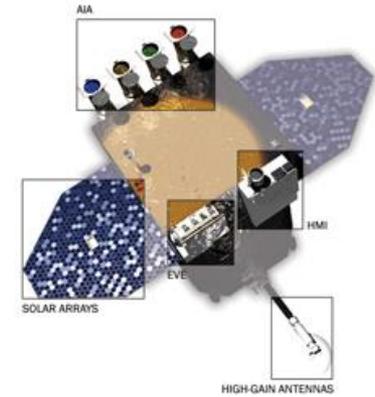# Multi-Messenger Solar Physics Through Time
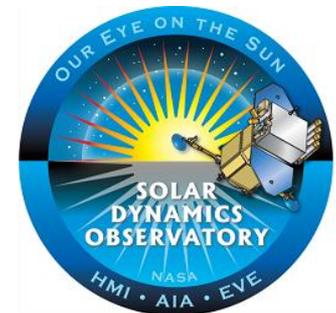
WSO

SDO

Leif Svalgaard
Stanford University
w/ Hugh Hudson

February 19, 2019 at UCB
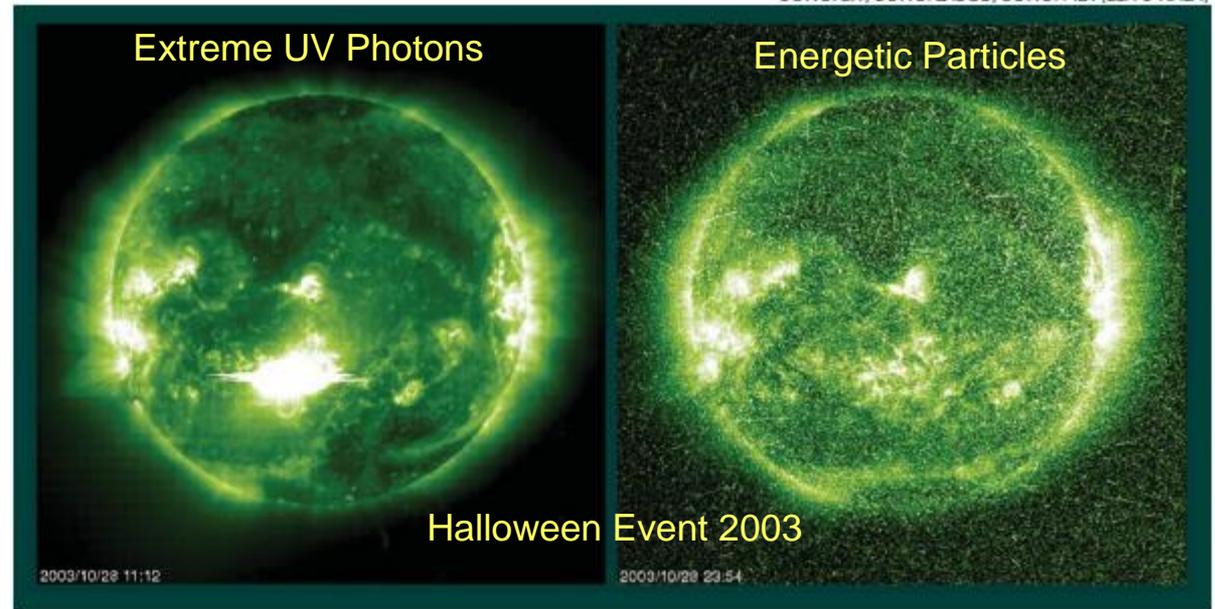https://leif.org/research

1

Solar Multi-Messengers
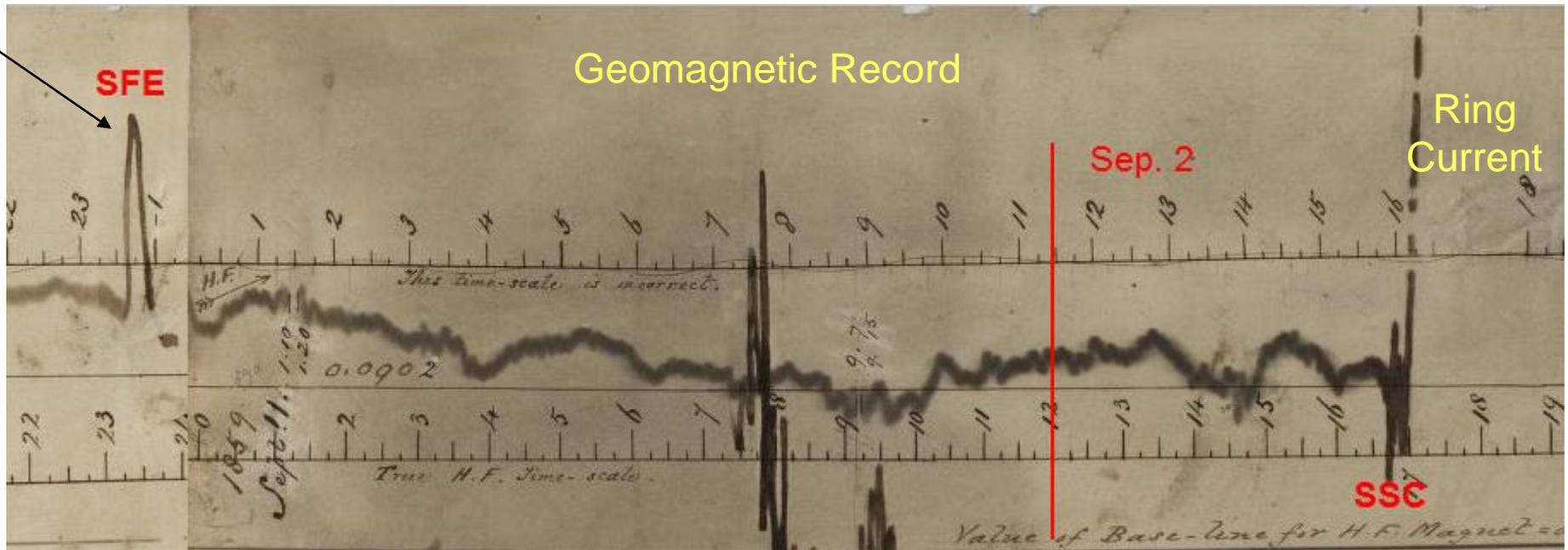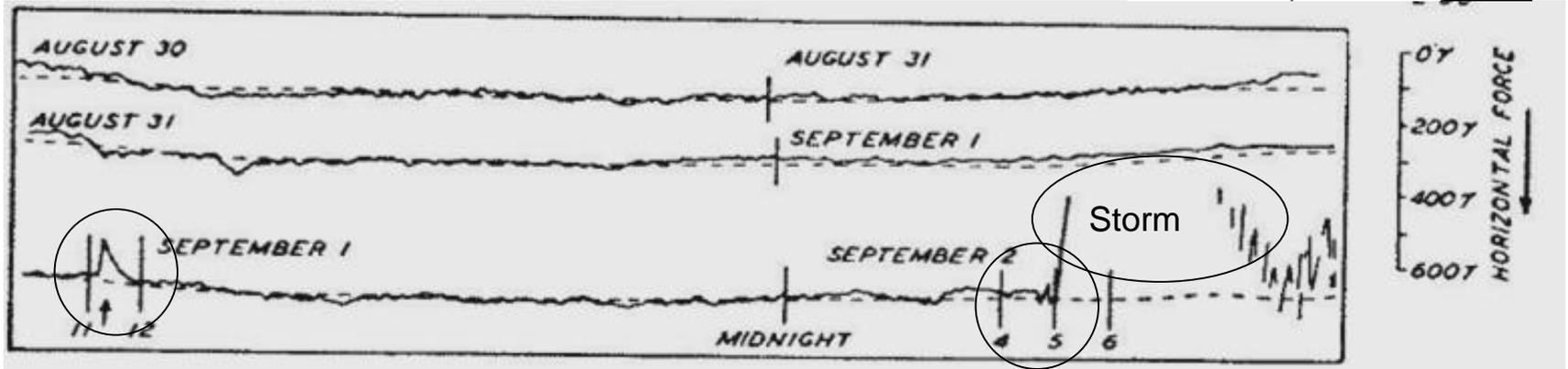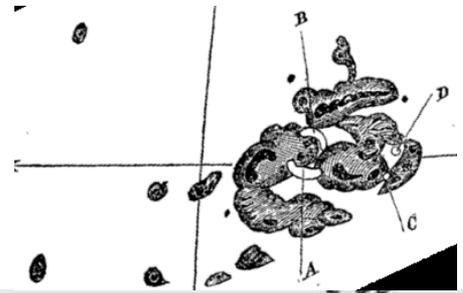
Multimessenger solar astrophysics

The term "multimessenger astronomy"—combining different signals, or messengers, from the same astrophysical event to obtain a deeper understanding of it—is in the air nowadays, largely because of the remarkable success of the Laser Interferometer Gravitational-Wave Observatory (LIGO) in detecting gravitational waves[1] (see PHYSICS TODAY, December 2017, page 19). Four messengers reach us from beyond the solar system: photons, neutrinos, cosmic rays, and now gravitational waves. Lost amid the current buzz, though, is that the Sun produces many other messengers.

SOHO/EIT, SOHO/LASCO, SOHO/MDI (ESA & NASA)

Extreme UV Photons

Energetic Particles

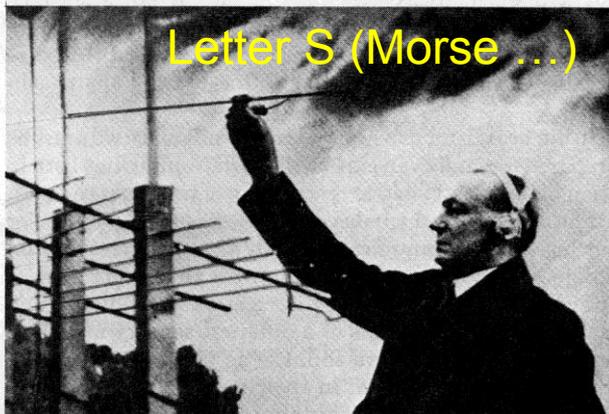Halloween Event 2003

2003/10/28 11:12   2003/10/28 23:54

Lost amid the current buzz, though, is that the Sun produces many other messengers. And each messenger often sends us several different messages

2

The Carrington Event 1859
Several Messages

AUGUST 30   AUGUST 31
AUGUST 31   SEPTEMBER 1
SEPTEMBER 1   SEPTEMBER 2   Storm
MIDNIGHT   4   5   6

HORIZONTAL FORCE
0 γ
200 γ
400 γ
600 γ

SFE

Geomagnetic Record

Sep. 2

Ring Current

SSC

This time-scale is incorrect.

True H.F. Time-scale.

Value of Base-line for H.F. Magnet =

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

Letter S (Morse …)

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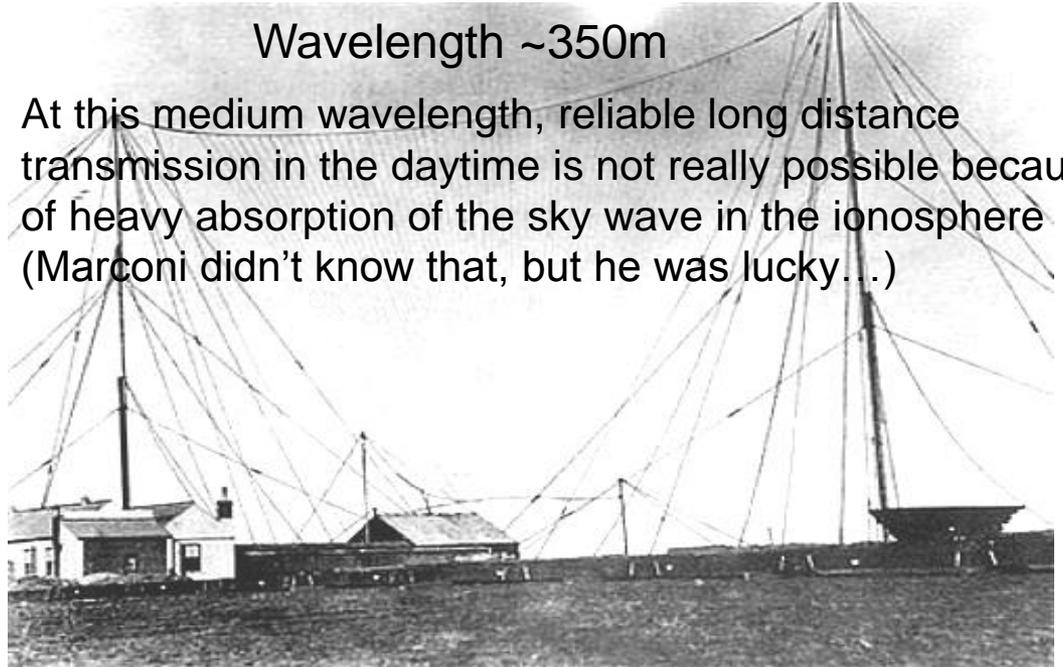
Later he managed to send a message from US president Theodore Roosevelt to the King of the UK via his Glace Bay station in Nova Scotia, Canada, across the Atlantic on 18 January 1903.

4

Kennelly Suggested a Wave Guide

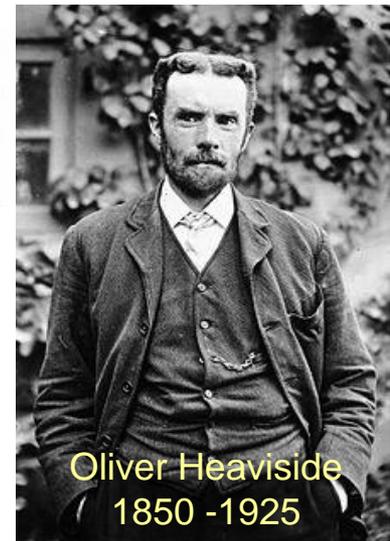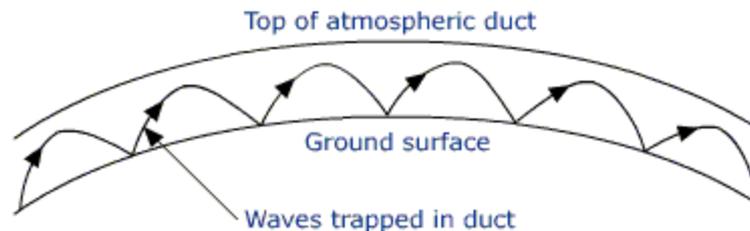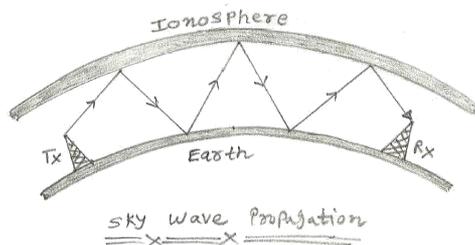On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere. 1902

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
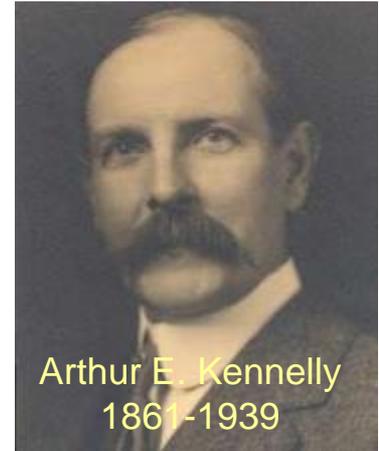
Oliver Heaviside Got the Same Idea

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."
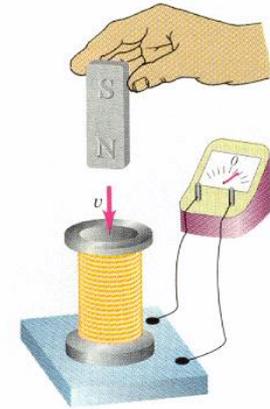
10th ed. of Enclycopedia Britannica

Ionosphere

Tx   Earth   Rx

sky wave Propagation

Top of atmospheric duct

Ground surface

Waves trapped in duct

Oliver Heaviside
1850 -1925

"there seems to be grounds for imagining that their **conductivity may be much greater than has hitherto been supposed**." B. Stewart 1882

5

# Ionospheric Conducting Layers

Dynamic
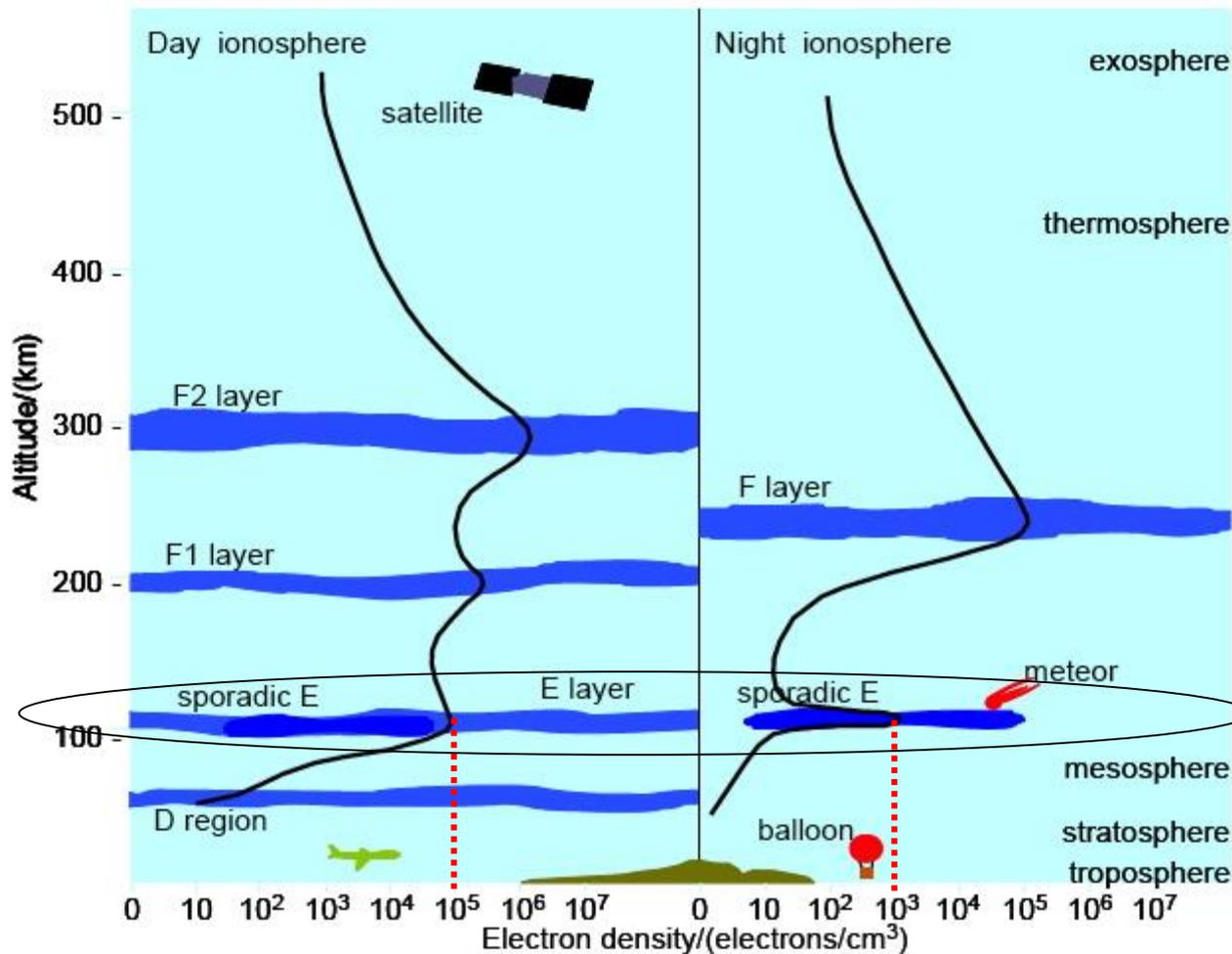
An effective dynamo process takes place in the dayside E-layer where the density, both of the neutral atmosphere and of the electrons are high enough.
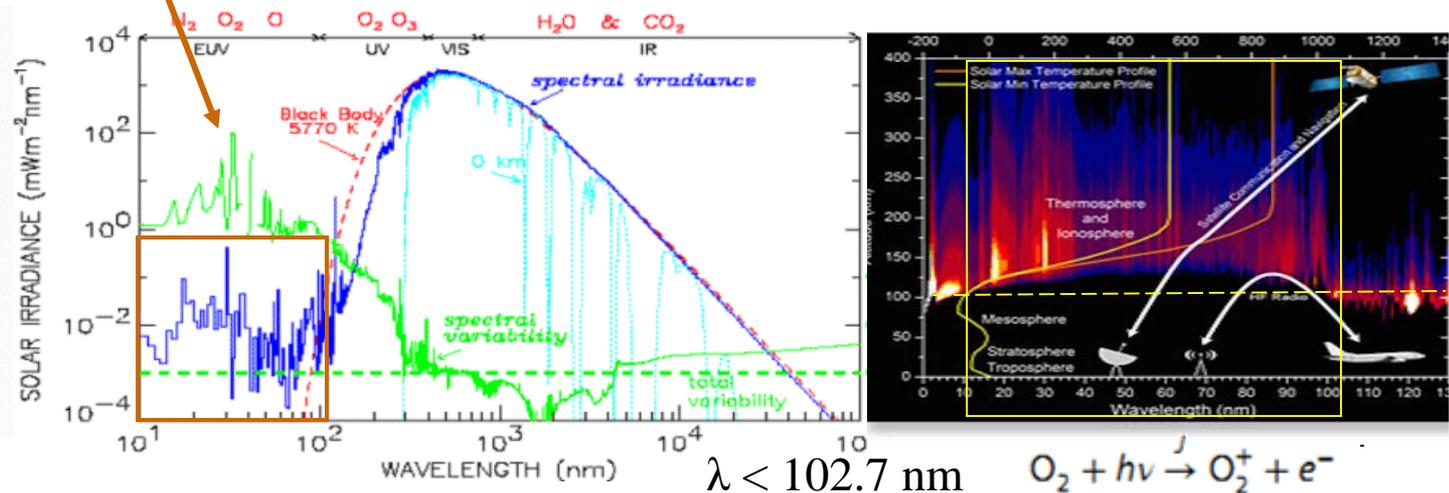
We thus expect a geomagnetic response due to electric currents induced in the E-layer.

