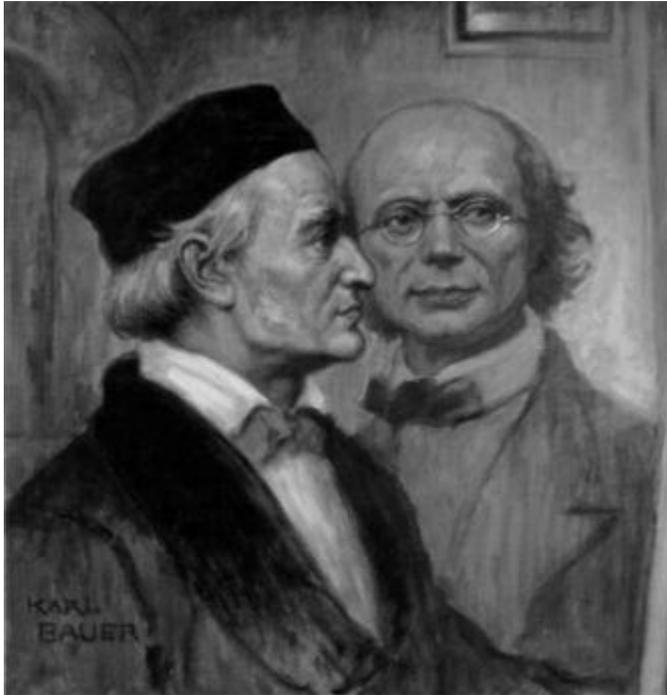




# Reconstruction of Heliospheric Magnetic Field Strength 1835-2014 and What that Means for the Sun

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Stanford University  
12 Feb. 2014

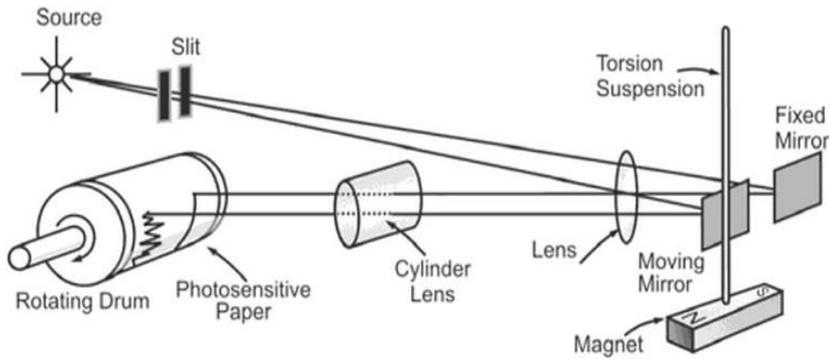
# The Invention of the Magnetometer



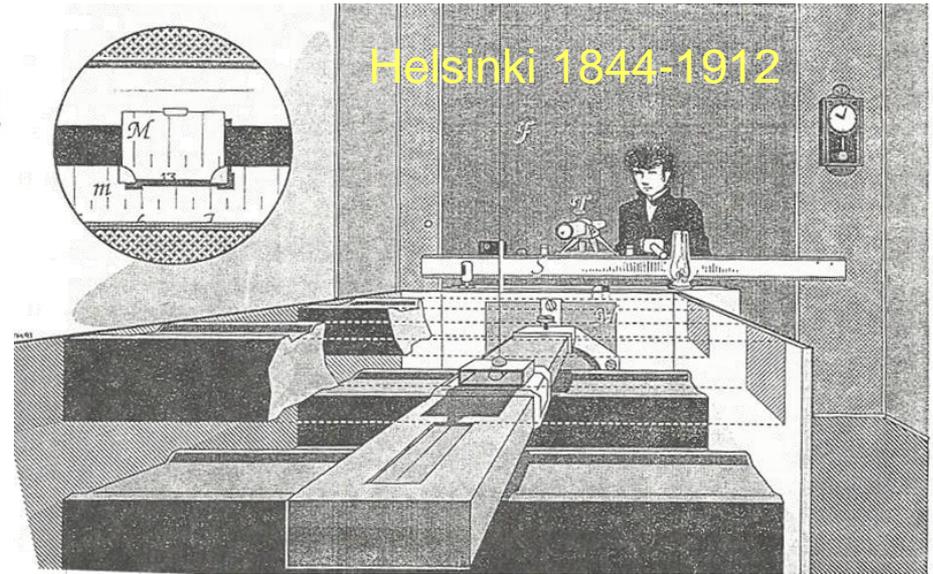
Carl Friedrich Gauss (1777-1855) left  
Wilhelm Eduard Weber (1804-1891) right

After C. F. Gauss and W. E. Weber's invention of the Magnetometer in 1833, systematic [e.g. hourly or daily] measurements of the variation of the Earth's magnetic field were begun at several newly erected observatories around the World ["the Magnetic Crusade"]. These observations [greatly expanded] continue to this day. Magnetometers on the first spacecrafts to explore interplanetary space in 1962 showed that the, long hypothesized and then detected, solar wind carried a measurable magnetic field, which was soon identified as the main driver of disturbances of the magnetic field observed on the Earth. Vigorous research during the last decade has shown that it is possible to 'invert' the causative effect of the magnetic field in near-Earth interplanetary space [the near-Earth Heliospheric Magnetic Field] and to infer with good accuracy the value of that field [and also of the solar wind speed and density] from the observed magnetic changes measured during almost two centuries at the surface of the Earth.

