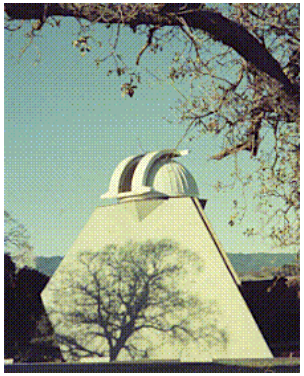
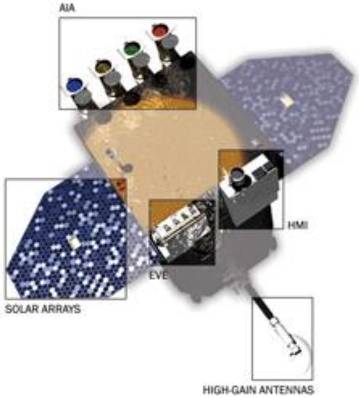




How to Predict Solar Cycle 25

Leif Svalgaard
Stanford University

HamSCI Workshop 2021, Feb. 18, 2021

Why do Hams Care?

Generally speaking, a dearth of solar activity makes working the bands from 14-28 MHz (20 through 10 meters) and 50 MHz (6 meters) a challenge. The amount of sunspots, and correlated solar activity, decreases or increases according to a 11-year cycle.

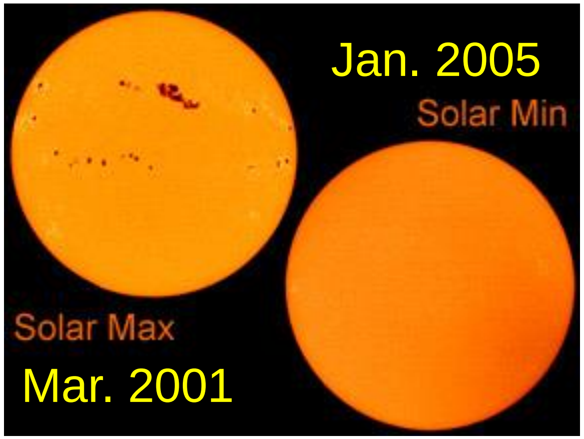
The presence of sunspots indicates solar mafneric activity which affects the ionosphere's ability to refract radio signals back to Earth. Fever sunspots means less solar activity, which leads to a lot of frustrated Hams.

Cycle 24 (2009-2019) was a very low activity cycle and DX-conditions were less than optimal. So, what will the new solar cycle, number 25 since the counting began with activity back in 1749, bring?

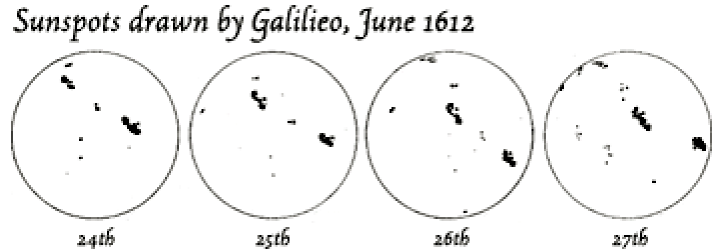
In this talk, I'll discuss what we (or at least I) think the cycle will bring, and more importantly *why* we think so.

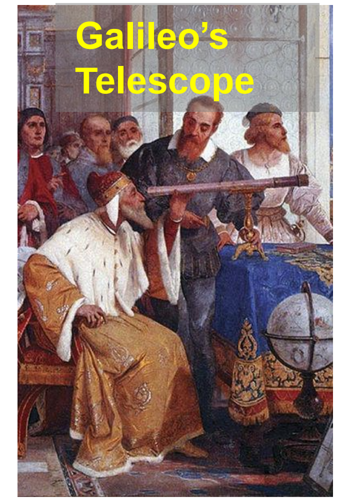
We'll start by showing our 400+ year long sunspot record…

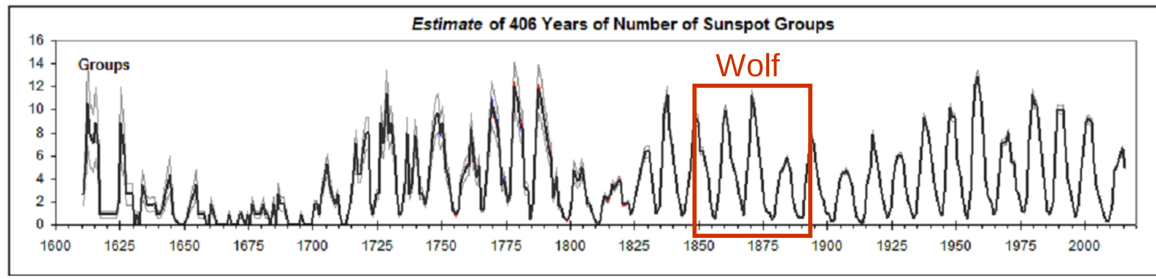
400-year Sunspot Cycle Record



SOHO Spacecraft





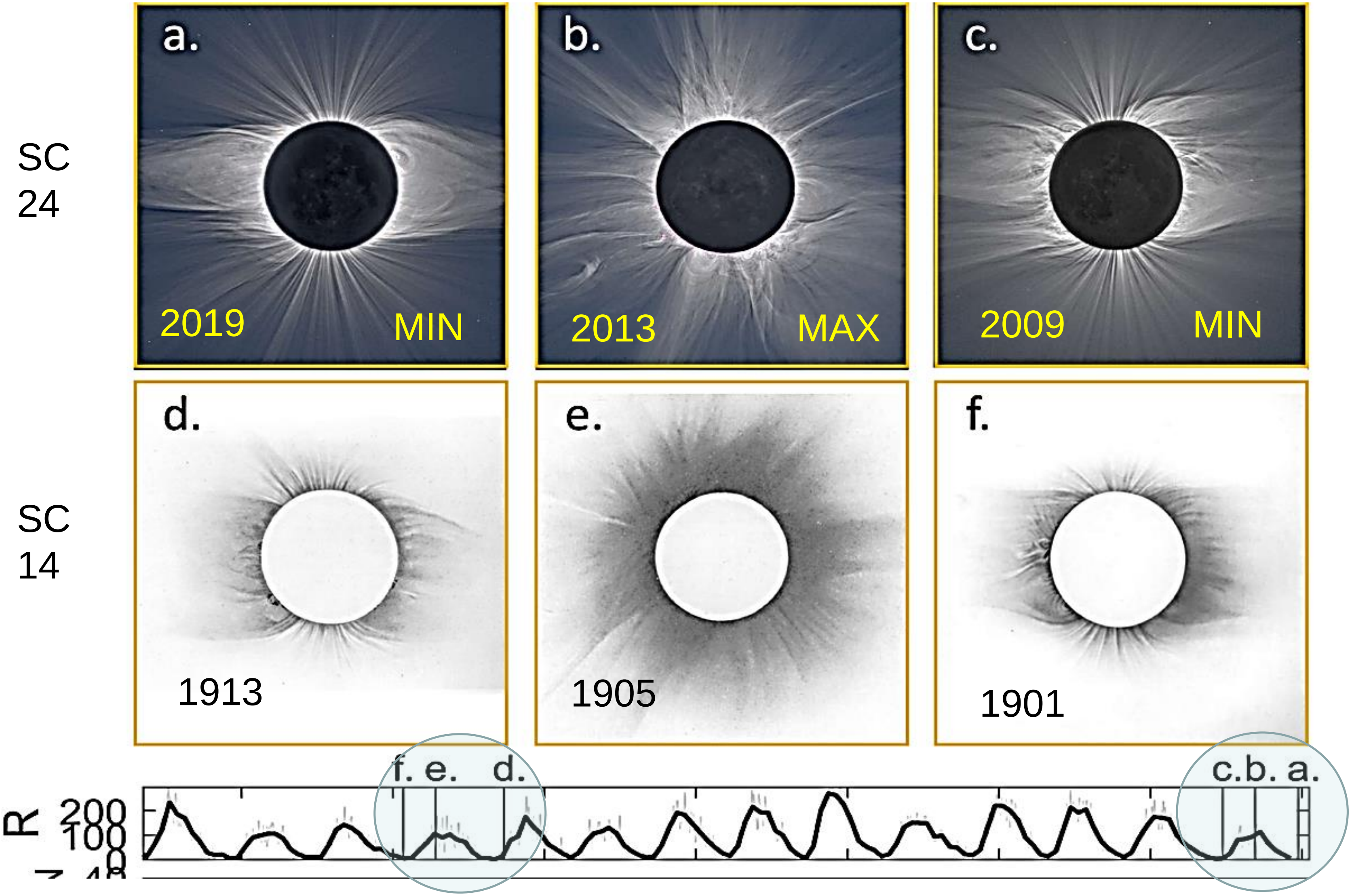


Samuel Heinrich Schwabe 1843

Rudolf Wolf 1852 SSN = 10G+S

The sunspot record is the longest running 'experiment'. The modern database with all observations since 1609 AD comprises over one million observations by almost a thousand observers (mostly amateurs; using small telescopes)

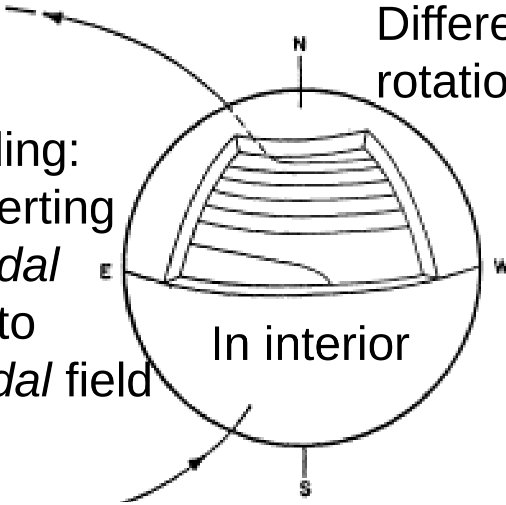
The Shape of the Corona Over the Poles Strongly Suggests that it is Structured by Magnetic Fields



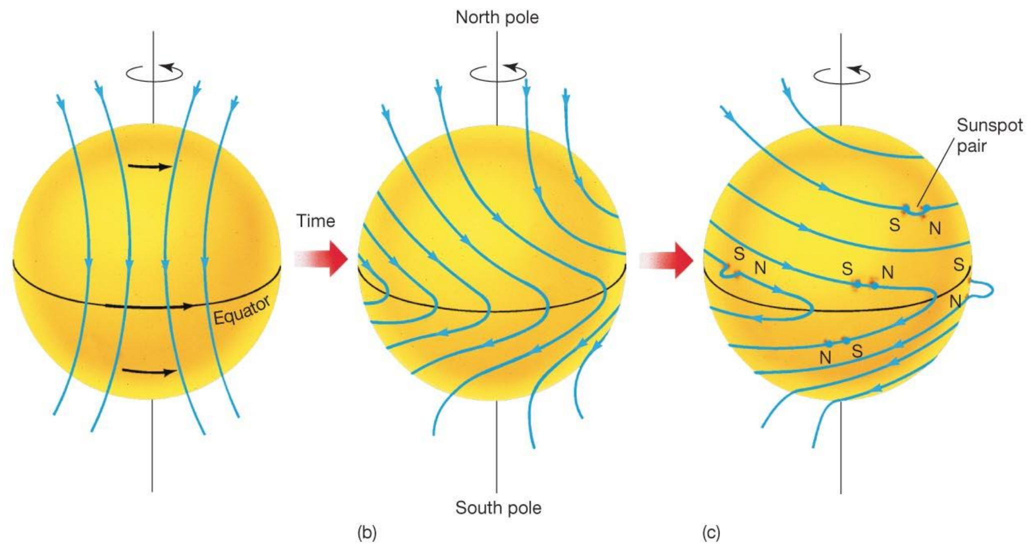
The Sun’s Large-Scale Magnetic Field is *Dynamic* (Babcock 1961)

Differential rotation

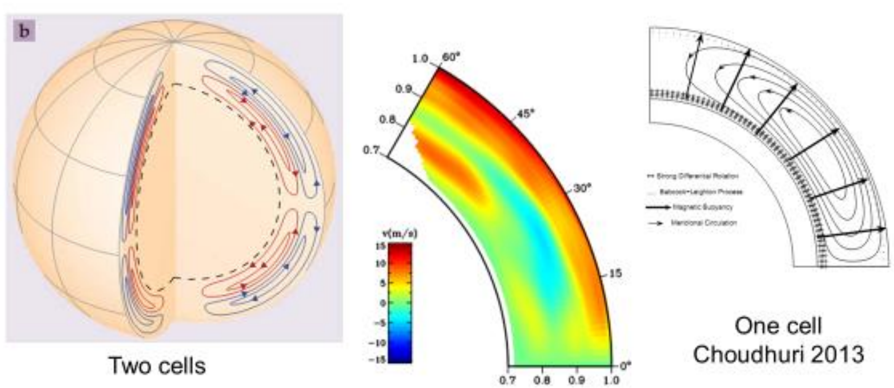
Winding: converting *poloidal* field to *toroidal* field



In interior



Meridional Circulation Cell(s)



Two cells

One cell
Choudhuri 2013

The Bob Leighton papers of 1965 and 1969 developed Backcock’s phenomenological theory into a physics-based dynamo theory ‘explaining’ the properties of the sunspot cycle incl. butterfly diagram

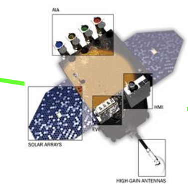
Polar Fields Predict Sunspot Cycle

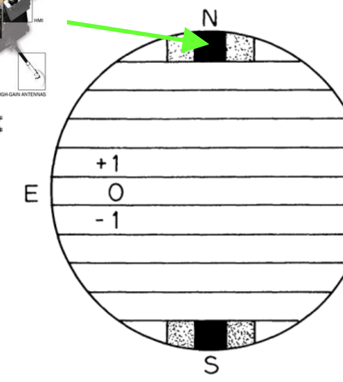
VOL. 5, NO. 5 GEOPHYSICAL RESEARCH LETTERS MAY 1978

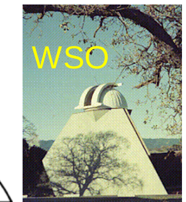
USING DYNAMO THEORY TO PREDICT
THE SUNSPOT NUMBER DURING SOLAR CYCLE 21

Kenneth H. Schatten, Philip H. Scherrer, Leif Svalgaard and John M. Wilcox
Institute for Plasma Research, Stanford University, Stanford, California

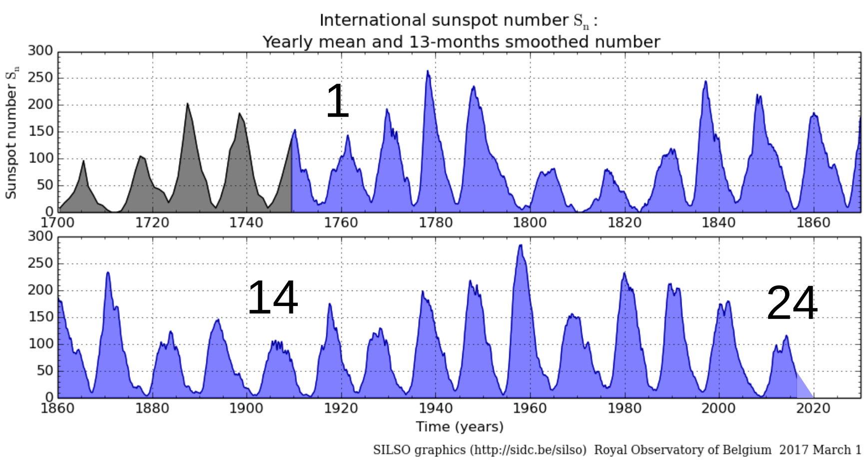
Abstract. On physical grounds it is suggested that the sun's polar field strength near a solar minimum is closely related to the following cycle's solar activity.