We need 1) something to produce the charges and 2) something to move them across the magnetic field
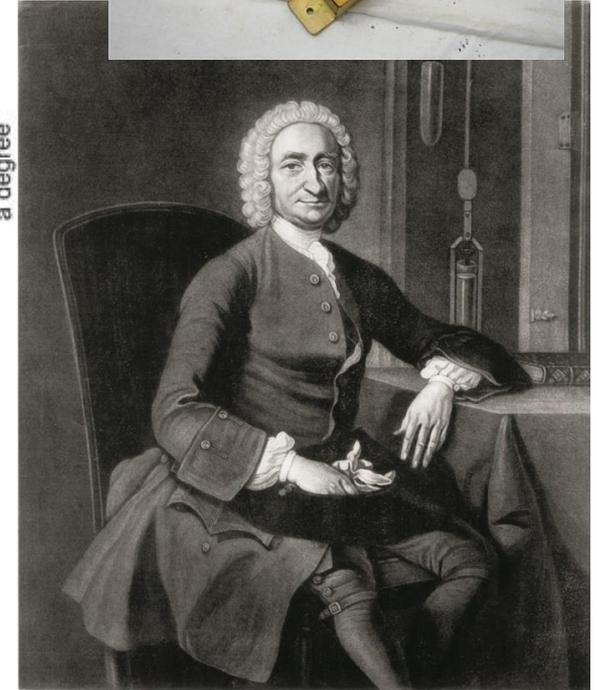
6

The Source of the Ionization

2011-09-10

Extreme Ultraviolet

Sunspots

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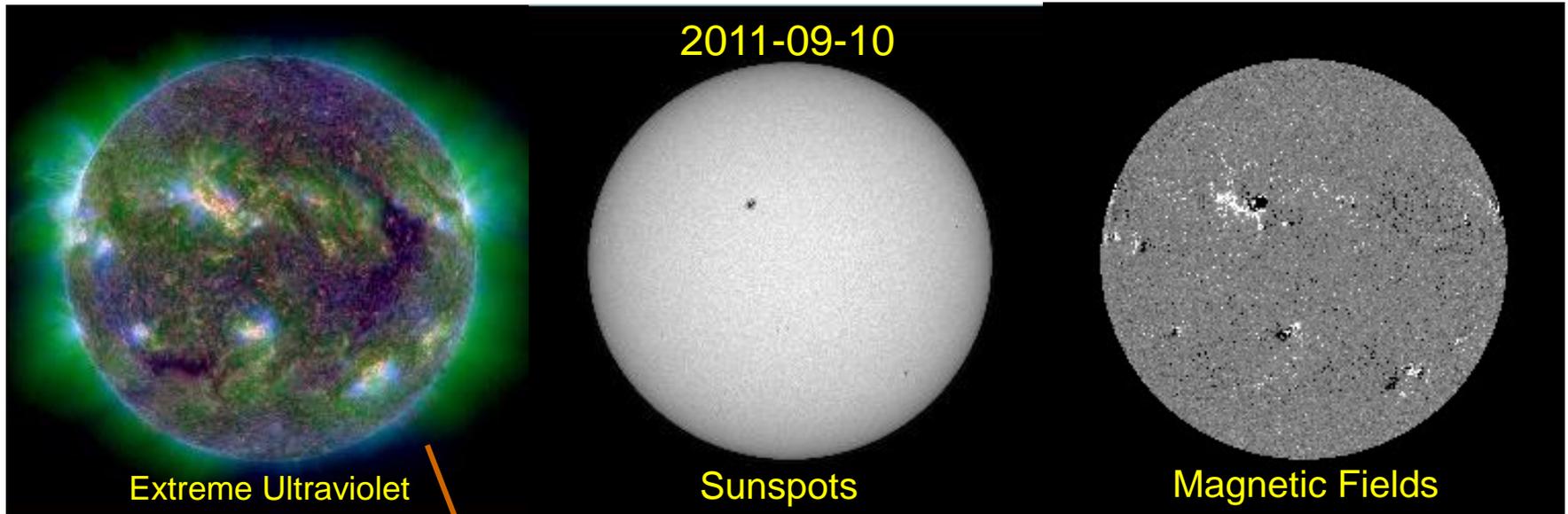
Extreme Ultraviolet (EUV), wavelengths 17.1-21.1-30.4 nm from chromosphere and corona with temperatures from 50,000 K to 2 million K
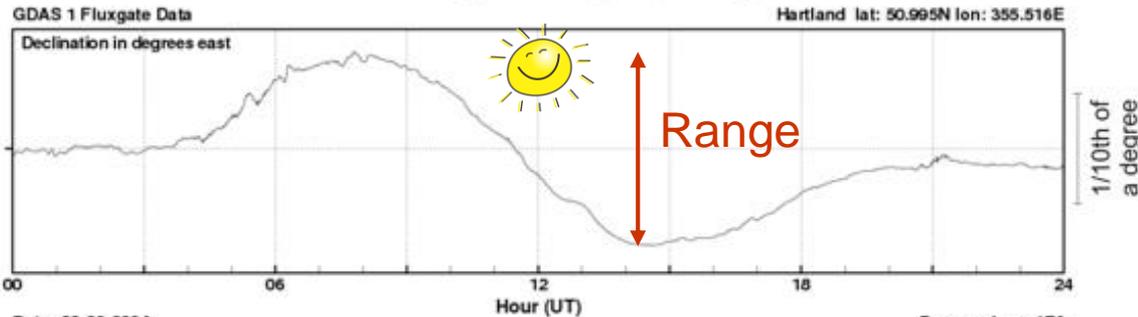

$\lambda < 102.7$ nm

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

The Diurnal Variation of the Direction of the Magnetic Needle

National Geomagnetic Service, BGS, Edinburgh

GDAS 1 Fluxgate Data

Declination in degrees east

Hartland lat: 50.995N lon: 355.516E

Range

1/10th of a degree

Hour (UT)

Date: 22-06-2004

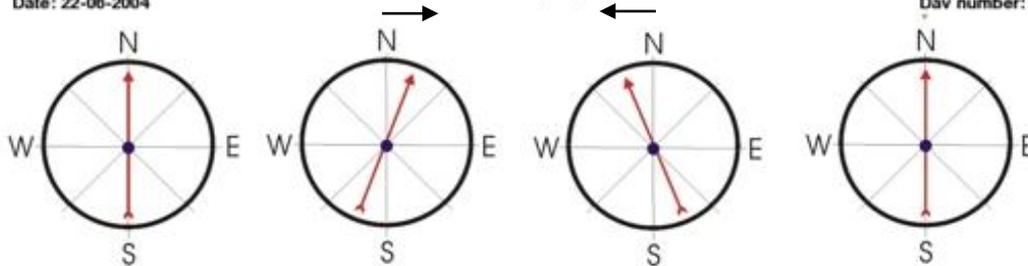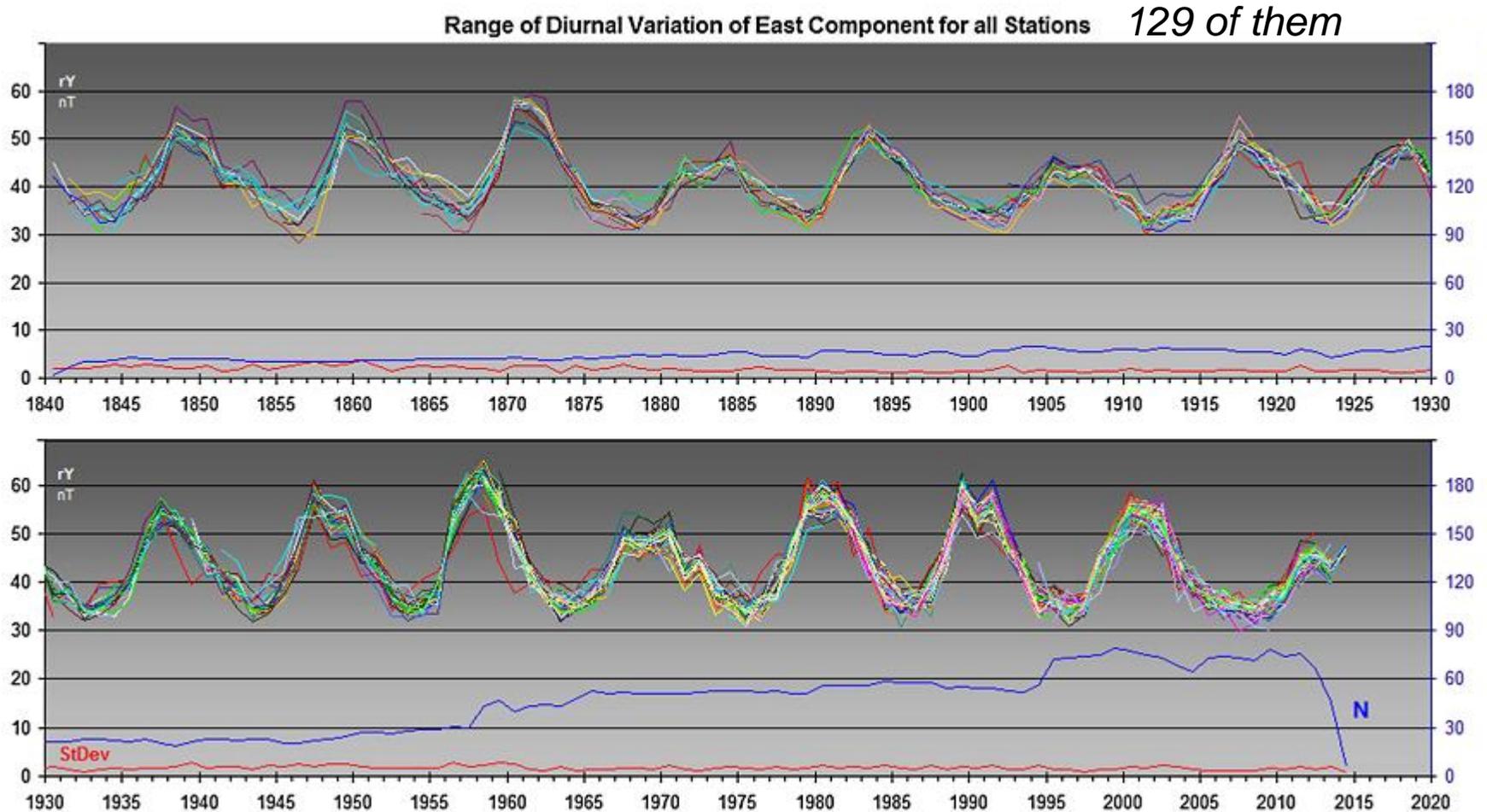Day number: 174

N W E S (×4 compass figures)

10 Days of Variation

Modern Station

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

8

Range of Diurnal Variation of East Component for all Stations   *129 of them*
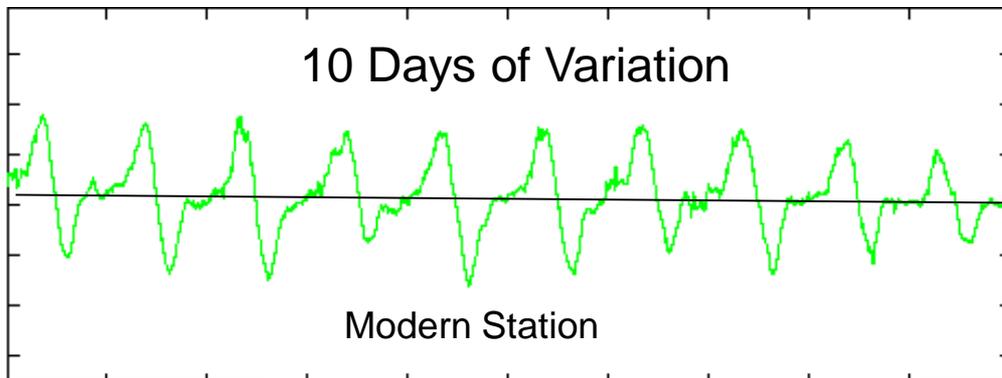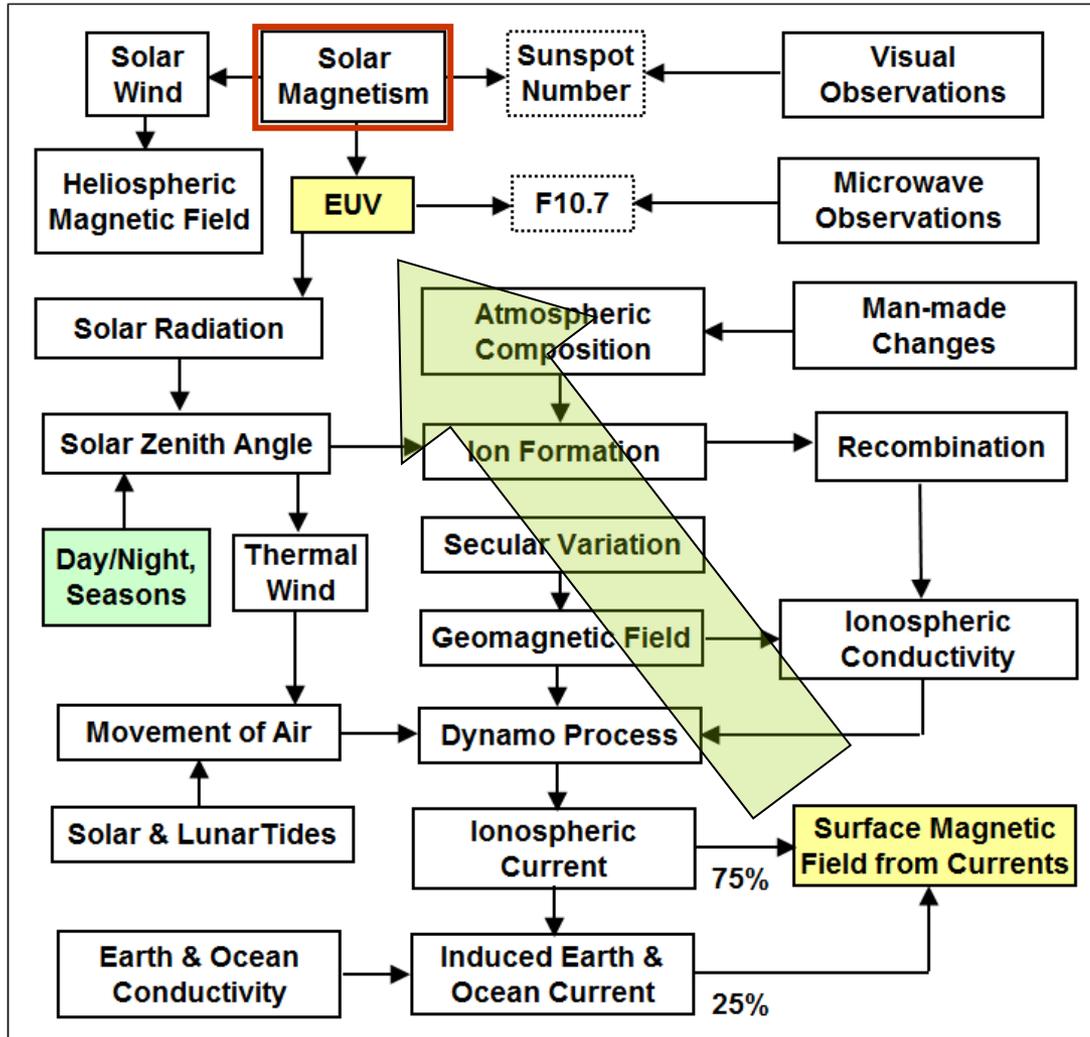
We plot the yearly average range to remove the effect of changing solar zenith angle through the seasons. What remains is the solar cycle modulation.

EUV and its proxy: F10.7 Microwave Flux

F10.7

The Microwave Flux Record Extends
70 years in the Past

Composite F2800 MHz Solar Microwave Flux

1947 **2016**

EUV Flux (1-103 nm) and F10.7 Flux

mW/m^2

sfu

F10.7

SEM*

TIMED/EVE

Spacecraft Data

Nobeyama

Quiet Sun
Free-Free
Gyroresonance
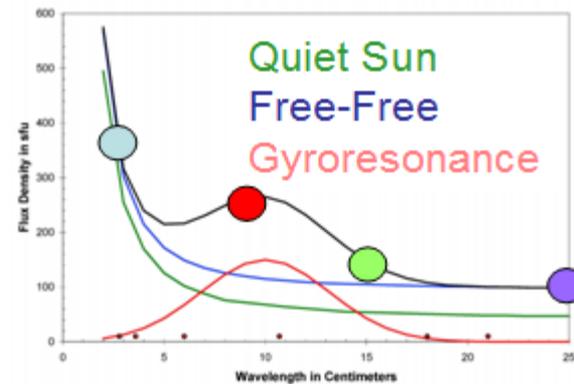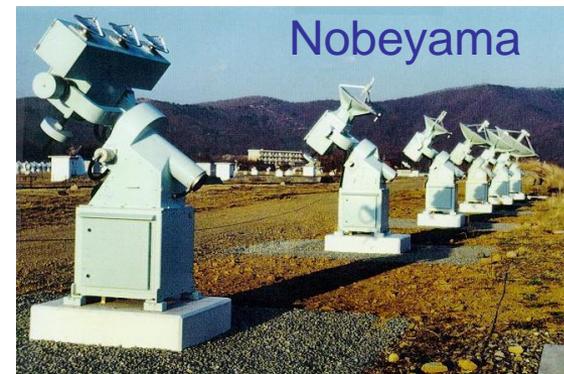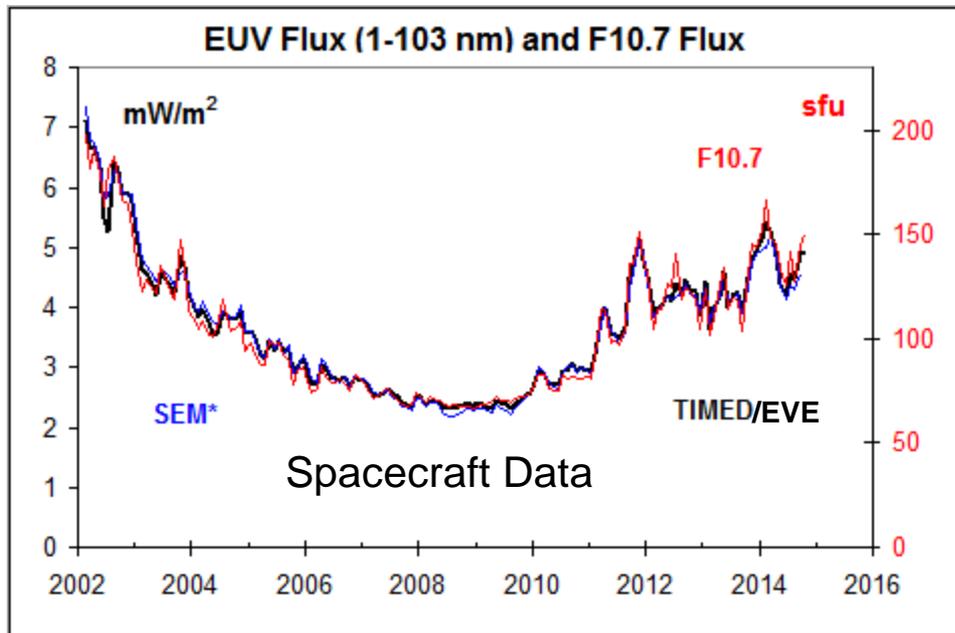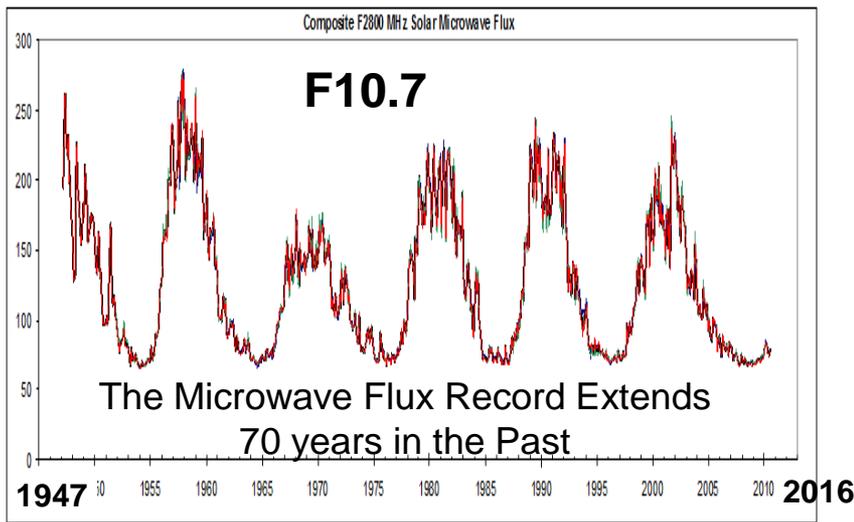
10.7 cm= 2800 MHz

