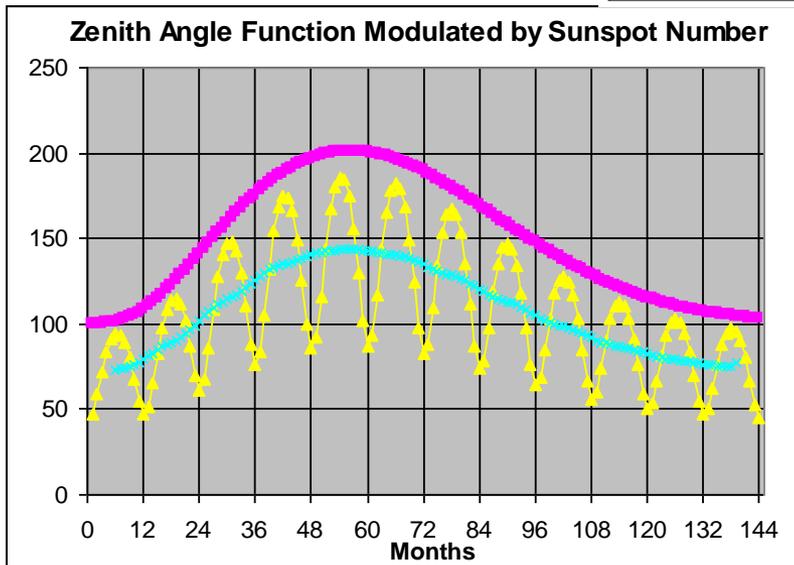
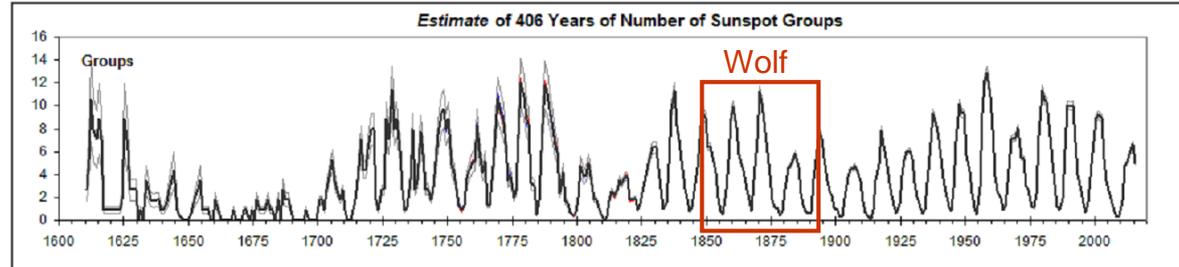
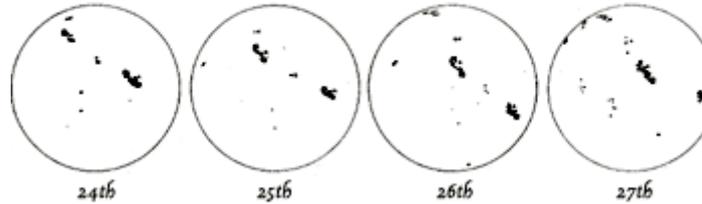


400-year Sunspot Cycle Record



SOHO Spacecraft

Sunspots drawn by Galileo, June 1612



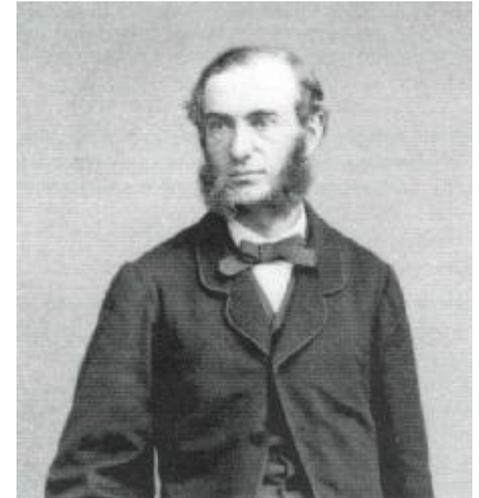
“Who would have thought just a few years ago that one could calculate a terrestrial phenomenon from observations of sunspots”



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.**”

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



Edward V. Appleton
1892-1965



Merle Anthony Tuve
1901-1982



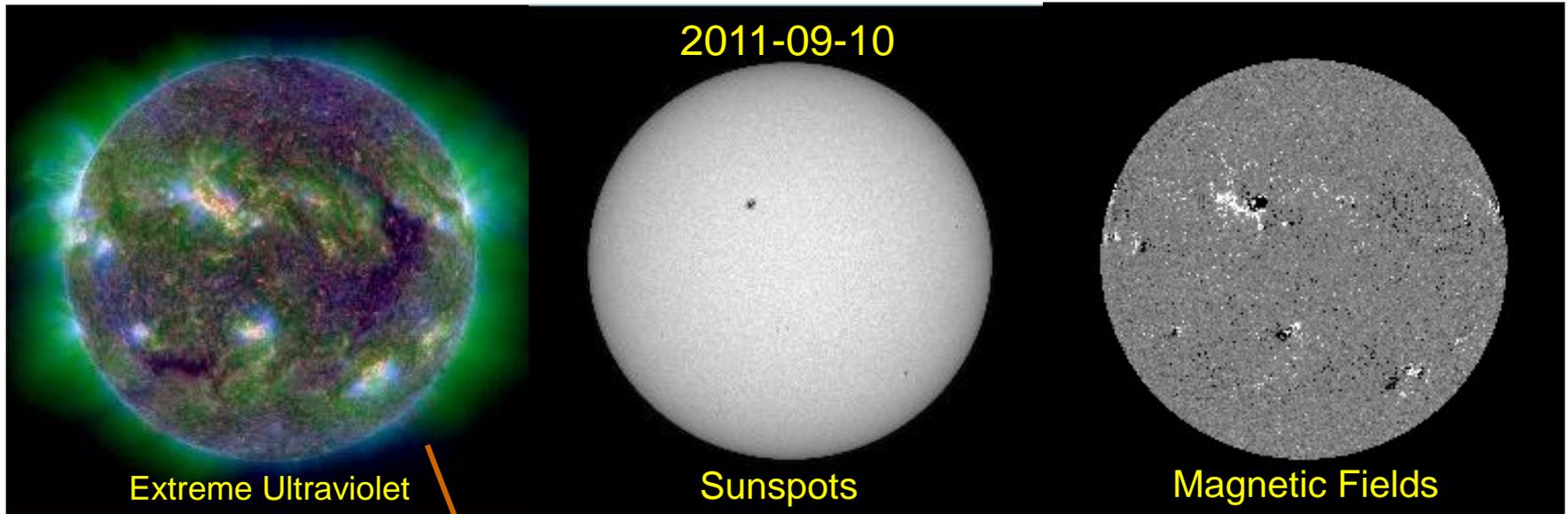
Grigory Breit
1899-1981

Discovered the
F-layer higher up

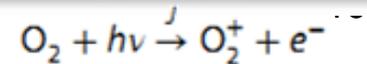
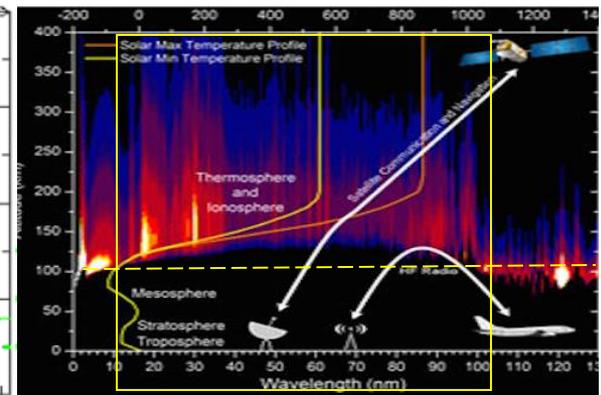
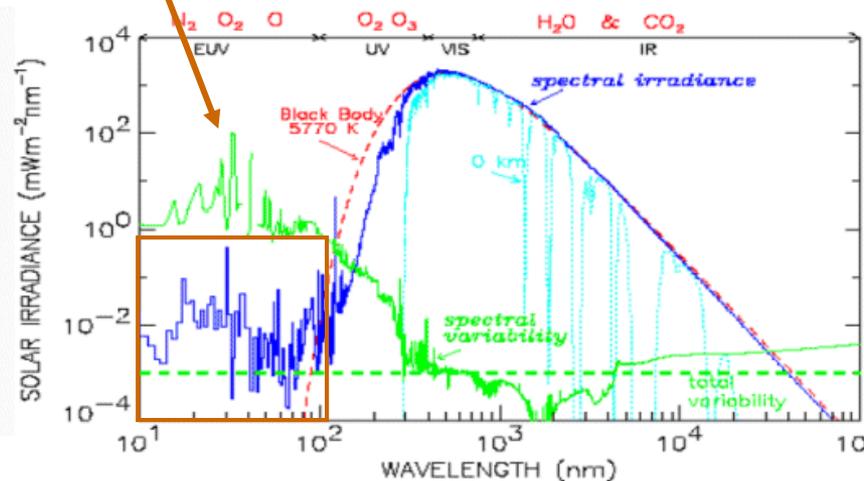
Nobel Prize 1947

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

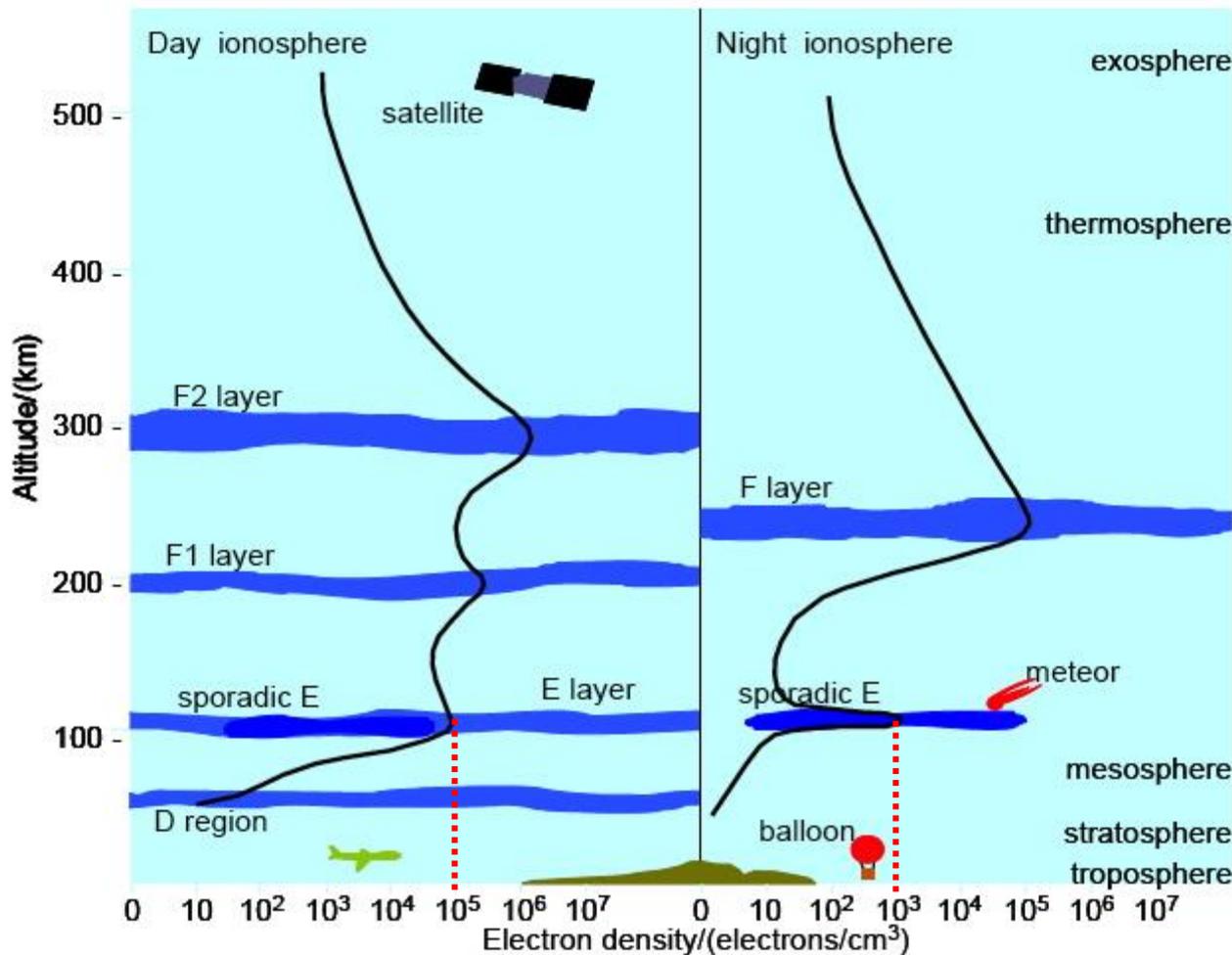
The Source of the Ionization



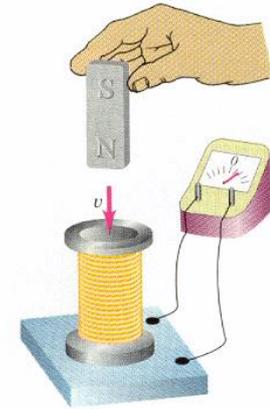
Extreme Ultraviolet (EUV), wavelengths 17.1-21.1-30.4 nm from chromosphere and corona with temperatures from 50,000 K to 2 million K



Ionospheric Conducting Layers



Dynamo

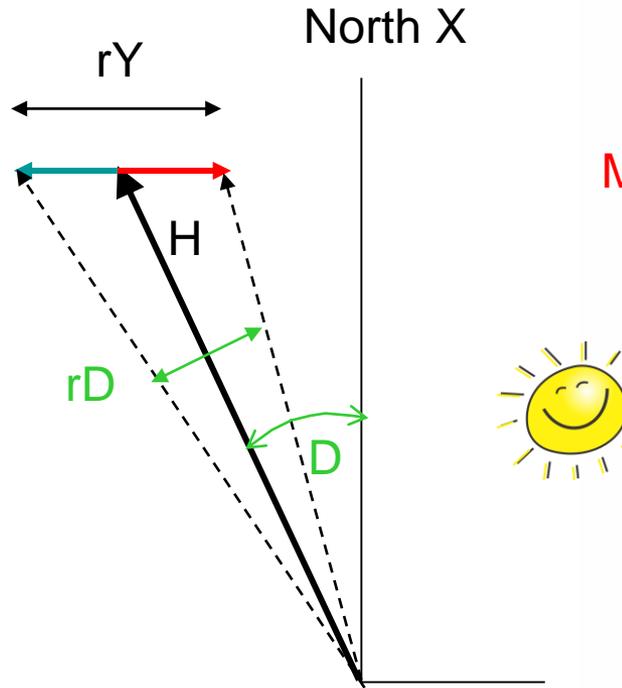
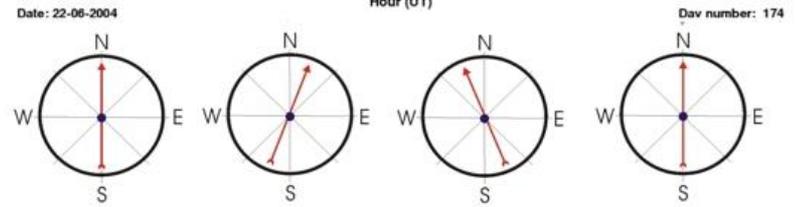


An effective dynamo process takes place in the dayside E-layer where the density, both of the neutral atmosphere and of the electrons are high enough.