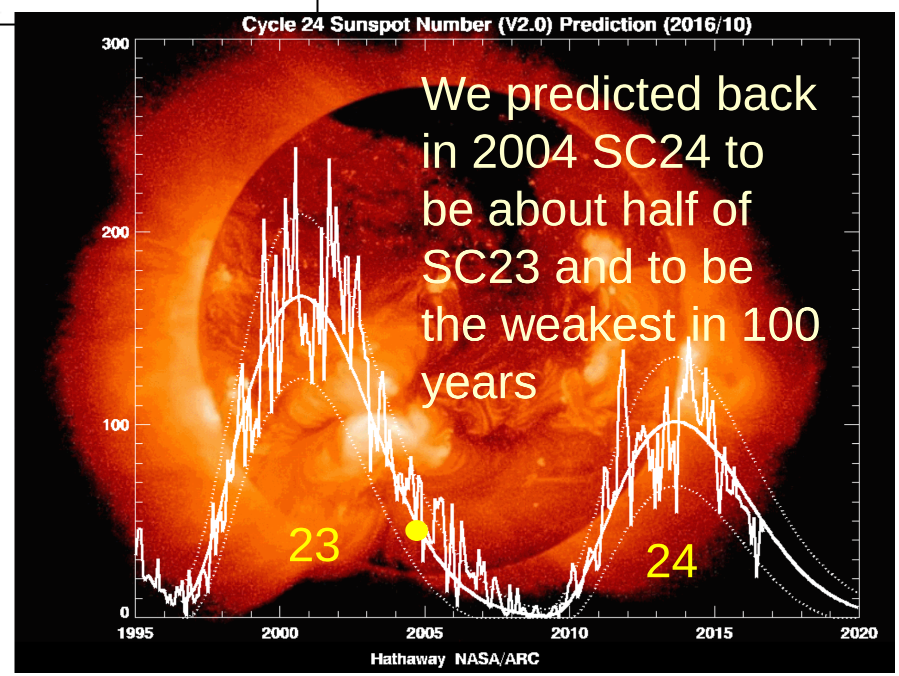






1976

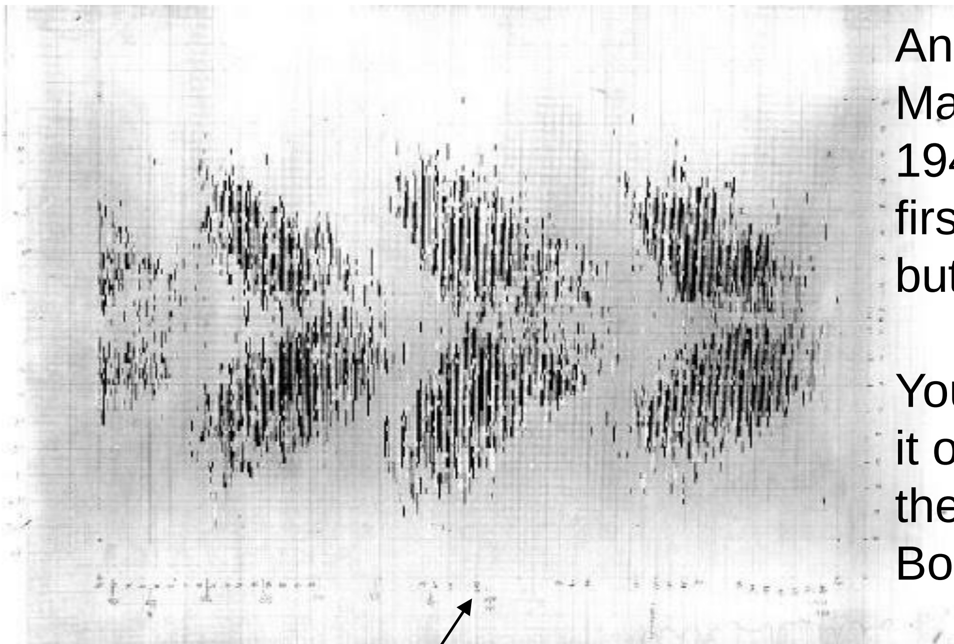




Currently, the polar fields are at least as strong as before cycle 24, so cycle 25 will be at least as strong as 24.

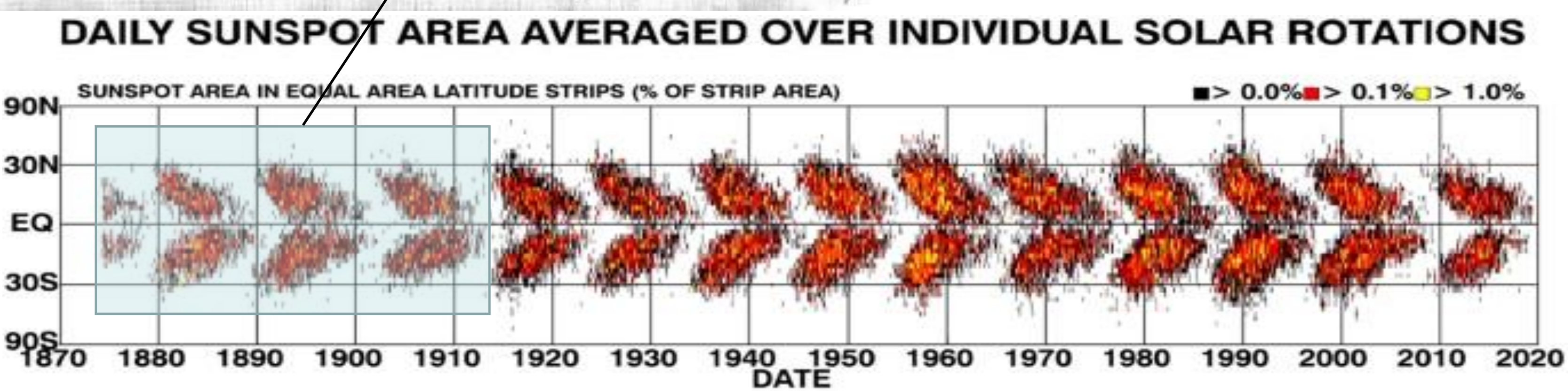
The Authors 31 years later

The Sunspot Butterfly Diagram



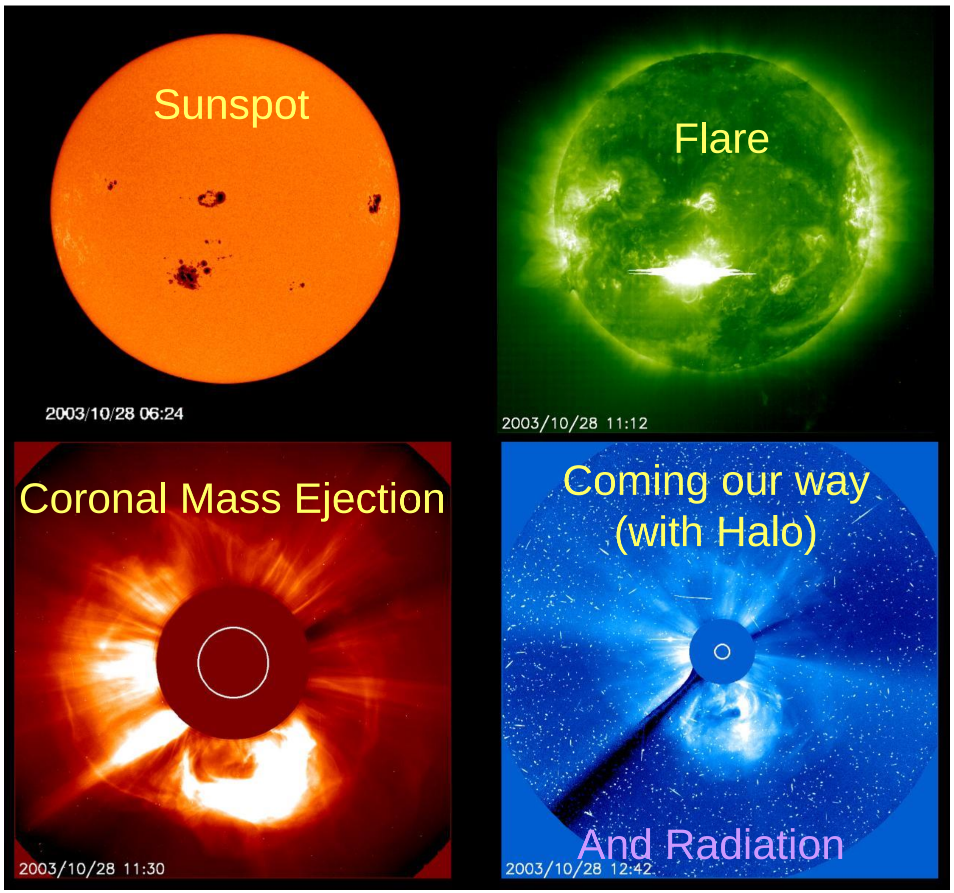
Annie Scott Dill Maunder (1868-1947) drew the first sunspot butterfly diagram.

You can still see it on the wall at the HAO in Boulder, CO.



Solar Storms and Consequences

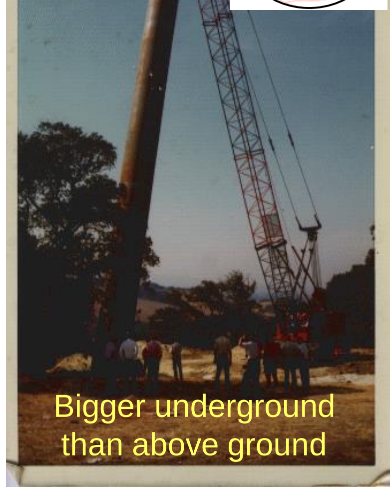
The energy stored in Sunspot Active Regions can be released explosively causing dangerous radiation and plasma hurled into space. If Earth-directed, this 'debris' from the explosions can have damaging and disturbing effects on our technological infrastructure



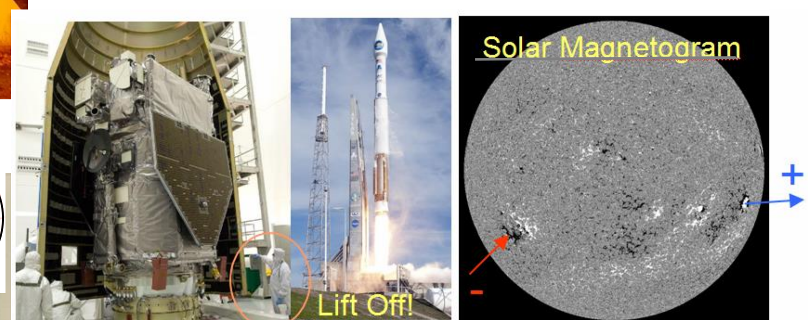
Where Does the Magnetized Solar Wind Come From?

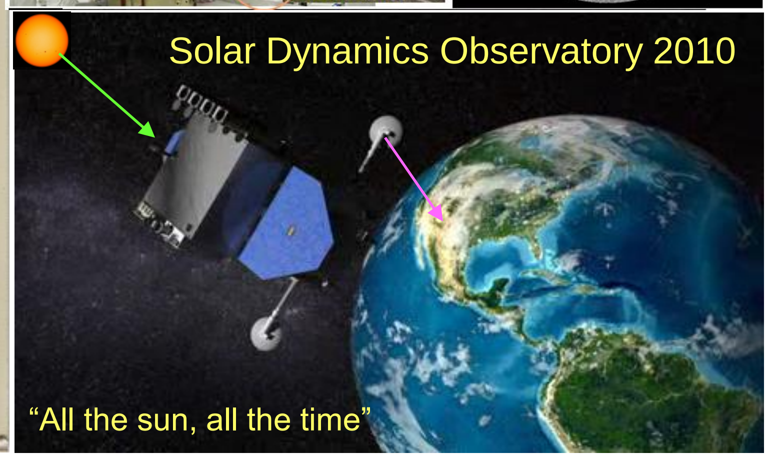
To find out, we build Solar Magnetic Field Observatories !