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.
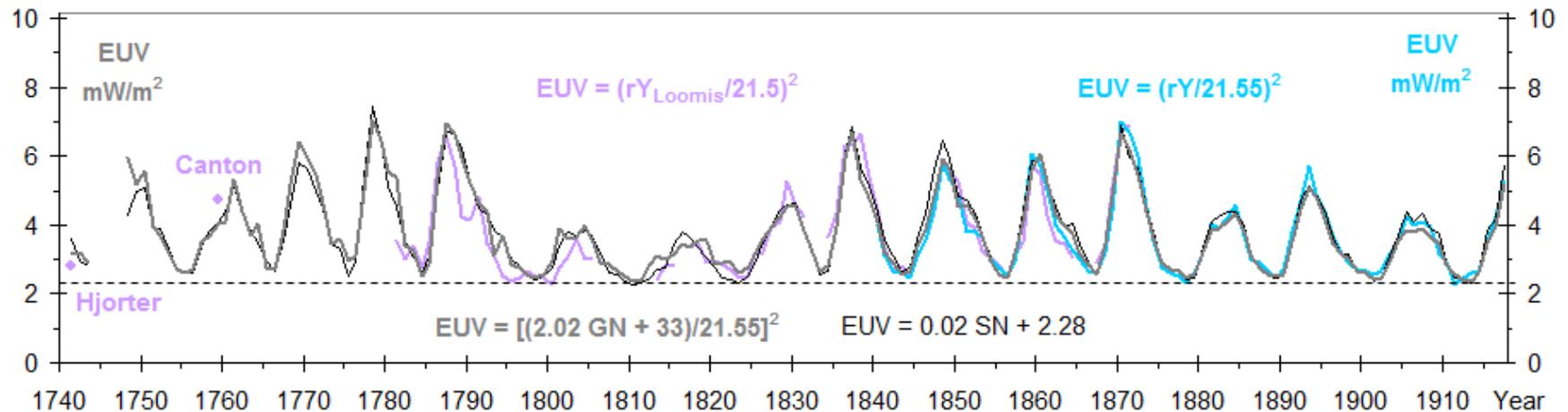
We use this chain in reverse to deduce the EUV flux from the geomagnetic variation.
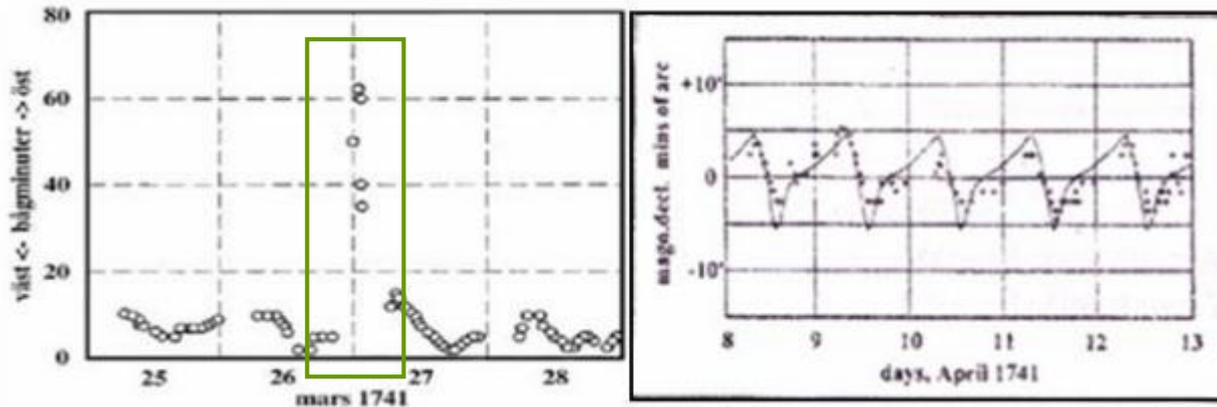
Reconstructions of EUV and F10.7
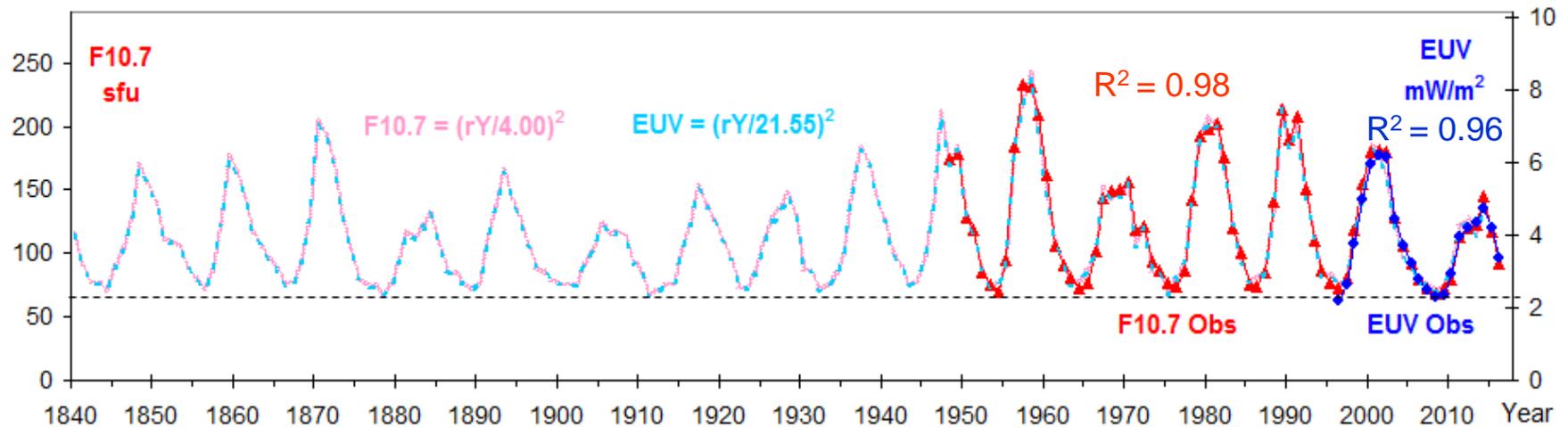
Observations in the 1740s

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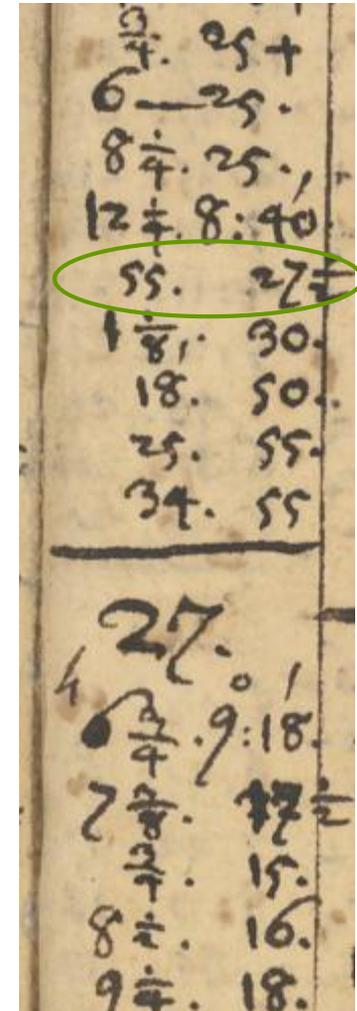

Right: Hjorter's measurements of the magnetic declination at Uppsala during April 8-12, 1741 (old style). The curve shows the average variation of the magnetic declination during April 1997 at nearby Lovö (Sweden).
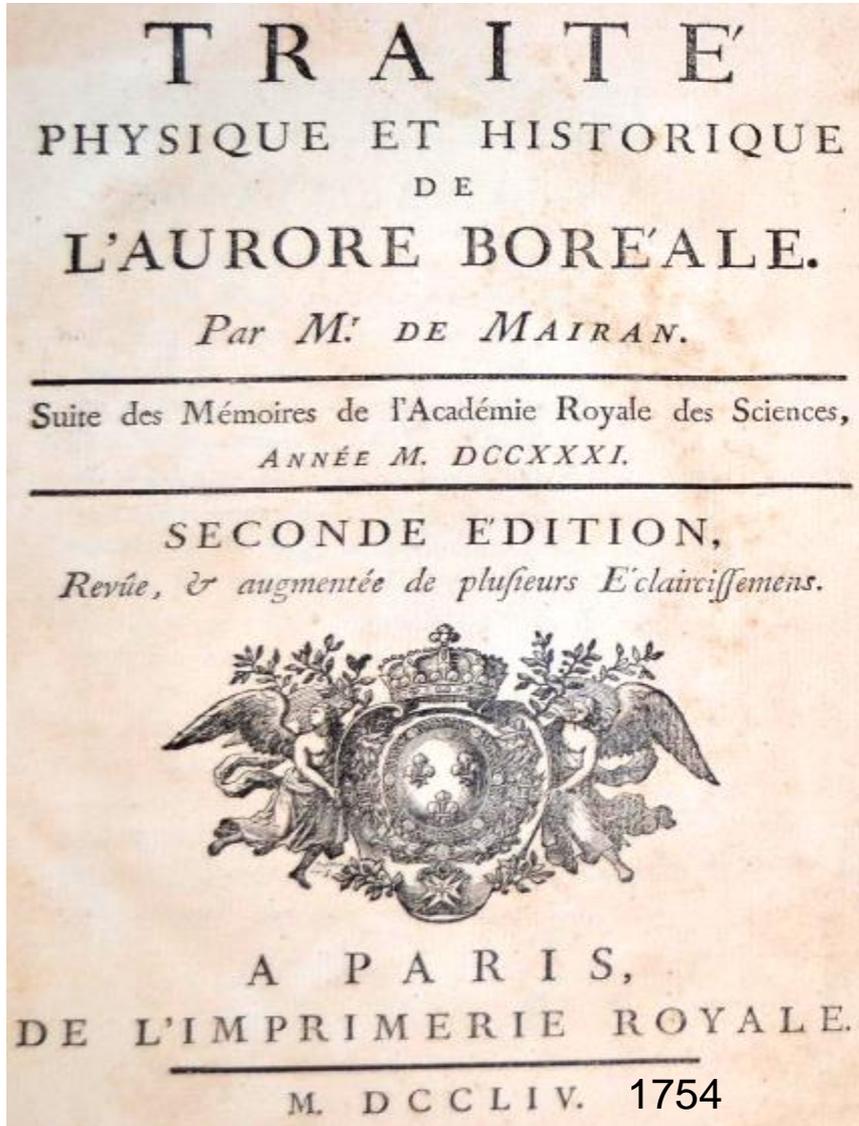
Left: Variation during strong Northern Light on March 27th. Also observed by Graham in London, showing that the aurorae and magnetic field are connected on a large scale and not just local meteorological phenomena.

Note there are really two phenomena going on, regular daily variation and sporadic, large aurora-related excursion…

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

3

The Science of Solar-Terrestrial Relations Began With Mairan's 1733 Book on the Aurora

TRAITÉ PHYSIQUE ET HISTORIQUE DE L'AURORE BORÉALE.

Par M. DE MAIRAN.

Suite des Mémoires de l'Académie Royale des Sciences, ANNÉE M. DCCXXXI.

SECONDE EDITION,

Revûe, & augmentée de plusieurs Eclaircissemens.

A PARIS,

DE L'IMPRIMERIE ROYALE.

M. DCCLIV.   1754

The extraordinary Auroral Display observed in much of Europe [but not in cloudy Paris] on 6 March 1716 was considered by E. Halley to be a purely Terrestrial phenomenon of "Magnetic Vapors" rising from the polar regions into the sky.

J.J.DORTOUS DE MAIRAN
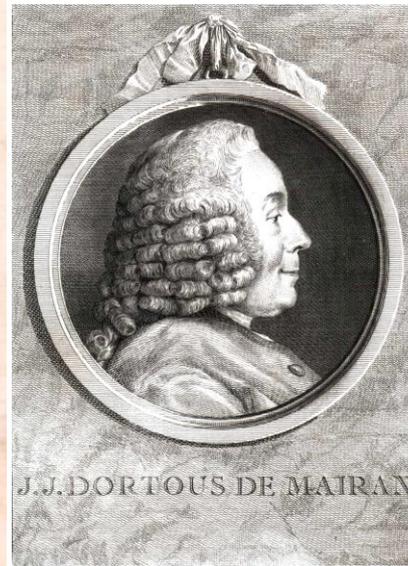
1678-1771

Following a similar strong display in 1726 that caused great panic in France, the French Government charged J.-J. Dortous de Mairan to provide a scientific explanation for the display just like the Royal Soc. had asked Halley to give ten years earlier.

14

Mairan's Speculation About a Solar-Terrestrial Relationship

p. 265

Supposé que la matière de l'Atmosphère Solaire ne soit ni lumineuse ni enflammée par elle-même & dans sa source, ne peut-il point arriver, 1.° Qu'elle devienne l'un & l'autre, en tout ou en partie, & plus ou moins vîte, en tombant dans les couches les plus élevées de l'Atmosphère Terreftre, de la même manière que certains Phofphores s'allument étant expofés à l'air, ou mêlés avec certaines liqueurs ?

Sur les modifications que la matière de l'Atmofphère Solaire peut recevoir, en fe mélant avec l'Atmofphère Terreftre.

Sur les Taches du Soleil.

Ne feroit-ce point à quelque femblable précipitation de parties de l'Atmofphère du Soleil, que feroient dûes les Taches qu'on voit fi fouvent fur la furface de fon Globe ? Et ne pourroit-on point découvrir quelque analogie entre la fréquence, les ceffations & les retours de ces Taches, & les apparitions, les retours & les ceffations de la Lumière Zodiacale ?

p. 264

Mairan speculated that the Aurora is due to the interaction of a material solar atmosphere [extending out past the orbit of the Earth] and visible during total eclipses. He raised the question whether the variation of the number of sunspots were also related to variations of the solar atmosphere.

There Must be More than One Cause

1718-1772

John Canton [1759] made more than 4000 observations of the Declination on 603 days in London. Most days were regular, but some were not, and on those an aurora was always seen
He concluded that "*The irregular diurnal variation must arise from some other cause than that of heat communicated by the sun*".

The different seasonal variations are important clues to the physical processes at work:

Solar 'Rays' dependence on Zenith Angle

Solar 'Matter' Semiannual variation

Canton, 1759 — Diurnal Variation of Declination Year 1759

Mairan, 1754 — Seasonal Variation of Aurora Borealis After Mairan [1754]
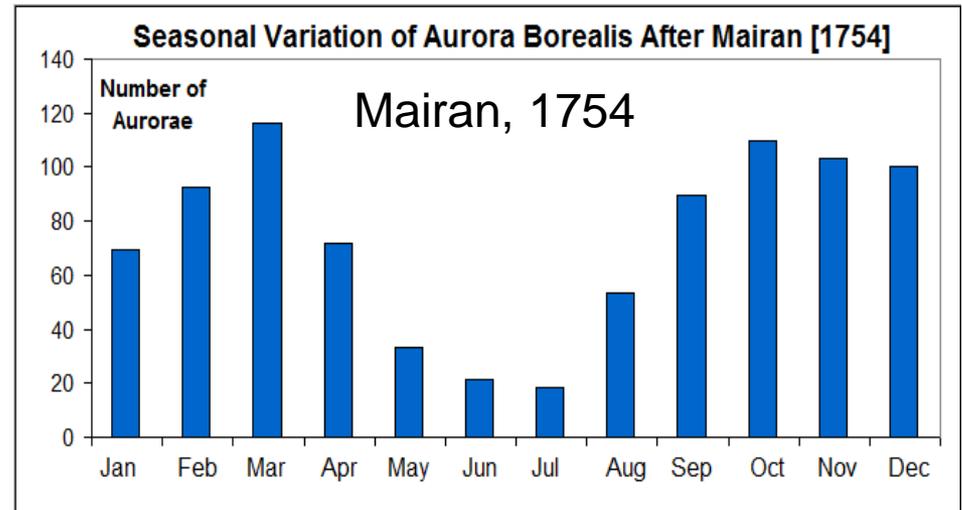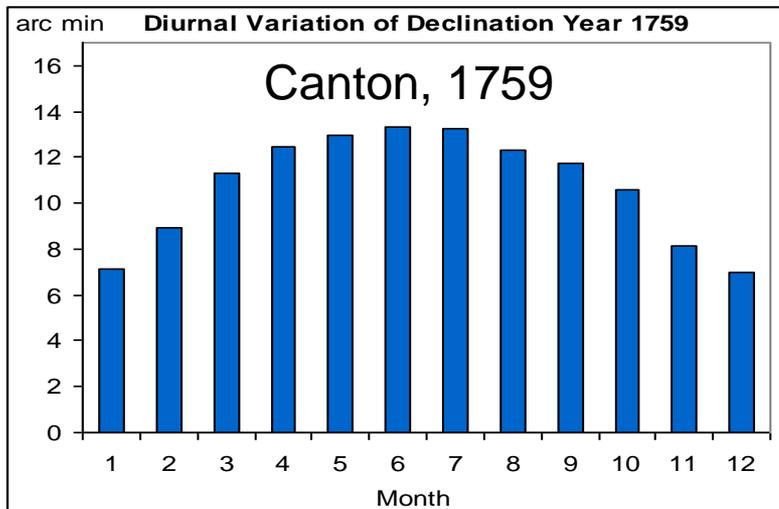
But a century would now pass before further progress could be made …

16

The Aurorae are Due to that "Other Cause" (Solar Wind)

Number of days per decade with Aurorae (30-yr averages) during the Middle Ages
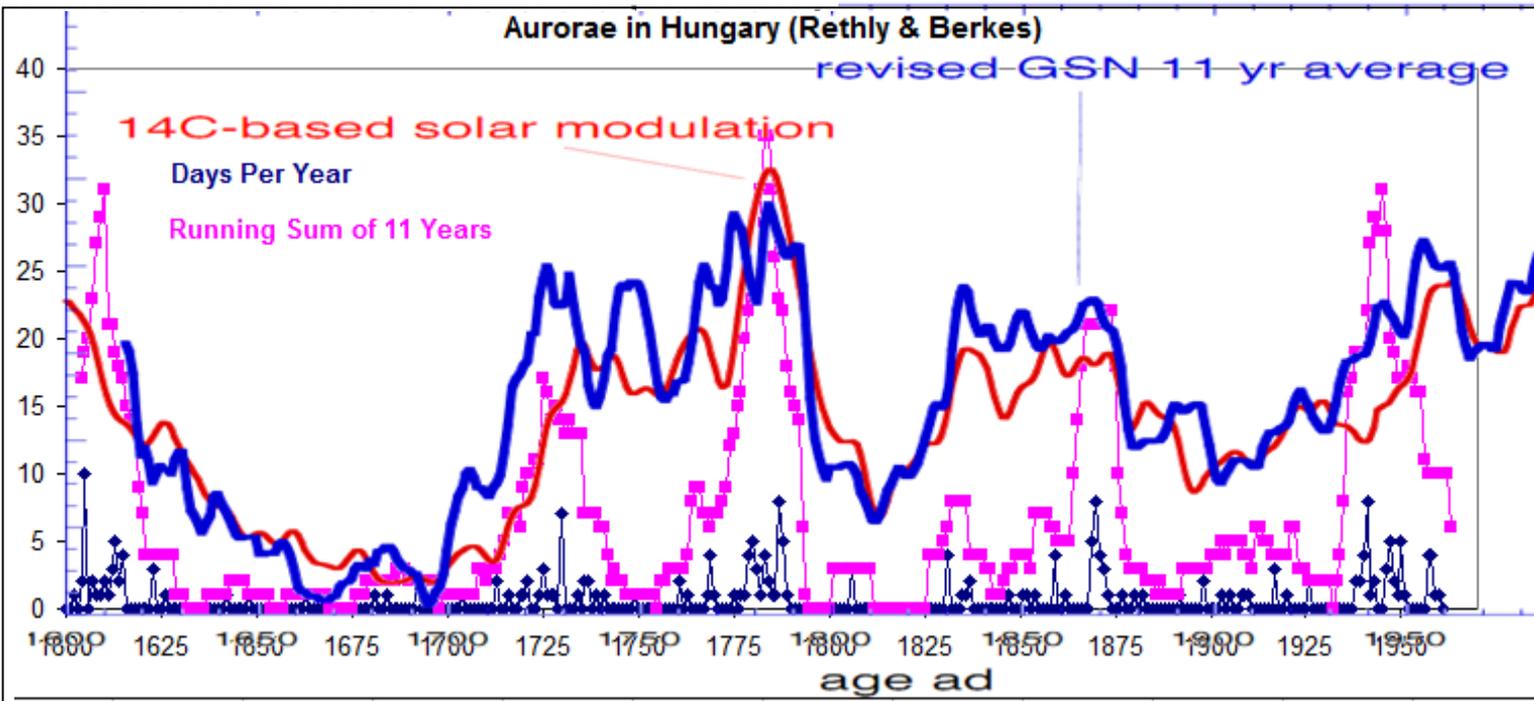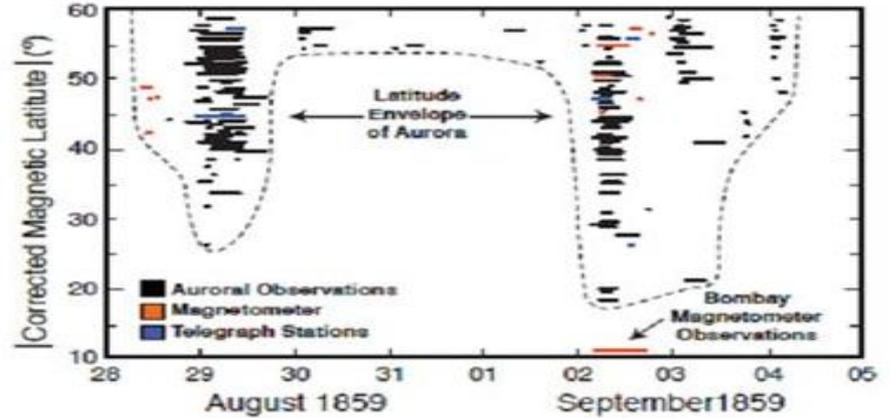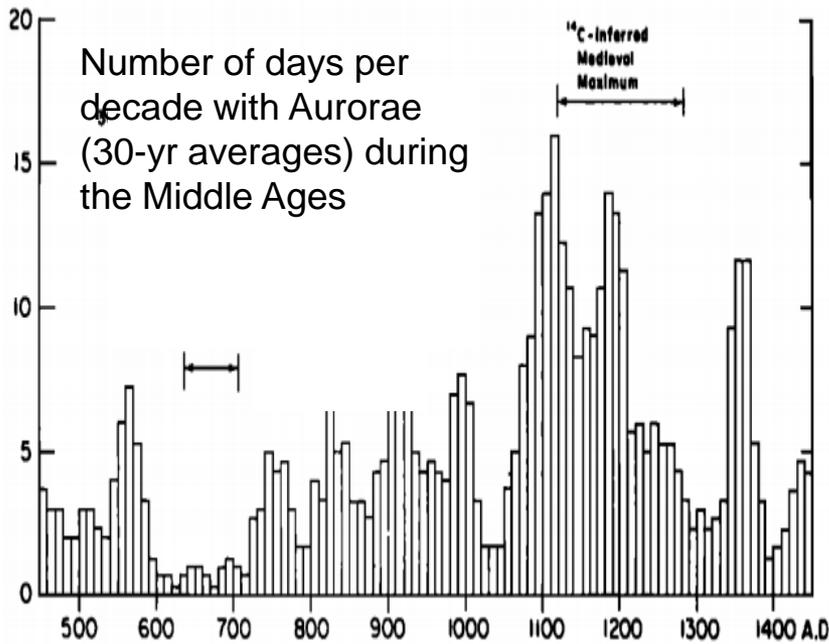
Observation in May 1921 of an Aurorae at Apia [Geom. Lat. 15 degrees] is the lowest latitude aurora known