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

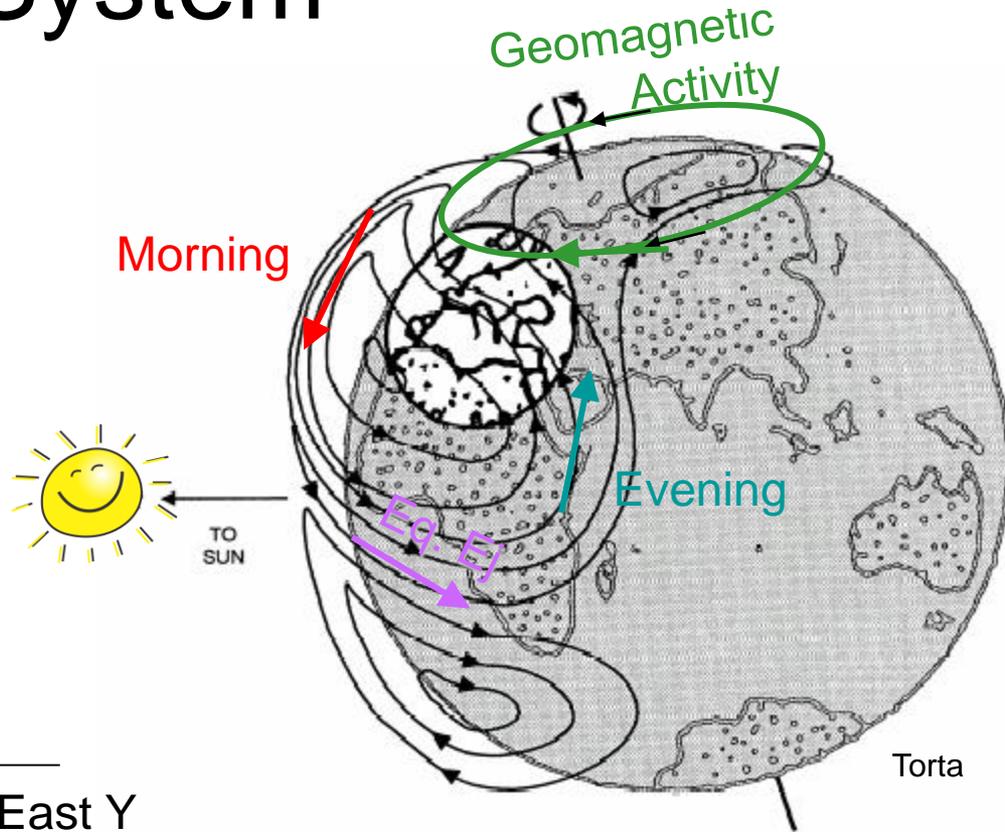
We need 1) something to produce the charges and 2) something to move them across the magnetic field

The E-layer Electric Current System



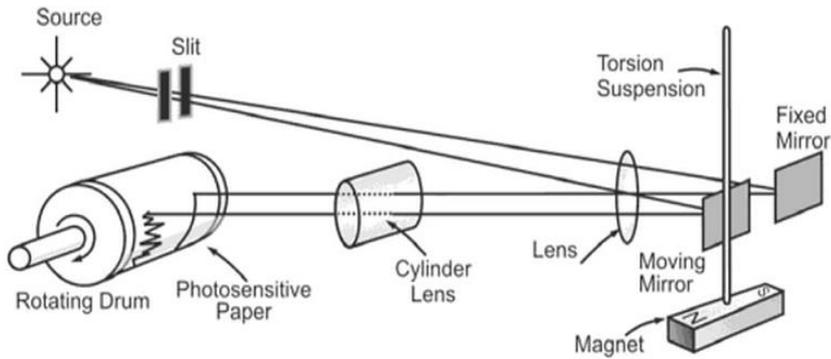
$$Y = H \sin(D)$$

$$dY = H \cos(D) dD \text{ For small } dD$$

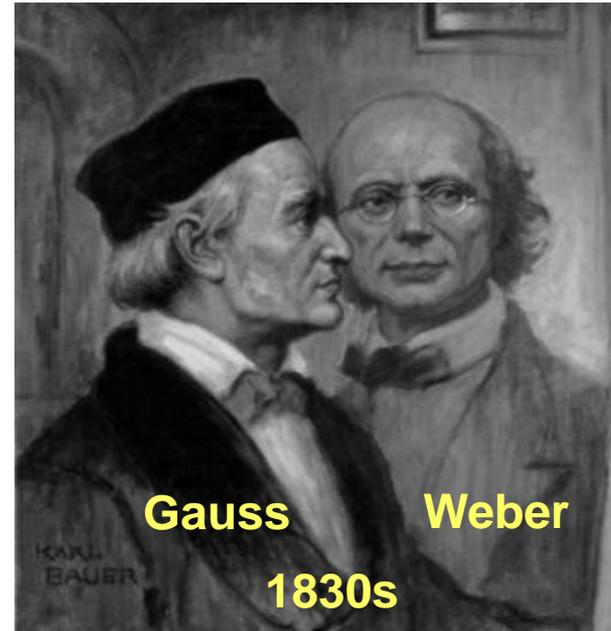
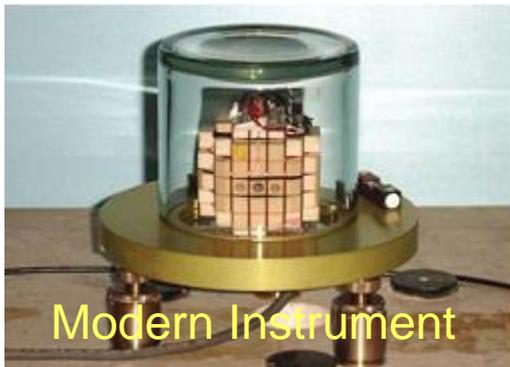
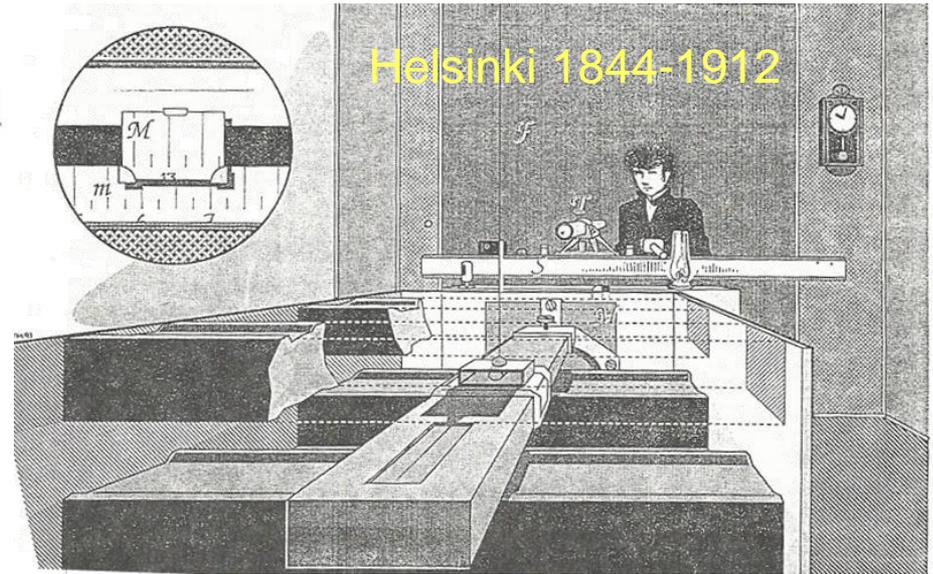


A current system in the ionosphere is created and maintained by solar EUV radiation

The magnetic effect of this system was what George Graham discovered

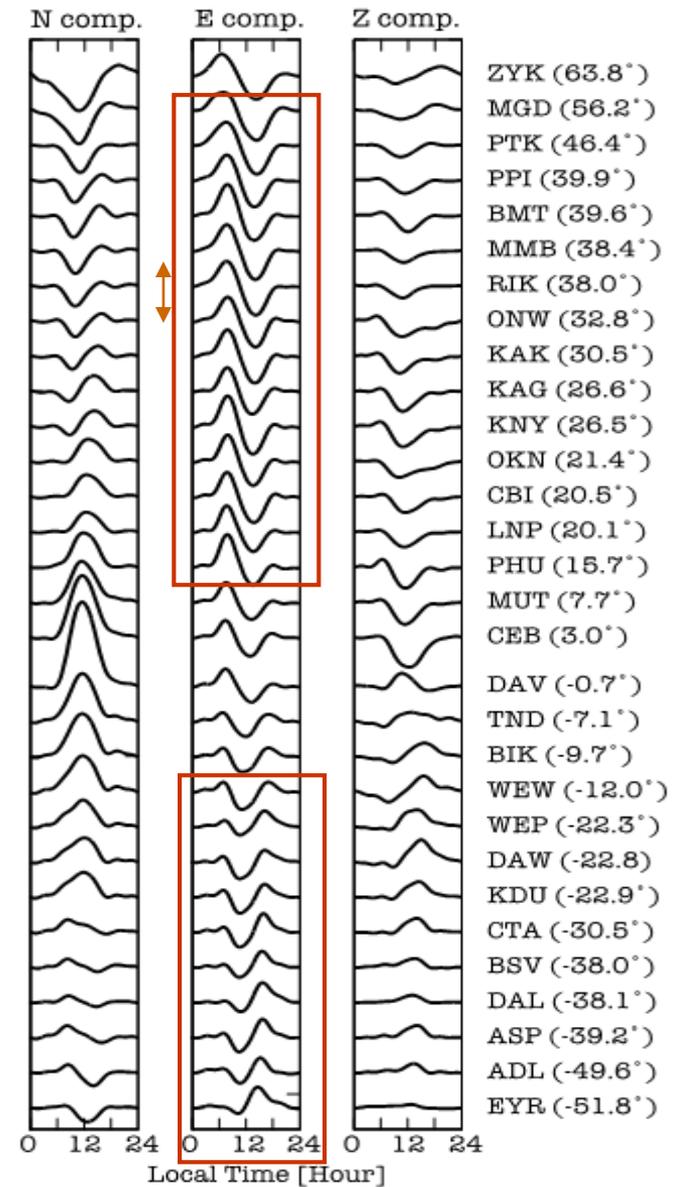
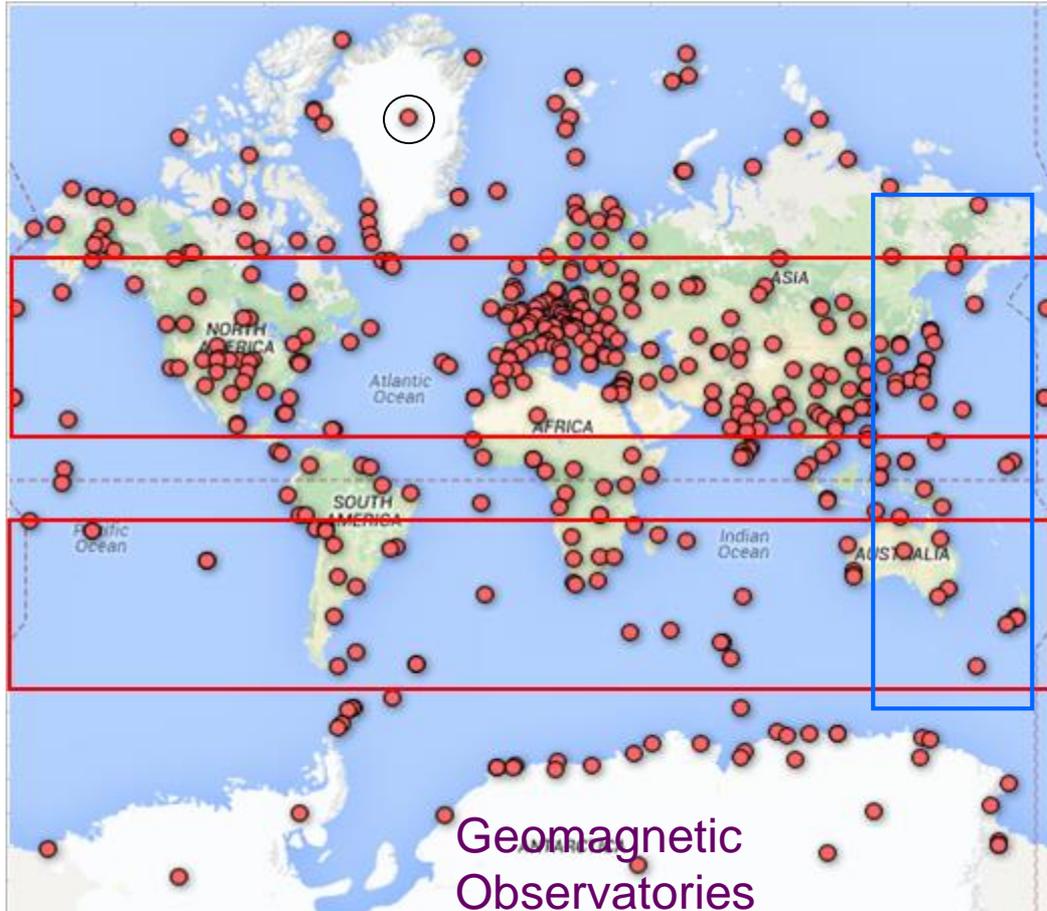