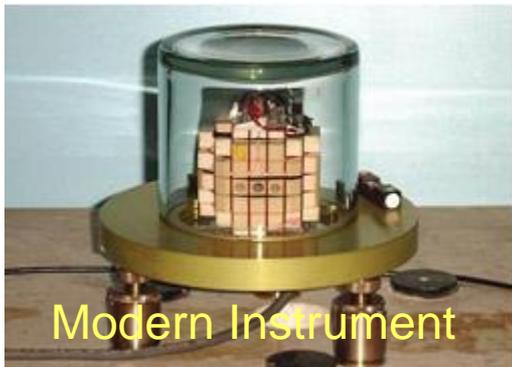
This talk is that story



Classic Method since 1846

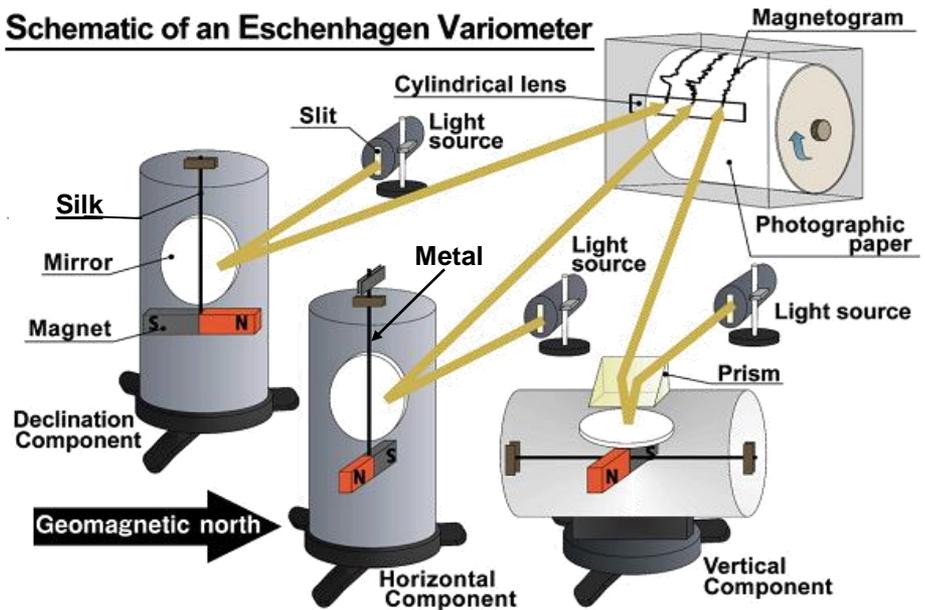


Instruments ca. 1910



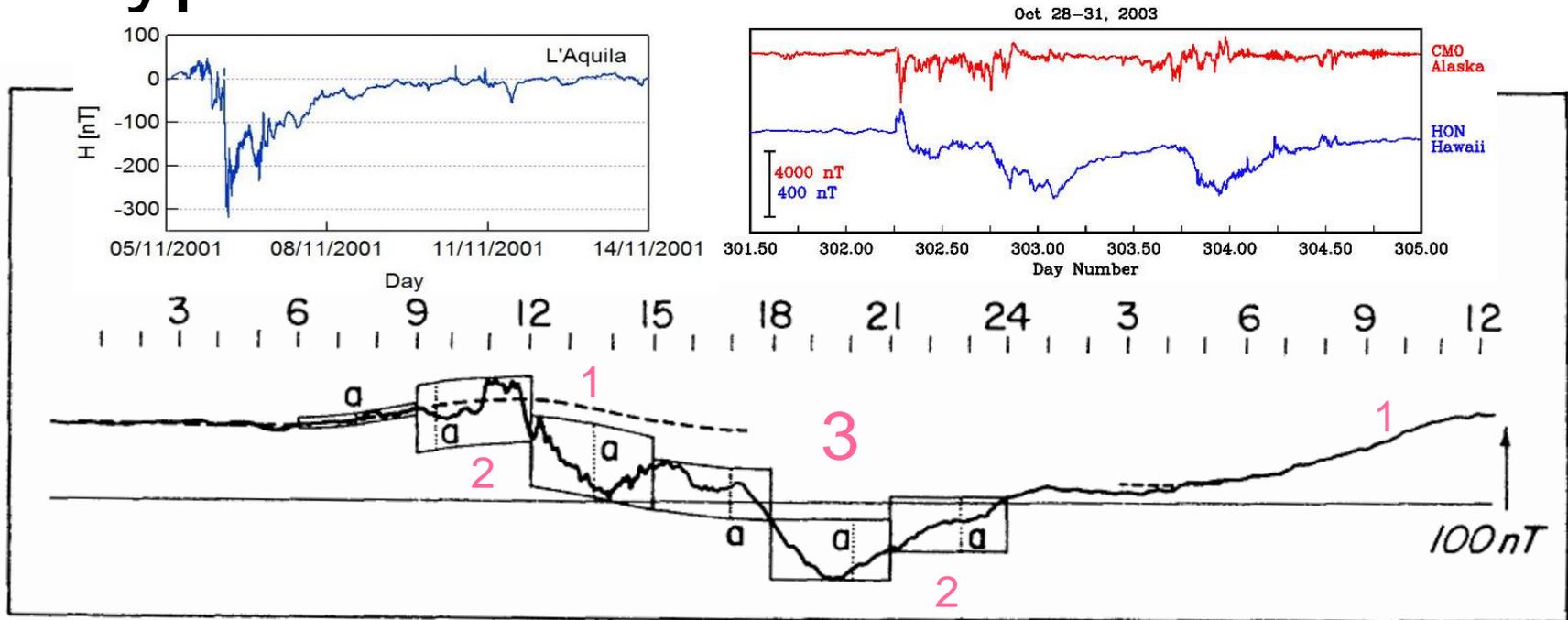
Modern Instrument

Schematic of an Eschenhagen Variometer



Magnetic Recording

# Typical Recording over 36 Hours

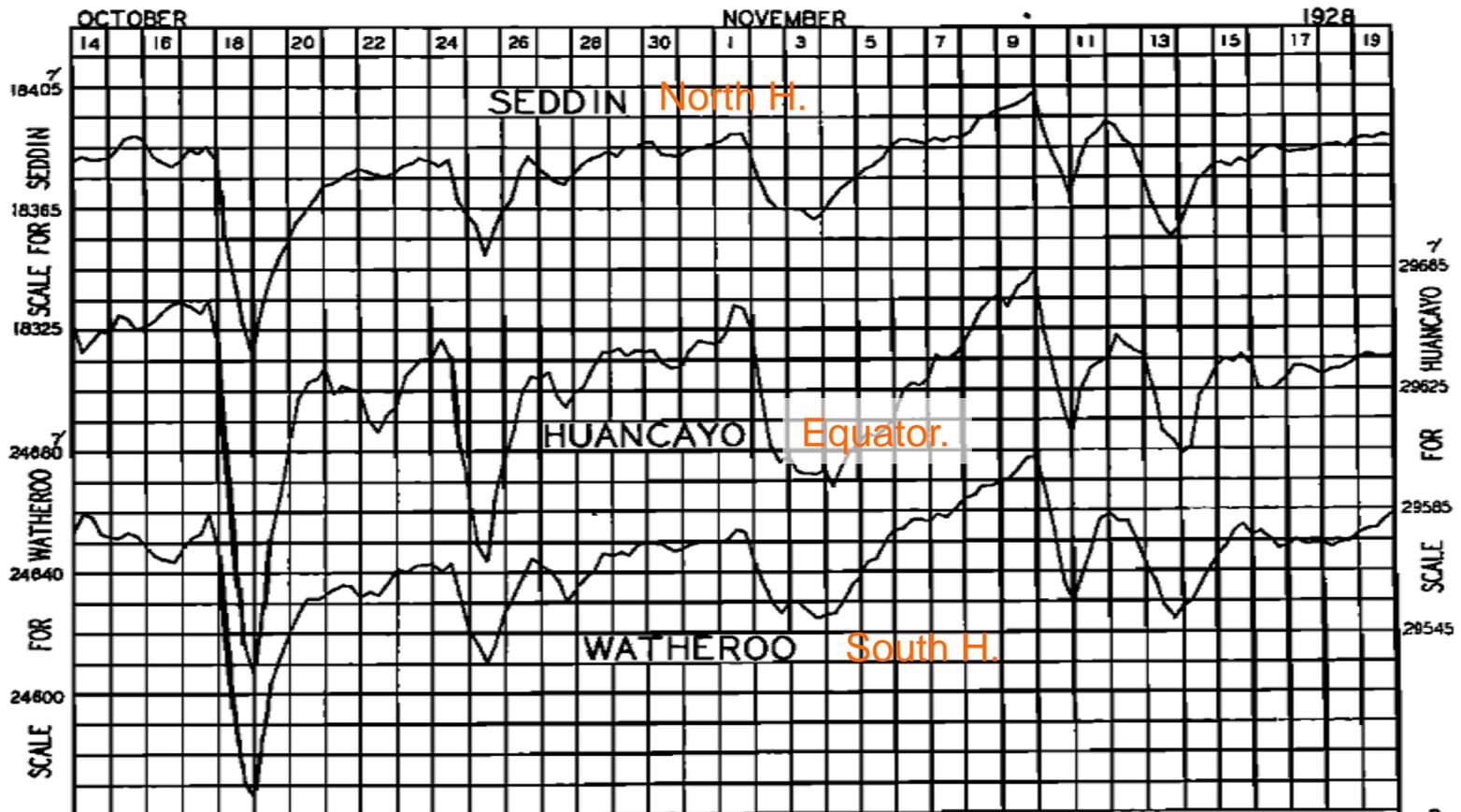


Three simultaneous features:

- 1: A Regular Daily Variation [it took 50 years to figure out the cause]
- 2: Shorter-term [ $\sim 3$  hour] fluctuations ['substorms' recognized in 1960s]
- 3: Large disturbances ['geomagnetic storms' explained in the 1960s]

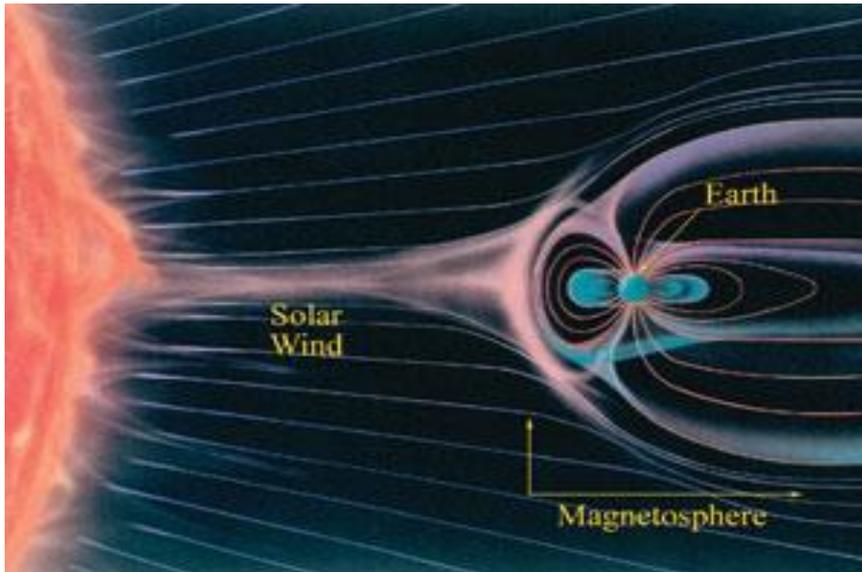
The complicated, simultaneous effects withstood understanding for a long time

24-hour running means of the Horizontal Component of the low- & mid-latitude geomagnetic field remove most of local time effects and leaves a Global imprint:



A quantitative measure of the effect can be formed as a series of the unsigned differences between consecutive days: The InterDiurnal Variability, IDV-index

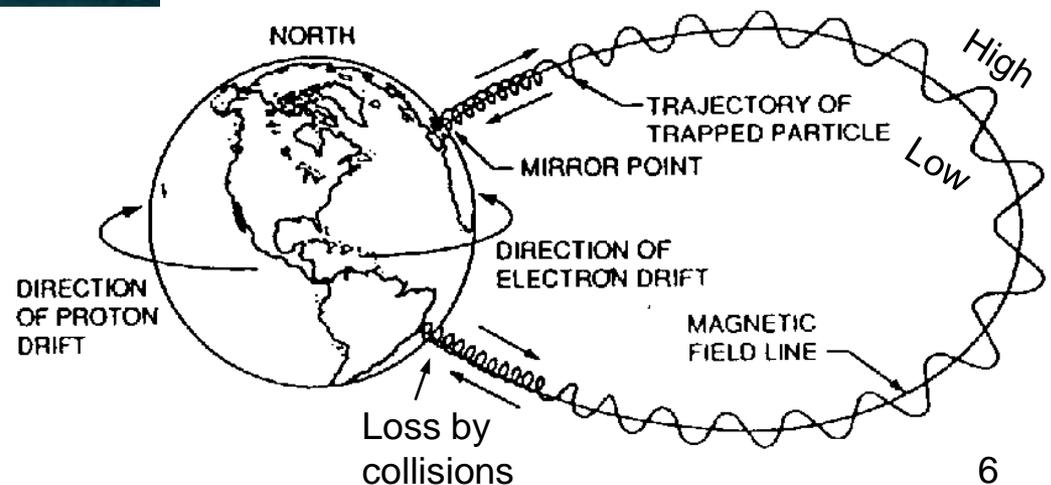
# Geomagnetic Storms Due to much Enhanced 'Ring Current'



The gyroradius ( $\sim B^{-1}$ ) is reduced on the high-field side of the Larmor orbit, while it is increased on the low-field side. The net result is that the orbit does not quite close. The resulting motion consists of the gyration around the magnetic field combined with a slow drift which is perpendicular to the local direction of the magnetic field.

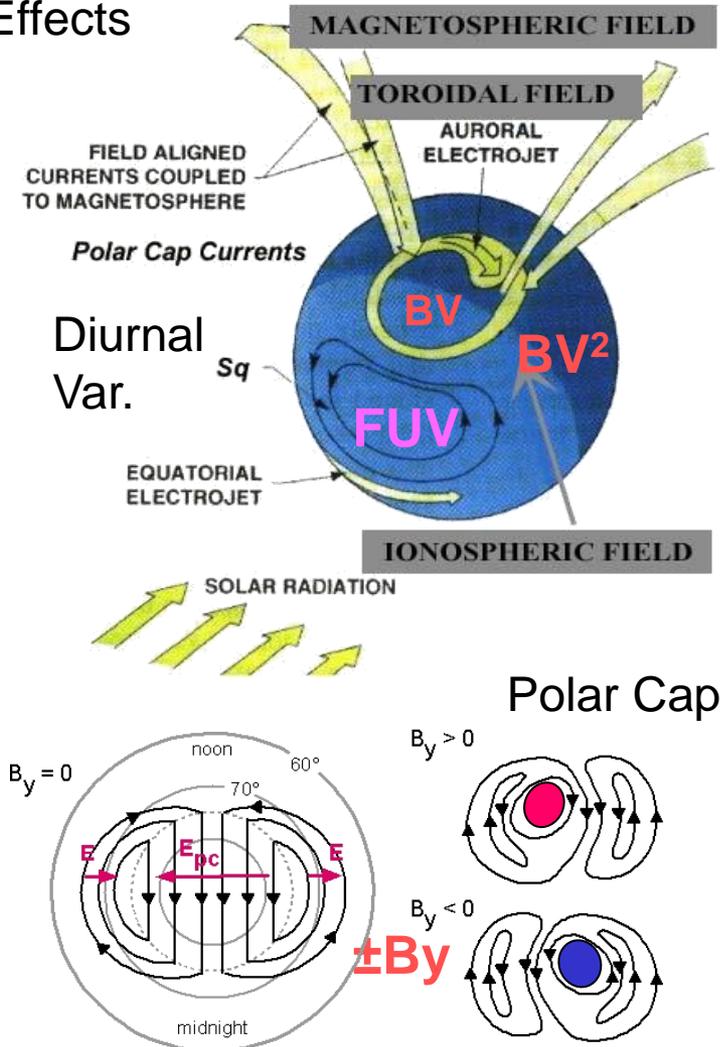
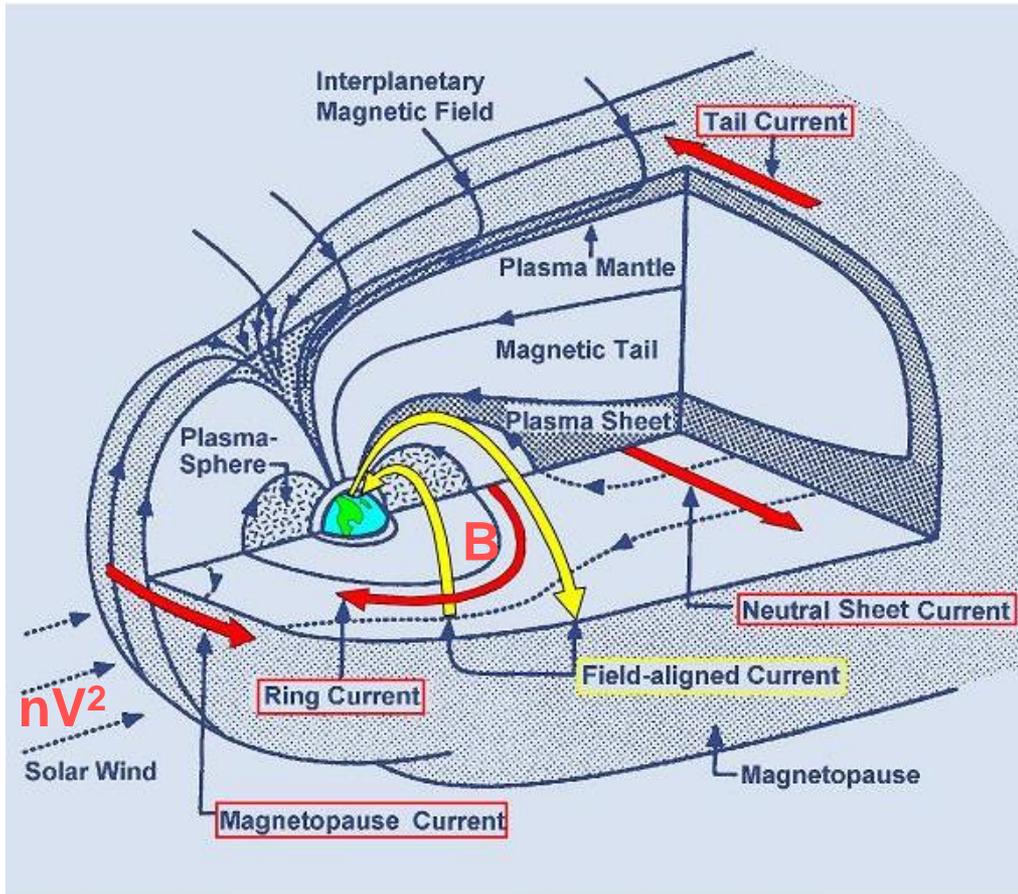
Oppositely particles trapped in the Van Allen Belts drift in opposite directions giving rise to a net westward 'Ring Current'.