Calibration is very difficult

17

We do have some Auroral data much further back in time …
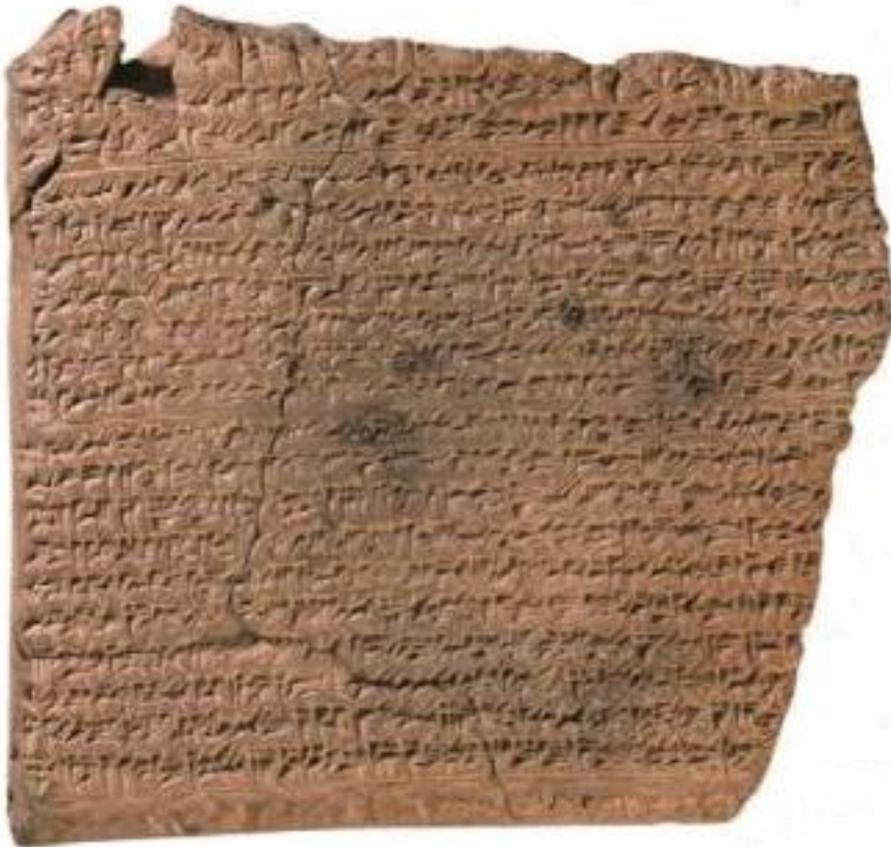
1: The reverse of the Babylonian tablet (VAT 4956) that contains the record of the aurora in 567 BC. (Staatliche Museen, Berlin/Olaf M Teßmer)
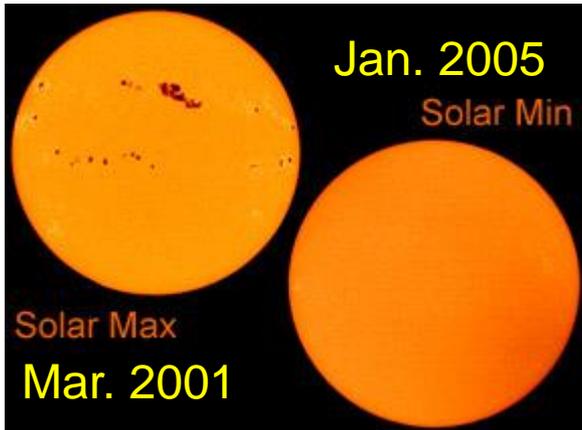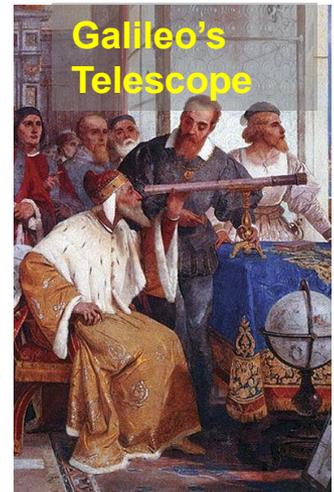
567 BC

But it is hard [impossible] to 'calibrate' such observations

Another possible aurora was described by the prophet Ezekiel (I: 1-28) in 593 BC in Baghdad
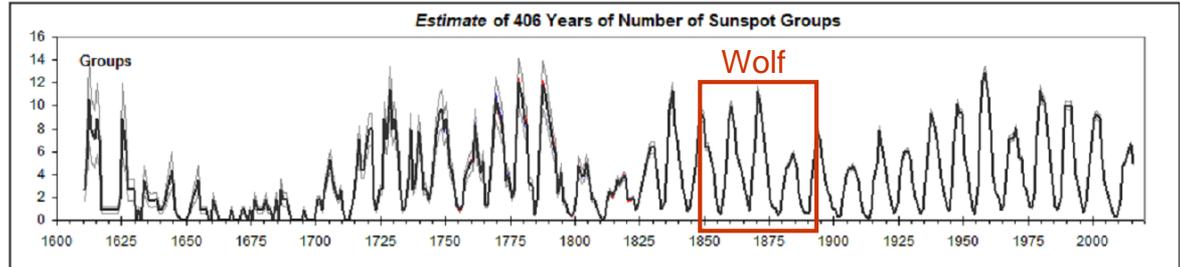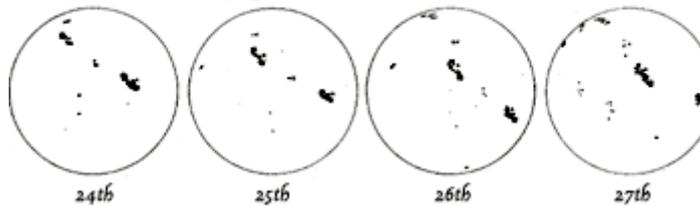
The geomagnetic Latitude of Baghdad back then was higher than today

400-year Sunspot Cycle Record

Galileo's Telescope

Jan. 2005
Solar Min

Solar Max
Mar. 2001

SOHO Spacecraft

Sunspots drawn by Galileo, June 1612

24th   25th   26th   27th

Estimate of 406 Years of Number of Sunspot Groups

Wolf

Wolf's Telescopes
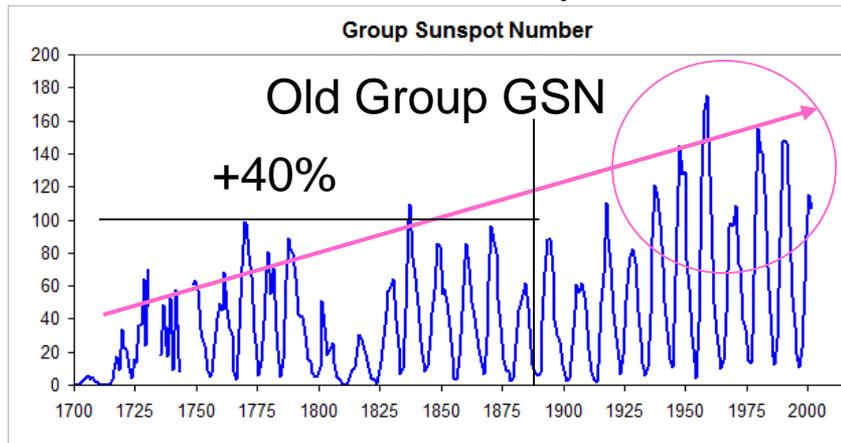
Zenith Angle Function Modulated by Sunspot Number
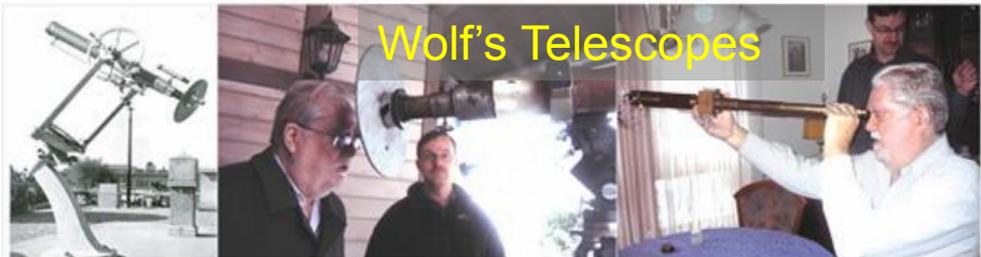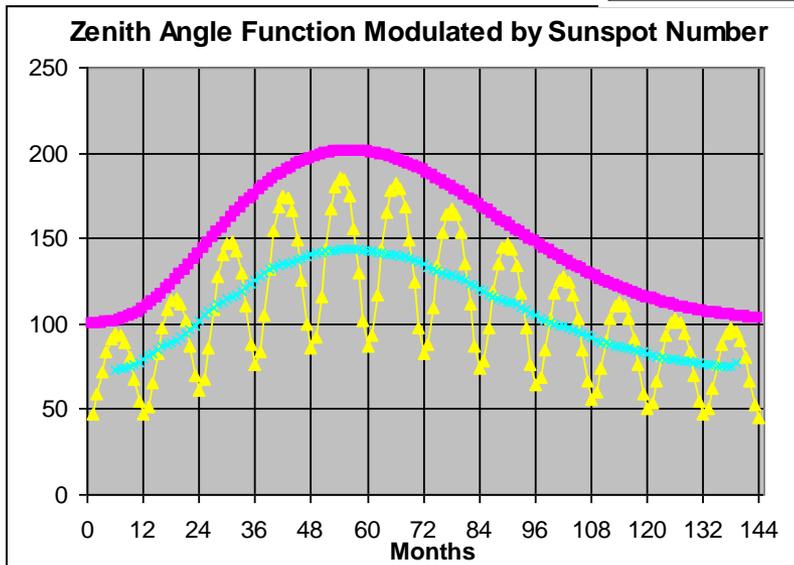
"Who would have thought just a few years ago that one could calculate a terrestrial phenomenon from observations of sunspots"
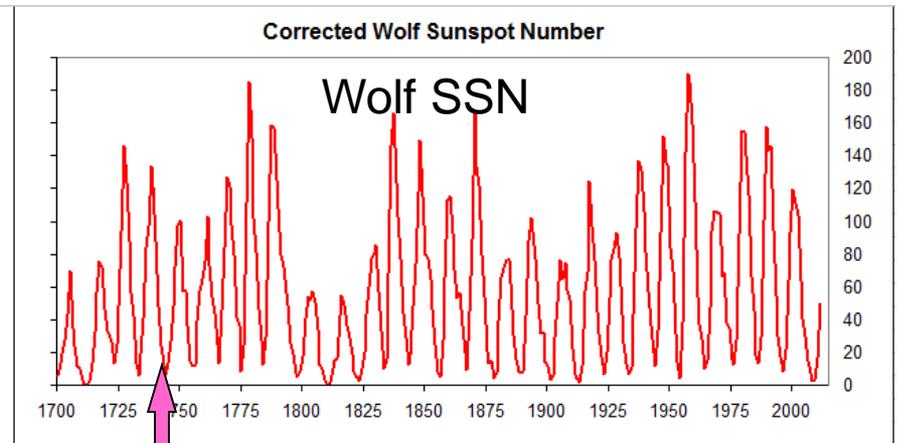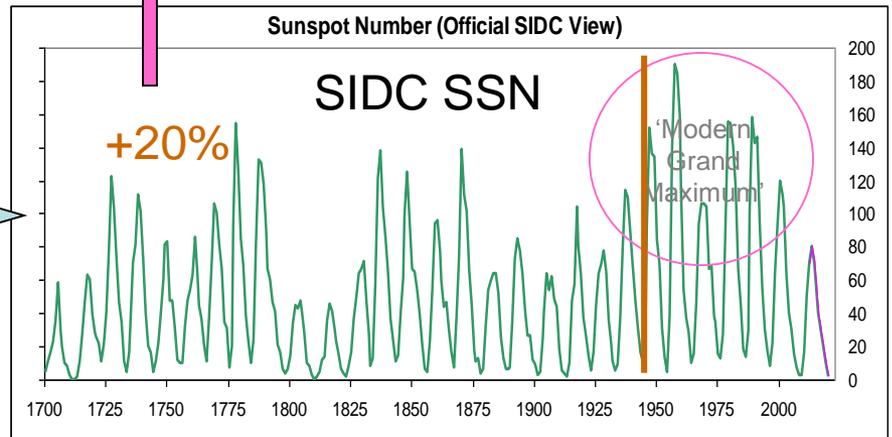
Rudolf Wolf, 1852

19

The Tale of Two Sunspot Numbers

GSN = 12 * Groups

WSN = 10 * Groups + Spots

Group Sunspot Number — Old Group GSN, +40%


Corrected Wolf Sunspot Number — Wolf SSN

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)

Sunspot Number (Official SIDC View) — SIDC SSN, +20%, 'Modern Grand Maximum'

The new SSN series suggest that there likely was no Modern Grand Maximum[20]

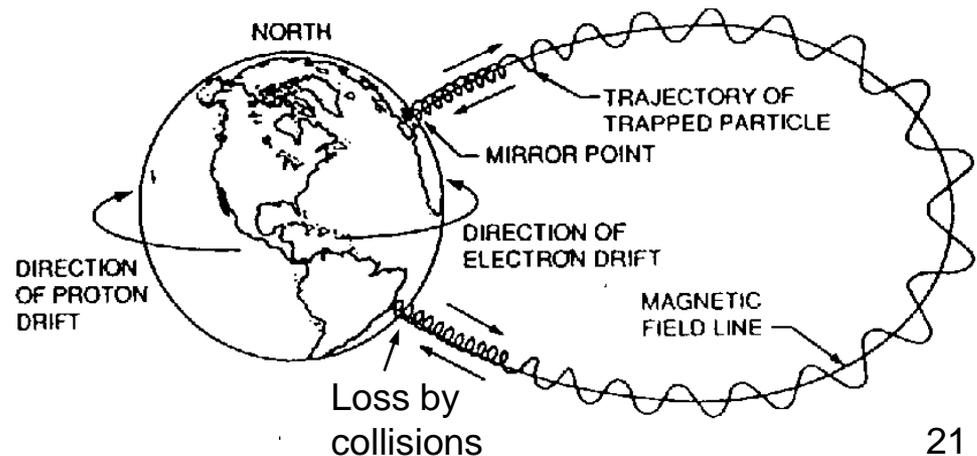# Geomagnetic Storms Due to Much Enhanced 'Ring Current'
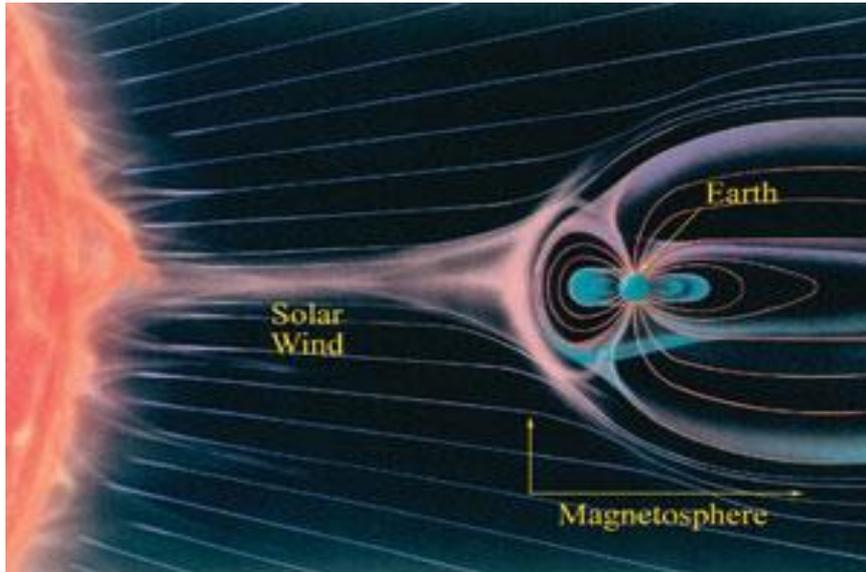
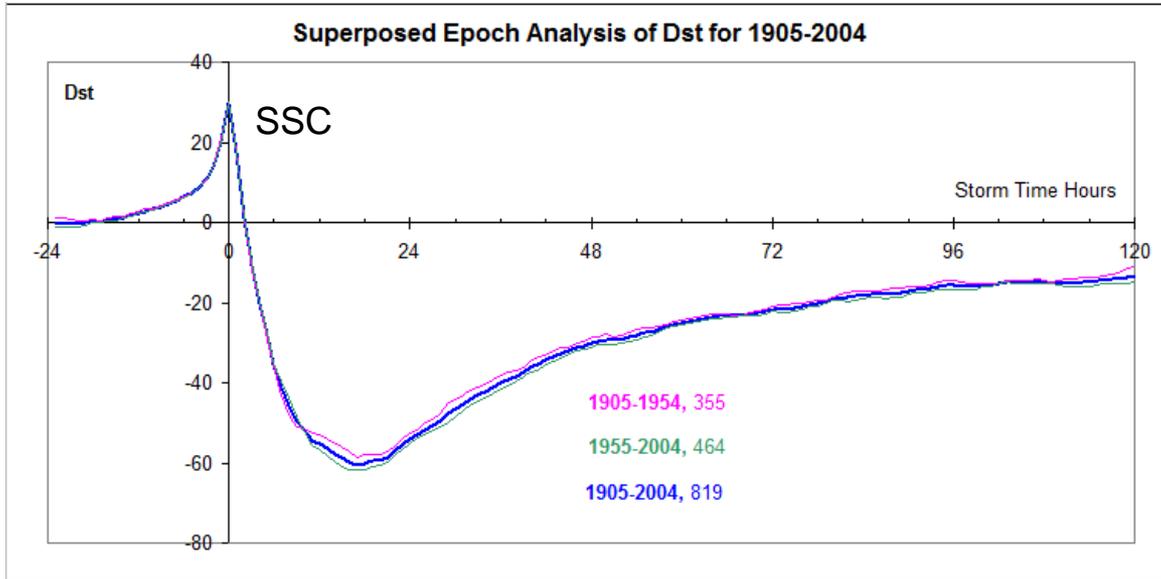The storms have a clear solar cycle dependence
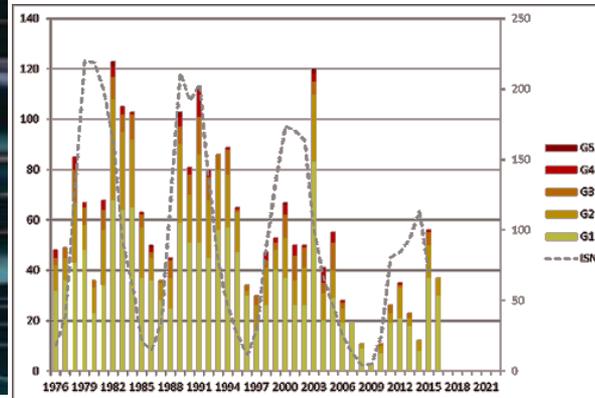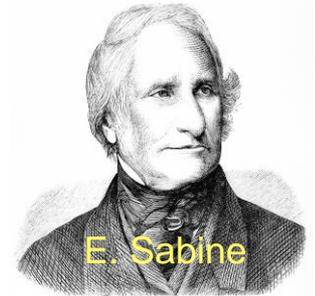
E. Sabine

In 1852, Sabine recognized that the irregular magnetic variations correlated very closely with the number of sunspots