Classic Method since 1846



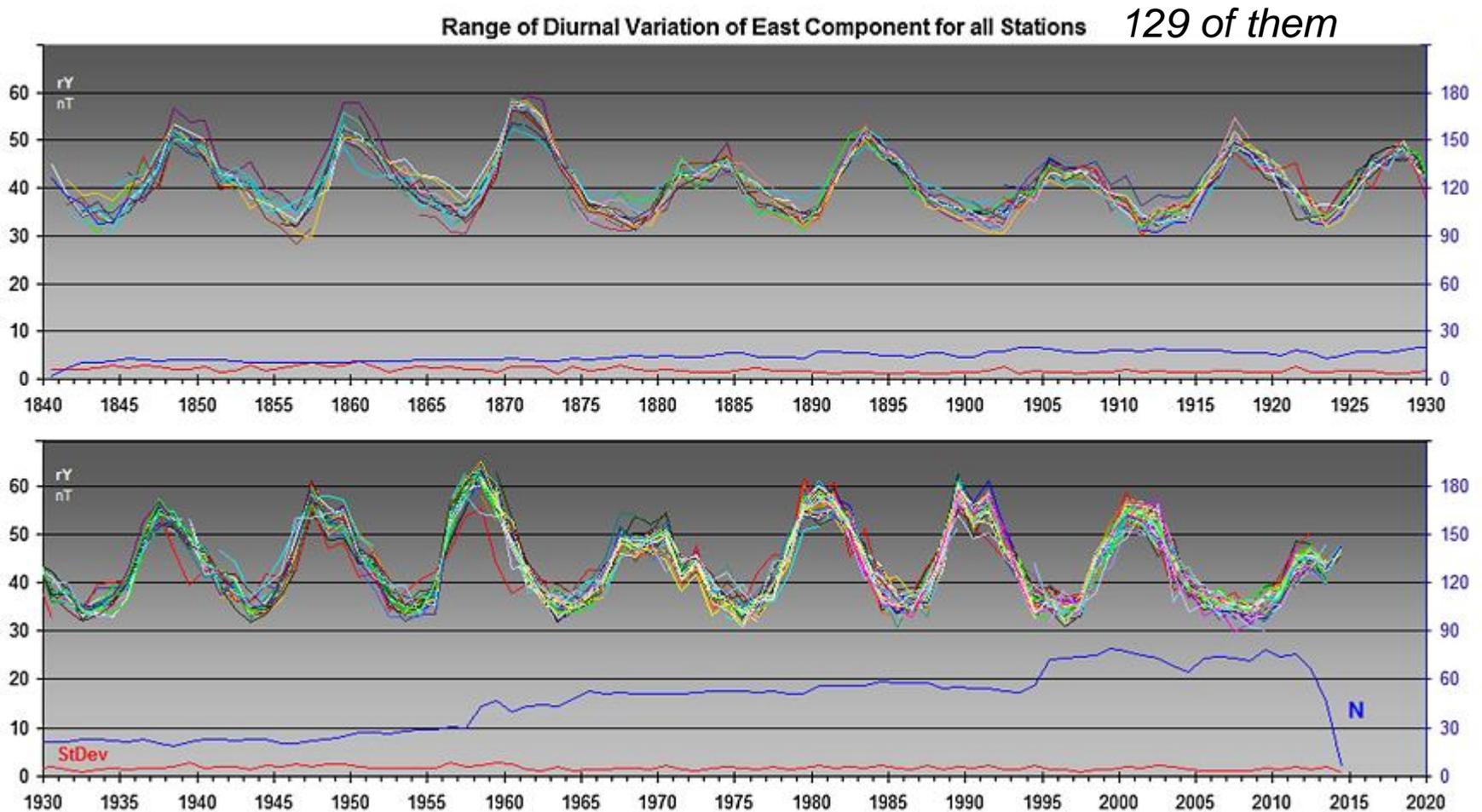
Magnetic Recording over Time

The Magnetic Signal at Mid-latitudes



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

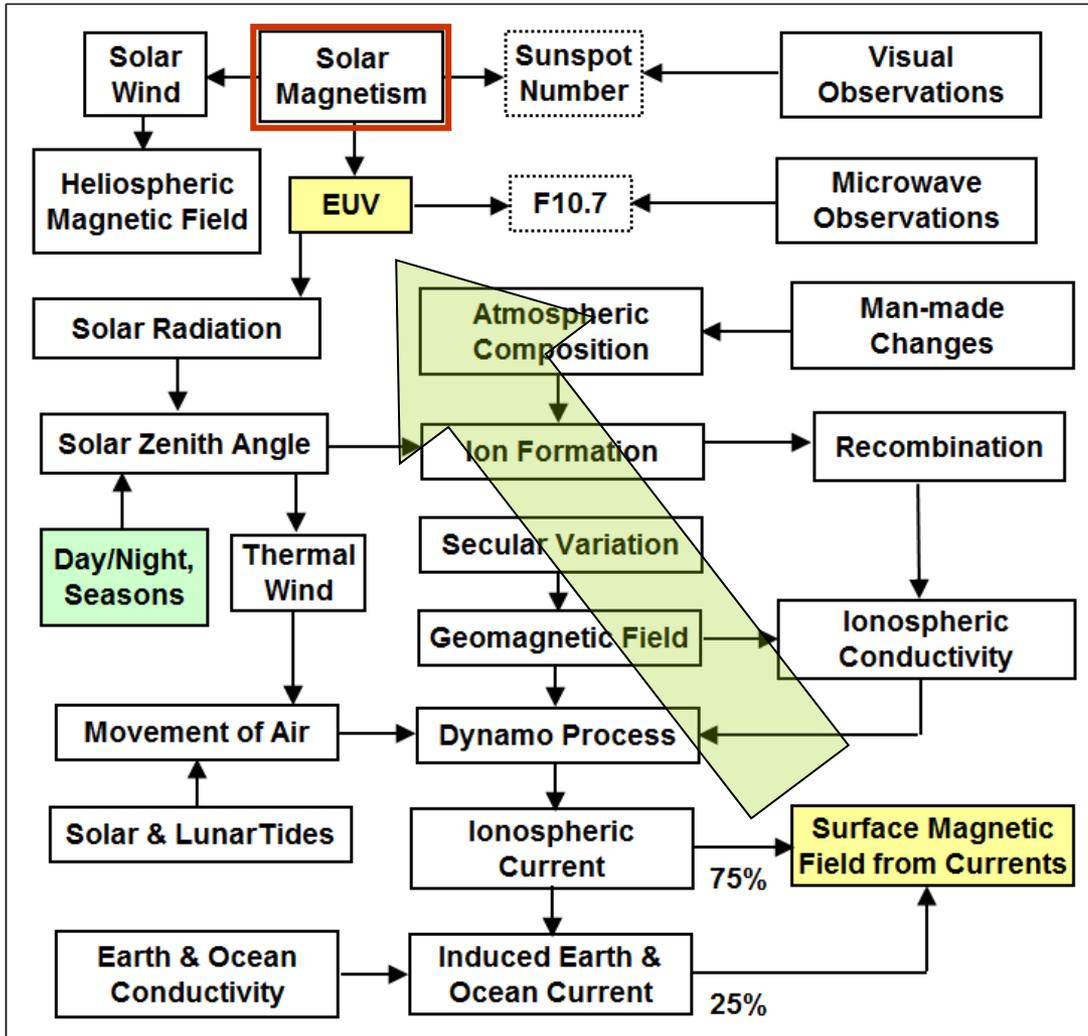
Observed Diurnal Ranges of the Geomagnetic East Component since 1840



We plot the yearly average range to remove the effect of changing solar zenith angle through the seasons. What remains is the solar cycle modulation.

The blue curve shows the number of stations

The Effect of Solar EUV

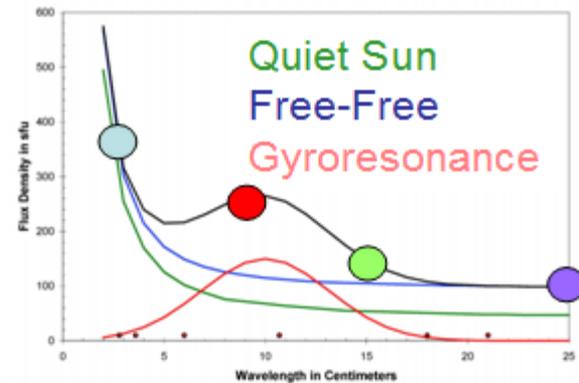
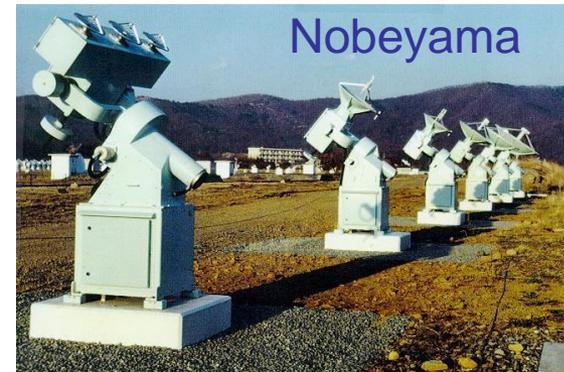
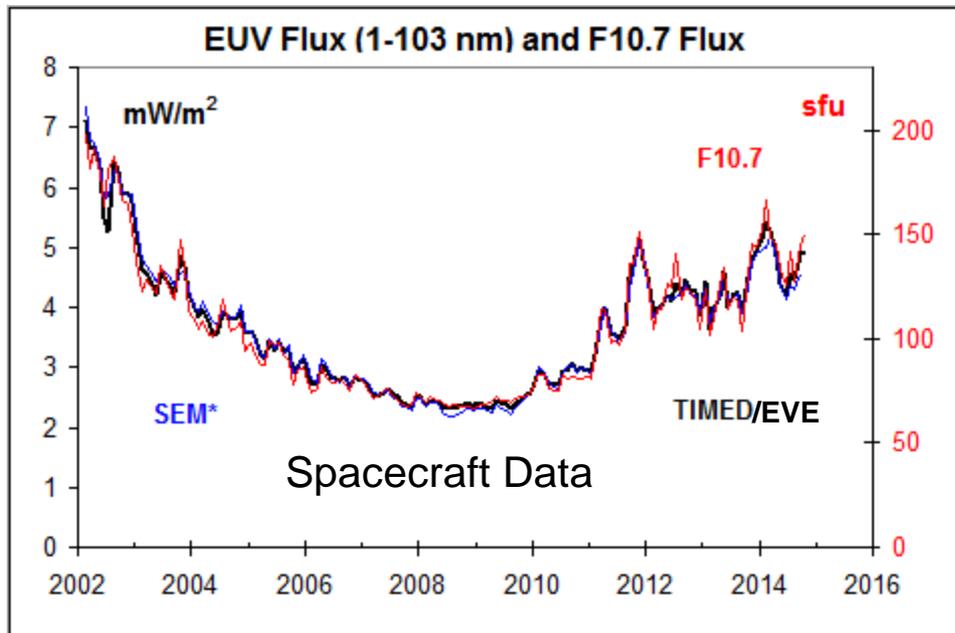
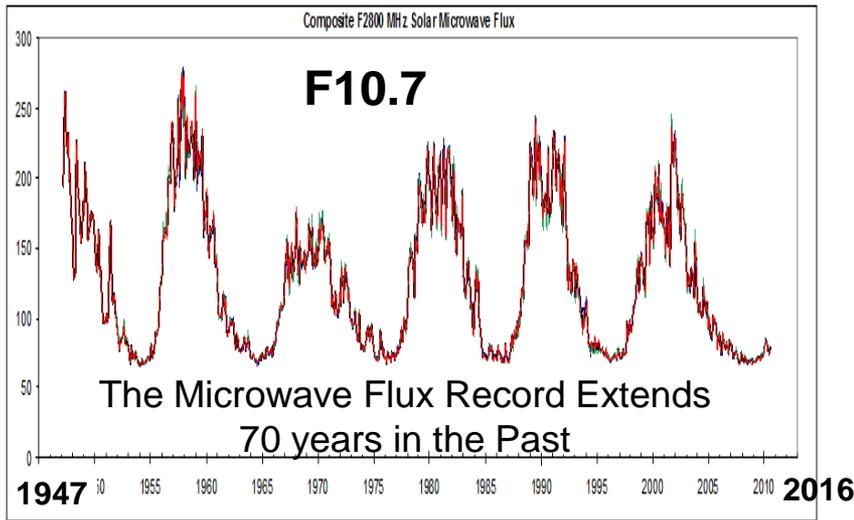


The EUV causes an observable variation of the geomagnetic field at the surface through a complex chain of physical connections.

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.