1975



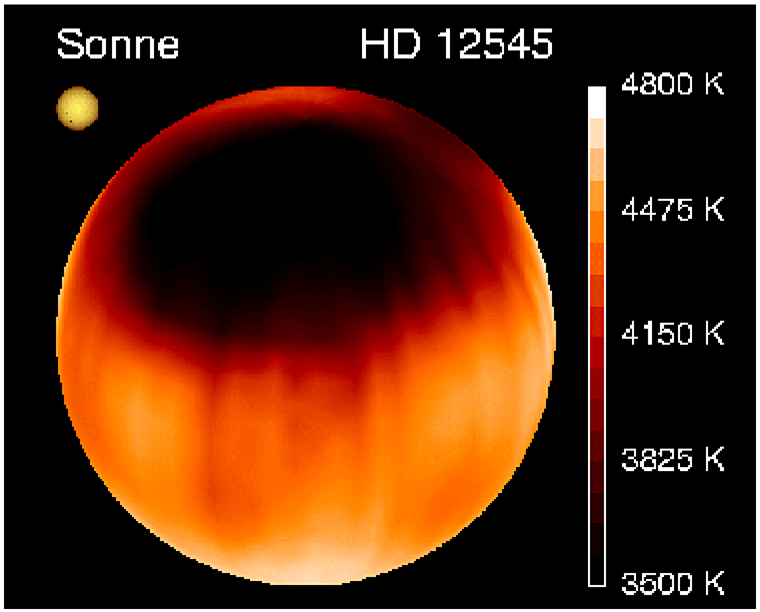
So, we go to sunny California to study the Magnetic Sun

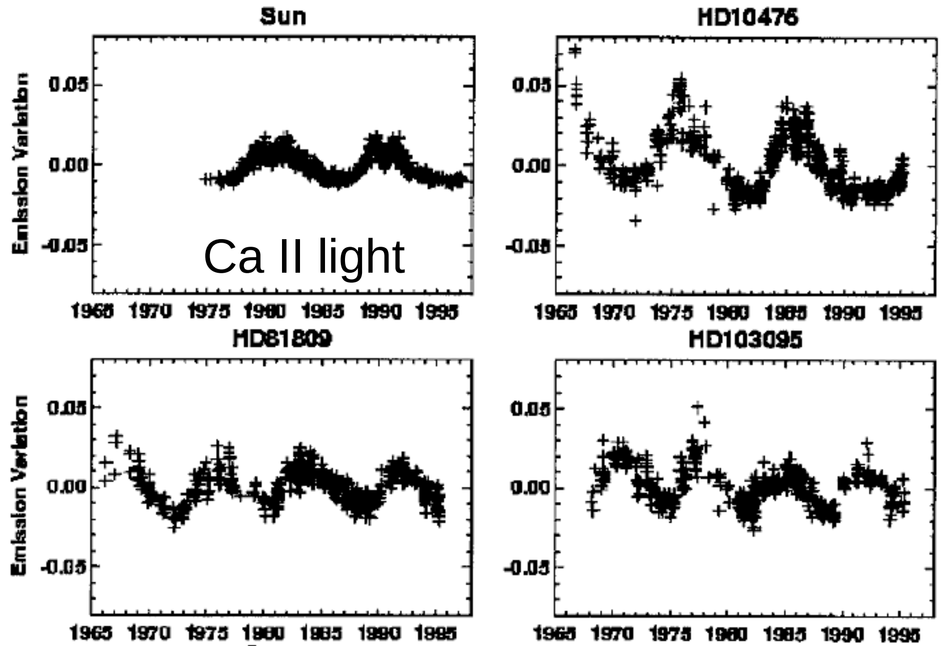


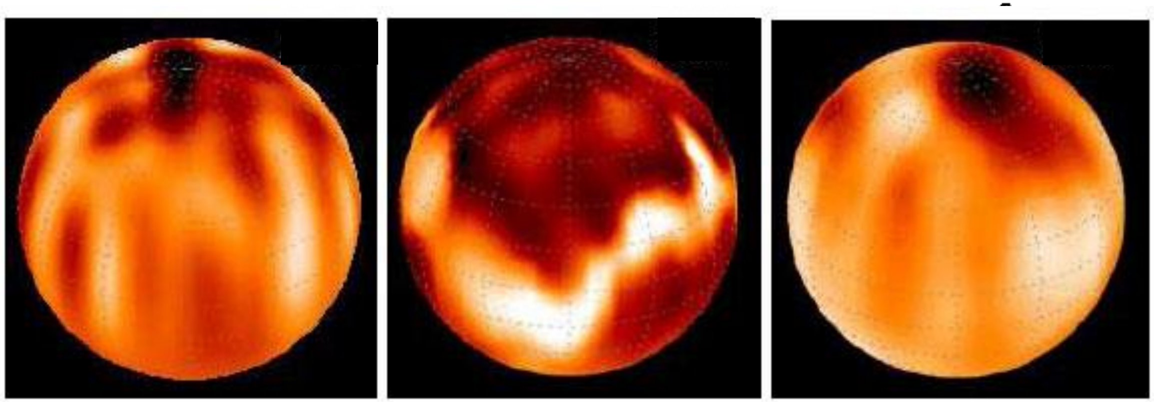


Stars have Spots too

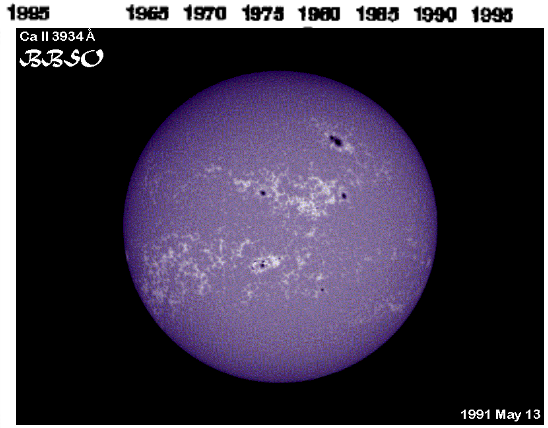
Largest starspot known







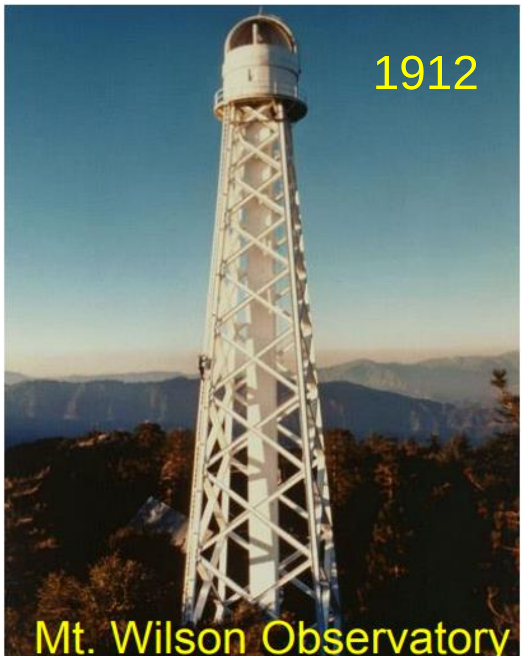
Some other stars



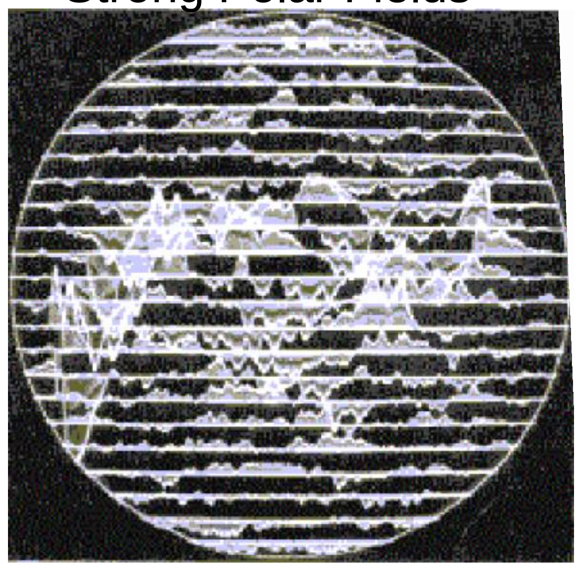
Sun in Ca II light 393 nm

Early MWO Observations

after Babcock Invented the Magnetograph “by doing everything right”



Strong Polar Fields



MWO Magnetogram 1953

Weak Polar Fields

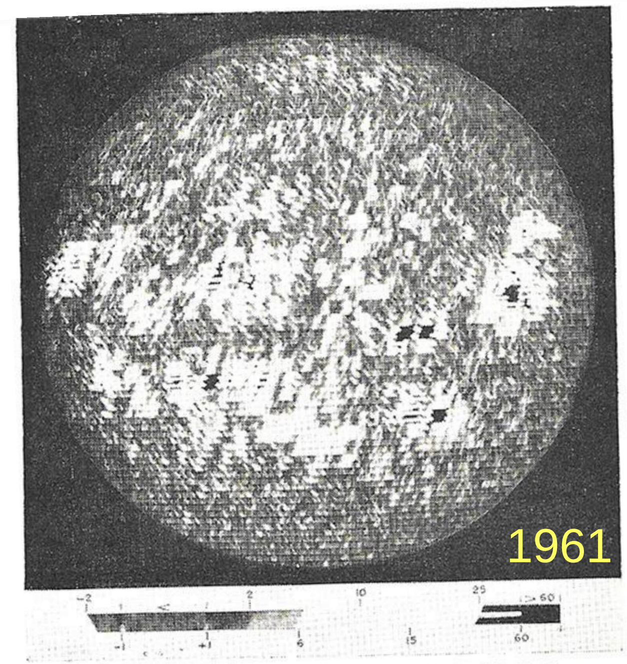
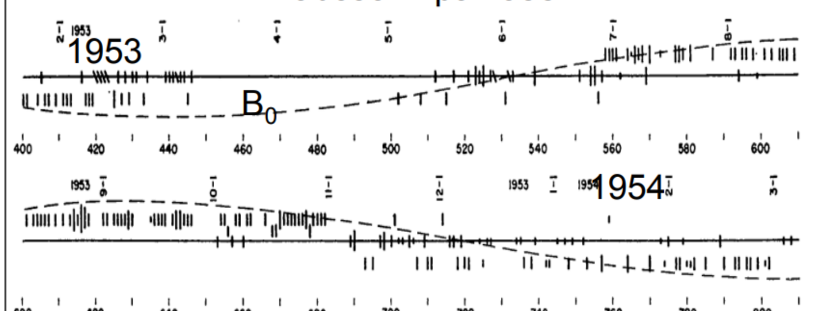
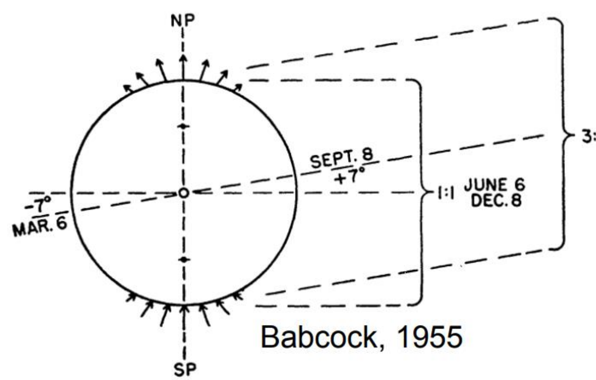


Fig. 1—The Solar Magnetogram for 21 July 1961.

Babcock ApJ 1955



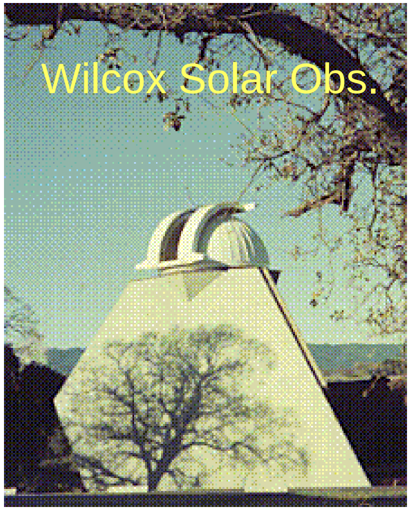
If the north polar flux appears greater than the south, a mark is placed above the horizontal and vice versa.