Oppositely particles trapped in the Van Allen Belts drift in opposite directions giving rise to a net westward 'Ring Current'.
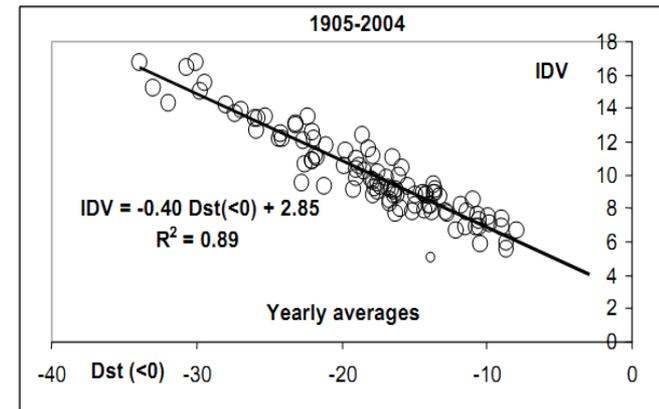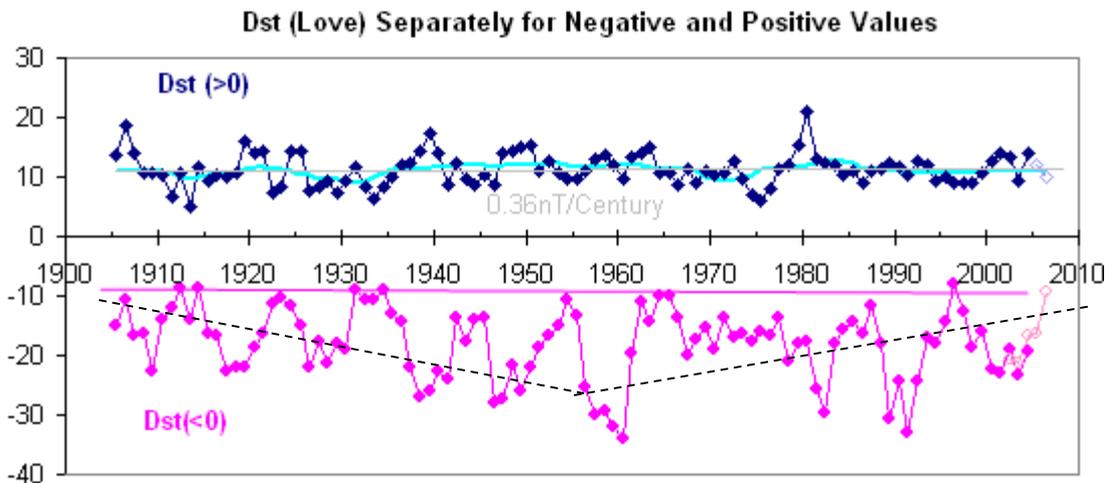
The Dst geomagnetic index [departure from quiet conditions] is a measure of the energy in the Ring Current

21

Dst Index and the Nachstörung

Superposed Epoch Analysis of Dst for 1905-2004
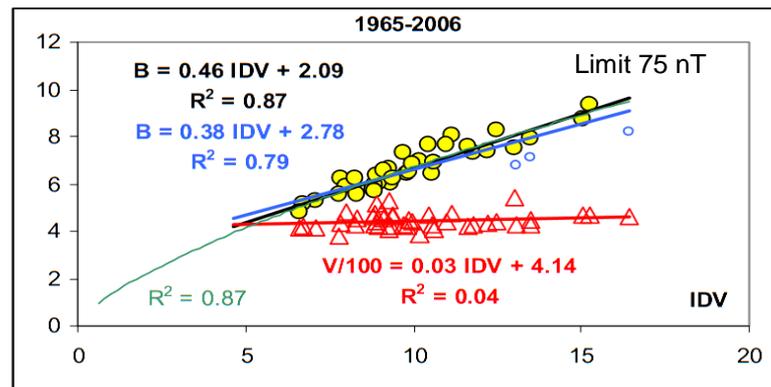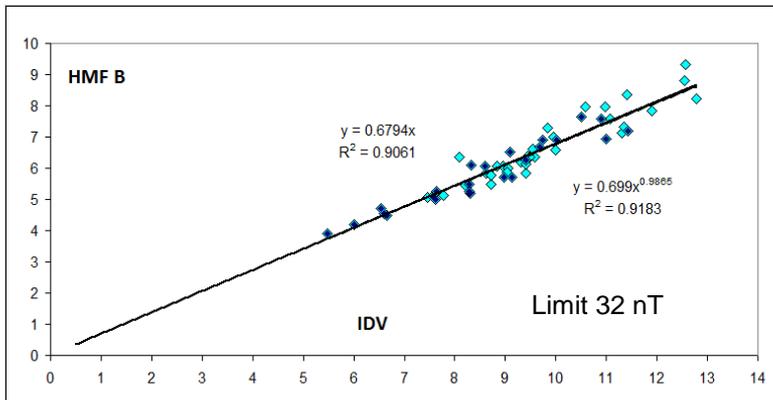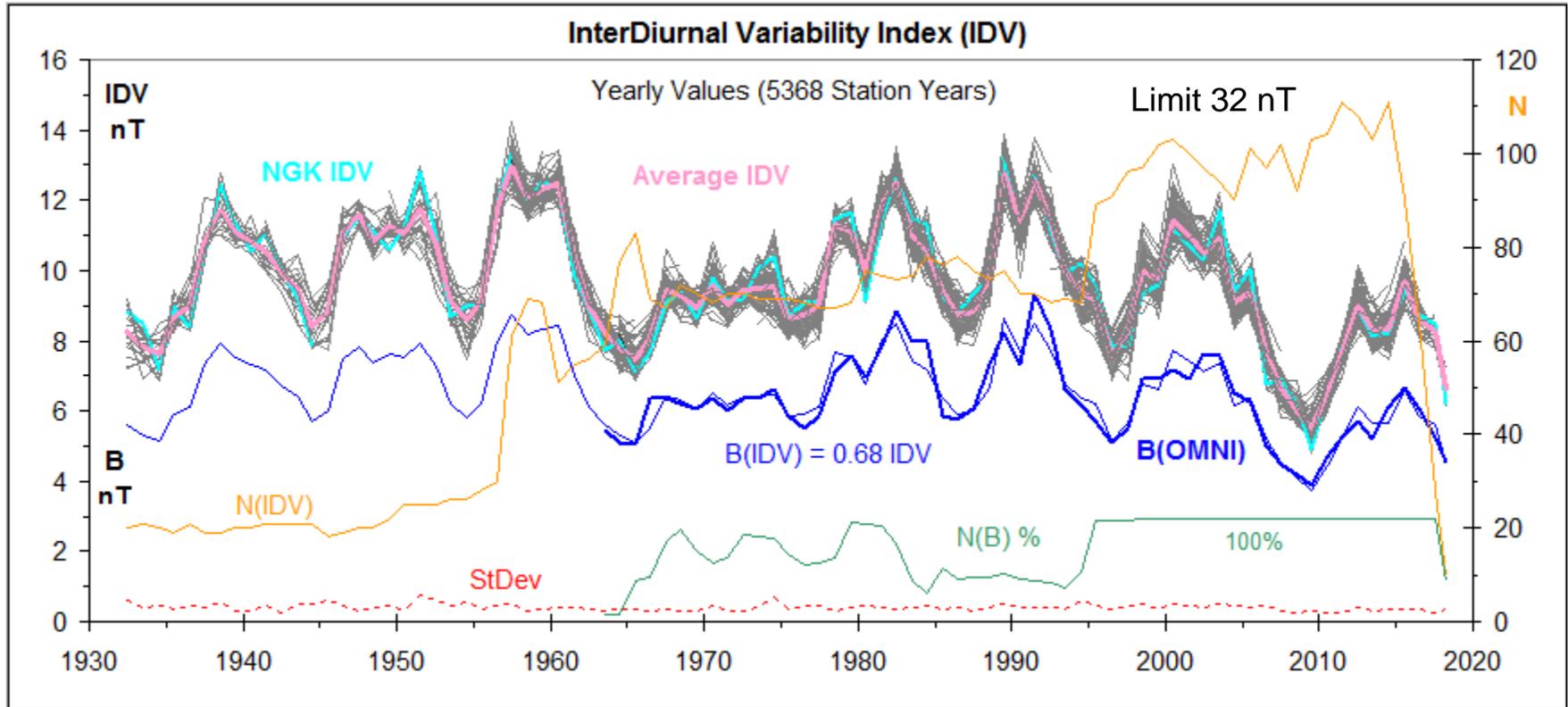
SSC

1905-1954, 355
1955-2004, 464
1905-2004, 819

Since the daily variation is fairly regular from day to day we can eliminate it by considering the difference between consecutive days. The new IDV-Index is the difference from one day to the next without regard of the sign between the midnight values of the horizontal component H. The importance of this quantity was first recognized by the Scotsman Broun in 1861
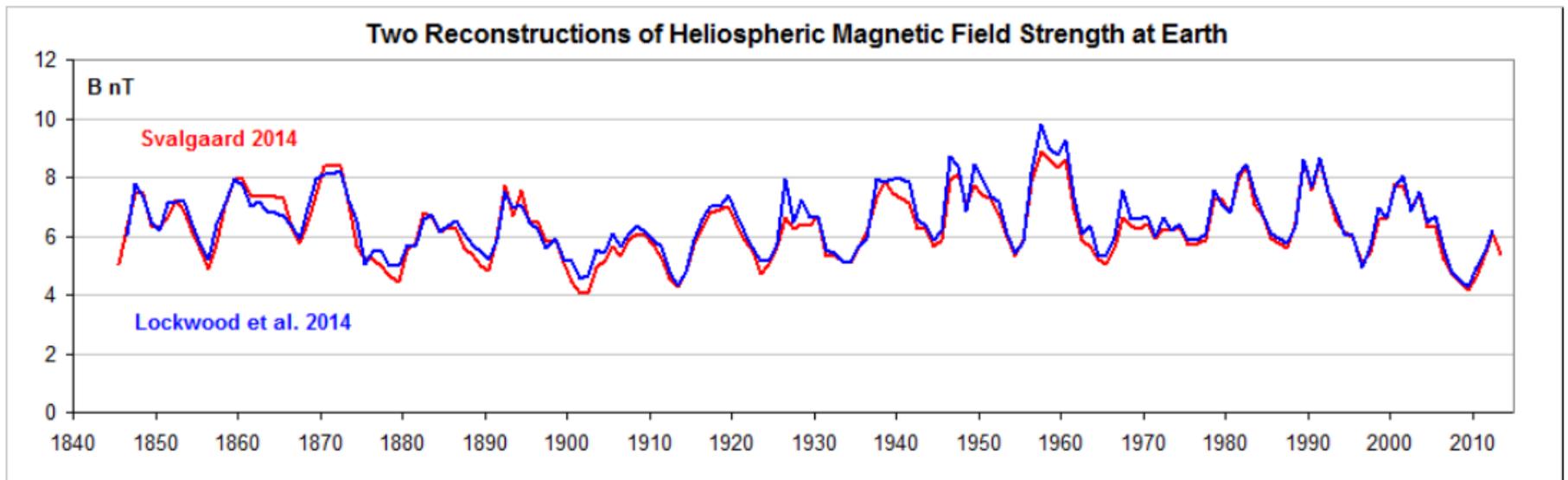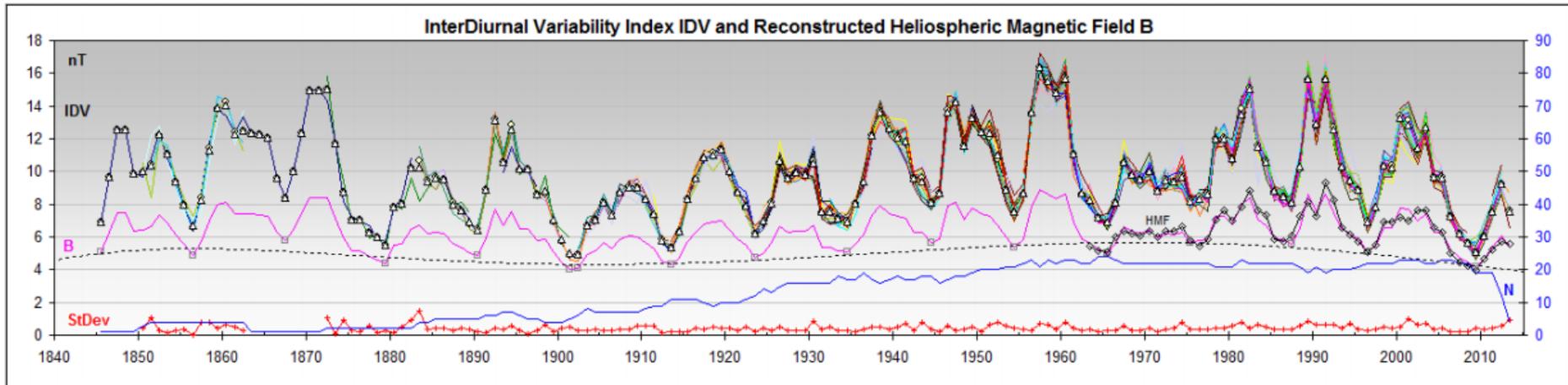

Dst (Love) Separately for Negative and Positive Values

Dst (>0)

0.36nT/Century

Dst(<0)

1905-2004

IDV

$IDV = -0.40 \; Dst(<0) + 2.85$
$R^2 = 0.89$

Yearly averages

Dst (<0)

The IDV-index is a good proxy for the negative part of Dst

22

IDV is a Good Proxy for HMF B

InterDiurnal Variability Index (IDV)

Yearly Values (5368 Station Years)

Limit 32 nT

IDV nT

NGK IDV

Average IDV

N

B nT

N(IDV)

$B(IDV) = 0.68$ IDV

B(OMNI)

StDev

N(B) %

100%

1965-2006

Limit 75 nT

HMF B

$y = 0.6794x$
$R^2 = 0.9061$

$y = 0.699x^{0.9865}$
$R^2 = 0.9183$

Limit 32 nT

IDV

$B = 0.46$ IDV $+ 2.09$
$R^2 = 0.87$

$B = 0.38$ IDV $+ 2.78$
$R^2 = 0.79$

$V/100 = 0.03$ IDV $+ 4.14$
$R^2 = 0.04$

$R^2 = 0.87$

IDV

IDV index depends on HMF B but is blind to speed V

23

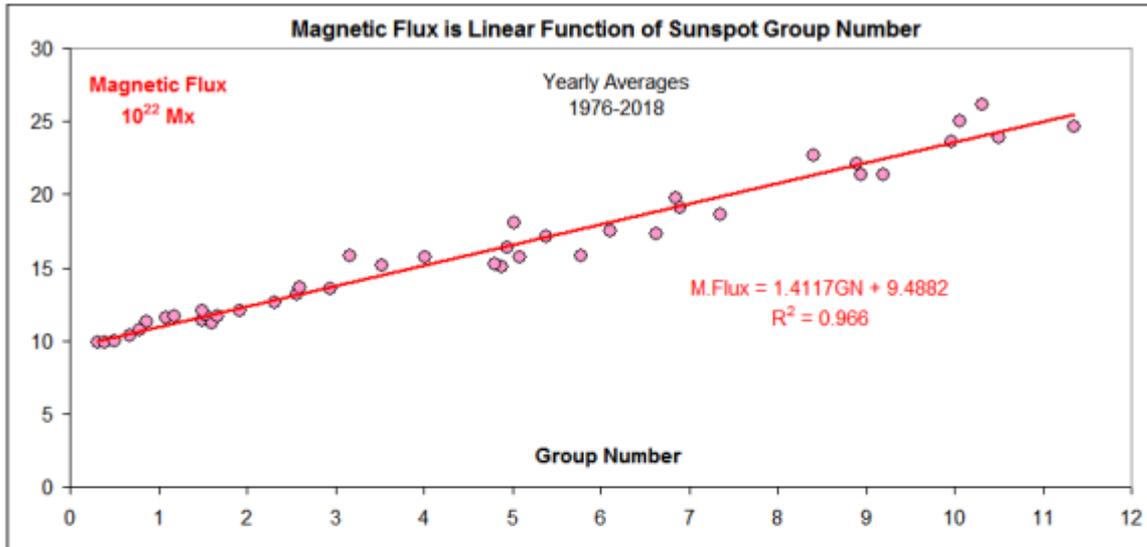# Applying the relationship we can reconstruct HMF magnetic field B with Confidence:

InterDiurnal Variability Index IDV and Reconstructed Heliospheric Magnetic Field B

Two Reconstructions of Heliospheric Magnetic Field Strength at Earth

HMF *B* and Sunspot Number

HMF B as a Function of Sunspot Number

1835-1871
1872-2011
1963-2011 Obs

Floor

$B = 0.3549 \, SQRT(Rz) + 3.83 \, nT$

$R^2 = 0.755$

SQRT(Rz corr)

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)

HMF B [at Earth] compared to Sunspot-based Values

B nT

B(u)   B(IDV)   B(Obs)

$B(Rz^{1/2})$
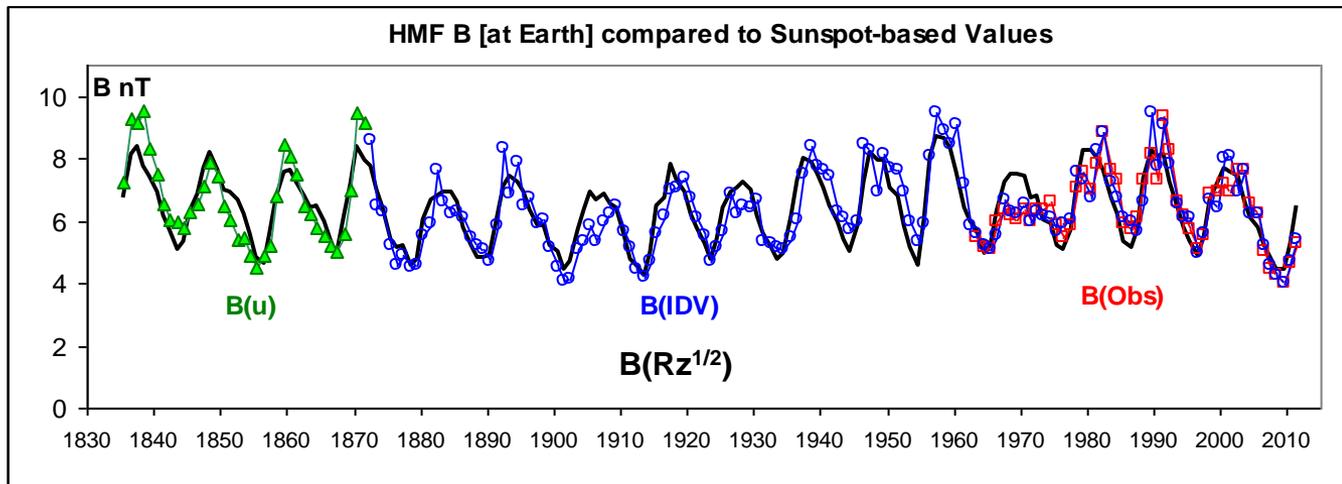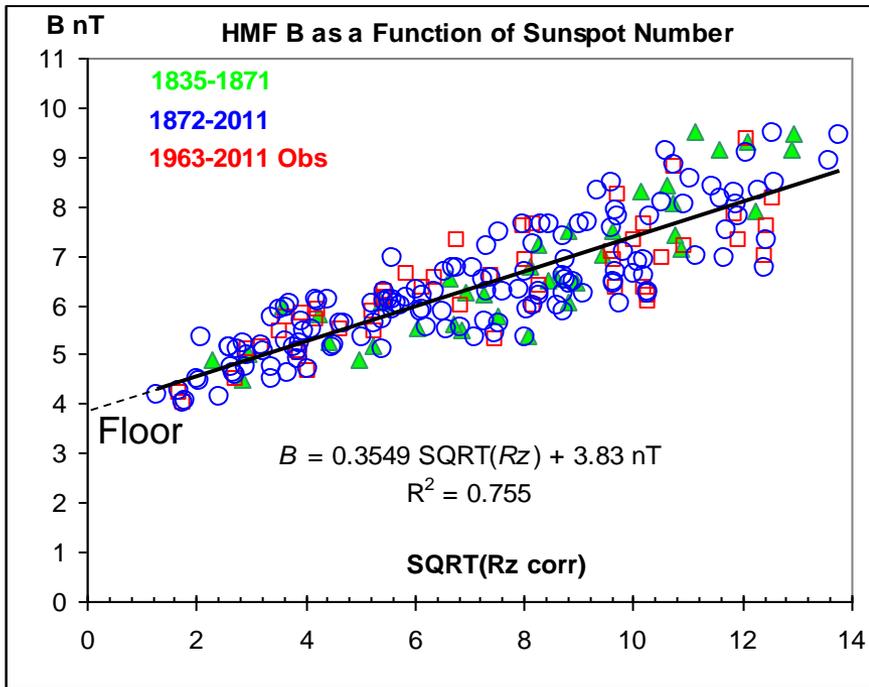
There does not seem to be evidence that the last 50 years were any more active than 150 years ago

Magnetic Flux and Group Number

Magnetic Flux is Linear Function of Sunspot Group Number

Magnetic Flux 10^{22} Mx

Yearly Averages 1976-2018

M.Flux = 1.4117GN + 9.4882
$R^2 = 0.966$

Group Number

Disk Total Unsigned Magnetic Flux (LOS)

Magn. Flux 10^{22} Mx

Monthly Average Normalized to MDI*-HMI

WSO*   MPSI*   MDI*-HMI

StdDev

The total magnetic flux has a strong linear correlation with the Sunspot Group Number