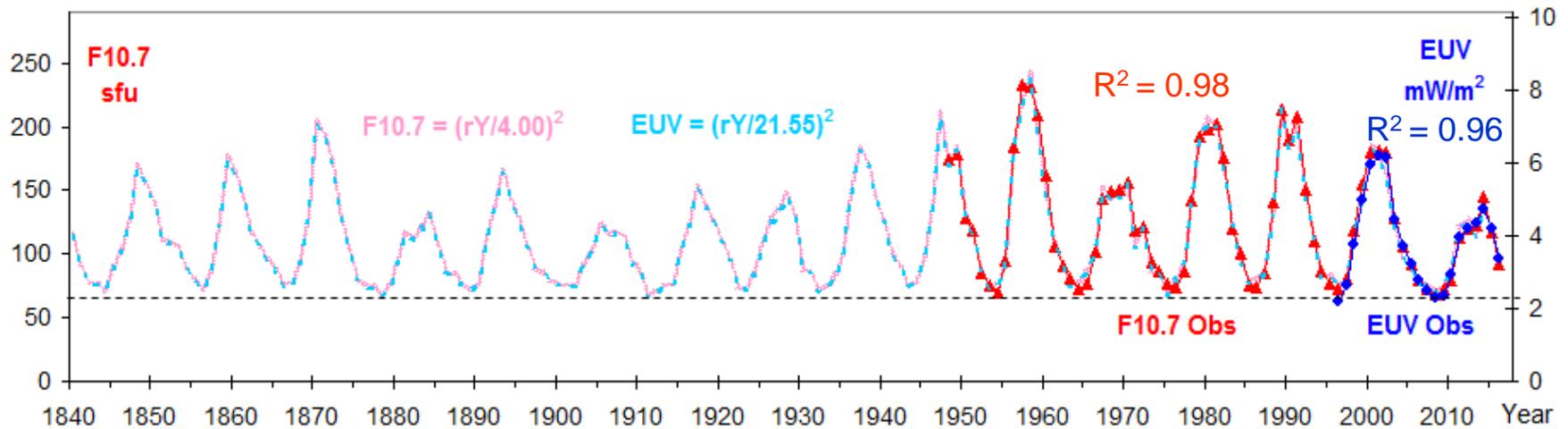
EUV and its proxy: F10.7 Microwave Flux



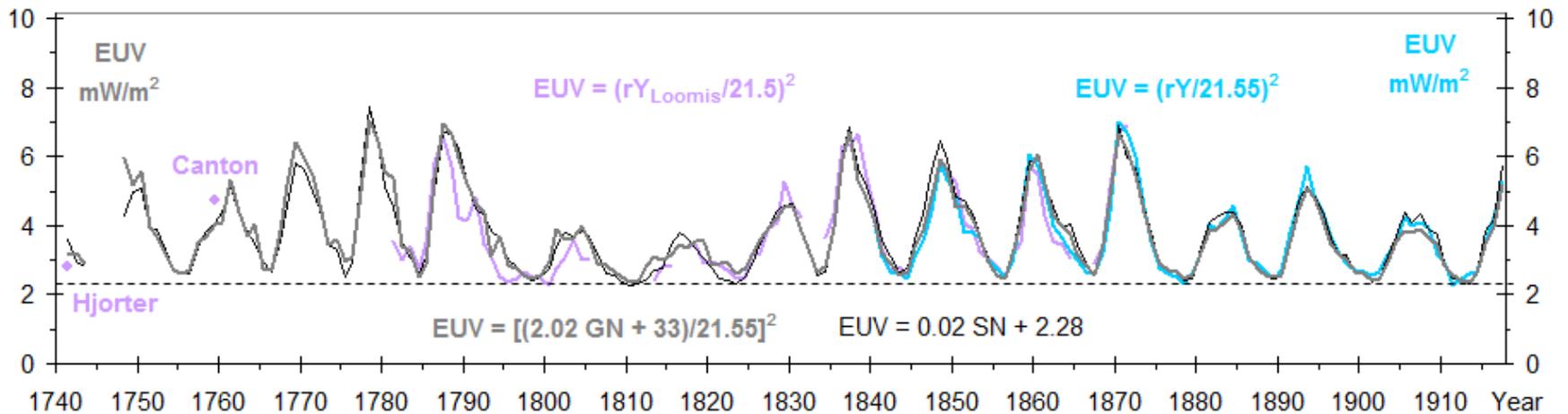
10.7 cm = 2800 MHz

Reconstructions of EUV and F10.7

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

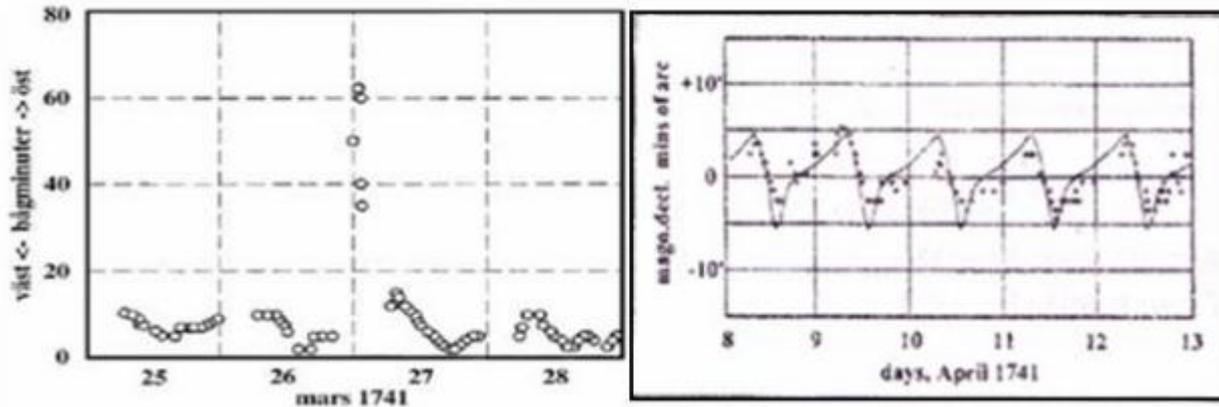


Reconstruction of EUV < 103 nm Flux



Observations in the 1740s

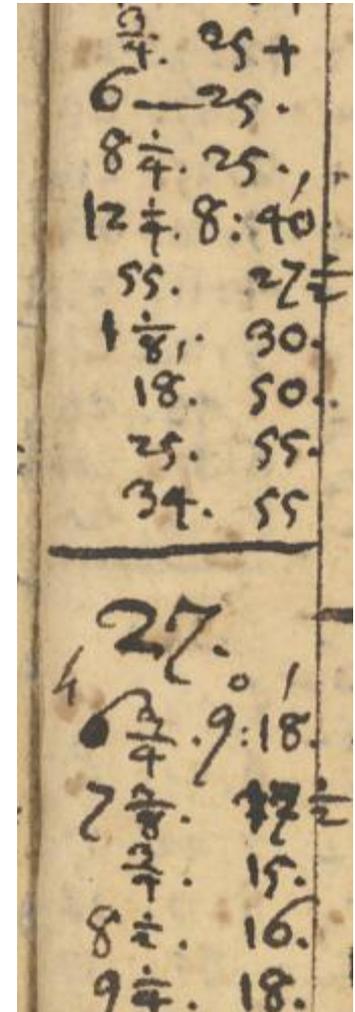
Olof Petrus Hjorter was married to Anders Celsius' sister and made more than 10,000 observations of the magnetic declination in the 1740s.



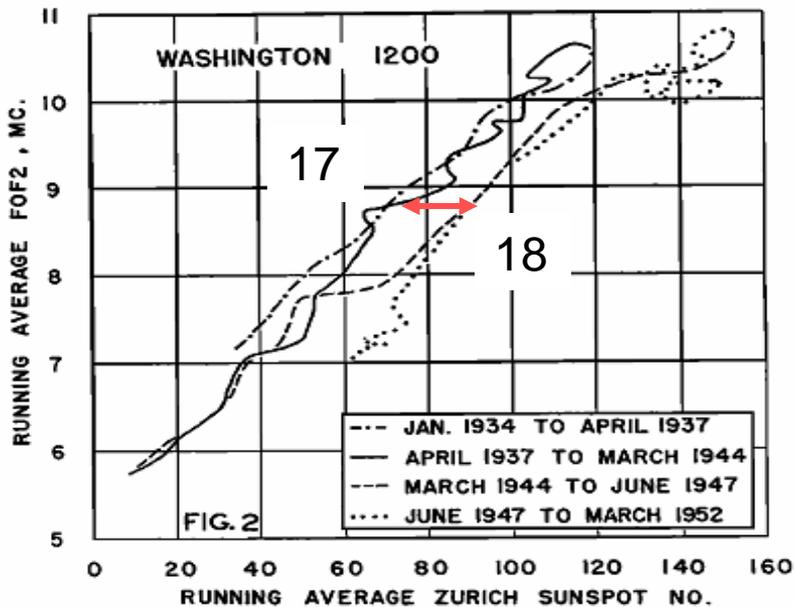
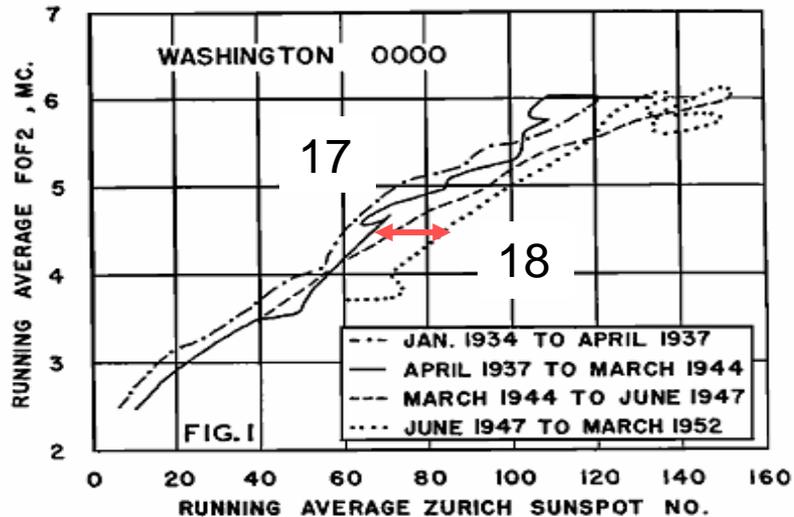
Right: Hjorter's measurements of the magnetic declination at Uppsala during April 8-12, 1741 (old style). The curve shows the average variation of the magnetic declination during April 1997 at nearby Lovö (Sweden).

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.



foF2



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

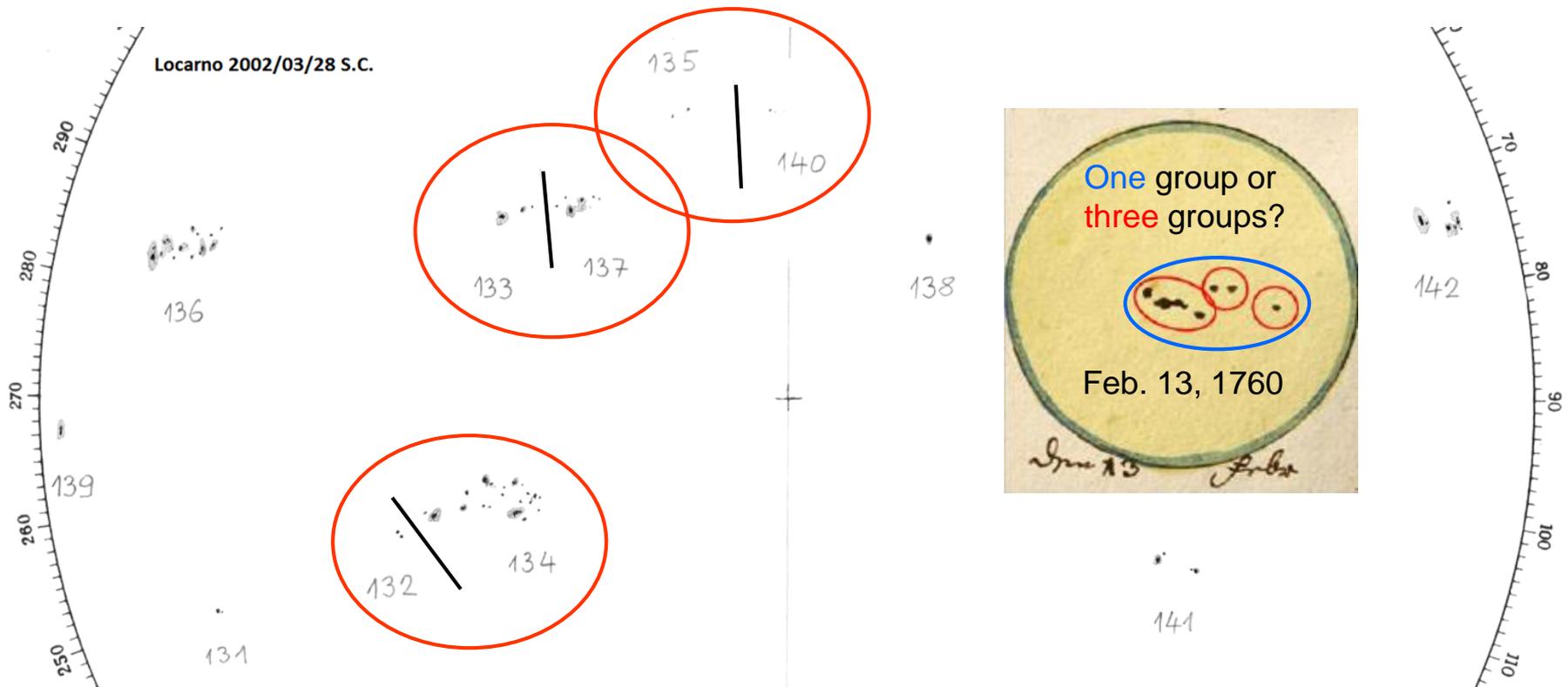
F2-layer critical frequency. This is the maximum radio frequency that can be reflected by the F2-region of the ionosphere at vertical incidence (that is, when the signal is transmitted straight up into the ionosphere). And has been found to have a profound solar cycle dependence.

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

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

One of the first signs that perhaps the sunspot number record was not quite correct...

Counting Sunspot Groups



Sunspots occur in Groups. It is sometimes hard to figure out which spots belong to which groups. The 'sunspot number' is defined as the number of groups times ten plus the number of spots: $W = 10 * G + S$

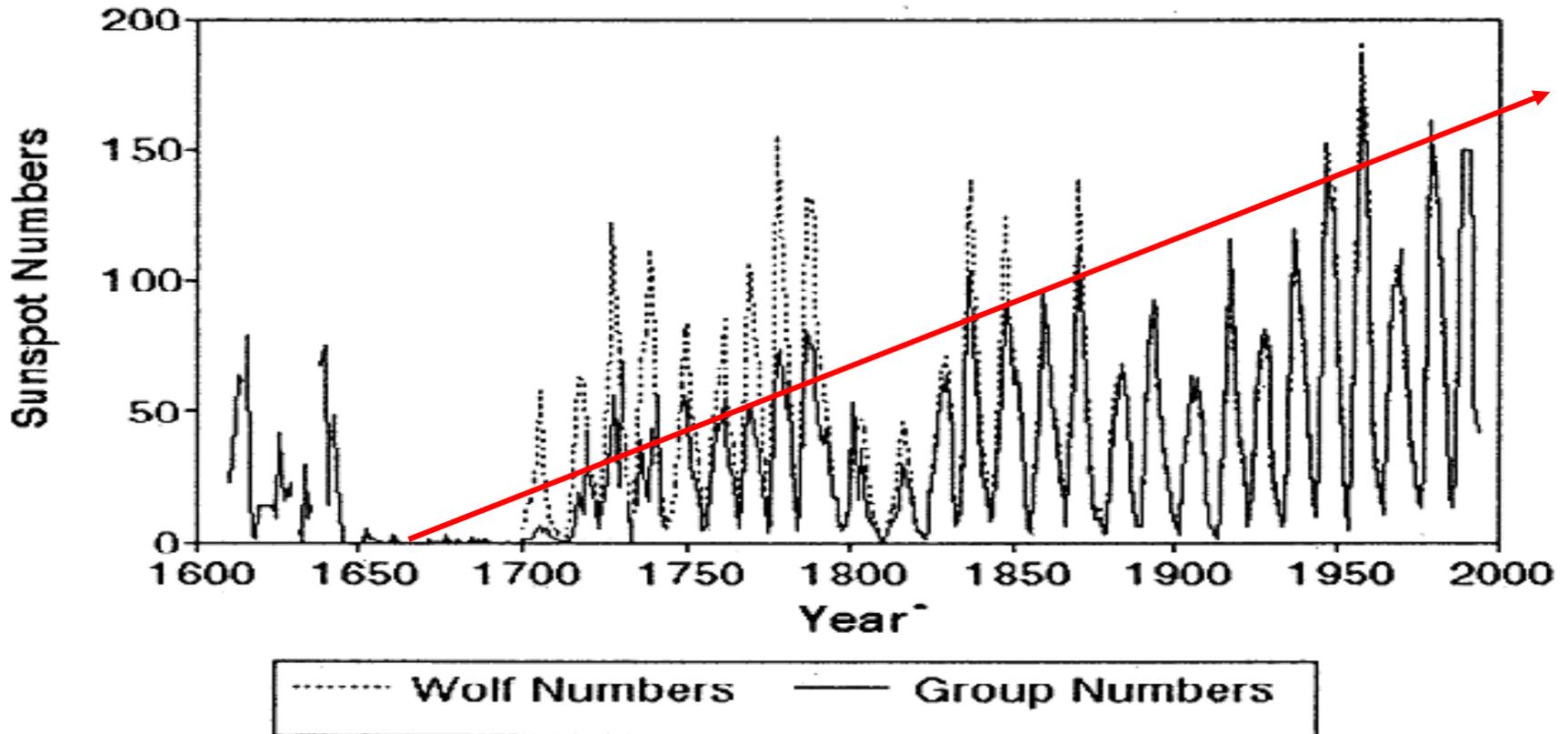
Some people thought it was easier (better?) to count just the groups instead of the much smaller and harder to see single spots