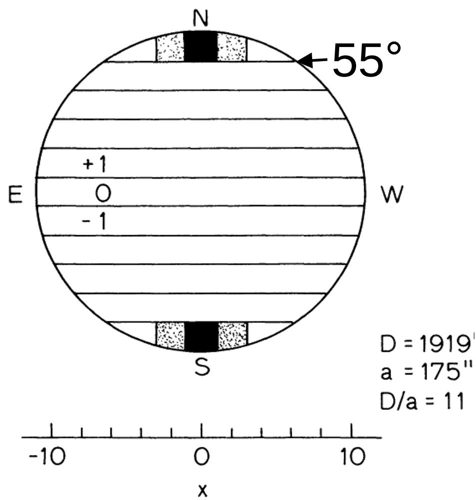


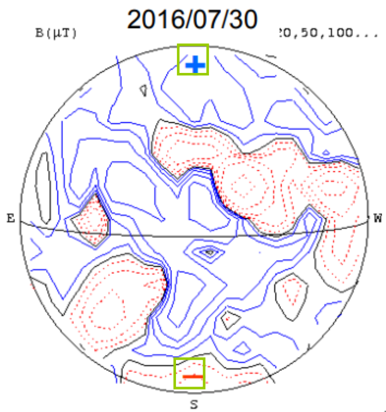
Babcock, 1955

Explanation of the annual variation: concentration at the poles

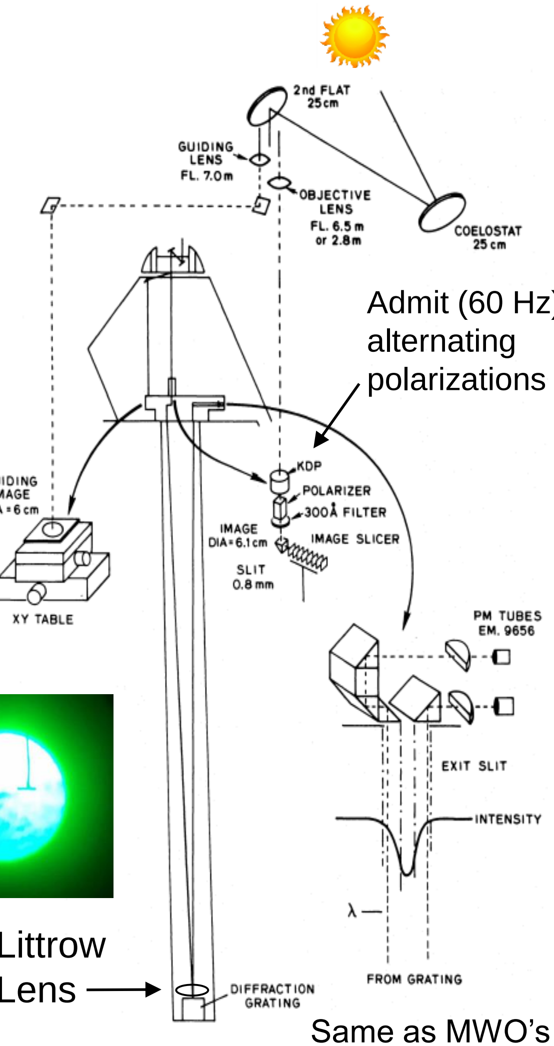
WSO Observations since 1976

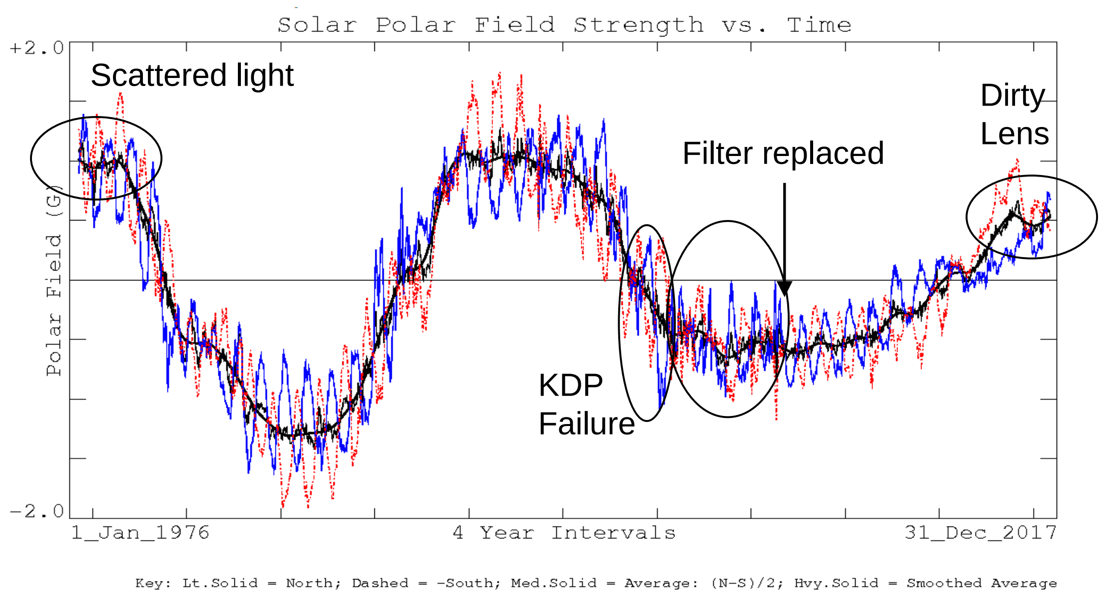


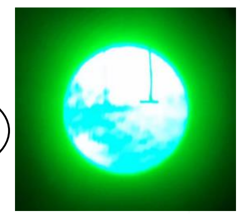




WSO Magnetogram

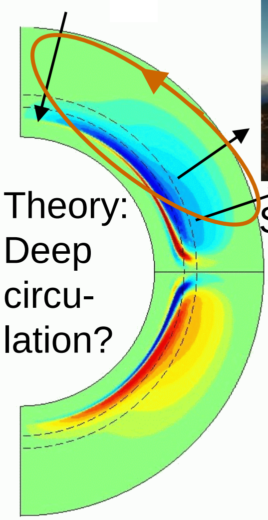


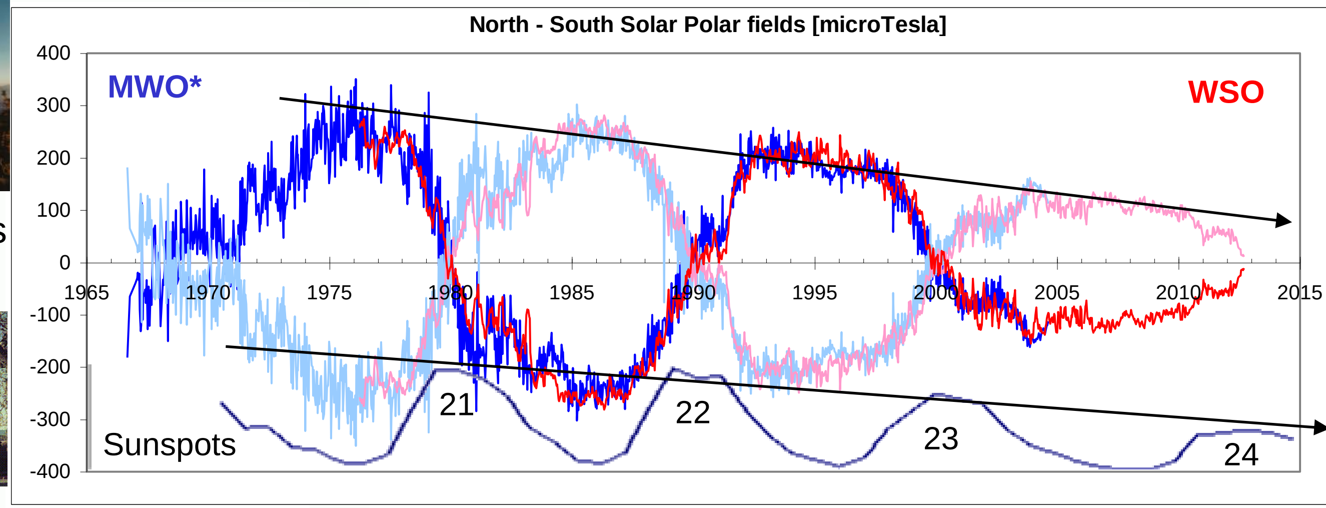


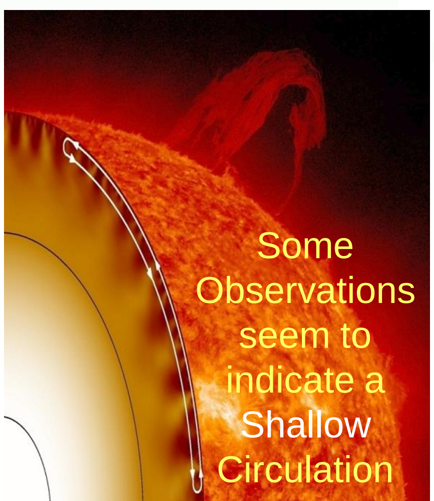


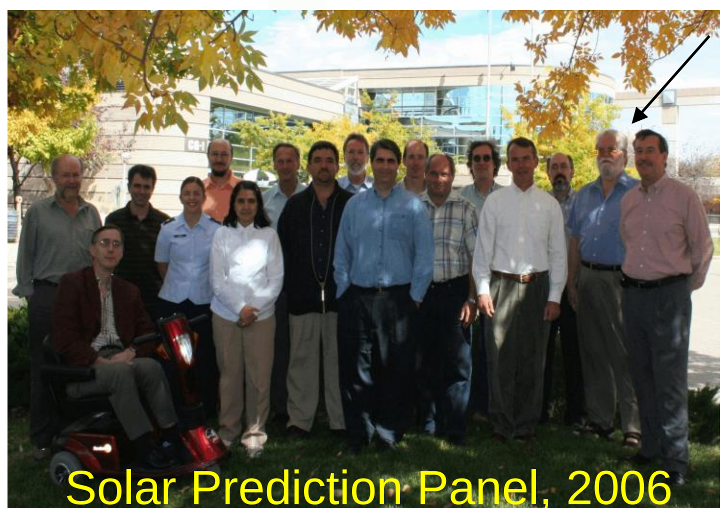
The magnetograph has never been upgraded

Combined Observations of the Polar Fields (Expressed as the 'Dipole Moment' = N – S)





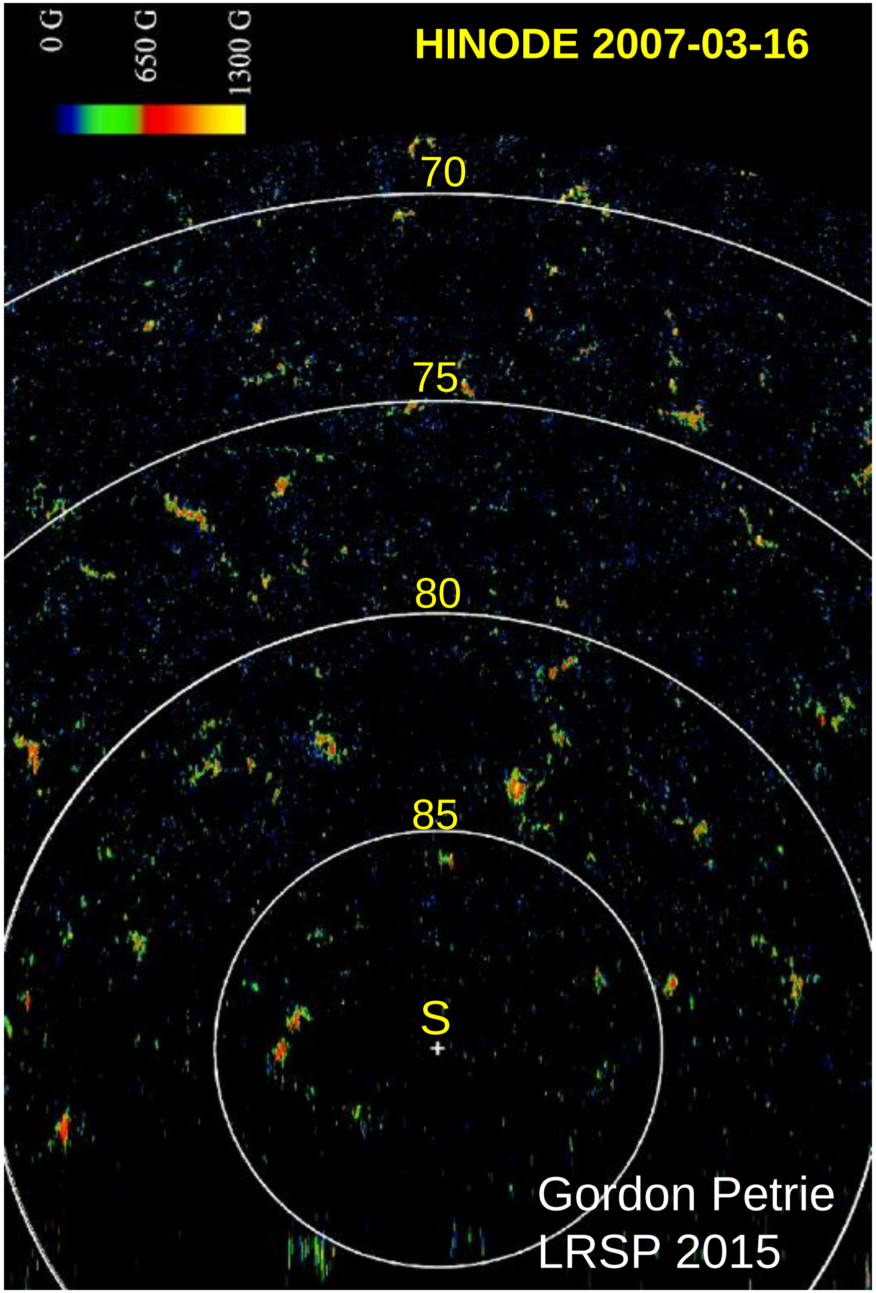




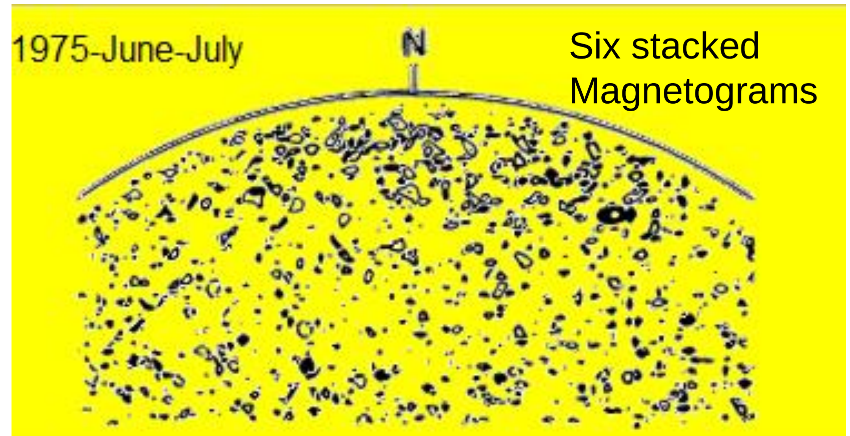
Observations and theory suggest that the magnetic field at the poles of the Sun at solar minimum is a good predictor of the next solar cycle.

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

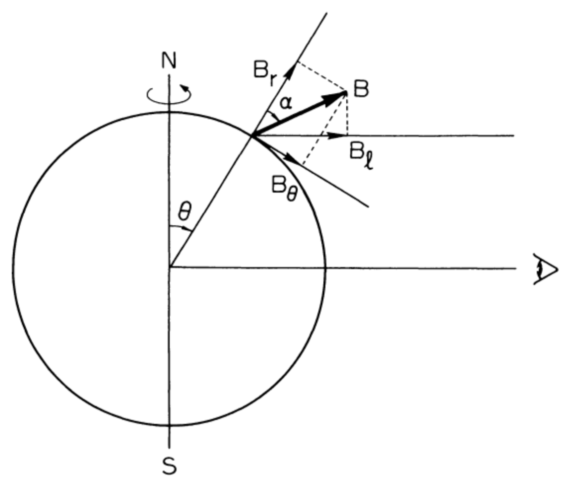
Fine Structure of the Polar Fields



The polar magnetic 'landscape'

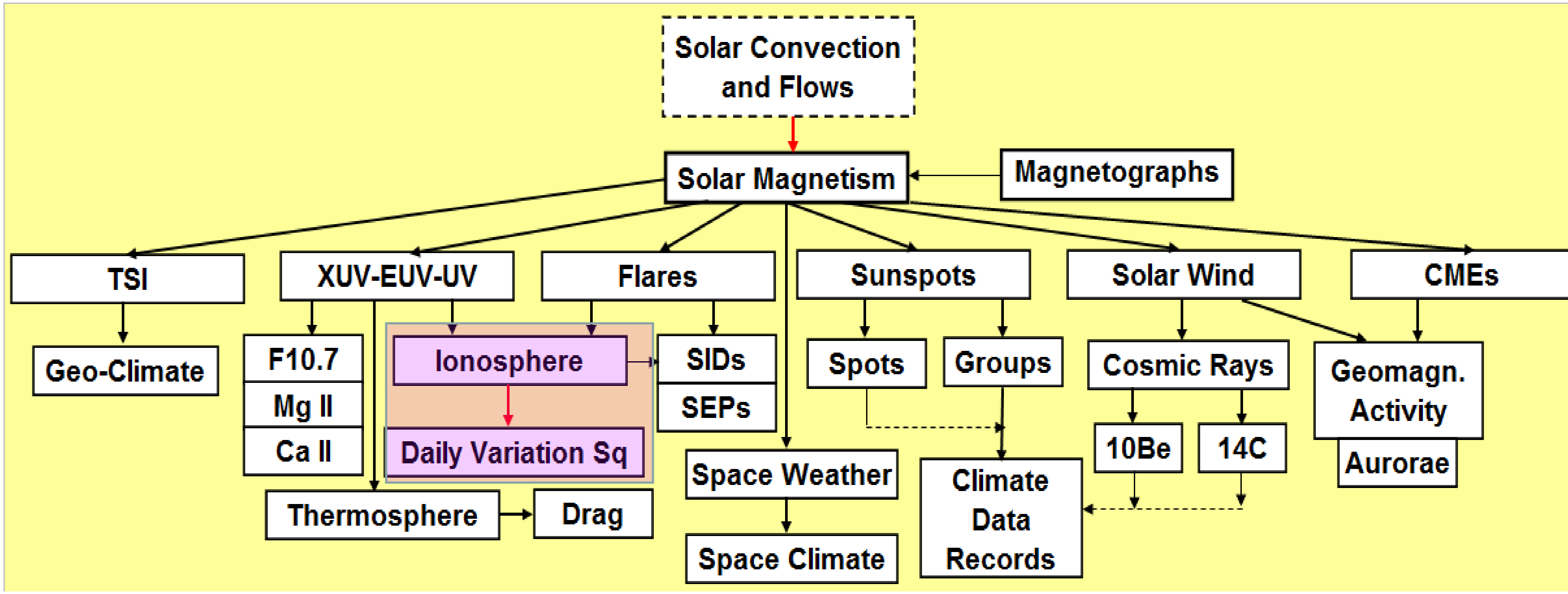


MWO: Howard, R., Solar Physics, 59, 243 (1978)