That is the cause of the global response we just saw.



# Electric Current Systems in Geospace

Different Current Systems  $\leftrightarrow$  Different Magnetic Effects



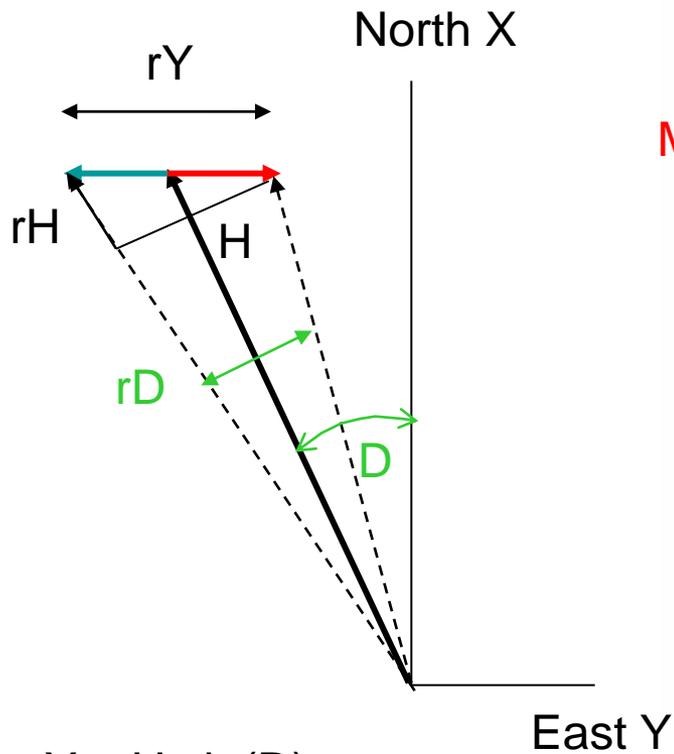
We can now invert the Solar Wind – Magnetosphere relationships...

# ‘Different Strokes for Different Folks’

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

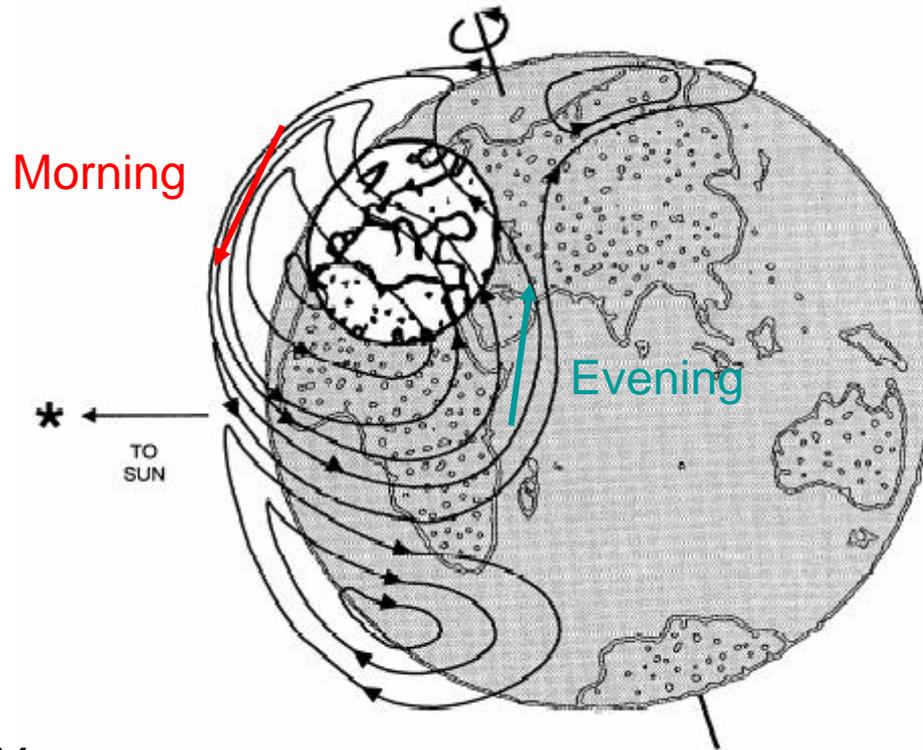
# Wolf's Discovery (1852): $rD = a + b R_W$