A Problem: Discordant Sunspot Numbers

$$\text{GSN} = 12 \text{ GN}$$

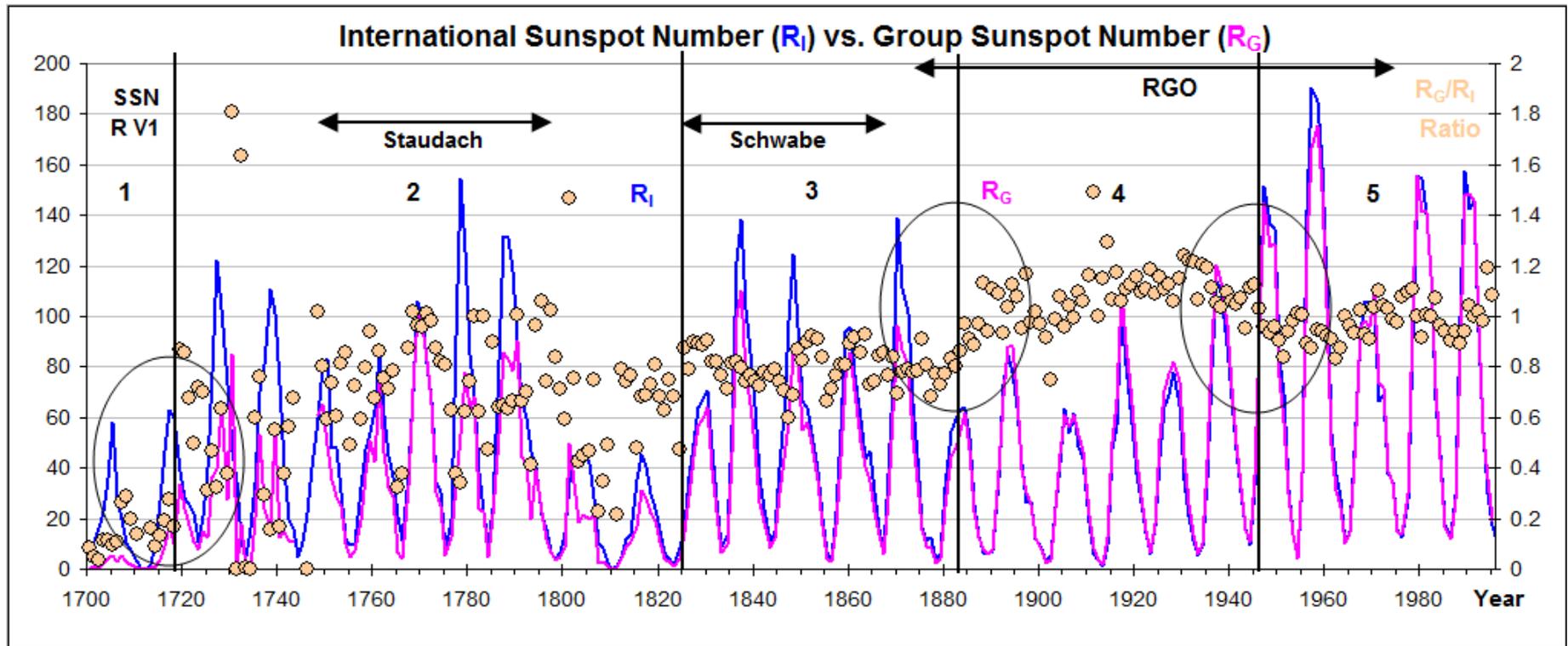
$$\text{WSN} = 0.6(10 * \text{GN} + \text{SN})$$

Group and Wolf Sunspot Numbers



Hoyt & Schatten, GRL 21, 1994

The Problem: Discordant Series



R_G : The Group Sunspot Number: the average number of sunspot groups per day multiplied by a scale factor (12.08) to match R_I for the interval of the RGO counts (Greenwich, 1874-1976)

R_I : The International Relative Sunspot Number introduced by Rudolf Wolf and now maintained by SILSO in Brussels (version 1)

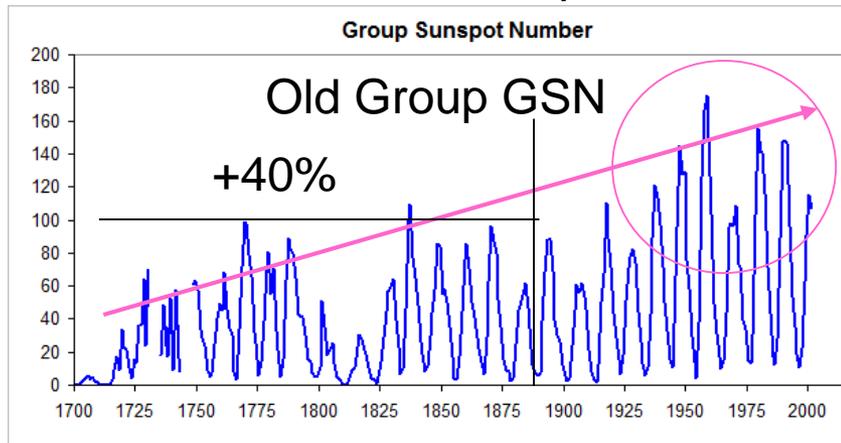
The SSN Workshops. The Work and Thoughts of Many People



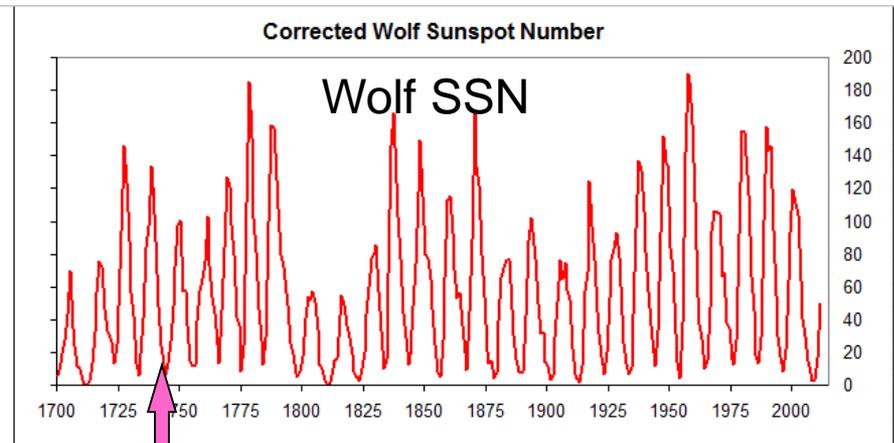
A revised Sunspot Number was announced at IAU Assembly in August, 2015 24

The Tale of Two Sunspot Numbers

GSN = 12 * Groups

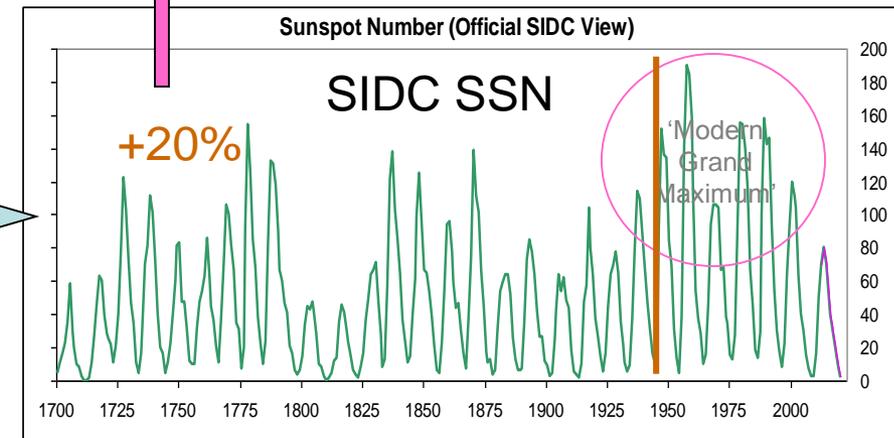


WSN = 10 * Groups + Spots



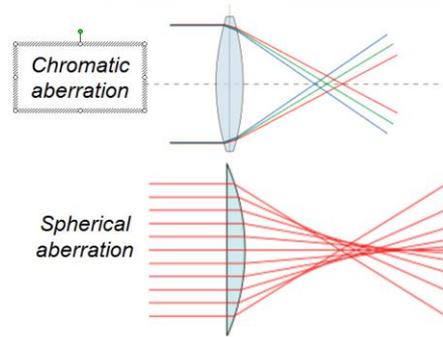
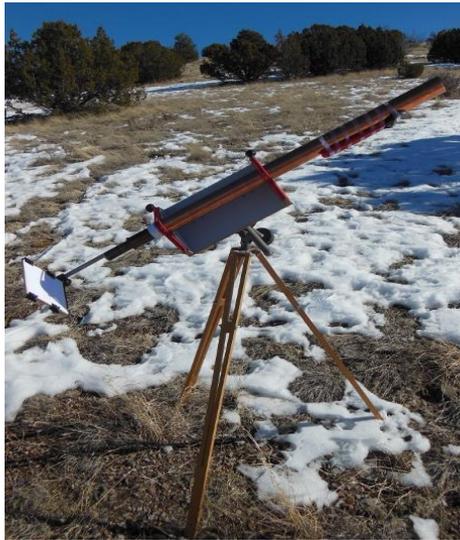
The old 'official' sunspot number [maintained by SIDC in Brussels] showed a clear 'Modern Maximum' in the last half of the 20th century. →

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

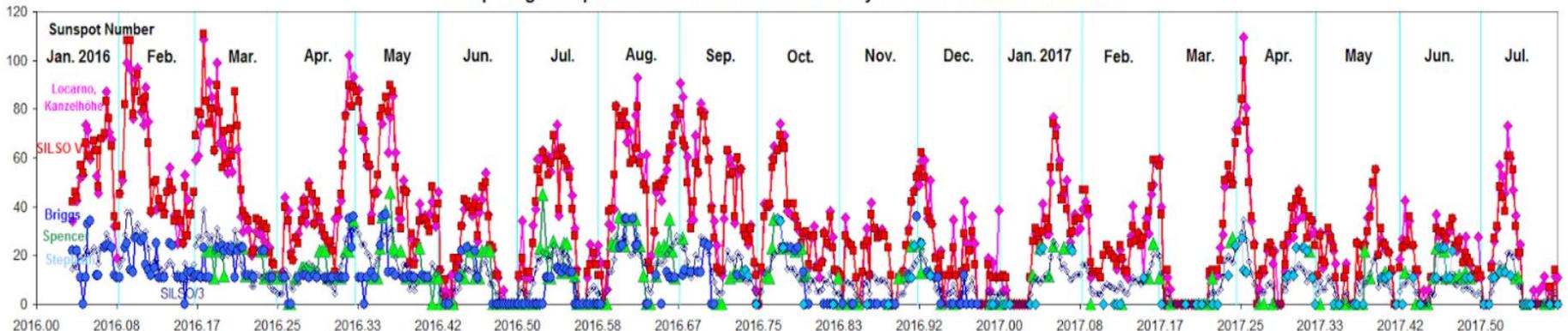


The new SSN series suggest that there likely was no Modern **Grand Maximum**²⁵

Checking the Calibration for the 18th Century: Build Replicas with the Same Optical Flaws



Comparing Sunspot *Relative* Numbers Observed by ATS and 'Modern' Observers



Modern observers see three times as many sunspots than our 18th century replicas

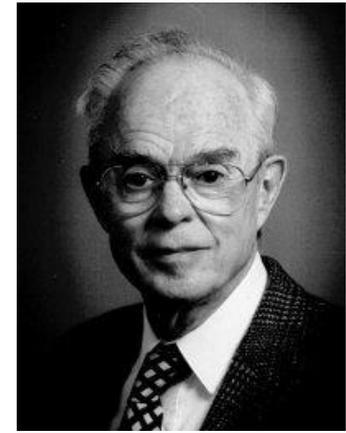
The Solar Wind

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



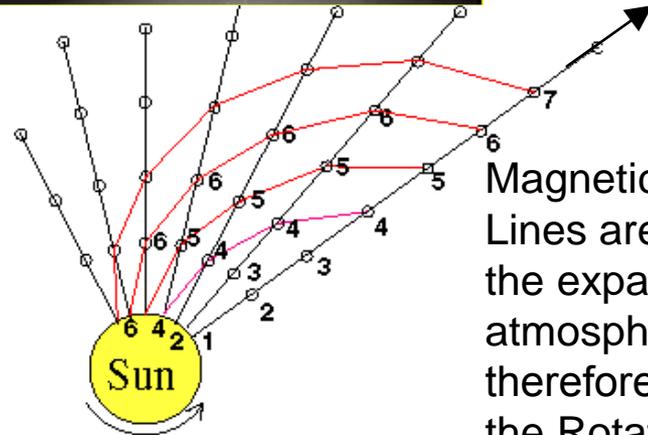
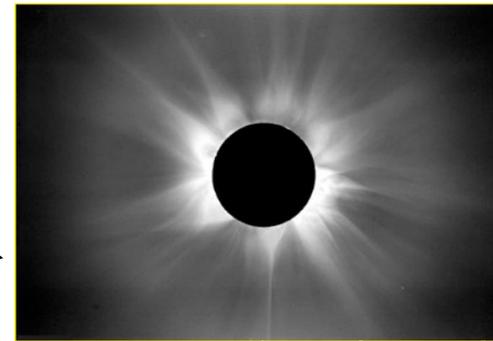
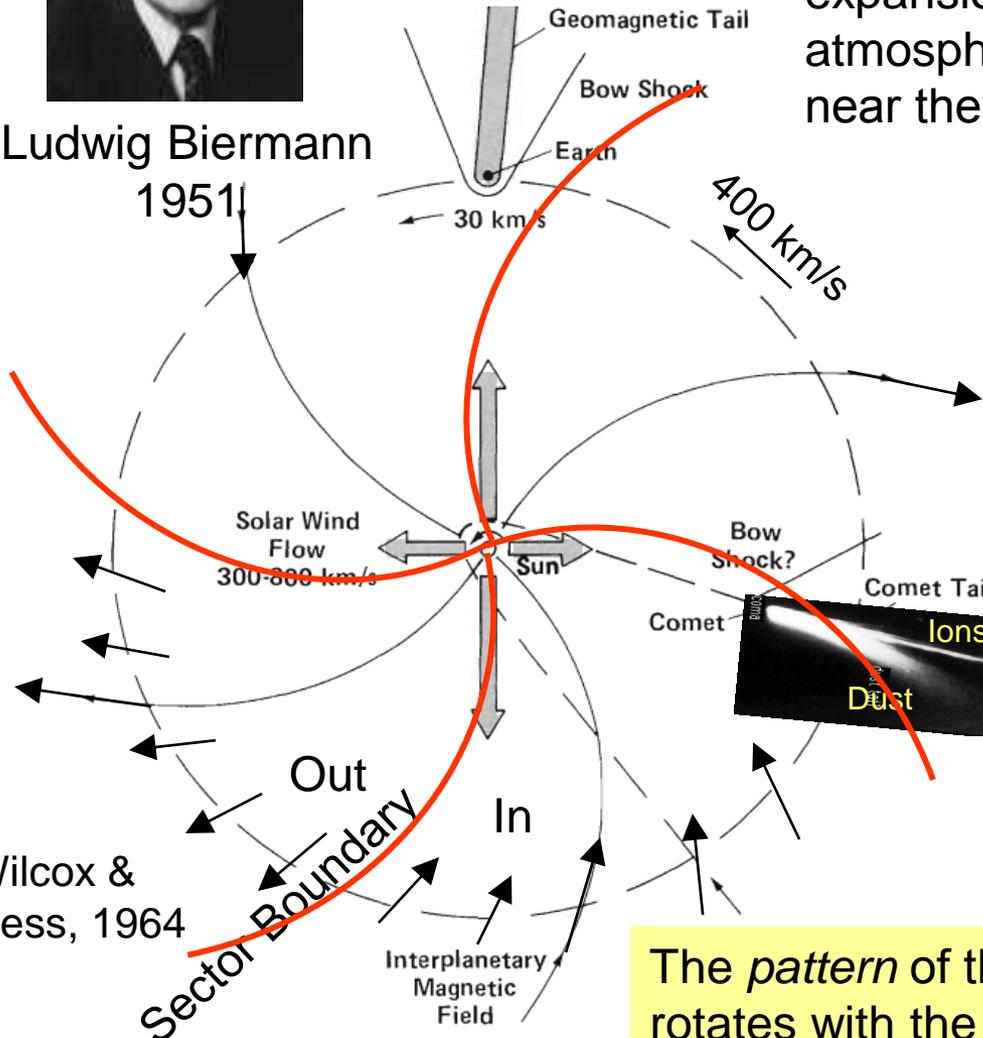
Ludwig Biermann