Line-of-Sight component is what we observe. Near the poles the real field is weakened by projection

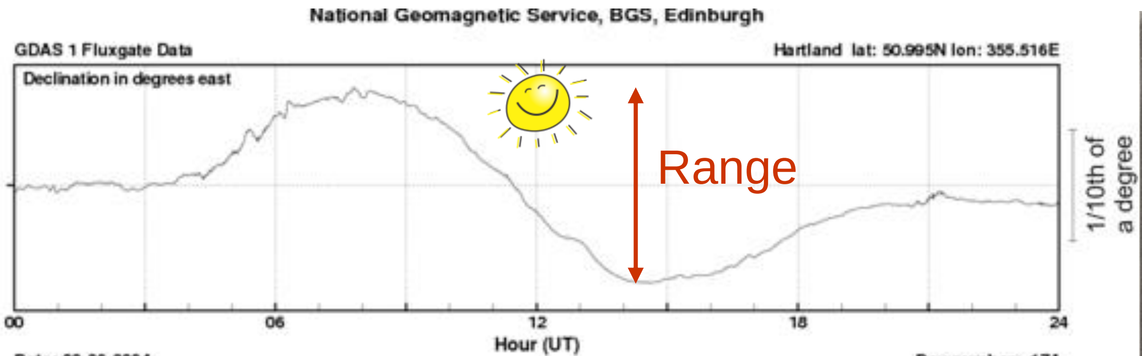
A Systems Approach: Everything Must Fit

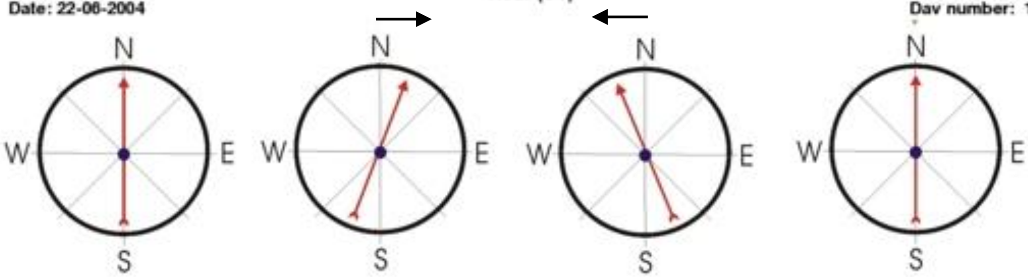


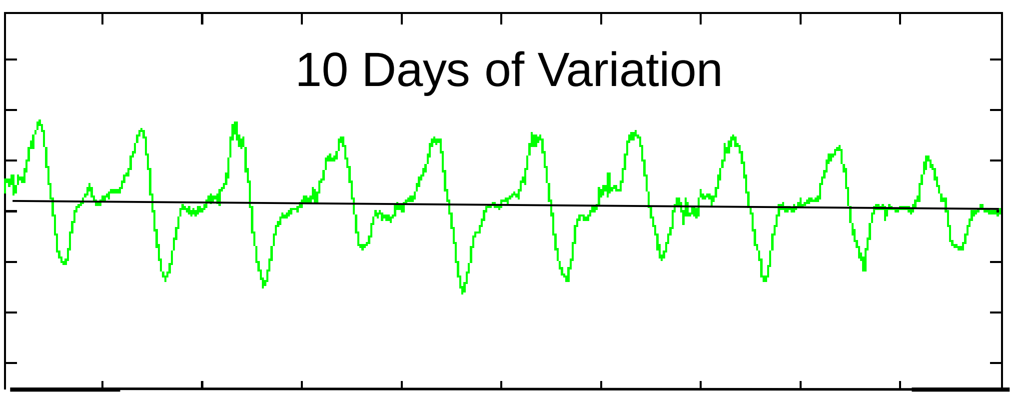
Faraday wrote to R. Wolf on 27th August, 1852: “I am greatly obliged and delighted by your kindness in speaking to me of your most remarkable enquiry, regarding the **relation existing between the condition of the Sun and the condition of the Earths magnetism**. The discovery of periods and the observation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

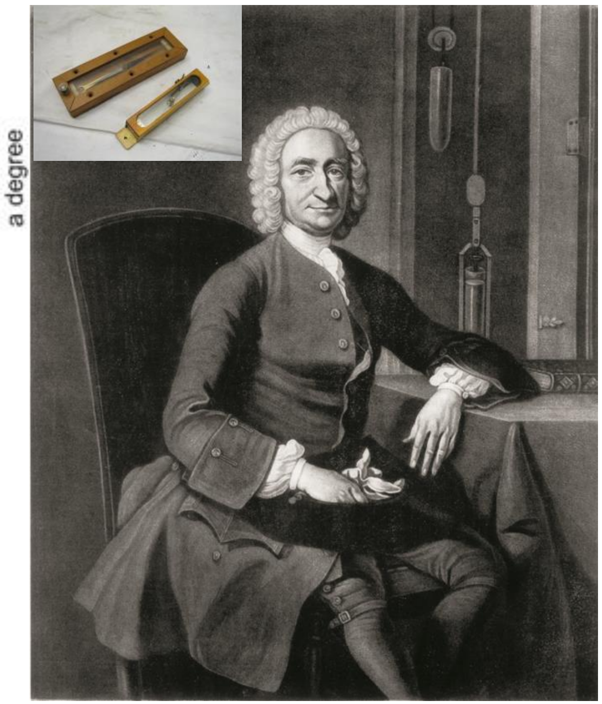
“everything must fit” is a lofty goal and we are not there yet, but it should be a guiding principle

The Diurnal Variation of the Direction of the Magnetic Needle





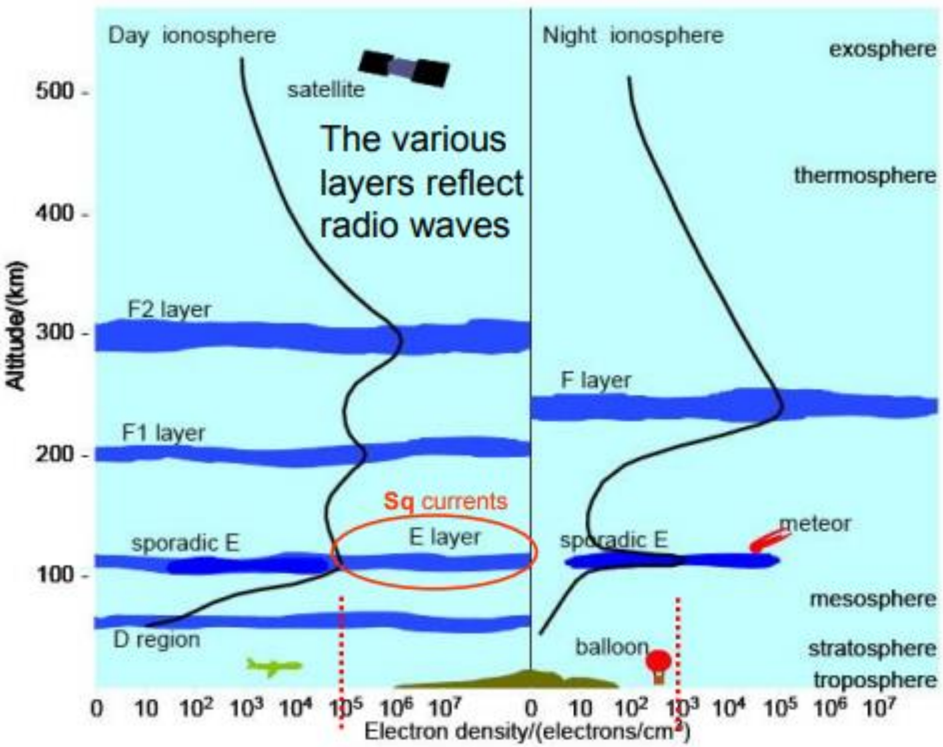




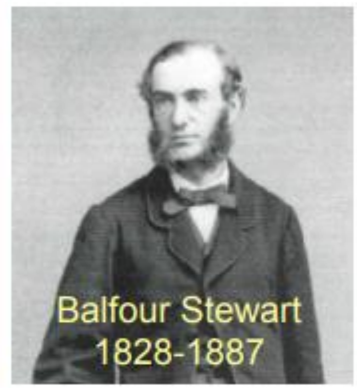
George Graham [London] discovered [1722] that the geomagnetic field varied during the day in a regular manner.

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



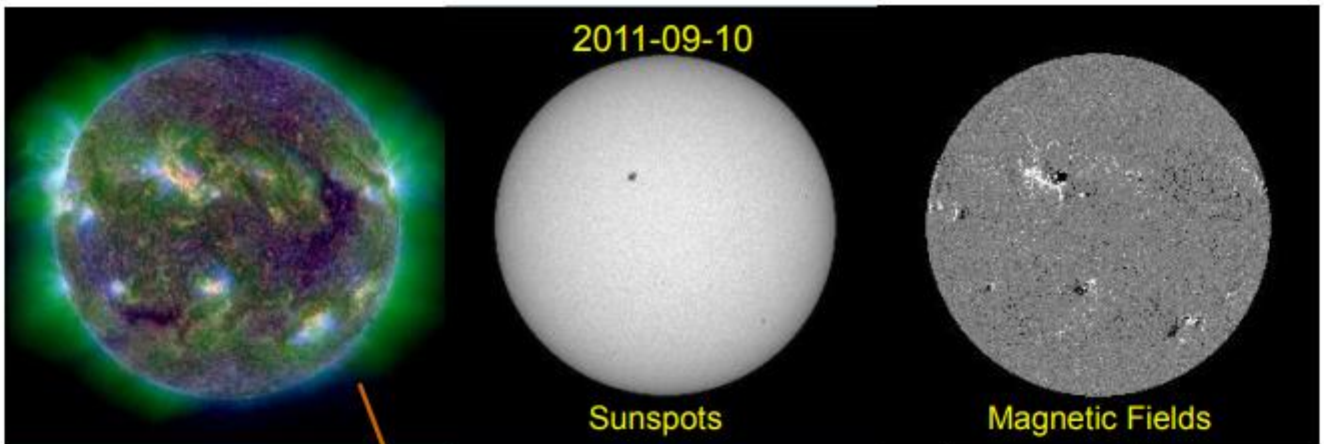
1882, Encyclopedia Britannica, 9th Ed.:

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

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.

The Source of the Ionization: EUV

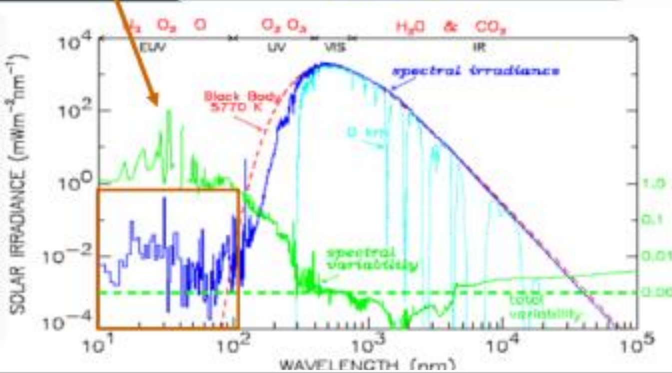


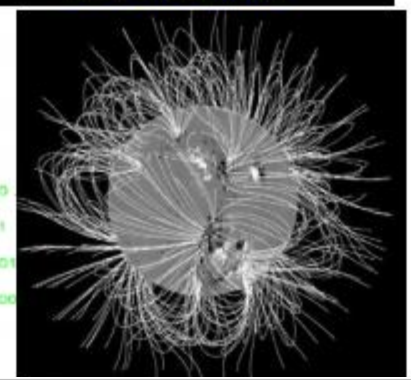
< 102.7 nm

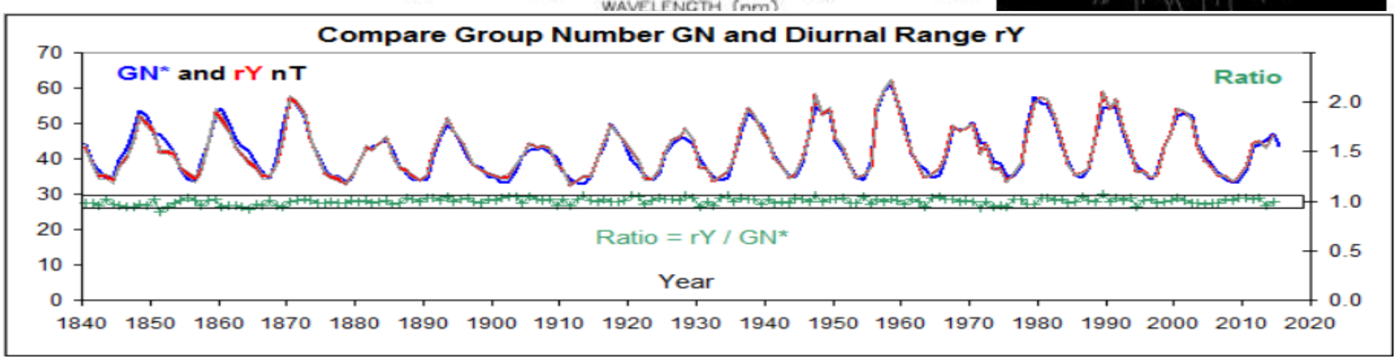
$$O_2 + h\nu \xrightarrow{J} O_2^+ + e^-$$

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

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

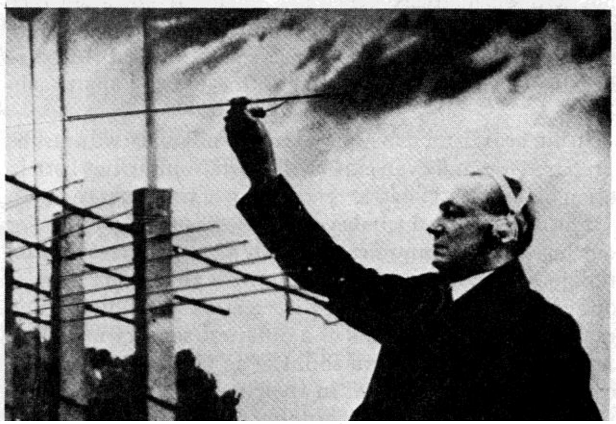






Because the process is slow (the Zenith angle χ changes slowly) we have a quasi steady-state, in which there is no net electric charge. The conductivity thus varies with the square root of the zenith angle and of the overhead EUV flux

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.