Sunspot  
number



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

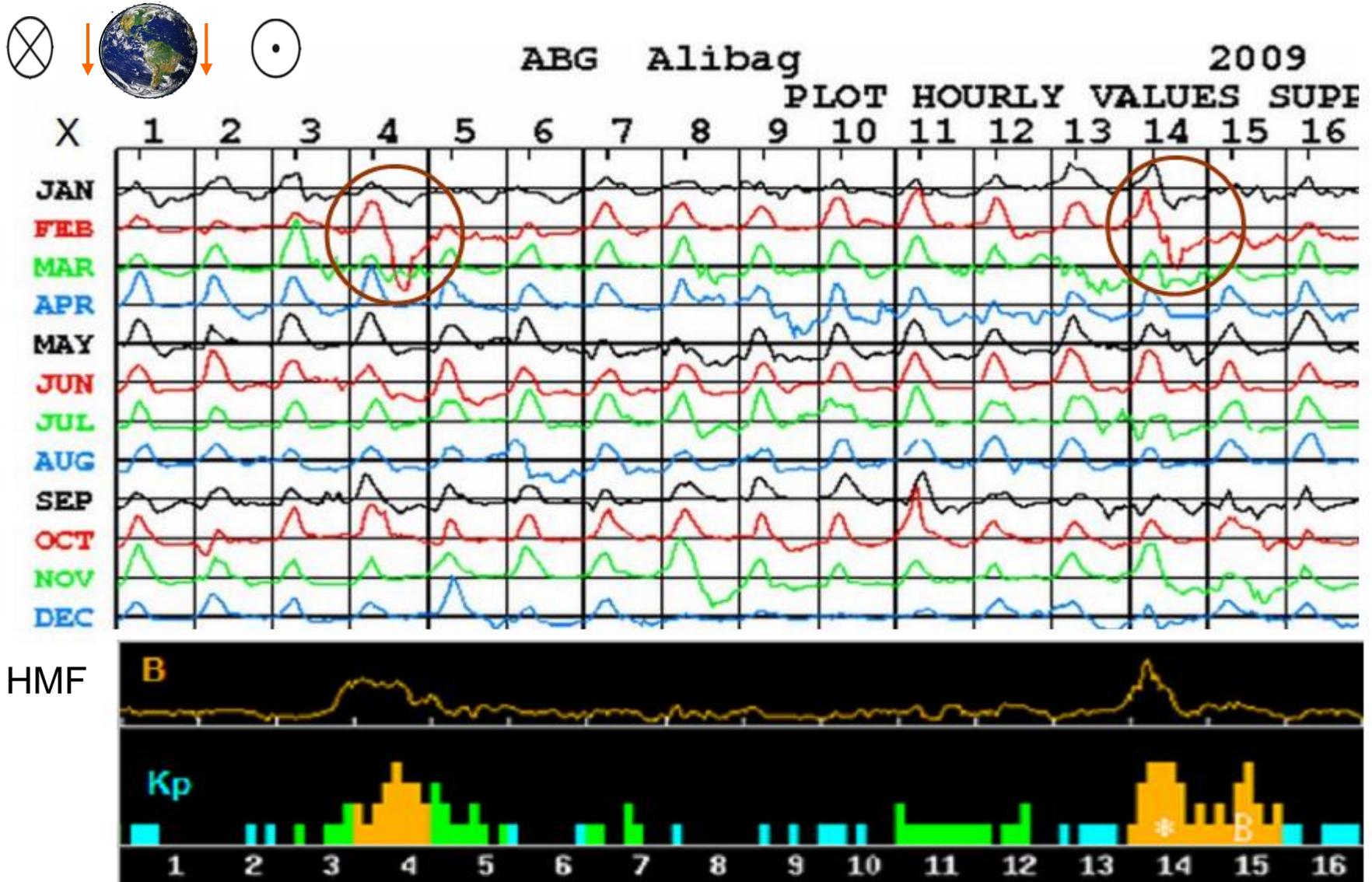
$$dY = H \cos(D) dD \quad \text{For small } dD$$



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

The magnetic effect of this system was discovered by George Graham in 1722

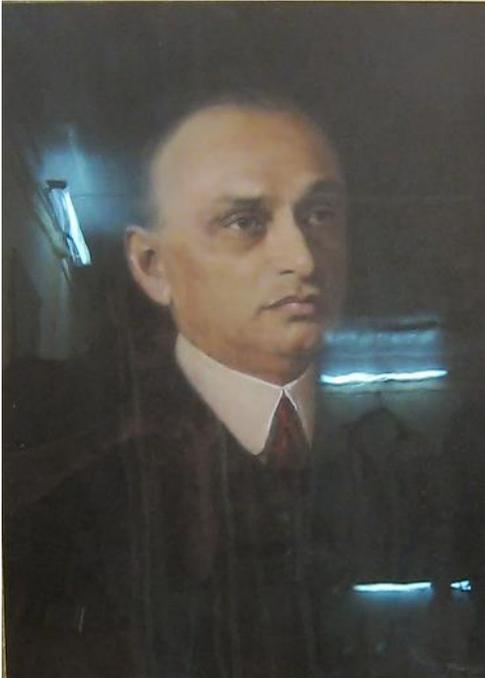
# Relation to HMF Strength B



# The IDV Geomagnetic Index

- Since the daily variation is fairly regular from day to day we can eliminate it by considering the difference between consecutive days
- Further suppression of the daily variation can be achieved by working only with the field during night hours
- That led to the definition of the Interdiurnal Variability Index [IDV] as the **unsigned difference between the geomagnetic field component on consecutive local nights**
- IDV is a Global index
- IDV is a modern version of the *u*-measure

# The $u$ -measure



N.A.F Moos (1859-1936)



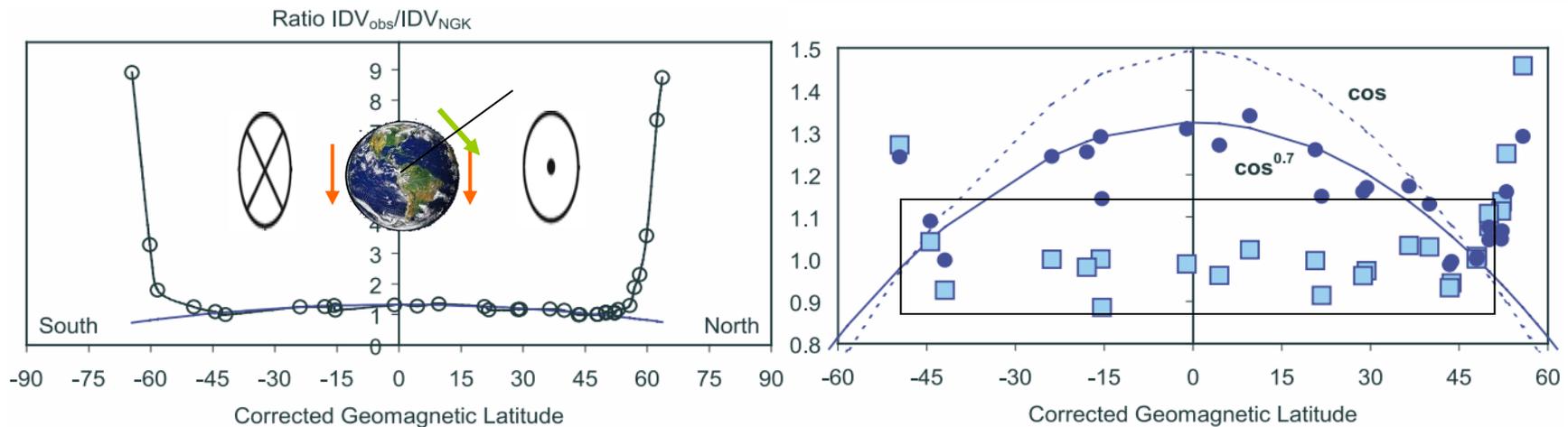
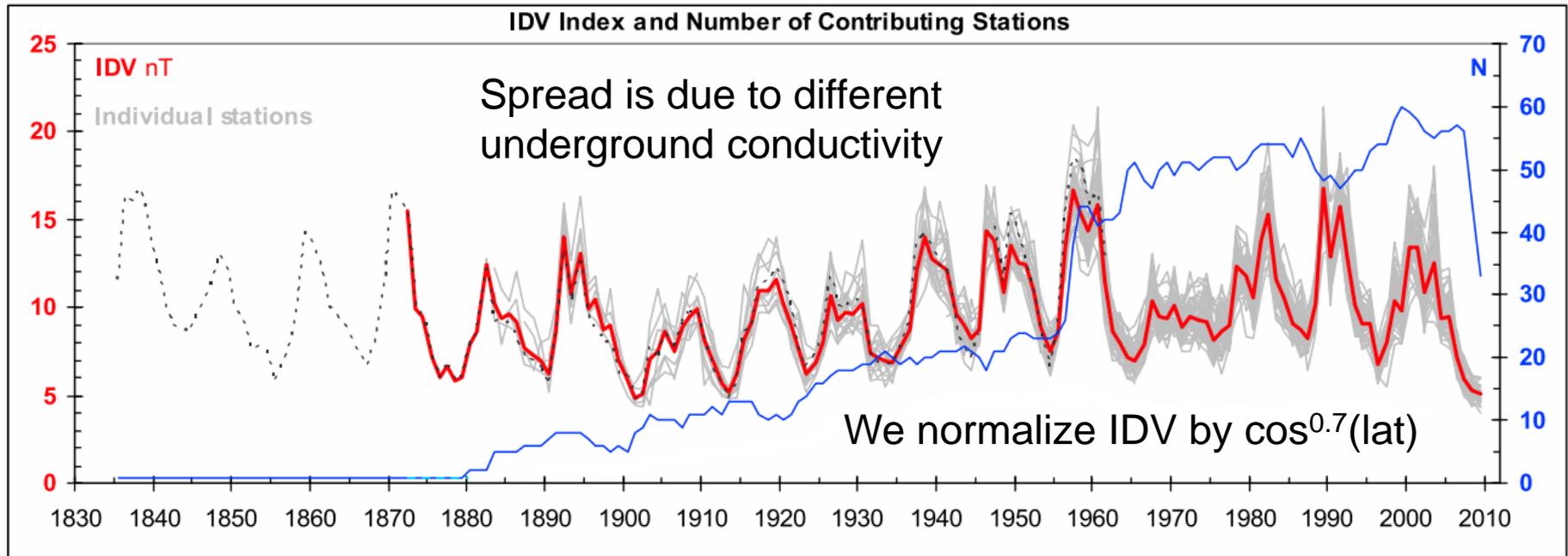
Adolf Schmidt (1860-1944)