1951



Gene Parker
1958

Expansion is radially outwards

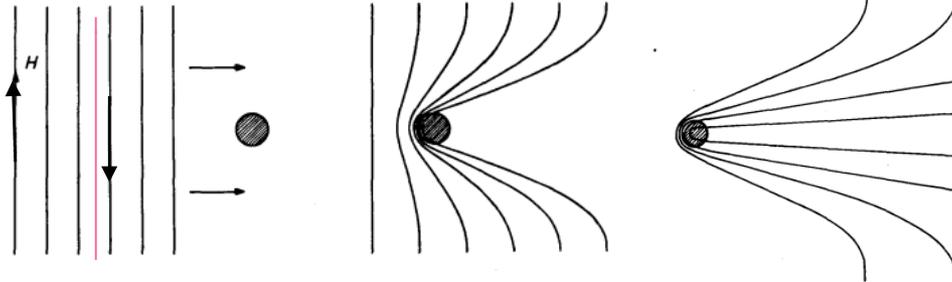


Magnetic Field Lines are tied to the expanding atmosphere and therefore 'rooted' in the Rotating Sun

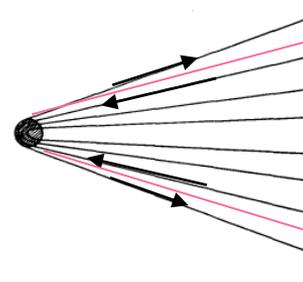
The *pattern* of the magnetic 'spiral' rotates with the Sun once in 25 days

Solar Wind Stealing a Comet Tail

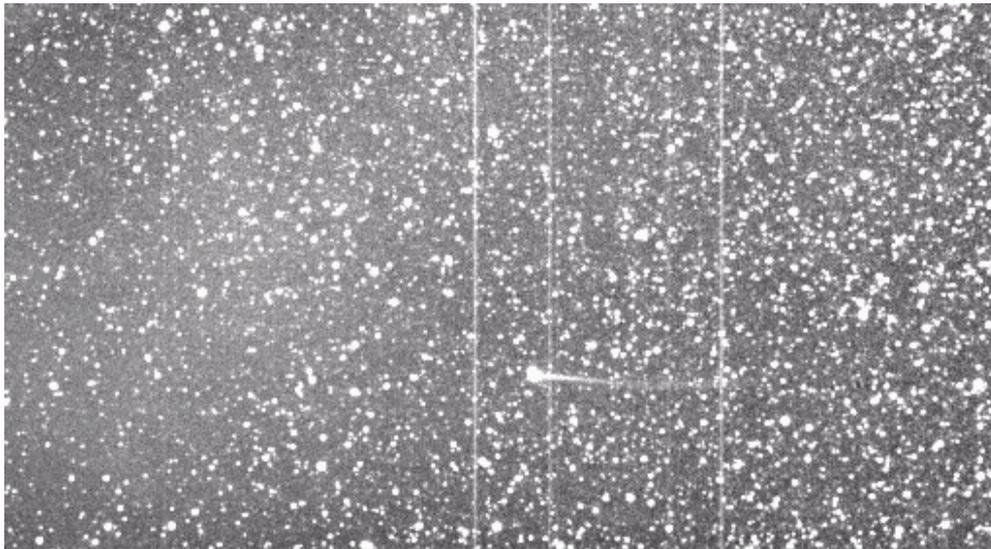
Sector Boundary



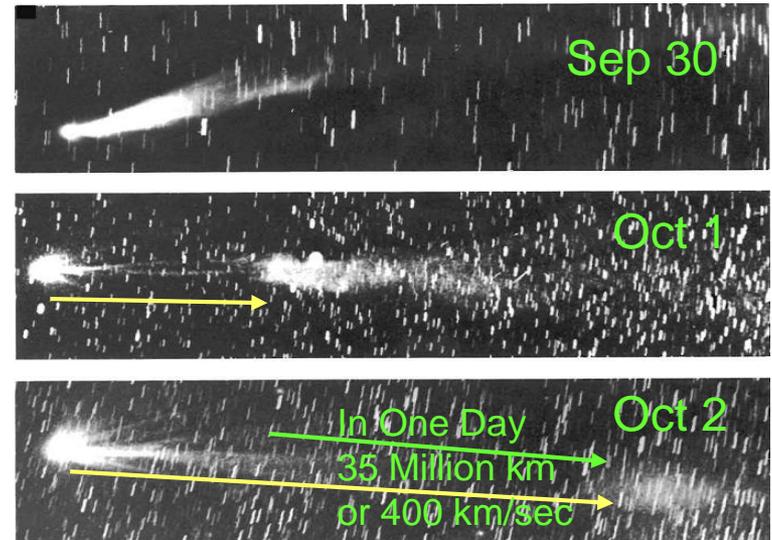
Reconnection



Fragile: Comet ion tail inside



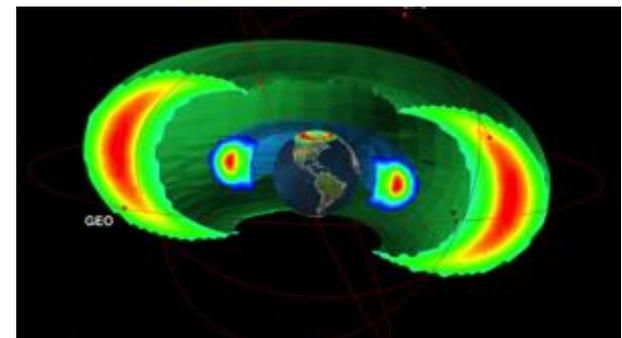
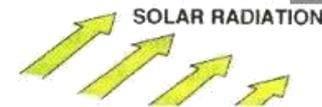
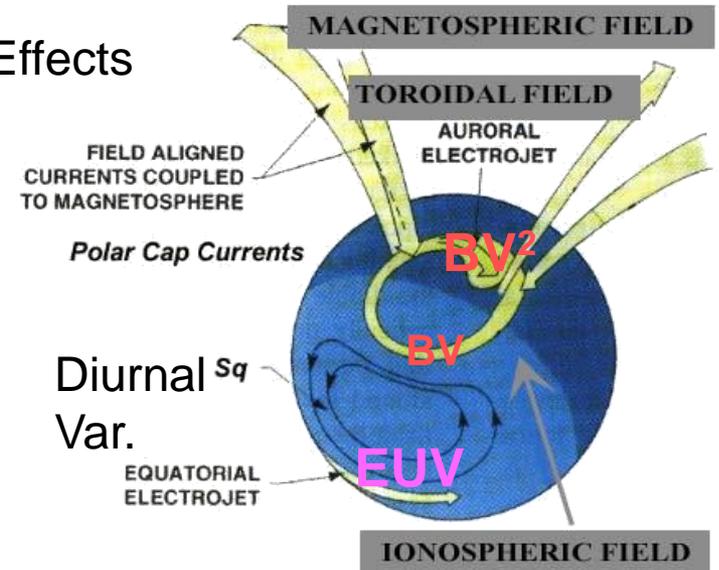
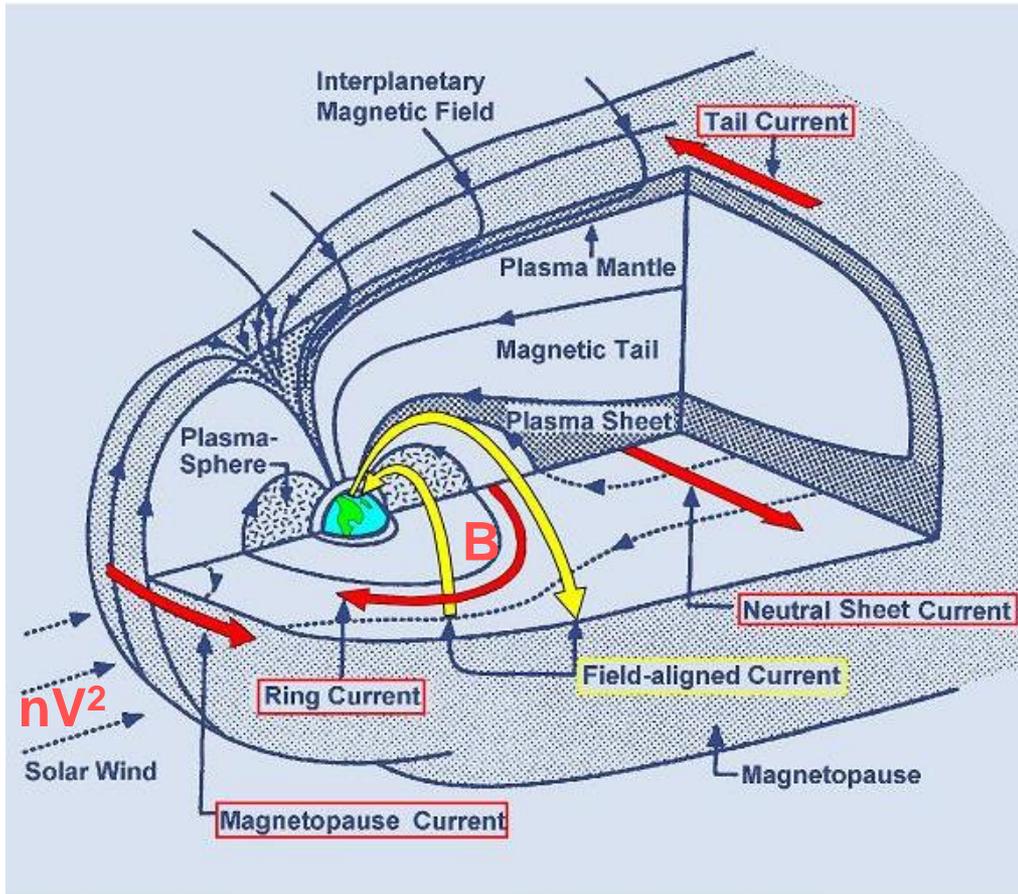
Comet Encke, 2007/04/20



Comet Morehouse, 1908

Electric Current Systems in Geospace

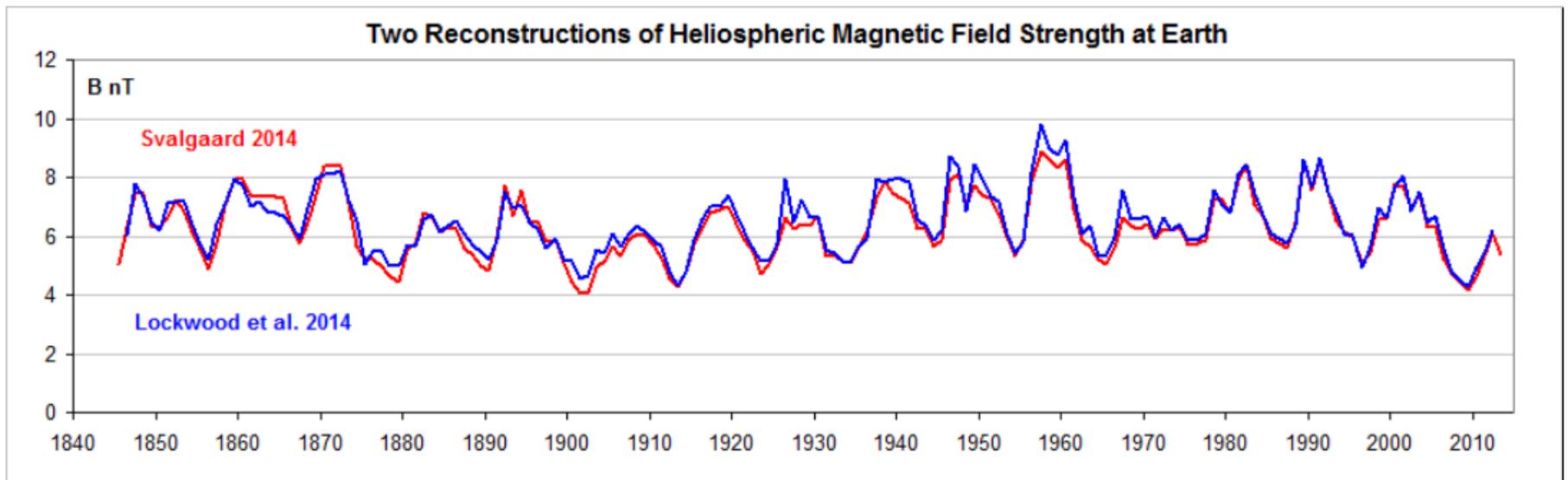
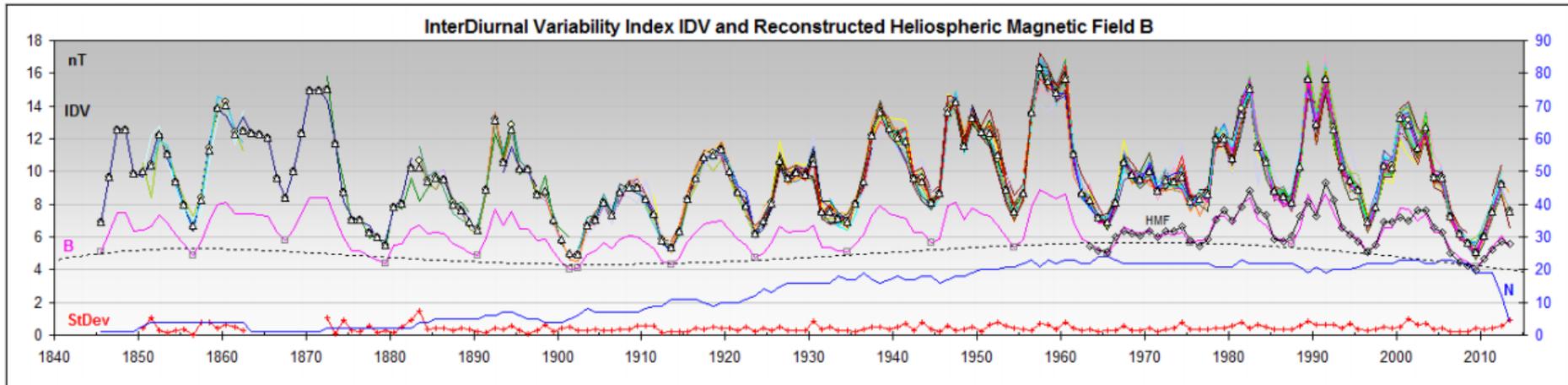
Different Current Systems \longleftrightarrow Different Magnetic Effects