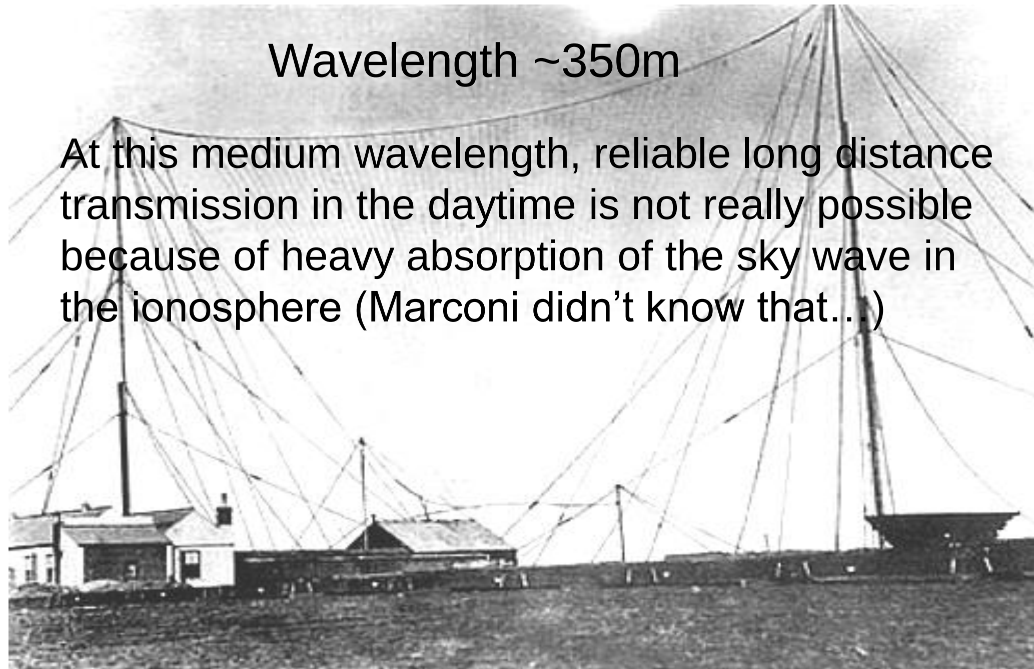
When Marconi realized the importance of his first discoveries in 1895, he asked the Italian Minister of Telecommunication to help him. But the minister found that Marconi's experiments were too extravagant. That's why Marconi went to England, where he won the support of Sir William Peace, the Postmaster 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

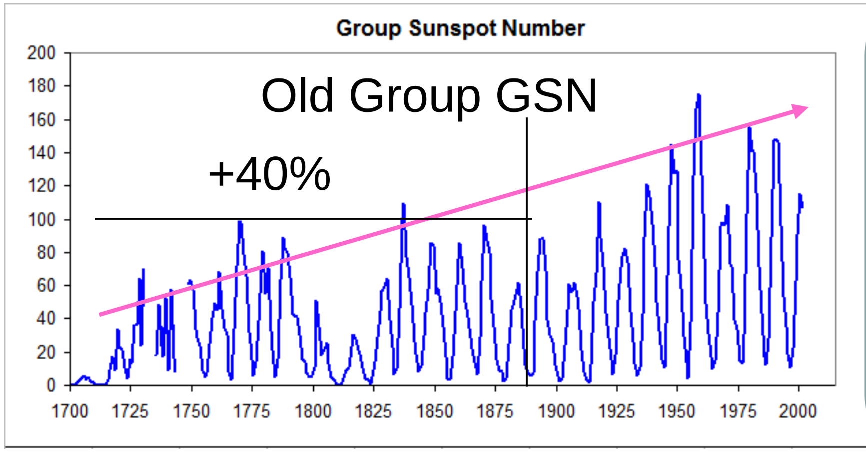
At this medium wavelength, reliable long distance transmission in the daytime is not really possible because of heavy absorption of the sky wave in the ionosphere (Marconi didn't know that…)

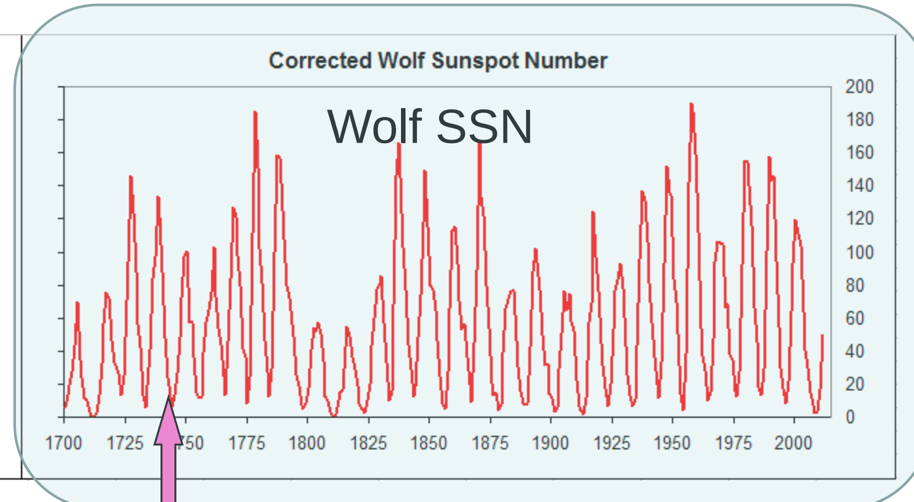


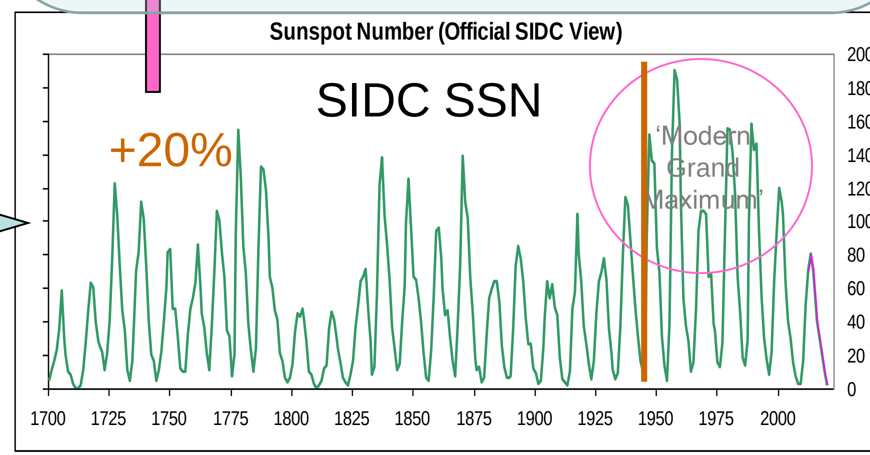
The Tale of Two Sunspot Numbers

WSN = 10 * Groups + Spots

GSN = 12 * Groups





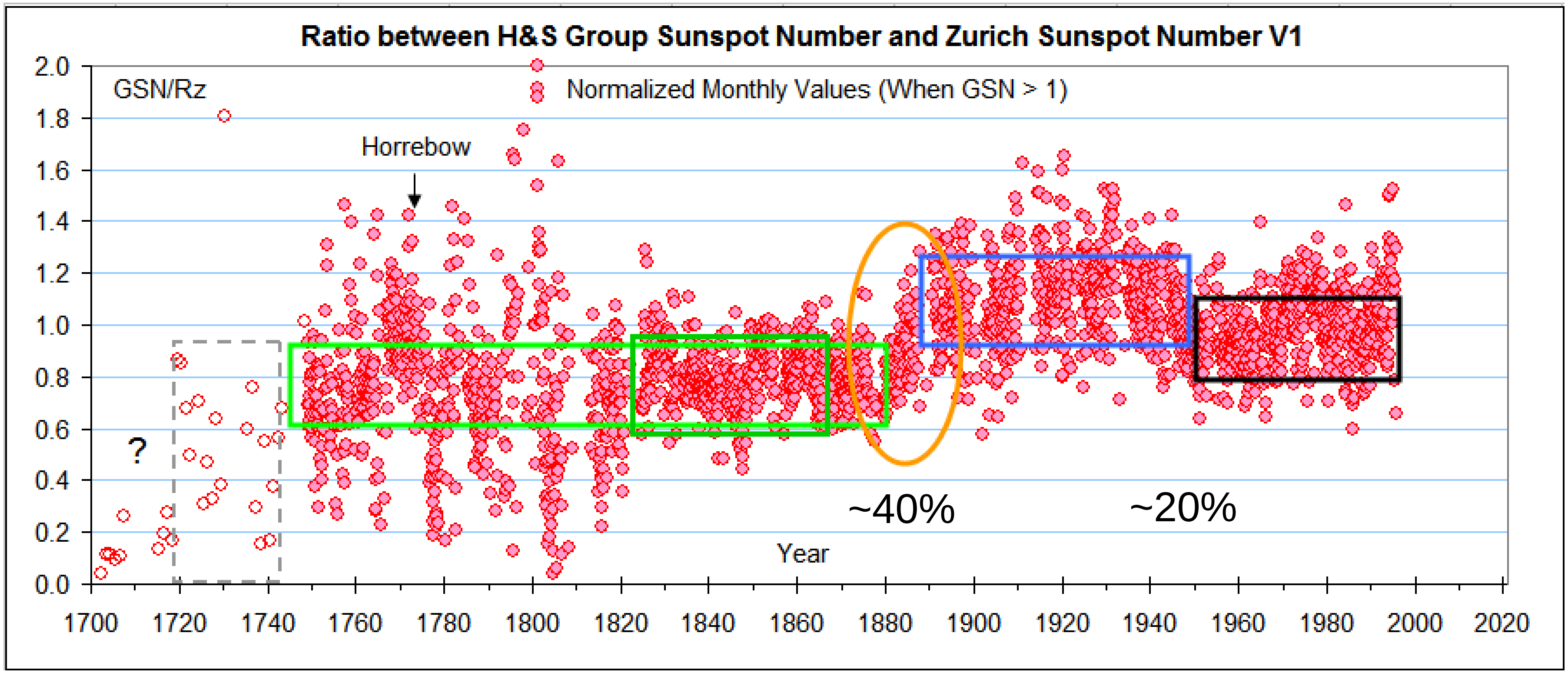


The old 'official' sunspot number [maintained by SIDC in Brussels] showed a clear 'Modern Maximum' in the last half of the 20^{th} century.

Correct GSN by +40% before ~1882
Correct WSN by -20% after 1946, because of weighting of the count introduced then (the Waldmeier Jump)

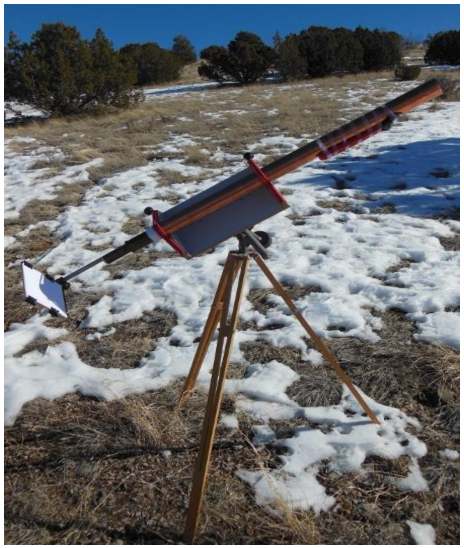
The new SSN series suggest that there likely was no Modern Grand Maximum

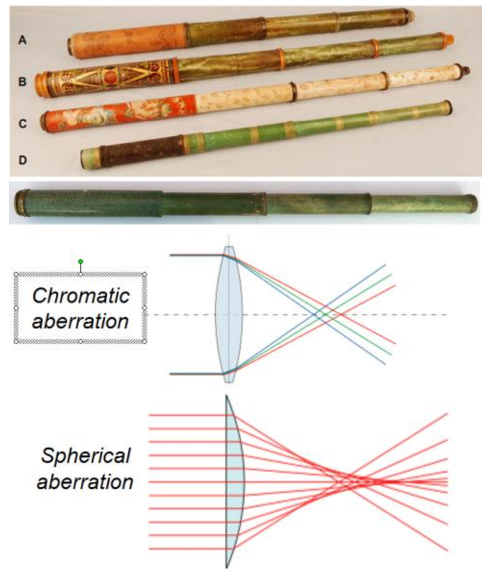
Discrepancies were Both Large and Systematic

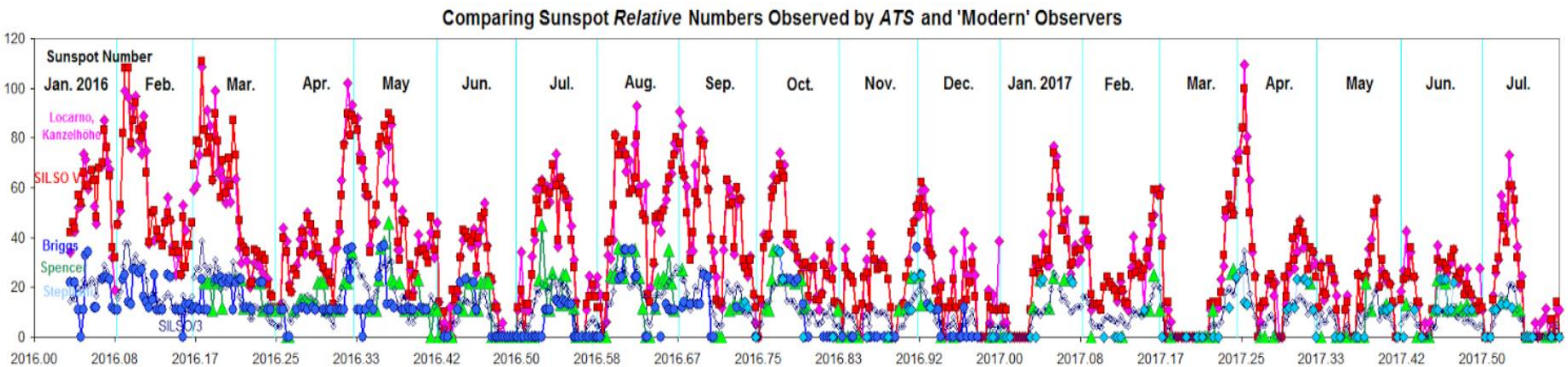


The ratio of the H&S GSN and the Official [“Zürich”] Relative Sunspot Number [version 1] (when not too small) reveals some systematic variations, related to choice of observers…