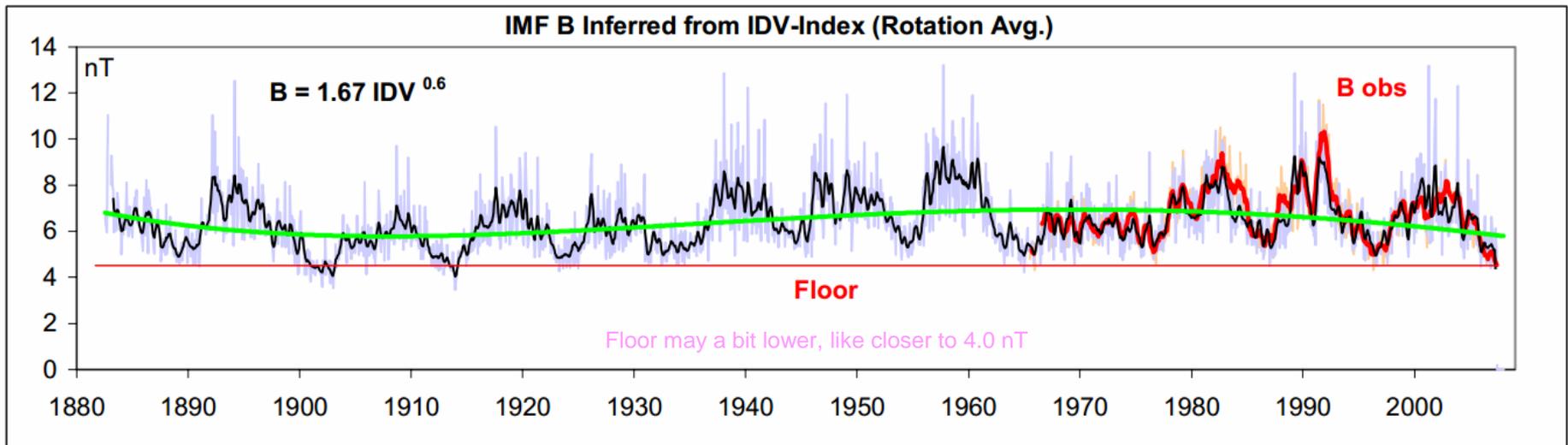
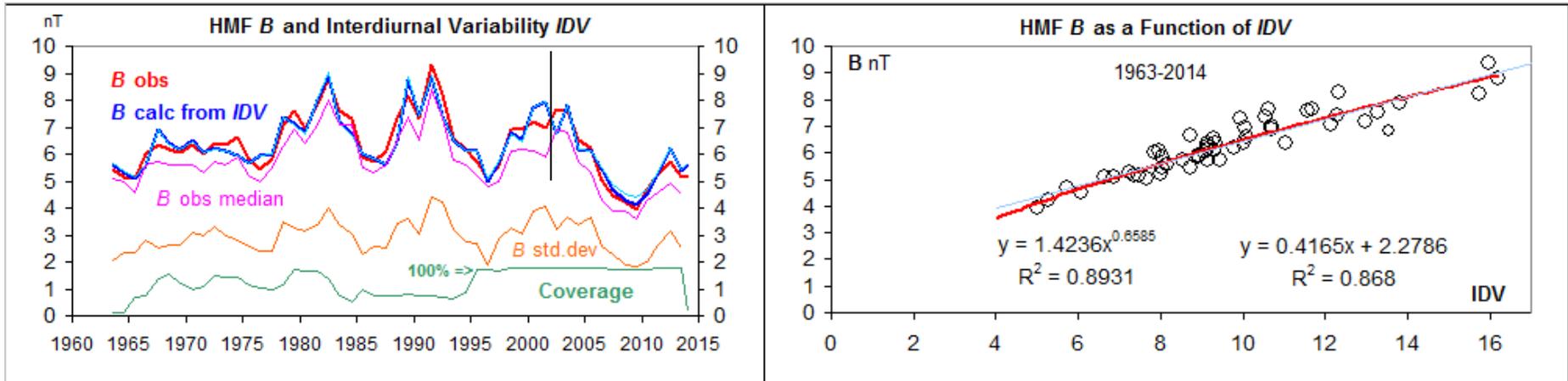
Julius Bartels(1899-1964)

The  $u$ -measure was an index defined as the unsigned difference of the daily means of the horizontal component from one day to the next