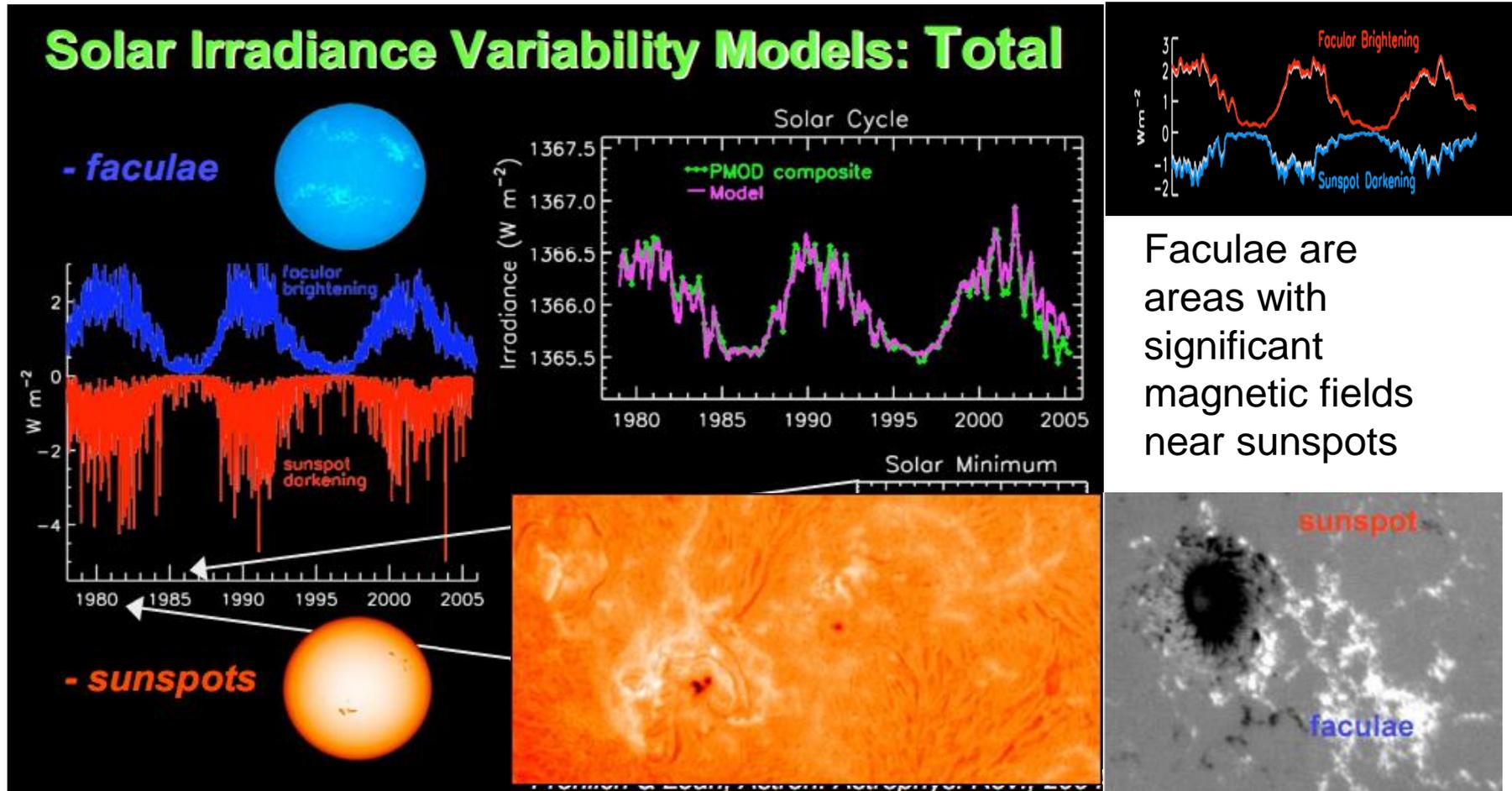
We can now invert the Solar Wind – Magnetosphere relationships...

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

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

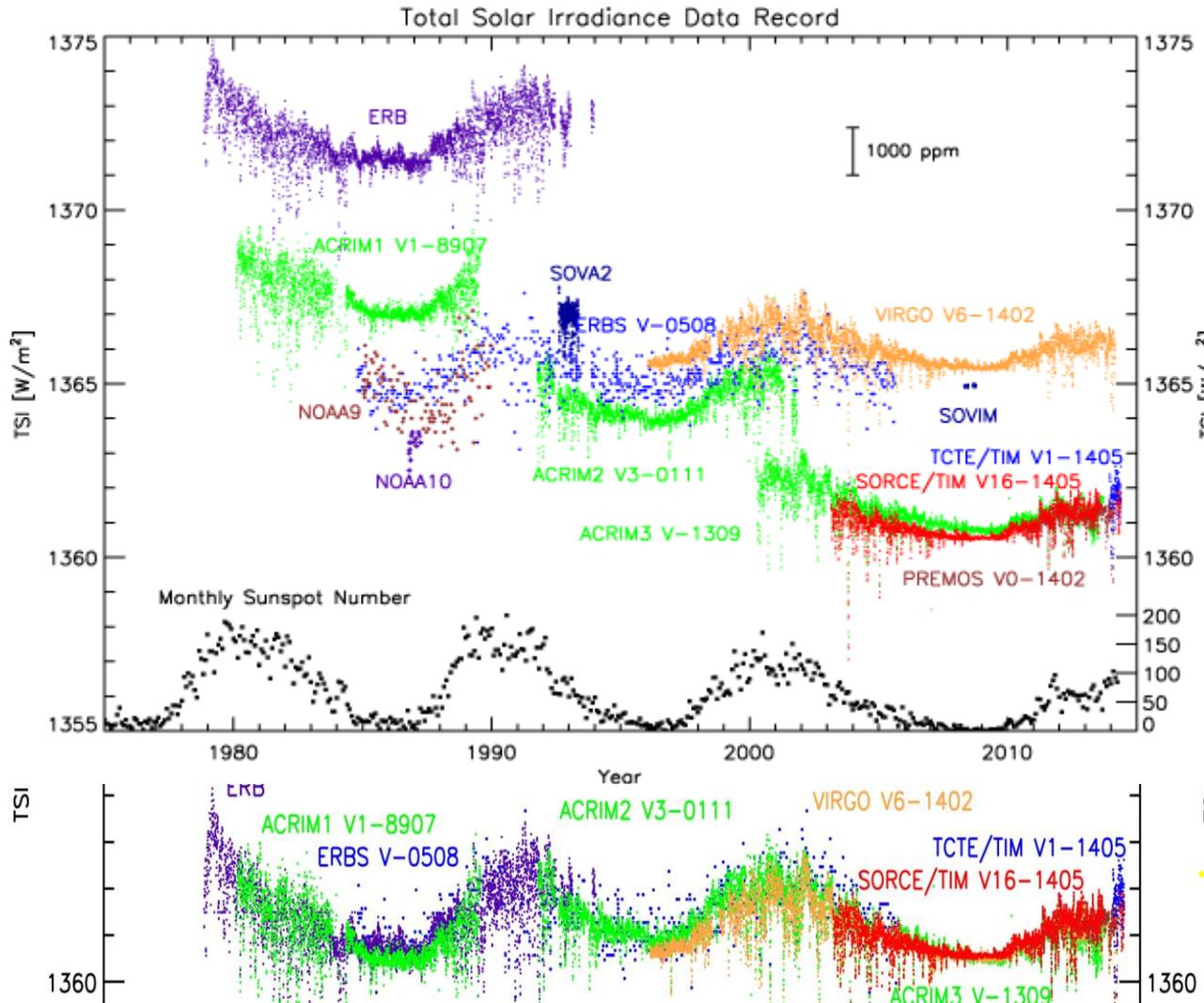


TSI is the combined effect of sunspot dimming and facular brightening (2x)

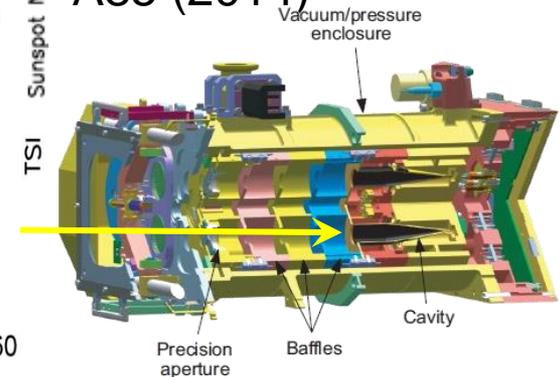


Faculae are areas with significant magnetic fields near sunspots

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



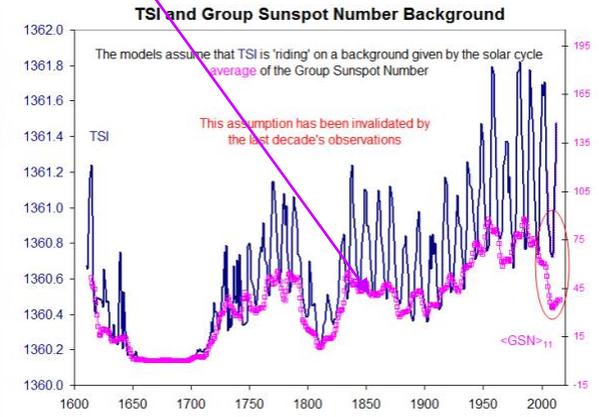
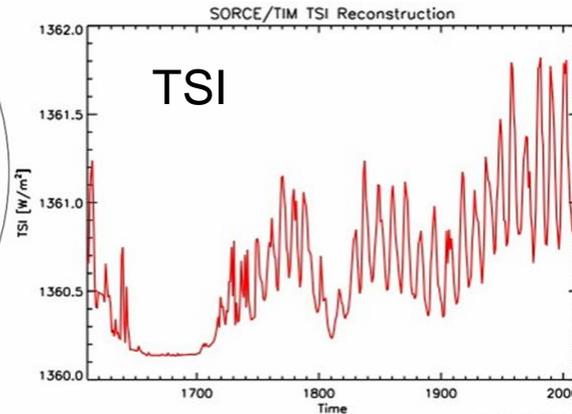
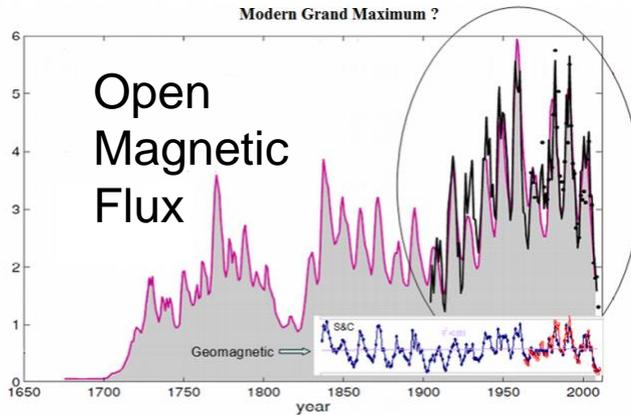
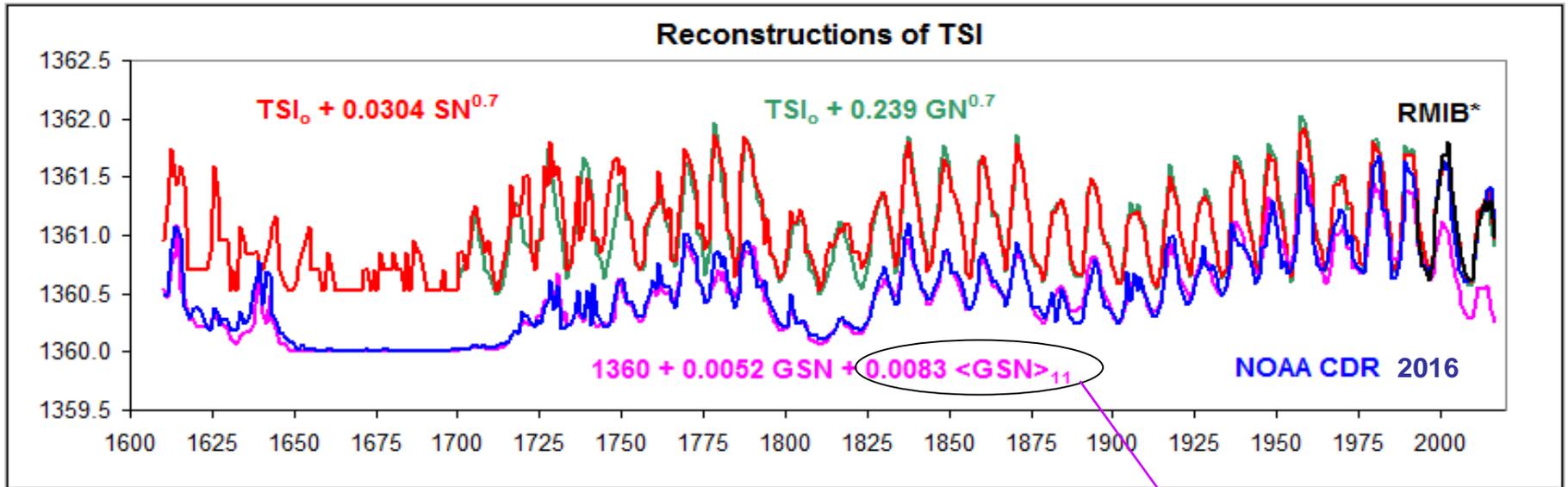
“The results of this work strengthen support for the hypothesis that variation in solar irradiance on timescales greater than a day is driven by **photospheric magnetic activity**”.
 Yeo et al., *A&A* **570**, A85 (2014)



Radiometer 32

Building a Composite from Different Spacecraft Datasets

Climate Data Records

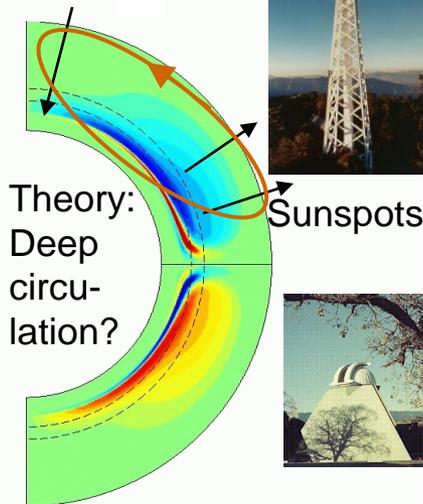


But there is no slowly varying Background acting as Climate Forcing.