There is an offset for zero GN giving us a 'floor' of the magnetic flux
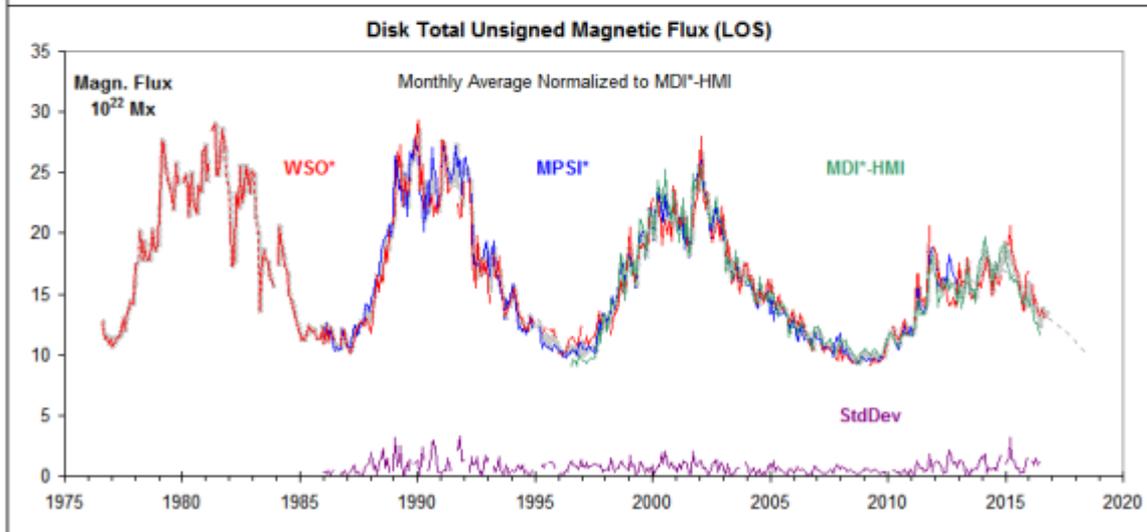
Total Disk Unsigned LOS magnetic flux from WSO, MWO, MDI, HMI (normalized to HMI)

"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)

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Solar Indices Mapped Linearly to TSI
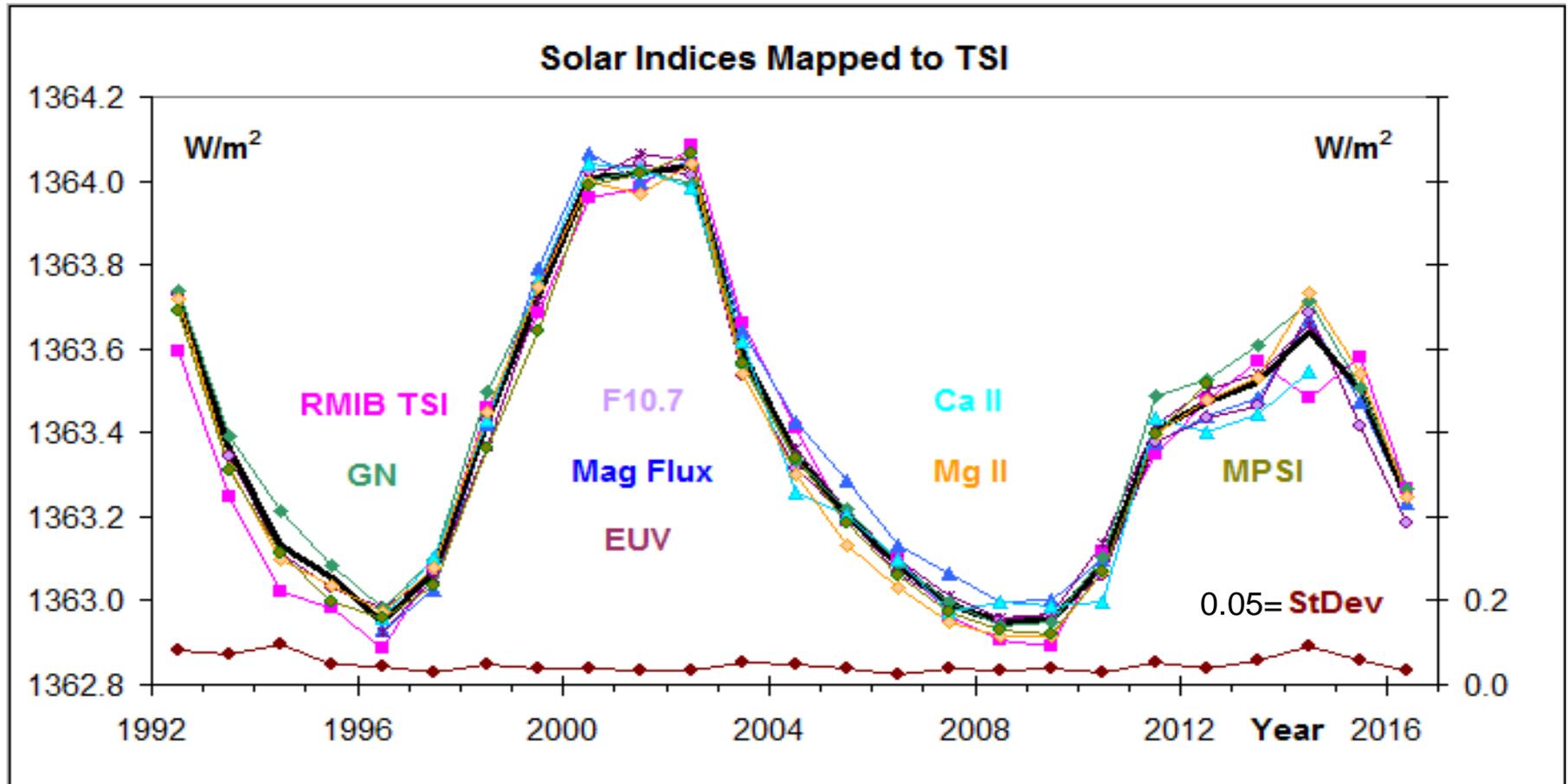
The TSI record is that by the Belgian Meteorological Institute [RMIB]

Tension Between B and Modelled TSI

Heliospheric Magnetic Field B (Cycle Averages)

B nT

SN

1900

2000

B (IDV)

B (GN)

B (Obs)

SN

Cycle Number

TSI W/m²

Egorova et al.
A&A 2018

CHRONOS, MC17
CHRONOS, SSR11
CHRONOS, US16
CHRONOS, MU16
SATIRE
NRL

Reconstructions of TSI

$TSI_o + 0.0304\ SN^{0.7}$

$TSI_o + 0.239\ GN^{0.7}$

RMIB*

$1360 + 0.0052\ GSN + 0.0083\ <GSN>_{11}$

NOAA CDR
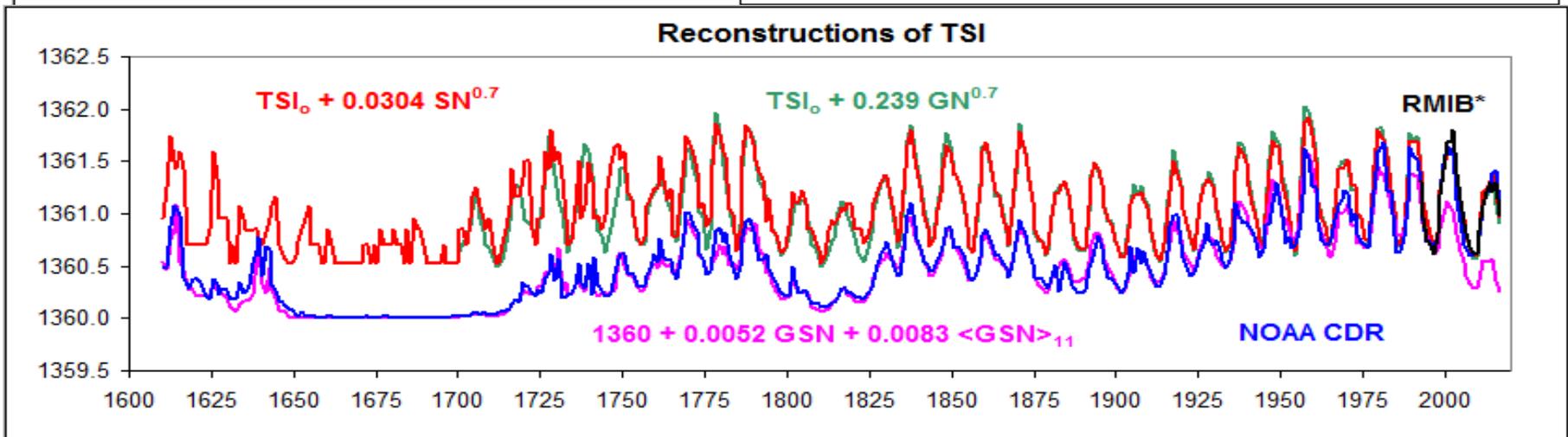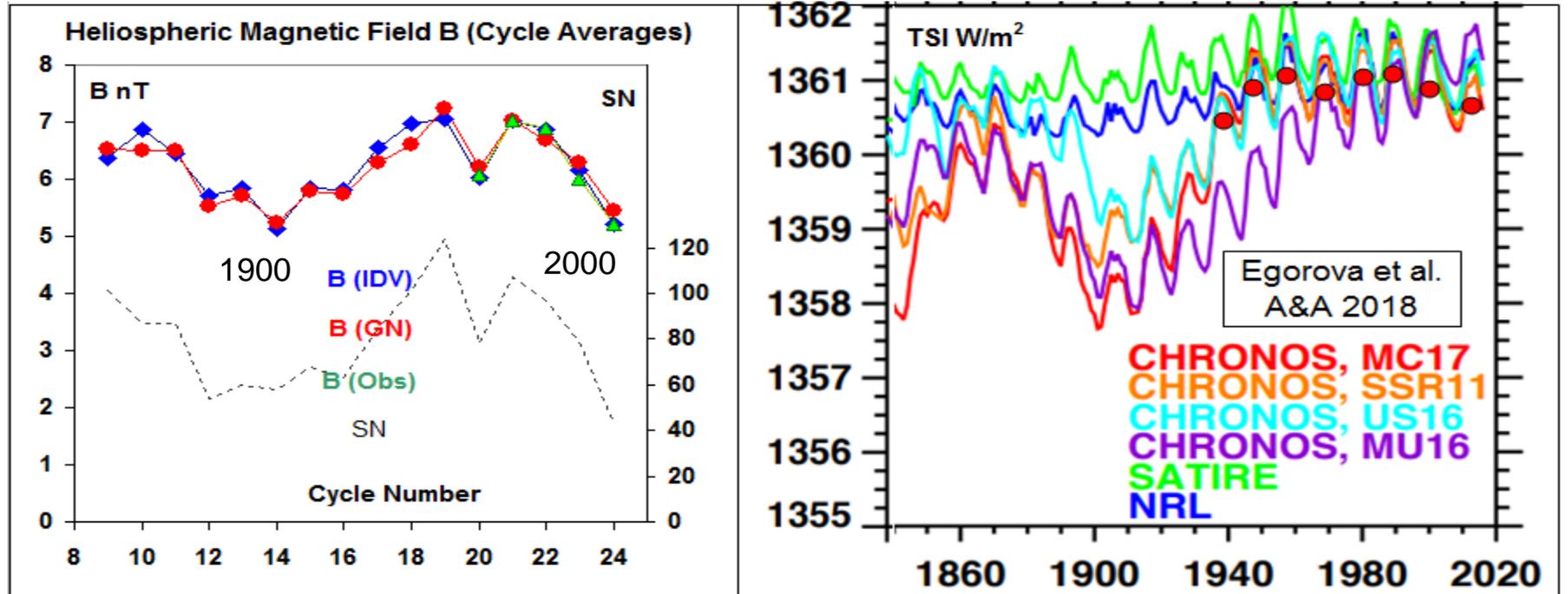
Magnetic Fields on Earth and in Space

The solar system is permeated by magnetic fields coming from the Sun with the Solar Wind and connecting with the field of the Earth [and other planets]

Godhavn 1926-Today

Svalgaard, 1968

Mansurov, 1969
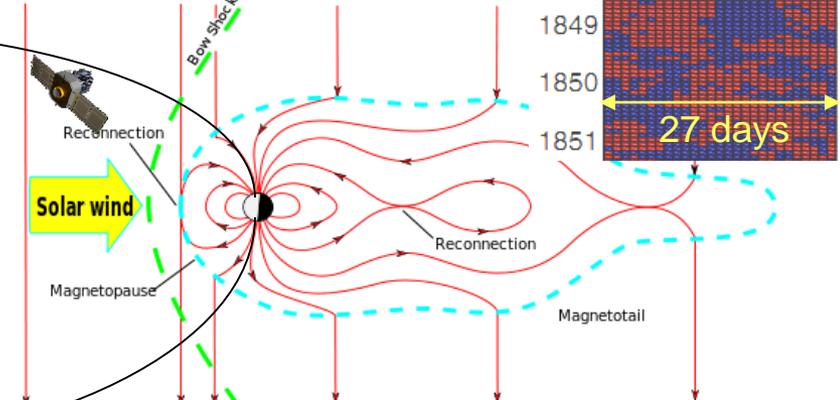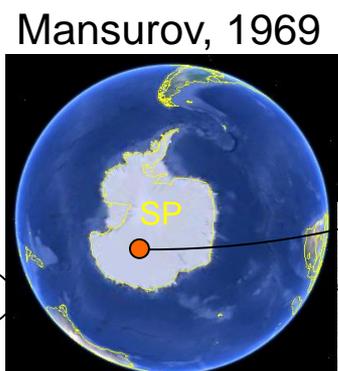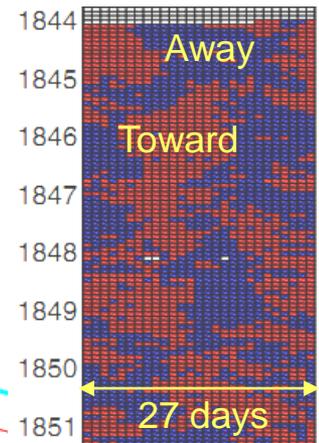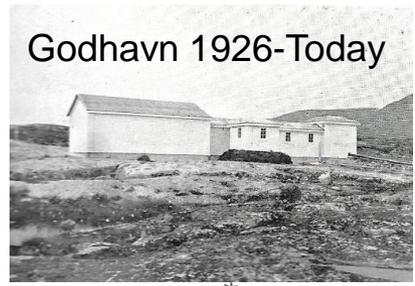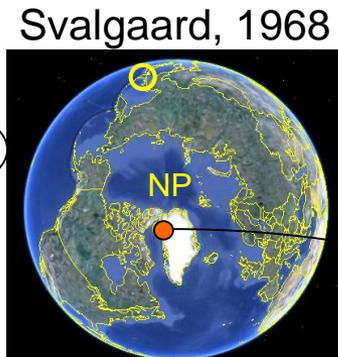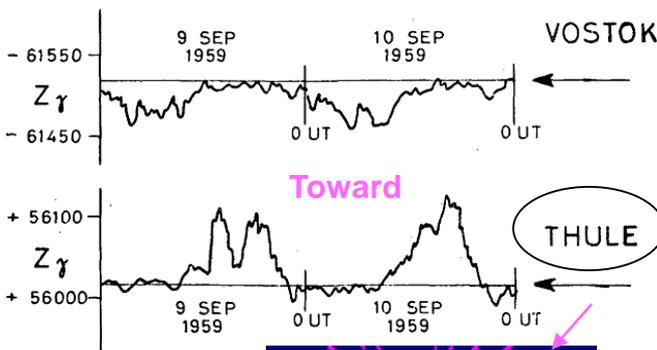
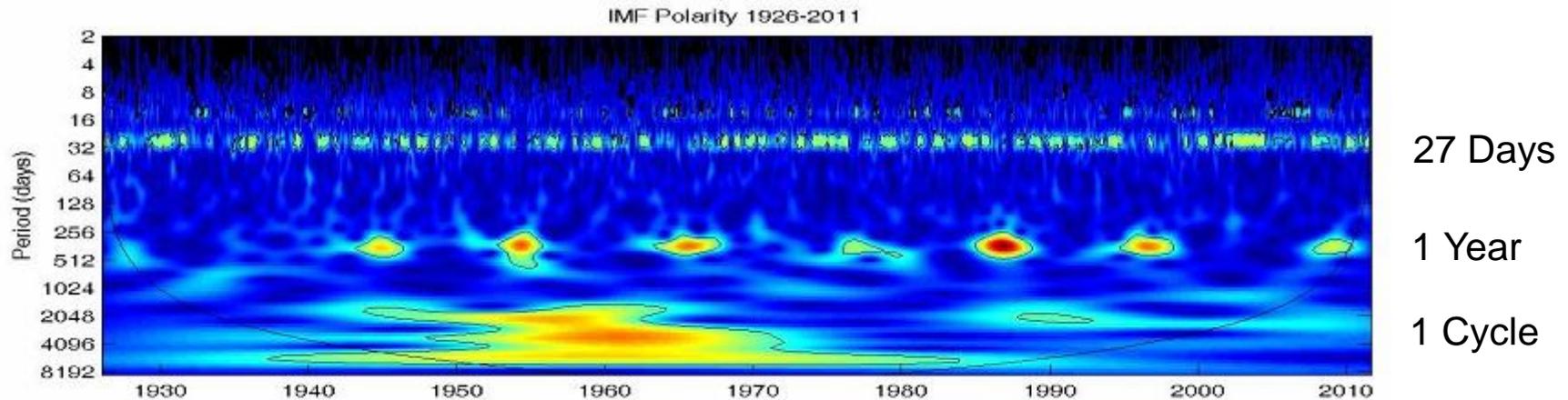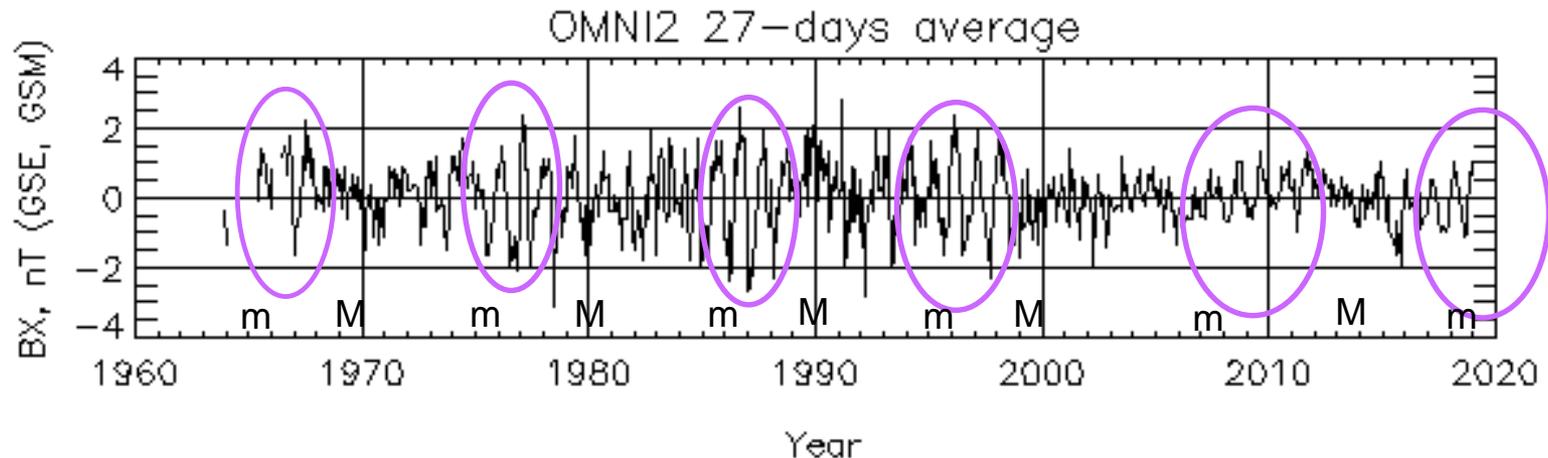The records from Earth's polar regions show the Sun's fields

Toward

Away

27 days
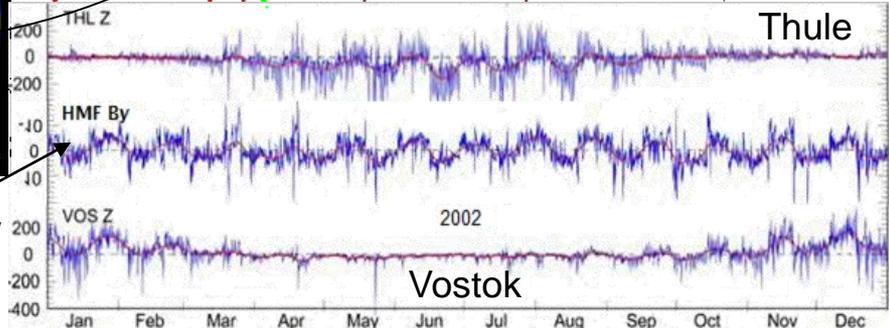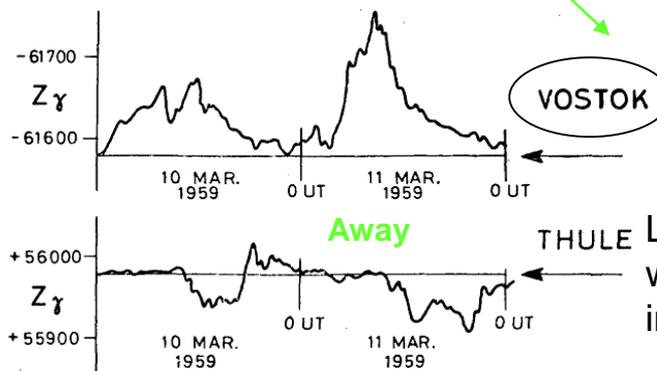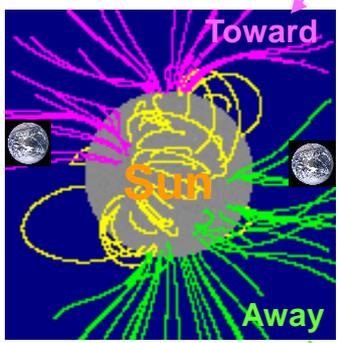
Look how accurately we can see the field in space from Earth