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

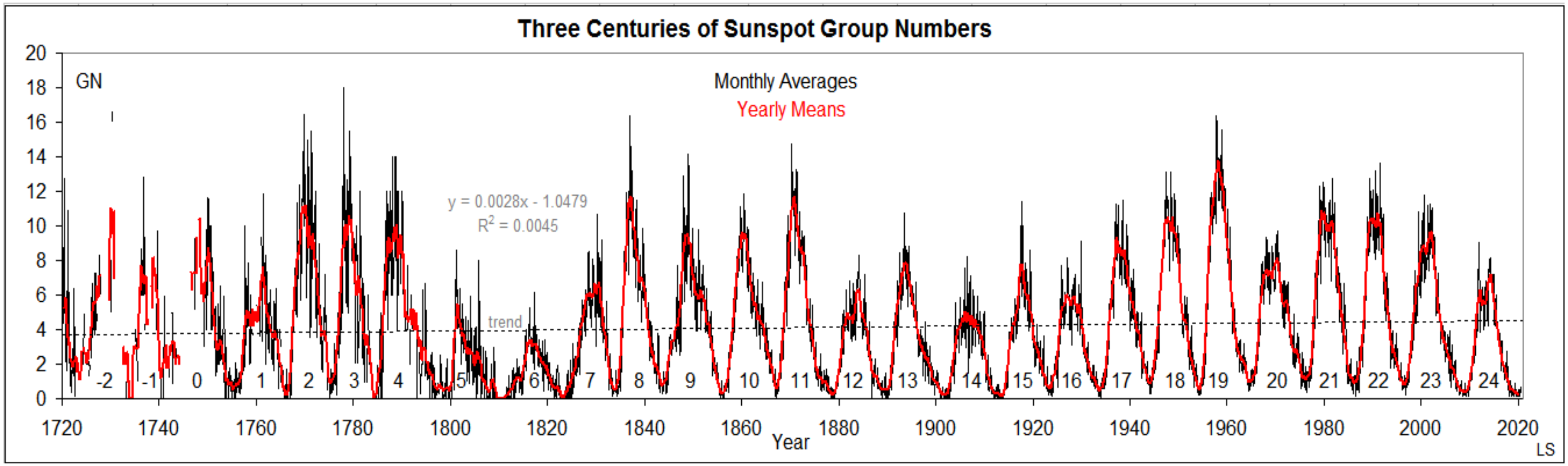


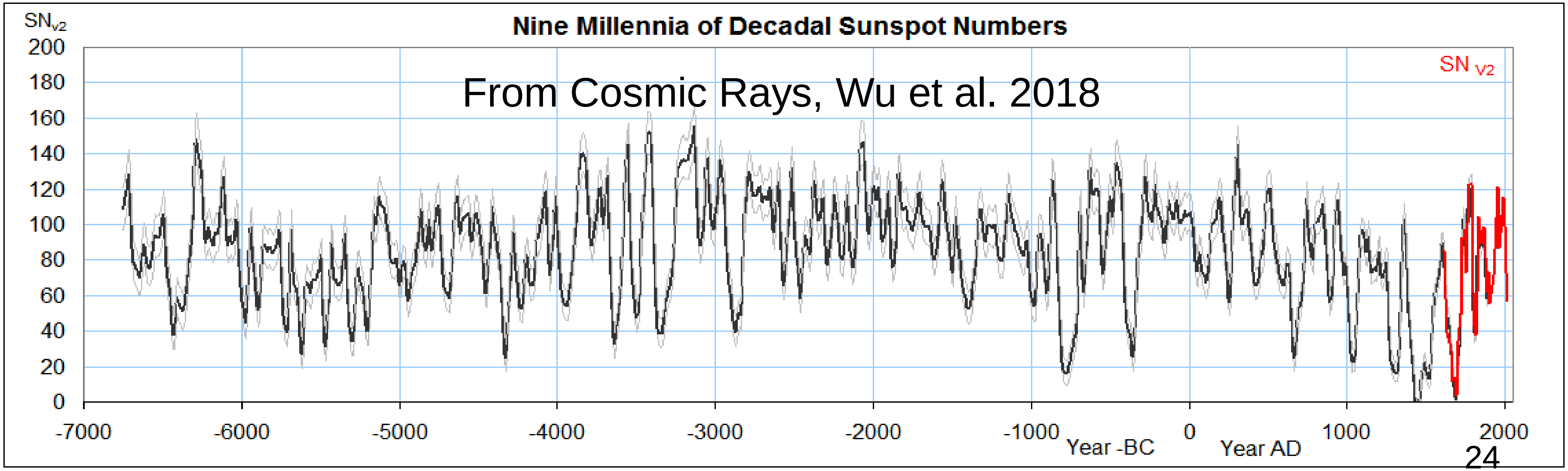




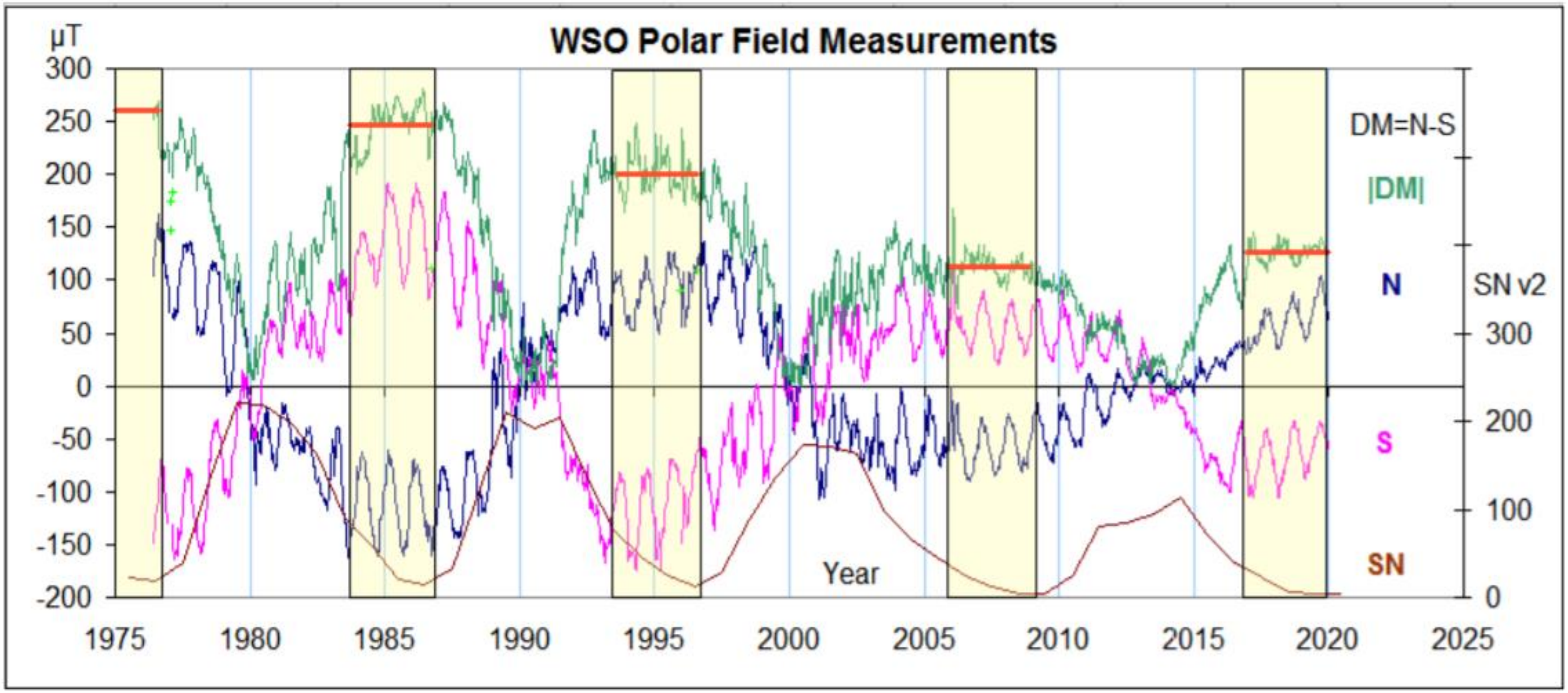
Modern observers see three times as many sunspots than our 18th century replicas

The Big Picture of Solar Activity



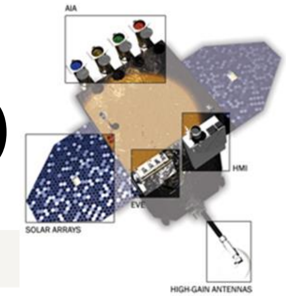


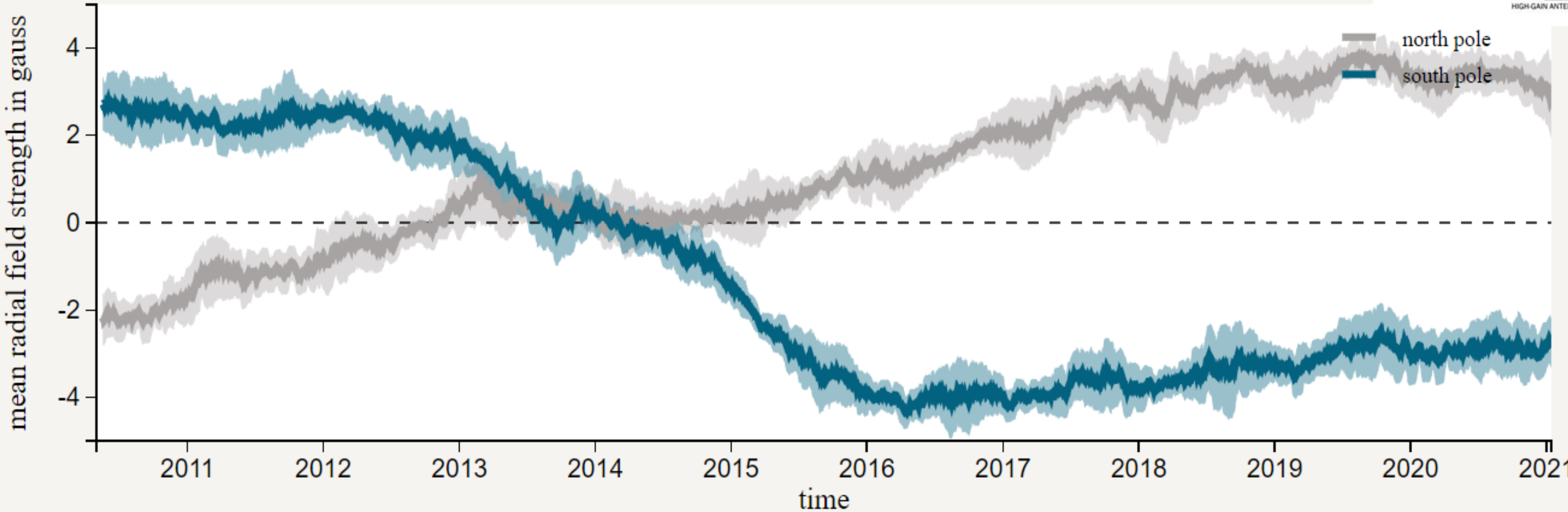
WSO Polar Field Measurements

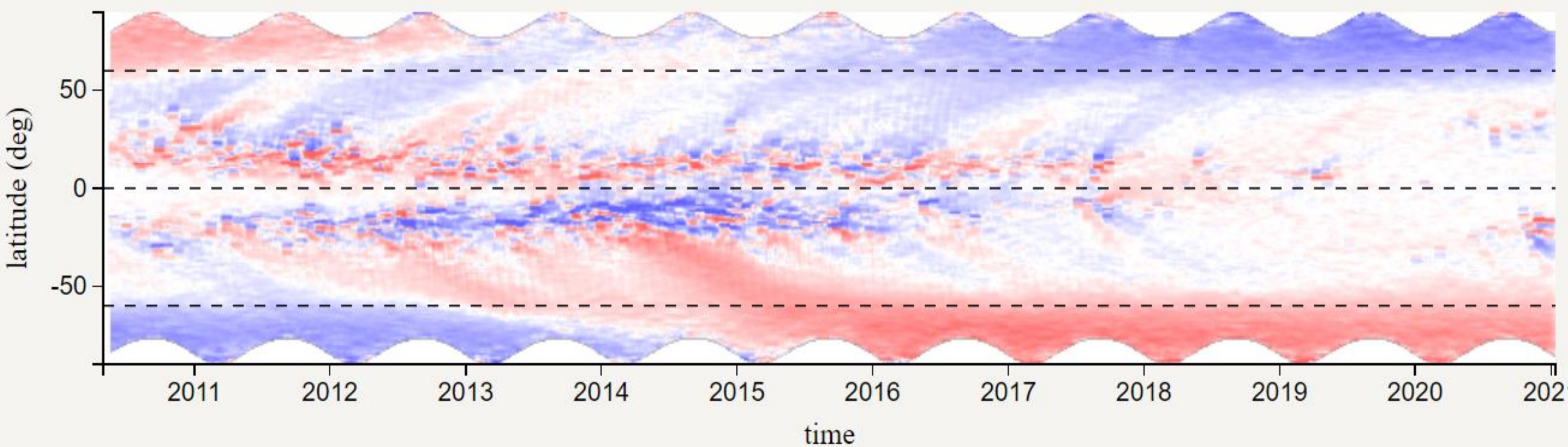


We found at the previous minimum that the ‘optimum’ measure of the polar dipole precursor was the average over three year before the minimum, shown here by the red lines