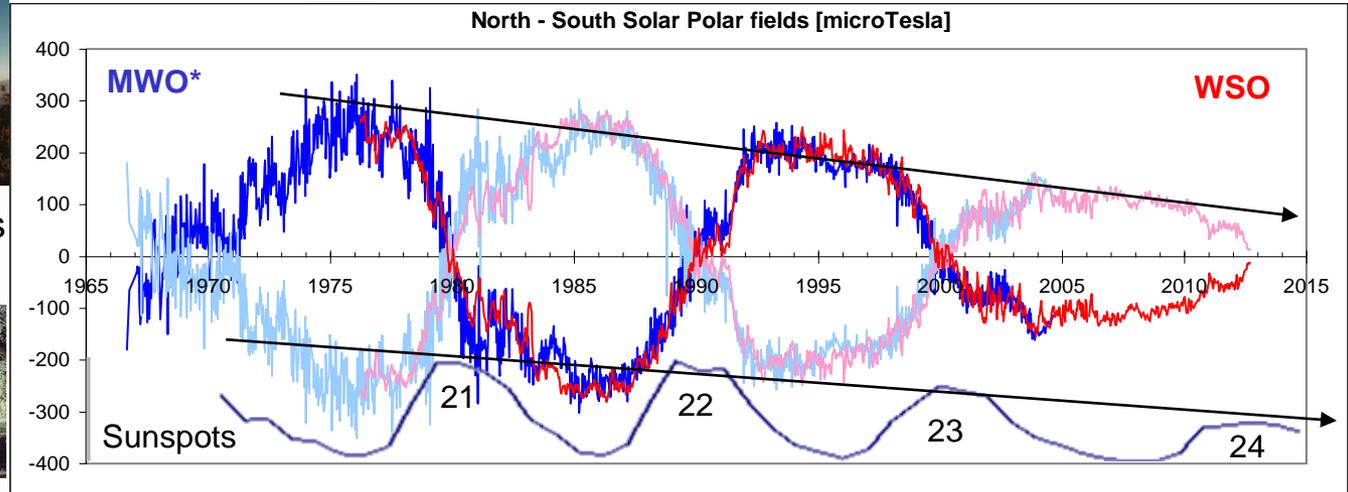
So, what will Solar Activity be in the Future? Can we predict Solar Activity?



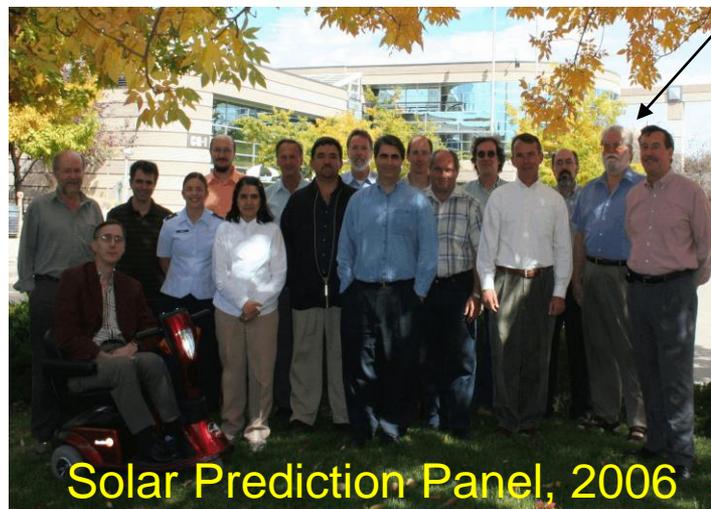
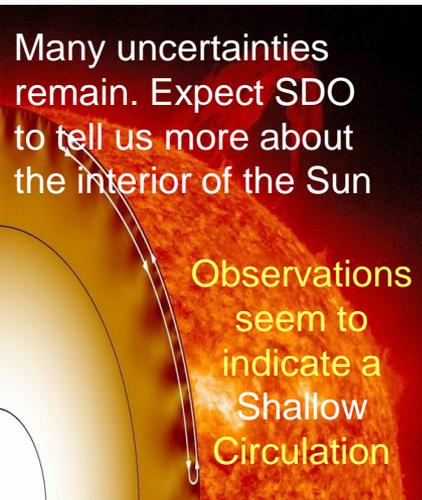
Polar Fields



Sunspots



Many uncertainties remain. Expect SDO to tell us more about the interior of the Sun



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 previous minimum predicted a small cycle 24

Polar Fields Predict Sunspot Cycle

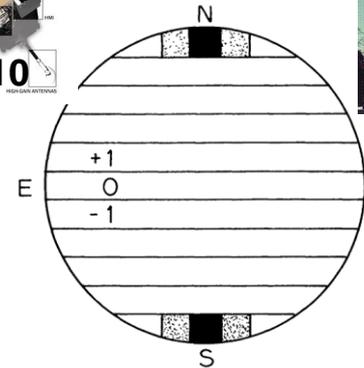
VOL. 5, NO. 5 GEOPHYSICAL RESEARCH LETTERS MAY 1978

USING DYNAMO THEORY TO PREDICT

THE SUNSPOT NUMBER DURING SOLAR CYCLE 21

Kenneth H. Schatten, Philip H. Scherrer, Leif Svalgaard and John M. Wilcox

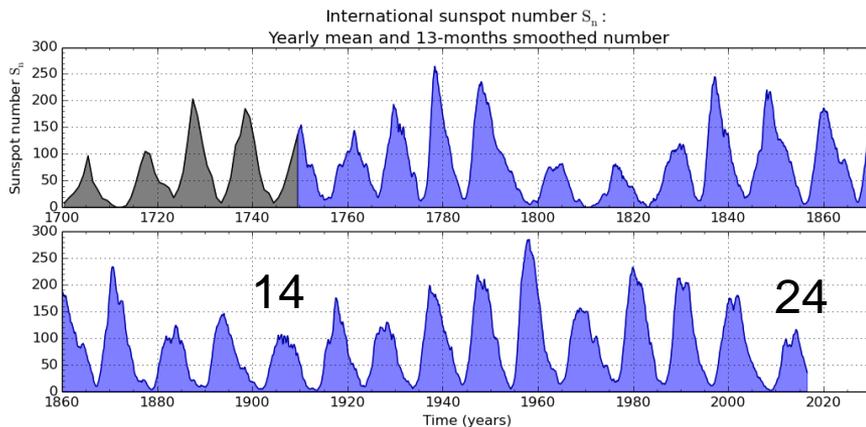
Institute for Plasma Research, Stanford University, Stanford, California



1976

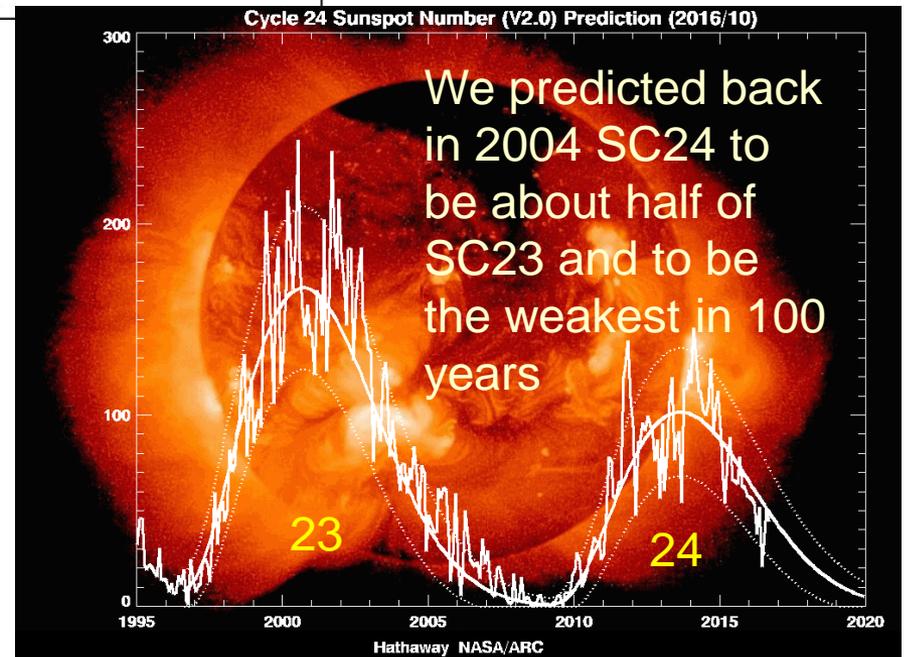
D = 1919".3
a = 175"

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.

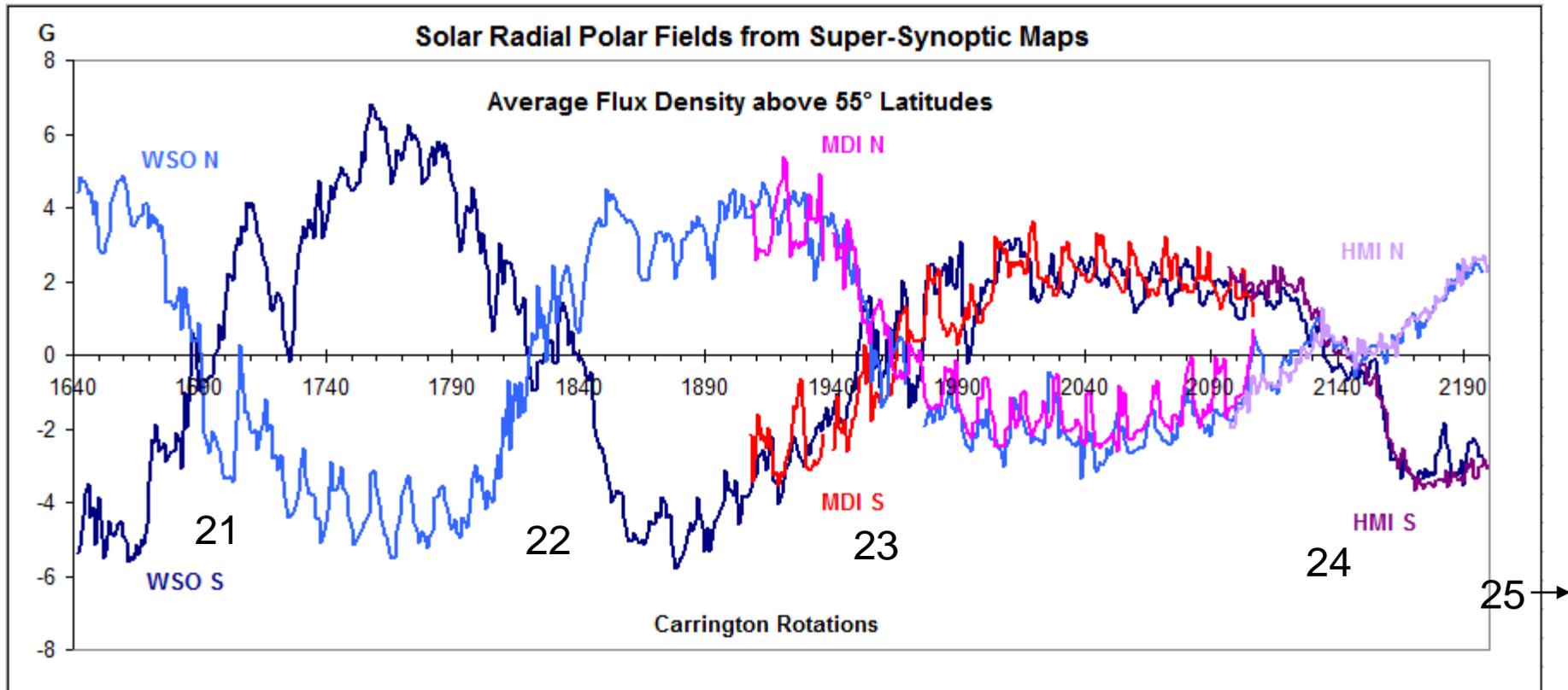


SILSO graphics (<http://sidc.be/silso>) Royal Observatory of Belgium 2017 March 1

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



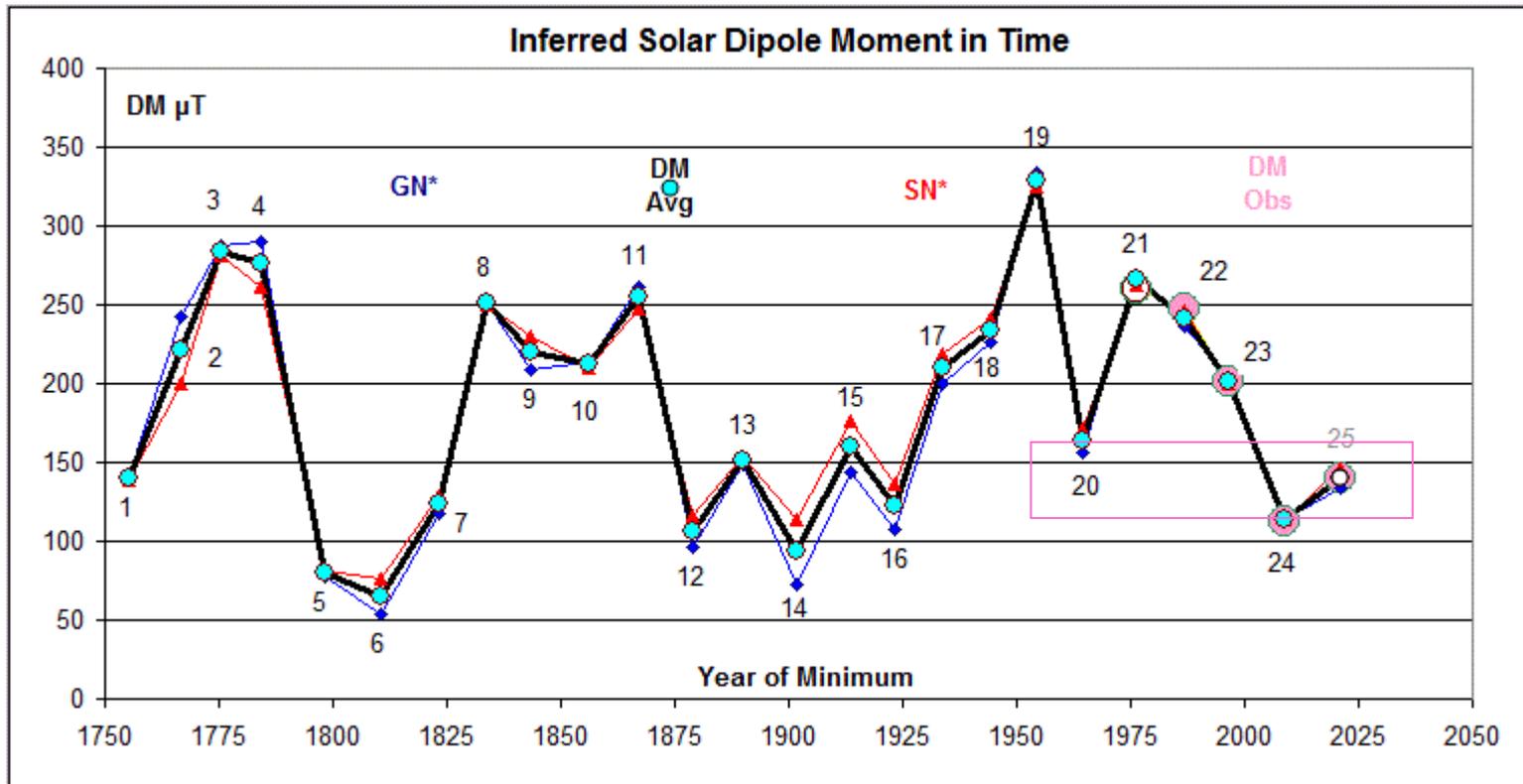
Polar Fields from WSO, MDI, and HMI from Radial Super-Synoptic Maps



WSO multiplied by 1.8 to correct for saturation.

MDI multiplied by 0.6 to put on HMI scale [for polar region]

The Prediction (At Last)



SC25 will be somewhere between SC24 and SC20, provided the Polar Field Precursor Relationship holds.

Abstract

When Marconi in late 1901 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 Appleton 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.