Thule

Vostok

Annual Variation of Dominant Polarity: Rosenberg-Coleman Effect

Caused by 'flatness' of the Heliospheric Current Sheet

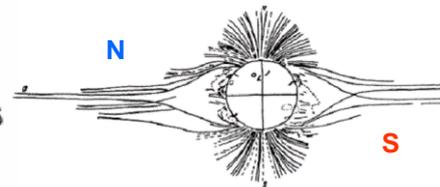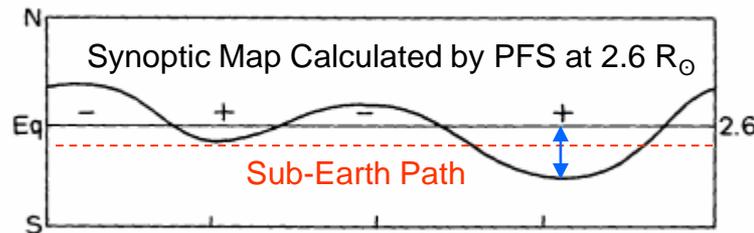Balance between polar fields and low-latitude fields determines the Flatness of HCS
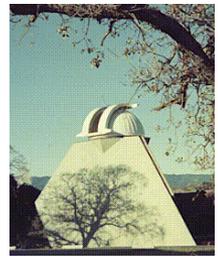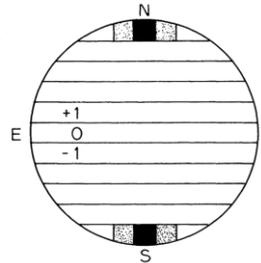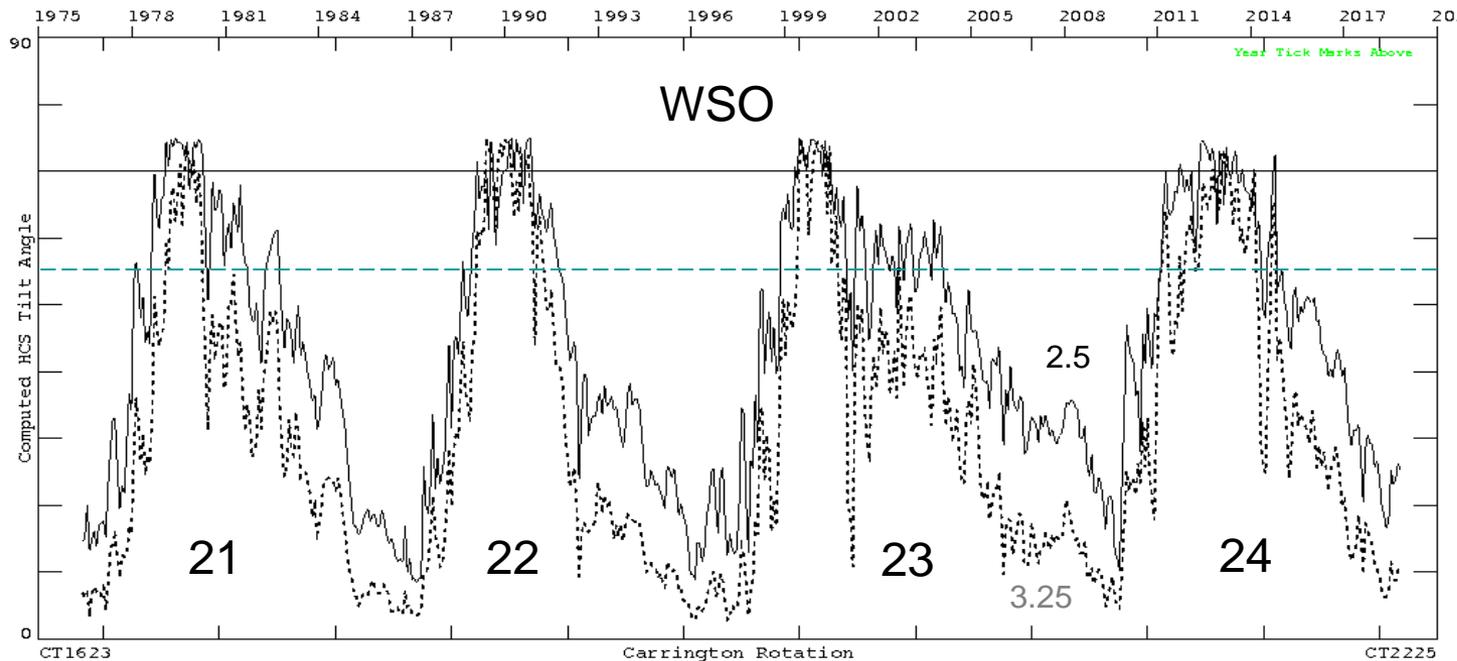

Proves Polar Field Reversals in the Past. Using the Svalgaard-Mansurov effect we can see the R-C effect all the way back to 1844

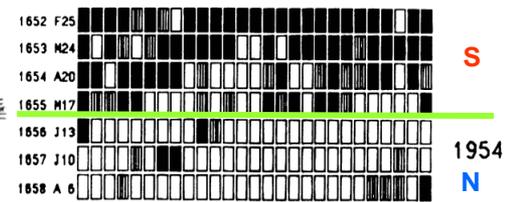# Latitudinal Extent of the HCS

Not the 'Tilt"

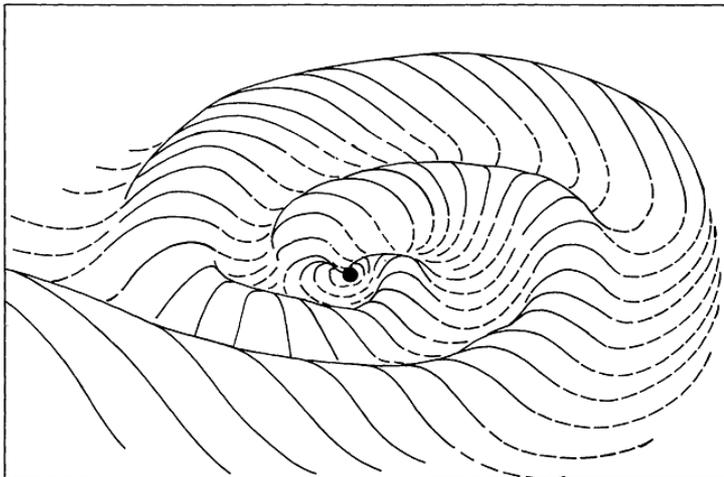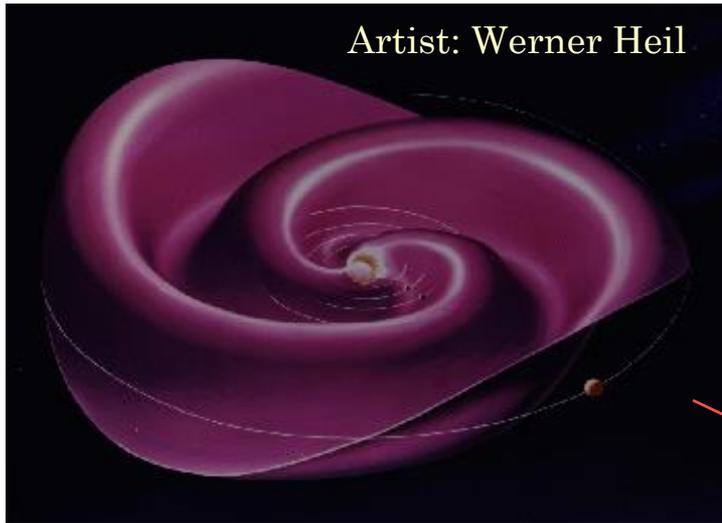**Maximum Inclination of the Current Sheet (N-S Mean): 1975–2019**

WSO

55⁰

2.5

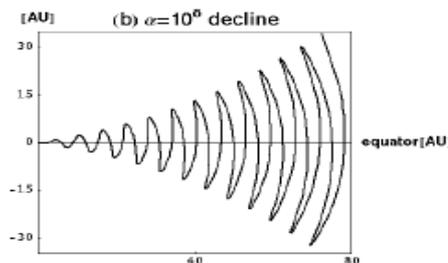21   22   23   3.25   24

Synoptic Map Calculated by PFS at 2.6 R_⊙

Sub-Earth Path

Solar Eclipse 1954

Sector Structure

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The Heliospheric Current Sheet

Artist: Werner Heil

Svalgaard & Wilcox, *Nature*, 1976

Cosmic Ray Modulation mainly caused by latitudinal variation of HCS and CIRs

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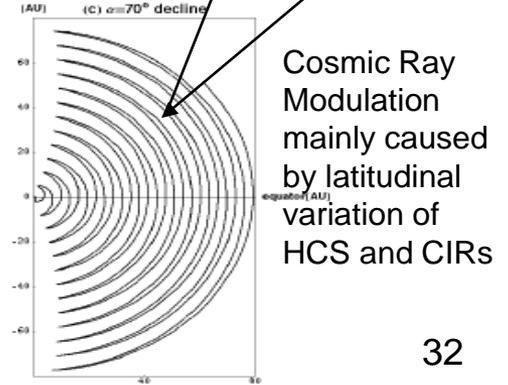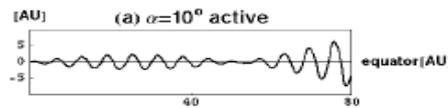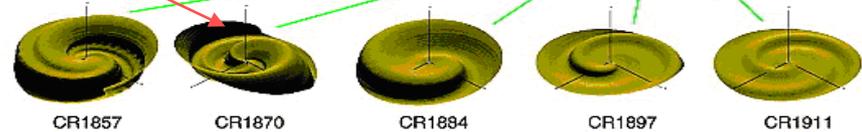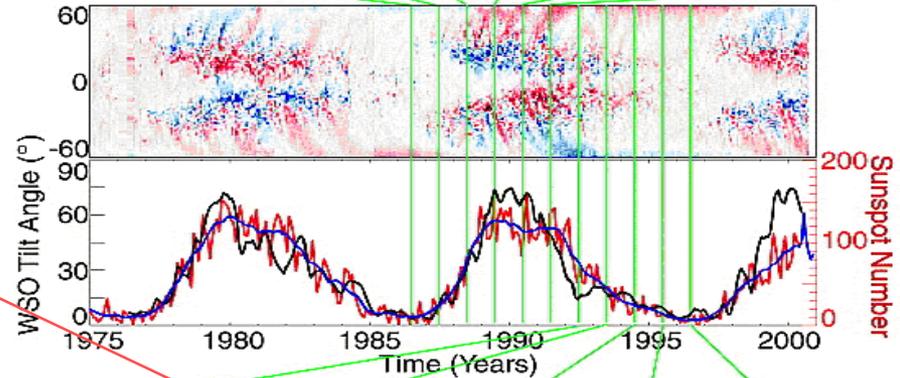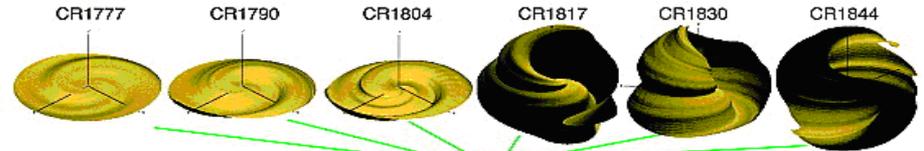
Nine Millennia of Solar Activity

10Be and 14C

Nine Millennia of Decadal Sunspot Numbers
SILSO Version 2

Obs

Wavelet Power Spectrum

88yr

~205yr

~350yr
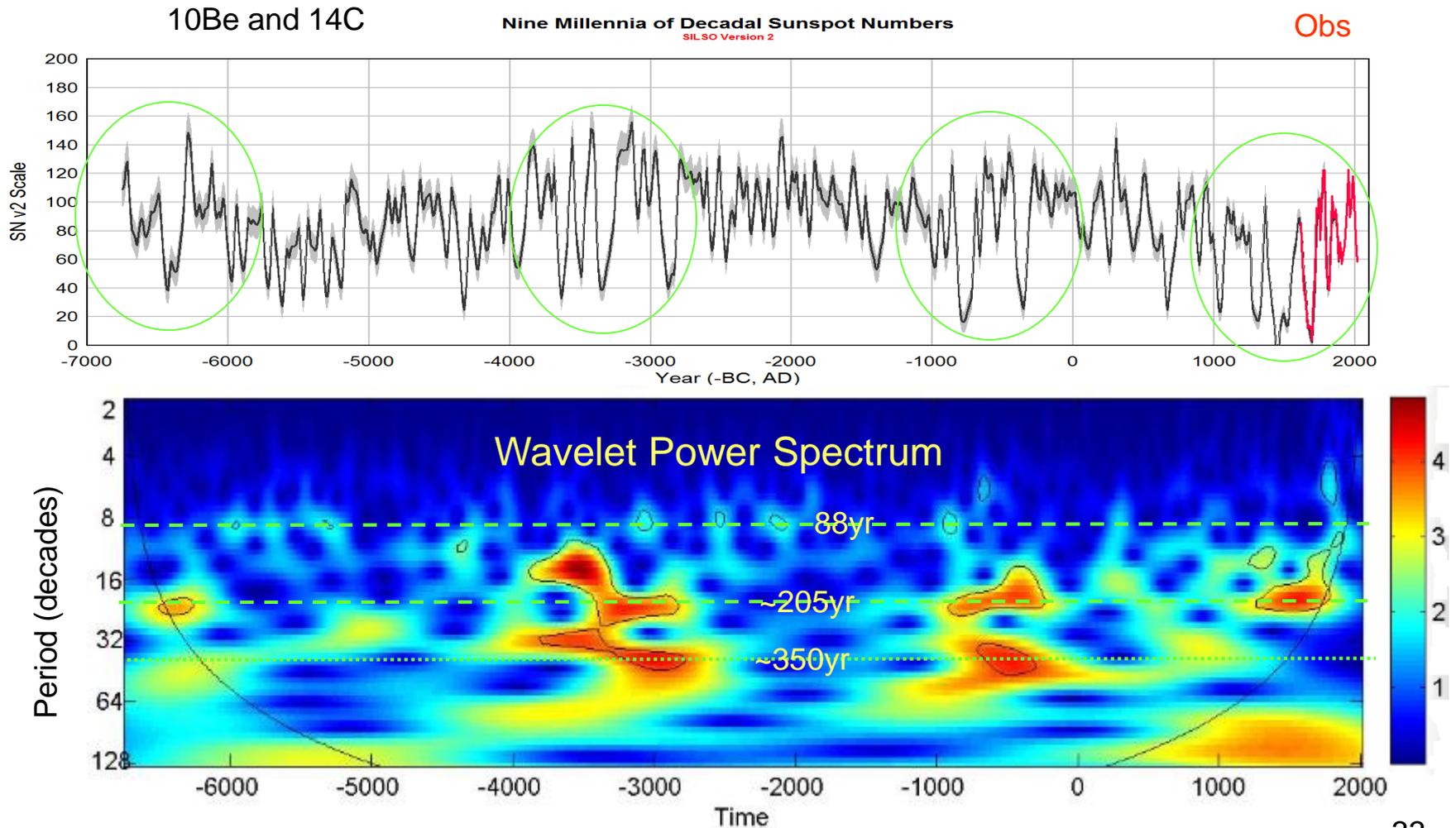
Non-stationary and intermittent 'periodicities' [if any]

The Sun's Cosmic Ray Shadow
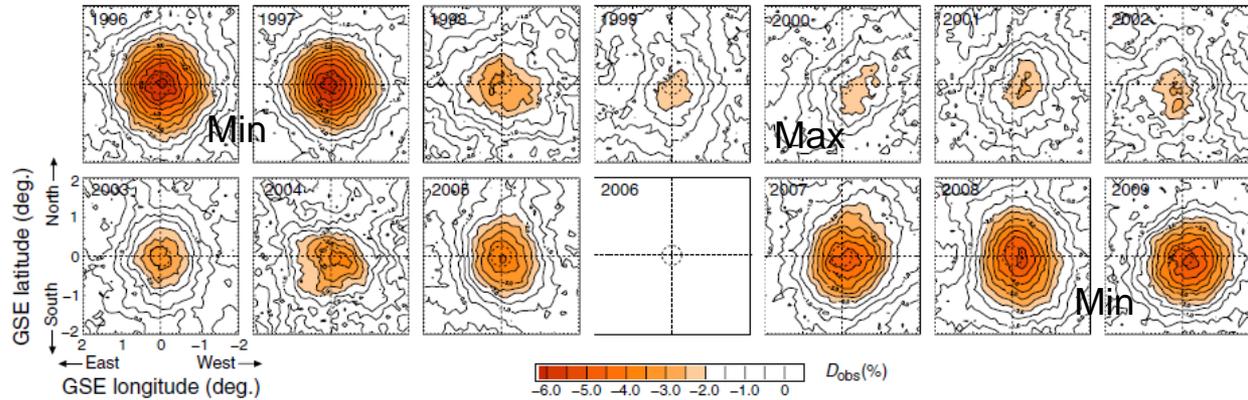
Tibet Air Shower Array

The Sun blocks cosmic rays arriving at the Earth from the direction of the Sun and casts a shadow in the cosmic-ray intensity. Cosmic rays are charged particles and their trajectories are deflected by the magnetic fiel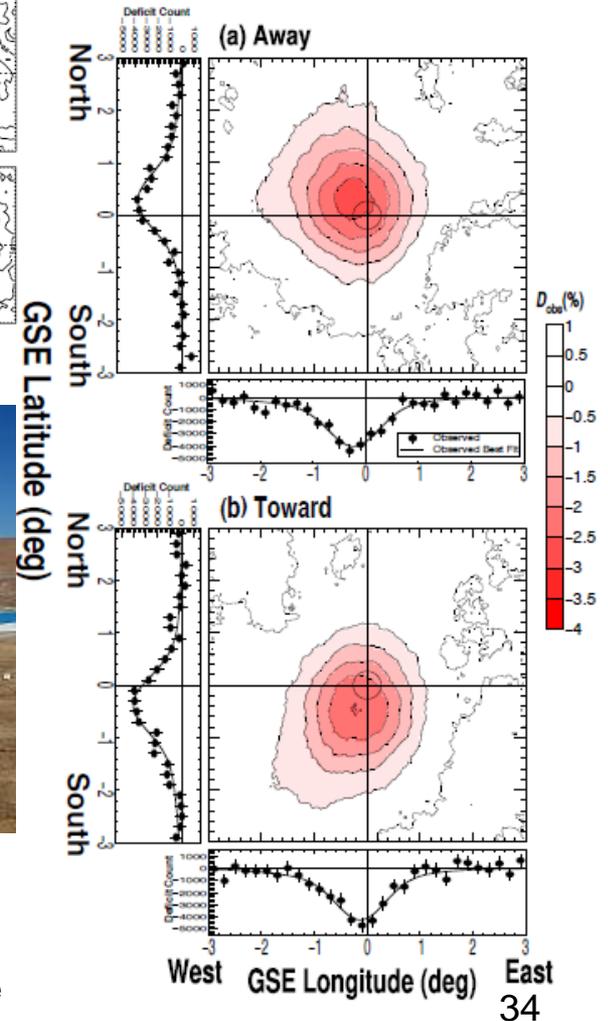d between the Sun and Earth, depending (inversely) on the magnetic field strength B and polarity, and can thus be used as probes of the field: yet another Messenger. Shows that the popular PFS model underestimates the field by at least 50%.

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The Gamma-Ray Spectrum of the Sun

The solar disk is a bright, hard-spectrum gamma-ray source due to its constant bombardment by cosmic rays, which interact with the solar atmosphere (including d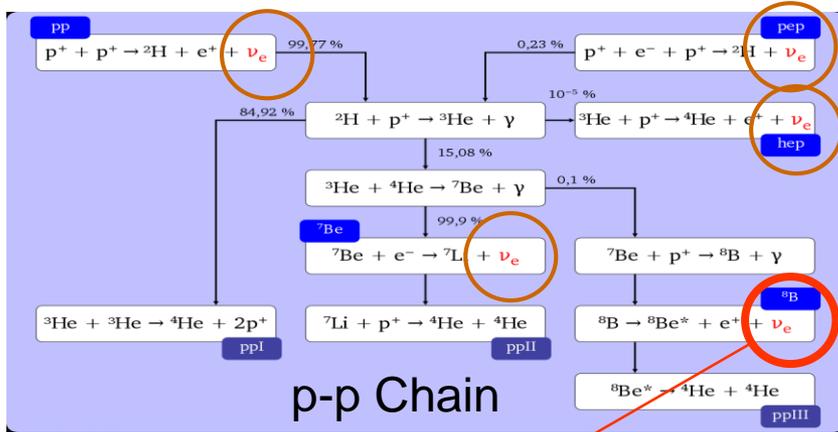eep under the optical photosphere) and produce gamma rays. The gamma rays from the solar disk (SAγ), are a new probe (Messenger) of cosmic rays in the solar system and of solar atmospheric magnetic fields.
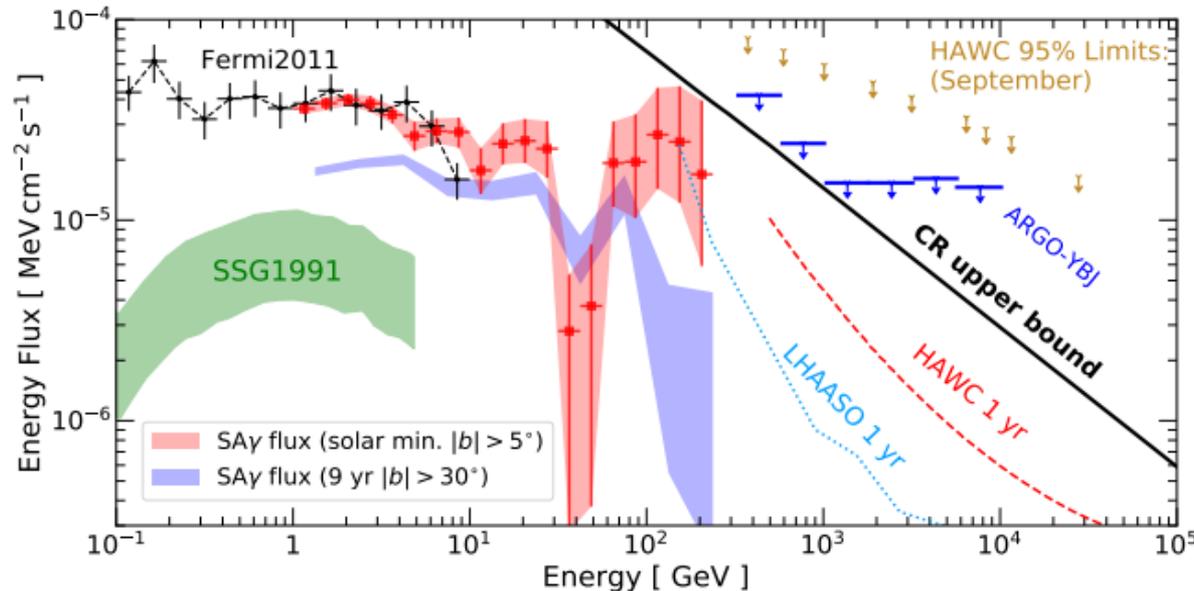
The 9-year averaged SAγ flux and the solar minimum SAγ flux. The 'dip' around 40 GeV is not understood. The theoretical maximum gamma-ray flux that the Sun can produce with cosmic rays is shown by the black solid line.