# IDV Derived from Many Stations (Observatories)

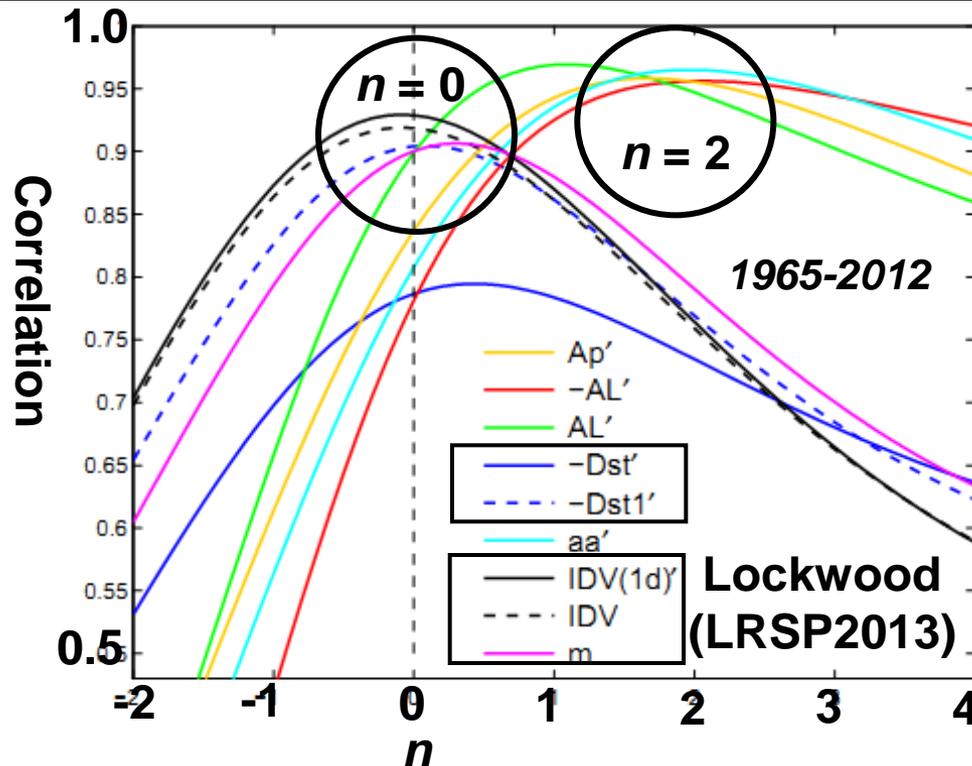
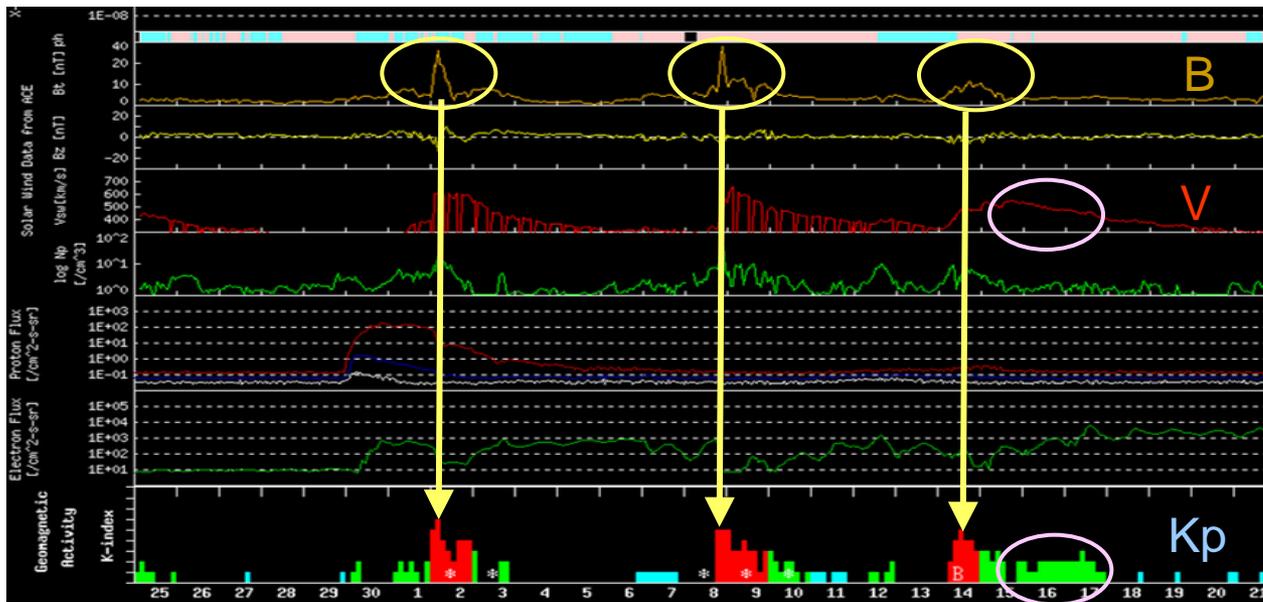


# Relationship between HMF $B$ and $IDV$



Also holds on timescales shorter than one year

# 27-day Bartels Rotation showing $B$ and $Kp$ peaks

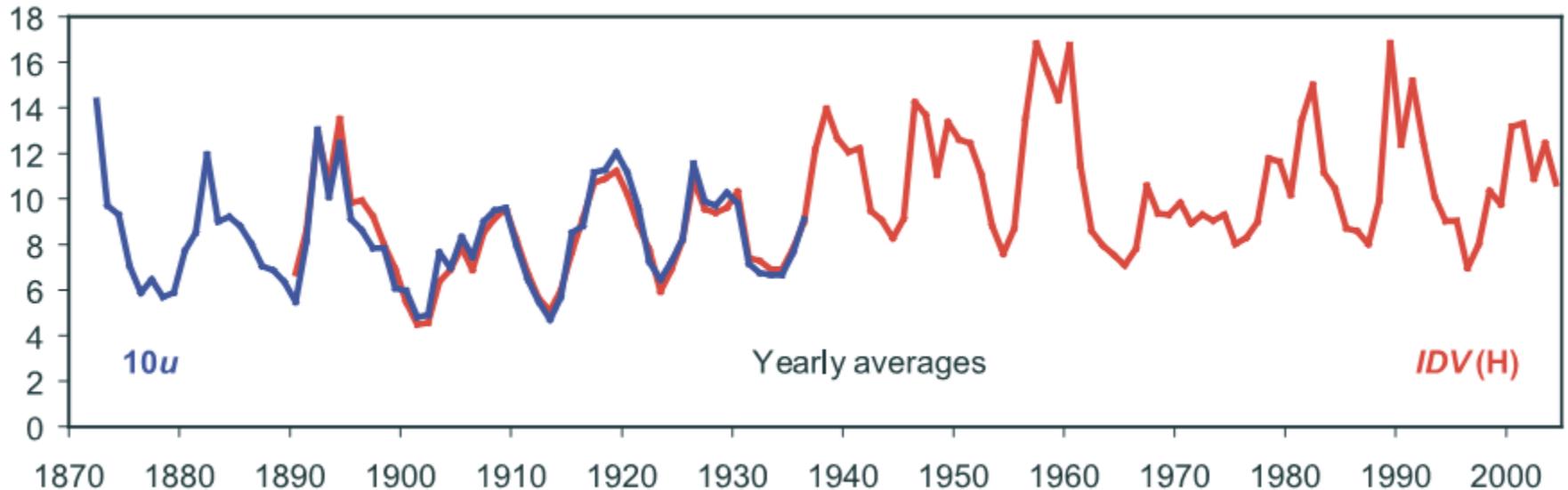


Correlation between  
Heliospheric  $BV^n$  and  
several geomagnetic  
indices as a function of  $n$

The IDV indices thus  
depend on  $B$  only ( $n = 0$ ).