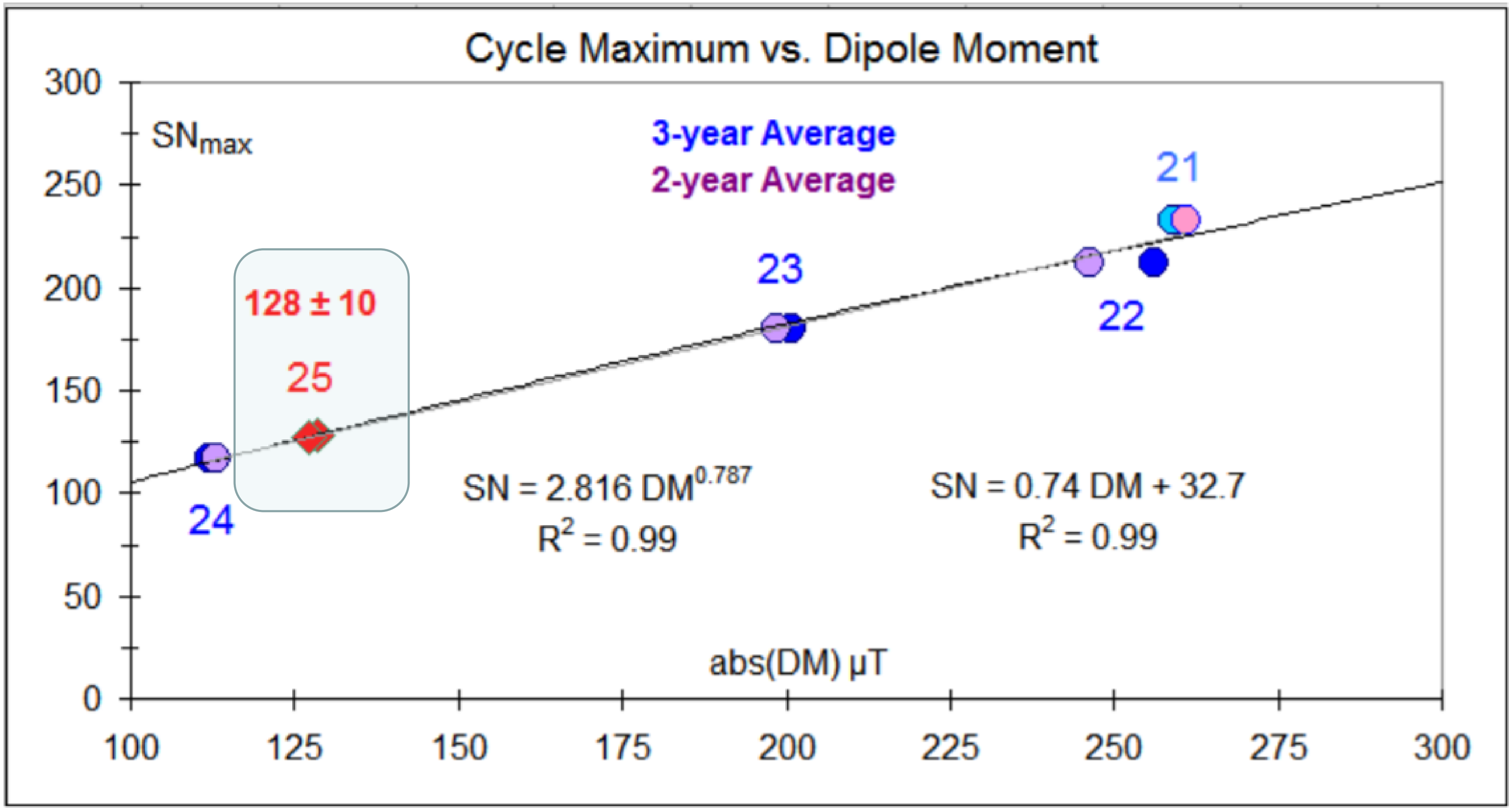
Polar Fields by HMI on SDO



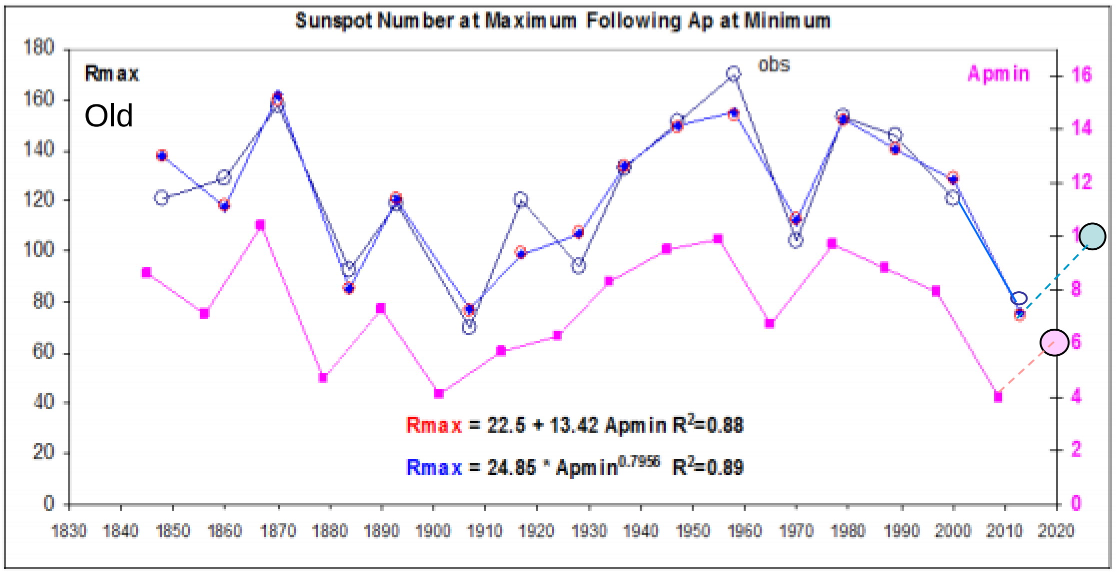


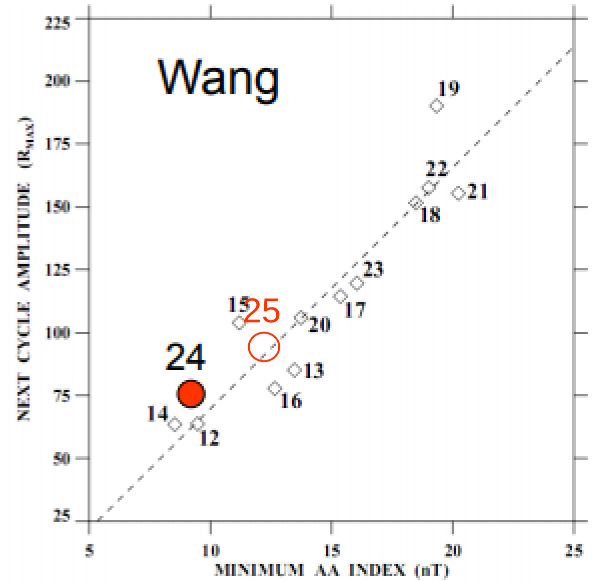


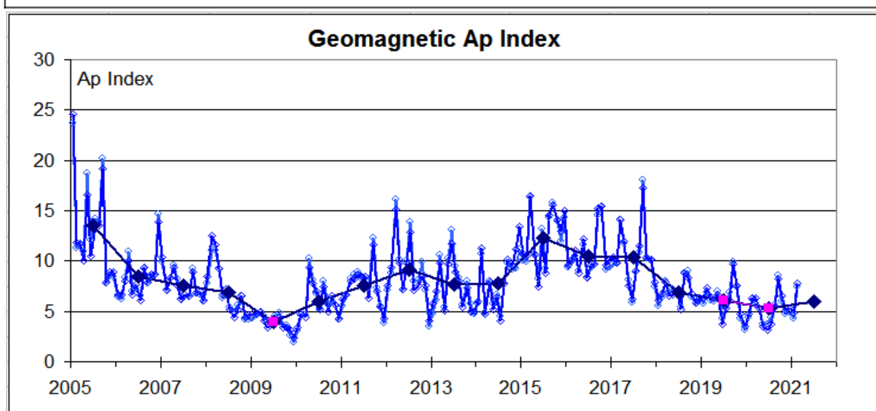
Using the Dipole Moment



Geomagnetic Activity Seems to be a Decent Precursor as Well



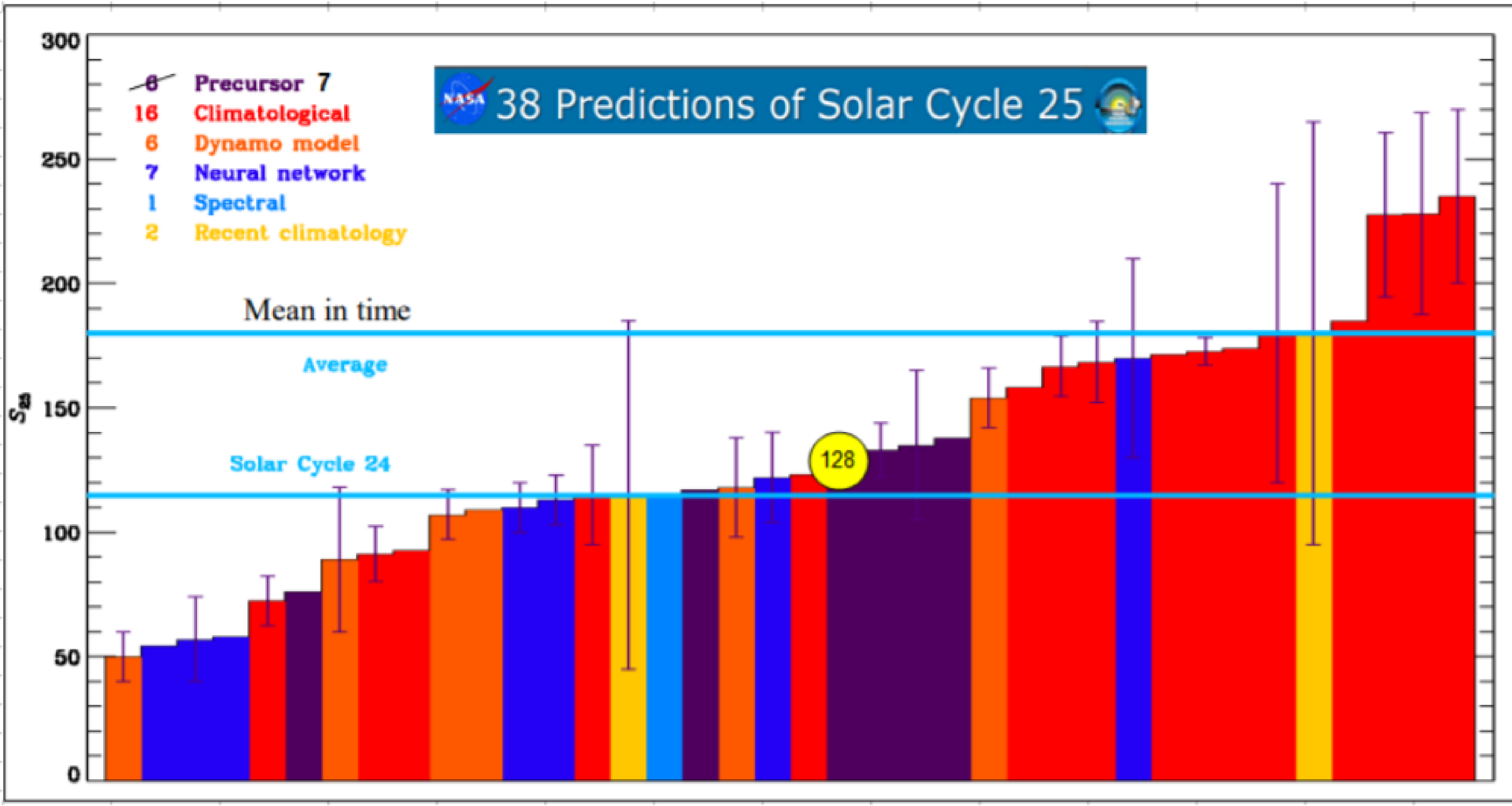




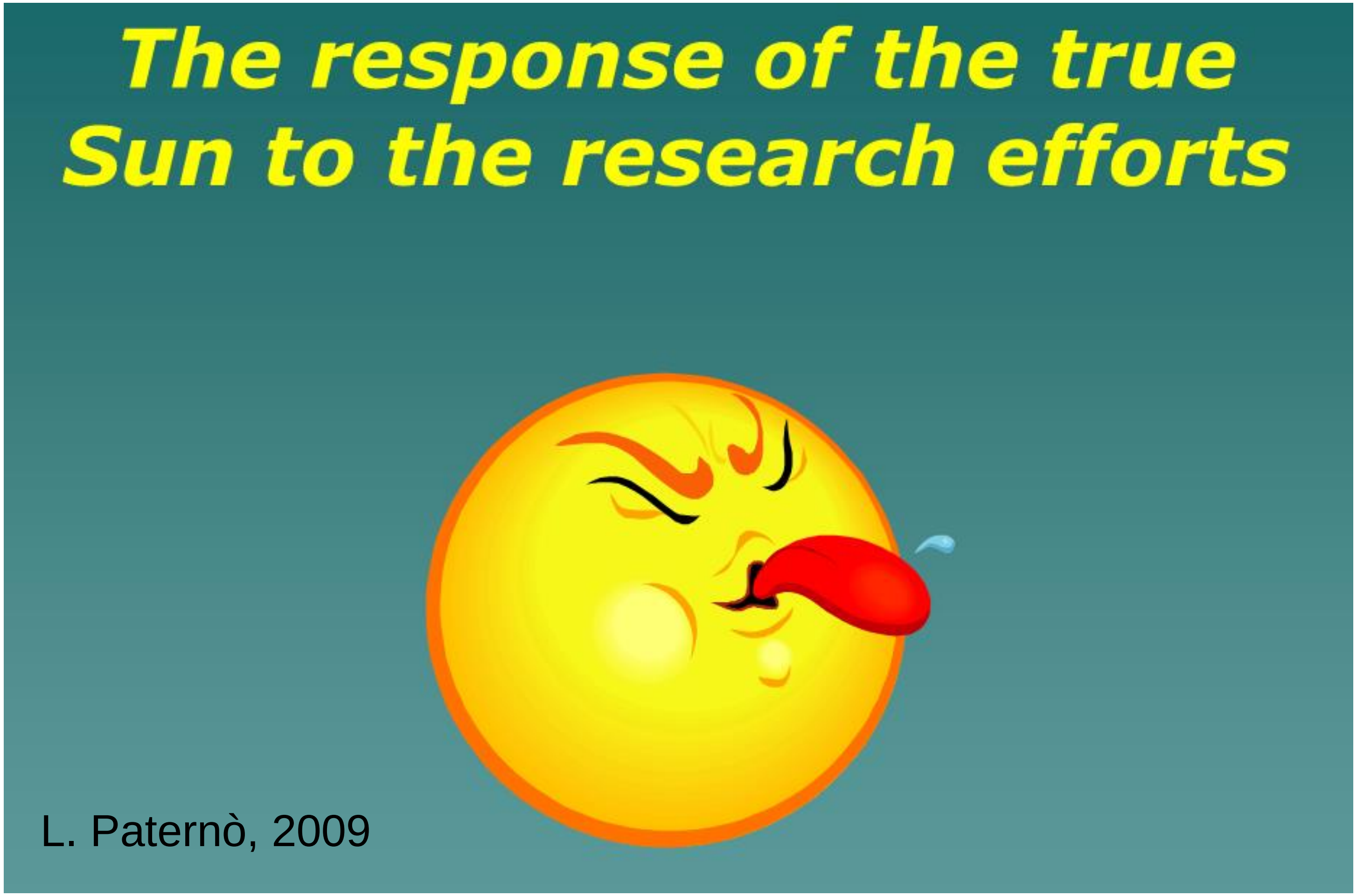
The idea is that the polar fields at sunspot minimum makes up most of the magnetic flux in the heliosphere and that geomagnetic activity depends on that flux.

SC25 perhaps between SC20 and SC24

Compare with Other Predictions



The Sun May Not Cooperate…



The End

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 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.