The production of SAγ also produces solar atmospheric neutrinos (yet another Messenger). The Sun can be detected by large neutrino telescopes, such as IceCube, where a search is ongoing. These neutrinos are backgrounds for solar dark matter searches…

Solar Neutrinos [Not a Problem Anymore]

p-p Chain

Detectors Sensitive to Different Energies

^{8}B Neutrino Flux

- SK data(Stat. only)
- Systematic error
- SK combined flux
- Sun spot number

Data/MC(Unoscillated)
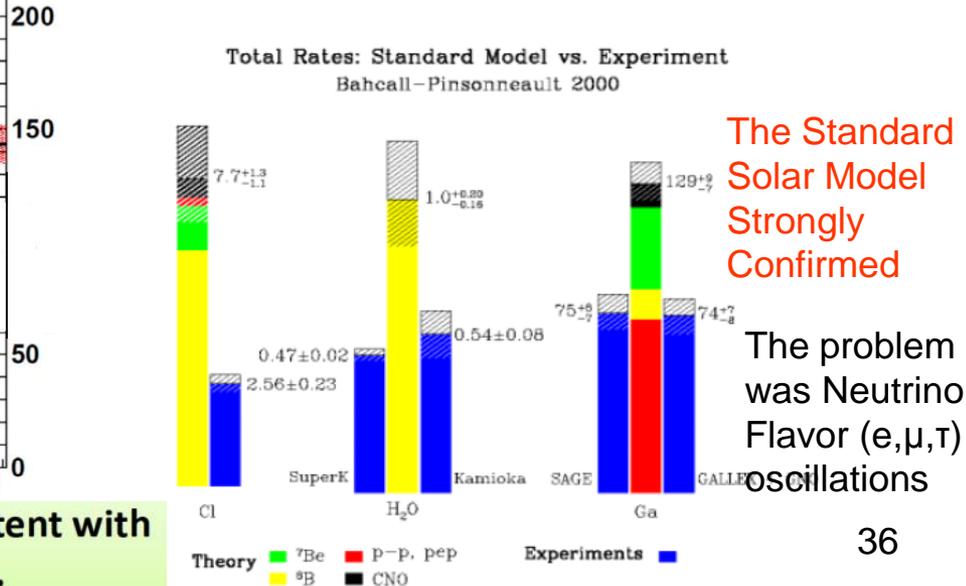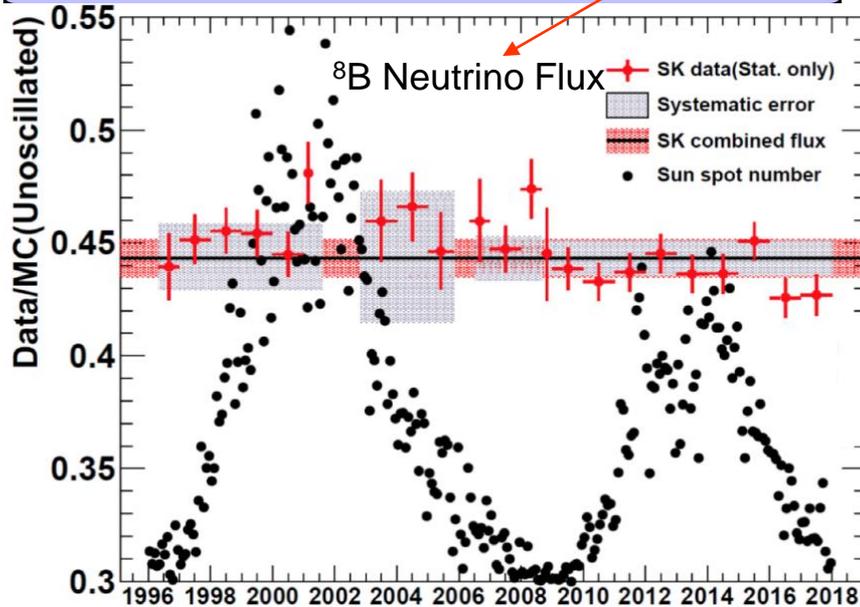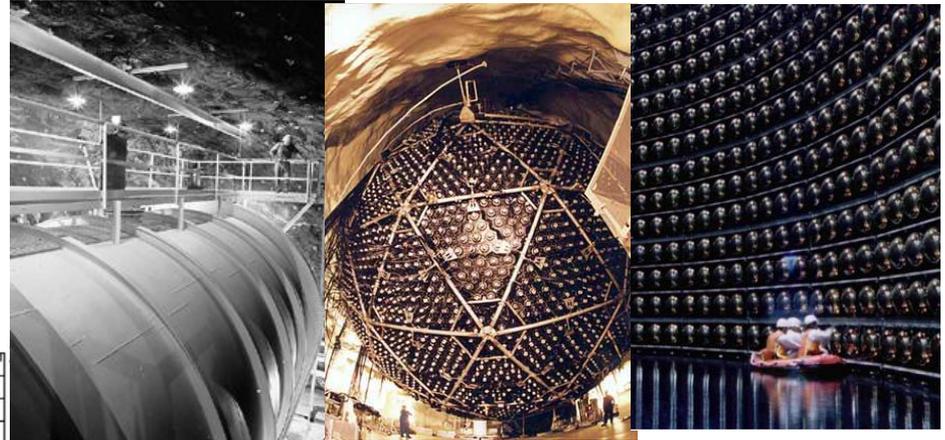
Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.
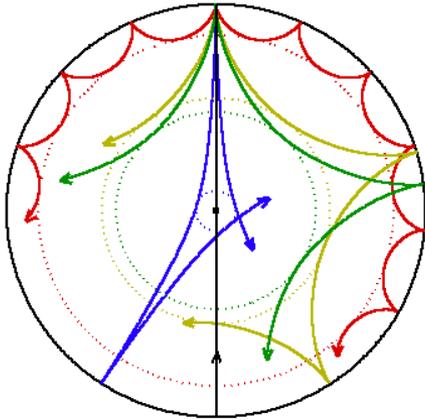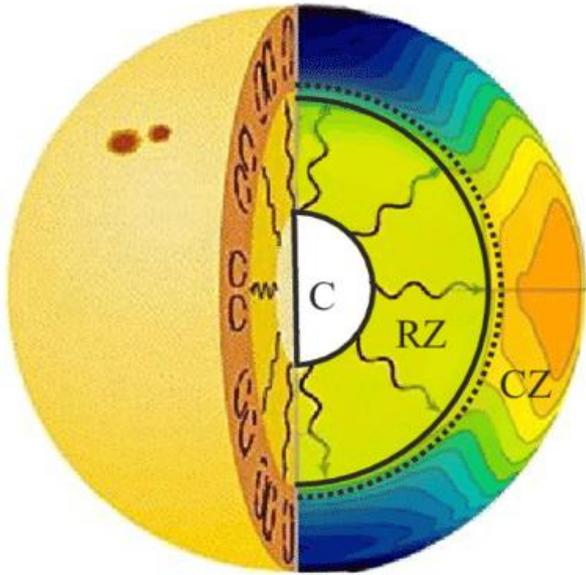
Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000

The Standard Solar Model Strongly Confirmed

The problem was Neutrino Flavor (e,μ,τ) oscillations

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Helioseismic Probing of the Interior

Helioseismology aims to measure Doppler data of the travel times of waves propagating between two points located on the solar surface. The travel times are then inverted to infer sub-surface properties .

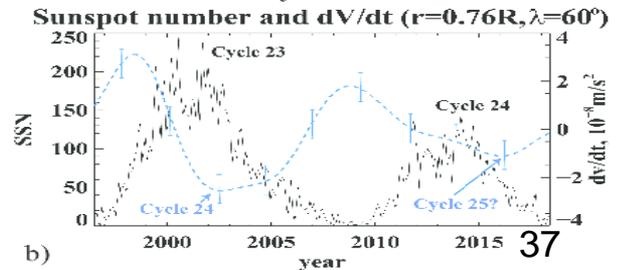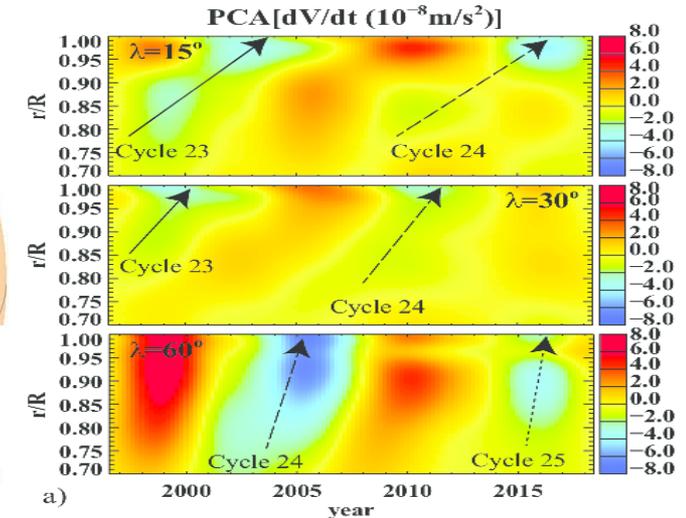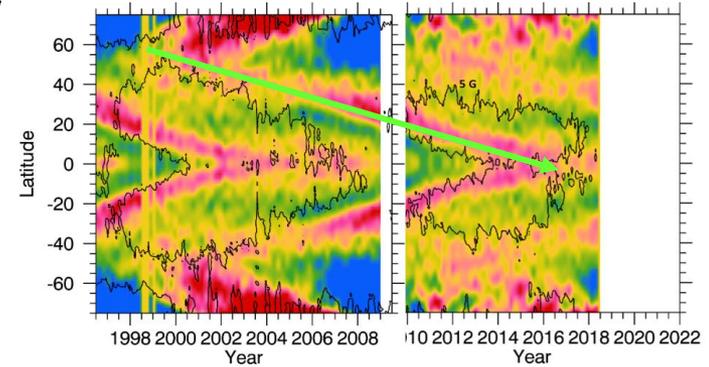Are there one or multiple cells of meridional circulation? Important for the solar dynamo

Surprise: 'solid body' rotation in radiative interior
Perhaps: 'rapid' rotation in solar core [??]

37
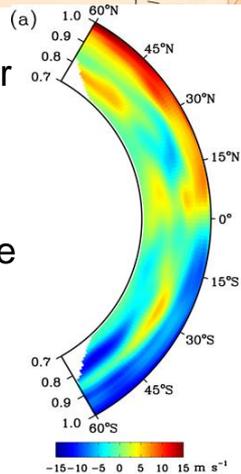
Spectroscopy: John W. Draper, first president of the American Chemical Society declared in 1876 in his inspiring presidential address:

Flash Spectrum   Solar Eclipse, 21 August 2017
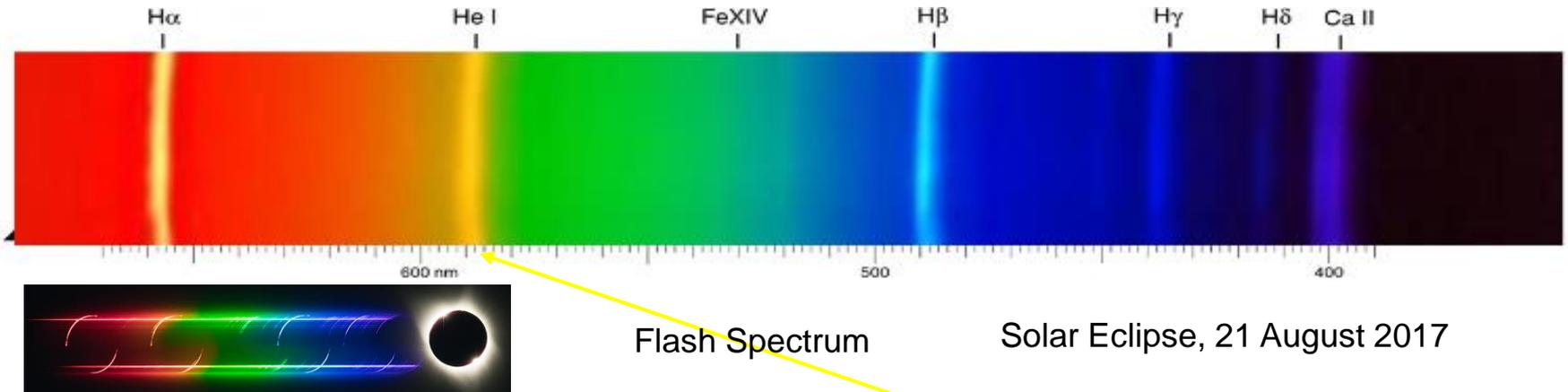
"And now, while we have accomplished only a most imperfect examination of objects that we find on the earth, see how, on a sudden, through the vista that has been opened by the spectroscope, what a prospects lies beyond us in the heavens! I often look at the bright yellow ray emitted from the chromosphere of the sun, by that unknown element, Helium, as the astronomers have ventured to call it. **It seems trembling with excitement to tell its story**, and how many unseen companions it has. And if this be the case with the sun, what shall we say of the magnificent hosts of the stars. […] Is not each a chemical laboratory in itself?"

The 'Xenon Paradox' May be Another Solar Messenger

Atmospheric xenon is strongly mass fractionated and Xe is the only noble gas that can escape as an ion in a photo-ionized hydrogen wind. Models suggest that a minimum requirement for Xe escape is that solar EUV irradiation needs to exceed 10×that of the modern Sun (Zahnle et al. 2018).

Terrestrial atmospheric Xe has two unique features. First, atmospheric Xe is depleted by a factor of 20 compared to the Ar/Kr/Xe elemental pattern defined by chondrites. Second, atmospheric xenon is strongly enriched in heavy relative to light isotopes compared to other known solar system components. These two features form the "xenon paradox".
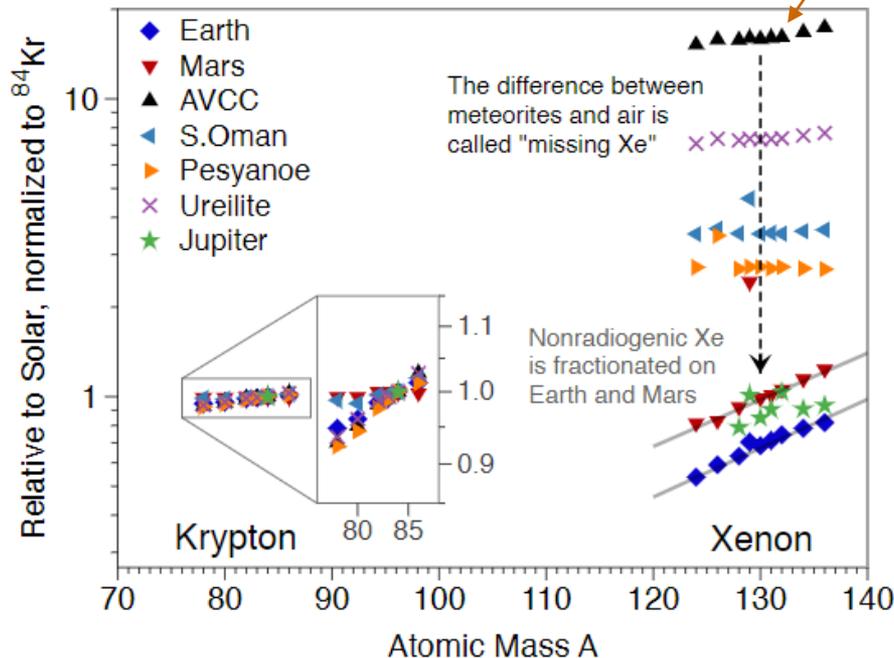
The Rosetta-Mission to Comet 67P/C-G found Xe isotopical abundances similar to that of the early Earth and very dissimilar to that in Chondrites and the Solar Wind possibly indicative of different conditions for solar activity [EUV] of the early Sun.

We have not yet fully decoded this particular message, but it is an example of messages hiding in unexpected places. There are undoubtedly many more…

Comet 67P/C-G
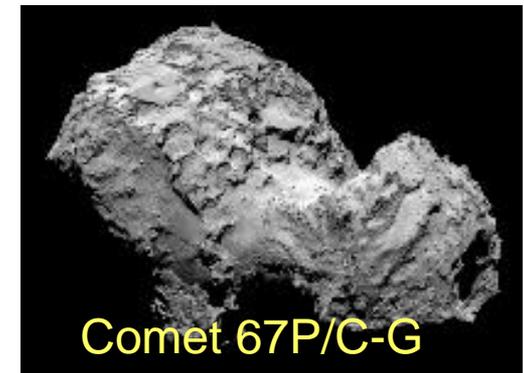
The Great System of Which We Make a Portion
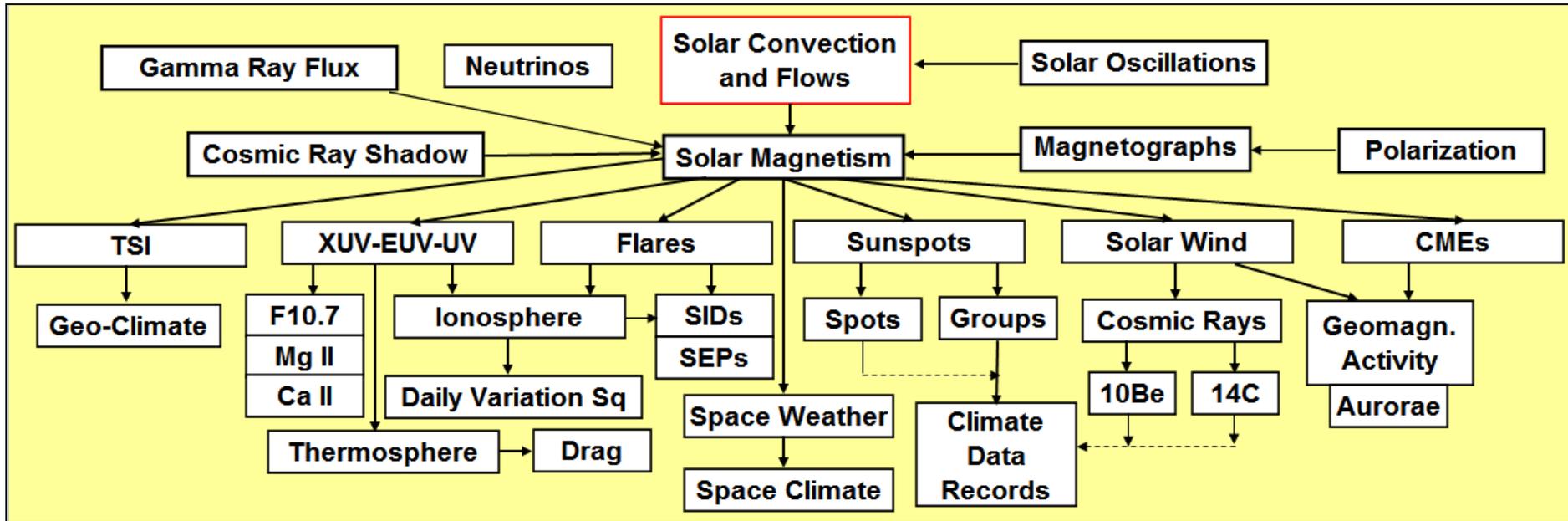
M. Faraday wrote to R. Wolf on 27th August, 1852: "I am greatly obliged and delighted by your kindness in speaking to me of your most remarkable enquiry, regarding the **relation existing between the condition of the Sun and the condition of the Earths magnetism**. The discovery of periods and the observation 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...

Abstract

The concept of Messengers from space that tell us about the physics of objects in the Universe has been much in the news lately with the discovery of gravitational waves, but the Sun is also sending us a diverse suite of astrophysical 'messages', some that only recently have been decoded and read. The true dawn of multi-messenger astronomy actually occurred with observations of phenomena caused by solar emissions. The [growing] list of such 'messengers' includes, among others, electromagnetic radiation, solar wind plasma interactions with the Earth's magnetic field, using the ionosphere for radio propagation, modulation of cosmic rays, neutrinos, and more. In fact, we have a broader array of messengers from the Sun than from any other astronomical object. In this talk, I'll discuss several of those messengers and what they teach us about the sun and especially about the long-term evolution of solar activity.