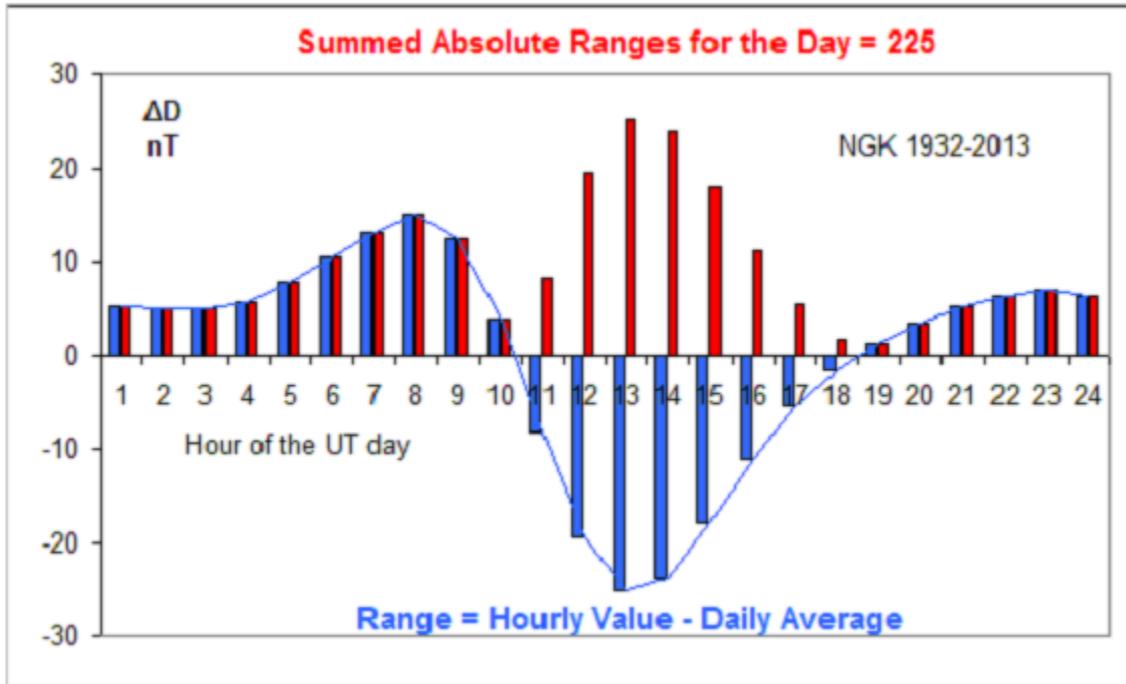
Substorm indices [Kp]  
depend on  $BV^2$

# Comparing the $u$ -measure and IDV



The IDV index and the  $u$ -measure track each other so well that either one can be used. We introduced the IDV based on only one hour per day because in the 19<sup>th</sup> century many stations did not observe at all hours throughout the day [not to speak about the night] so we wanted to see if only a few [as few as 1] hours worth of observations would be sufficient. As you can see, this hope seems fulfilled. The goal now is to extend the series to before 1872, potentially back to 1835 when Gauss and Co. initiated regular observations.

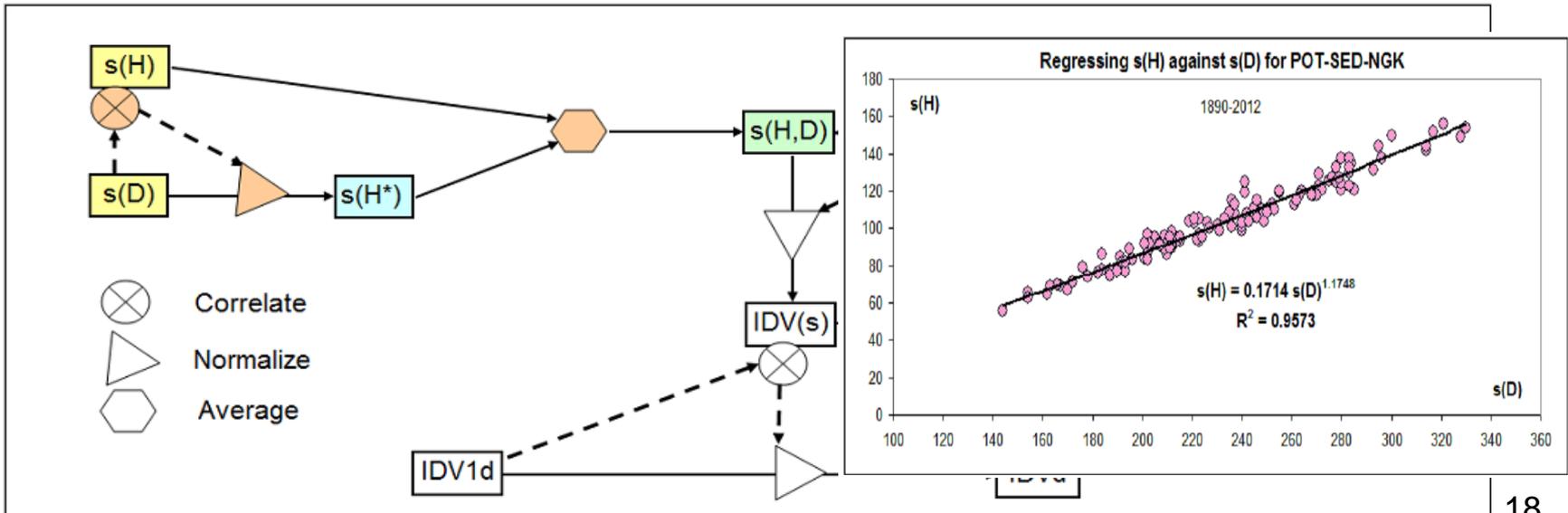
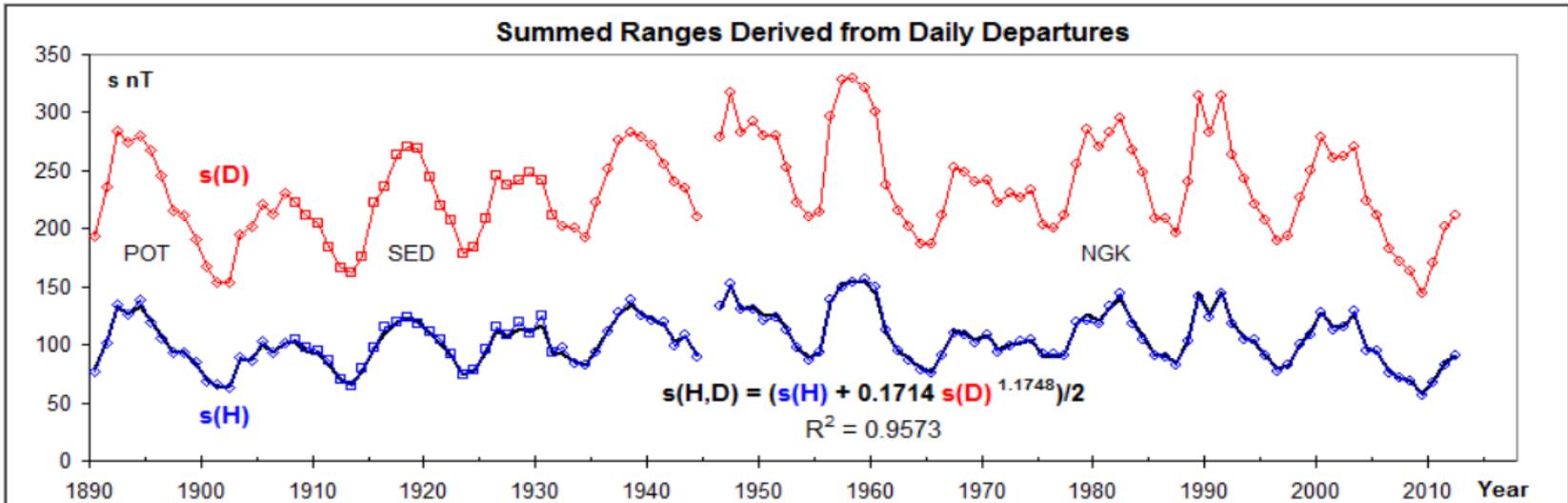
# Other Ways to get the IDV Index



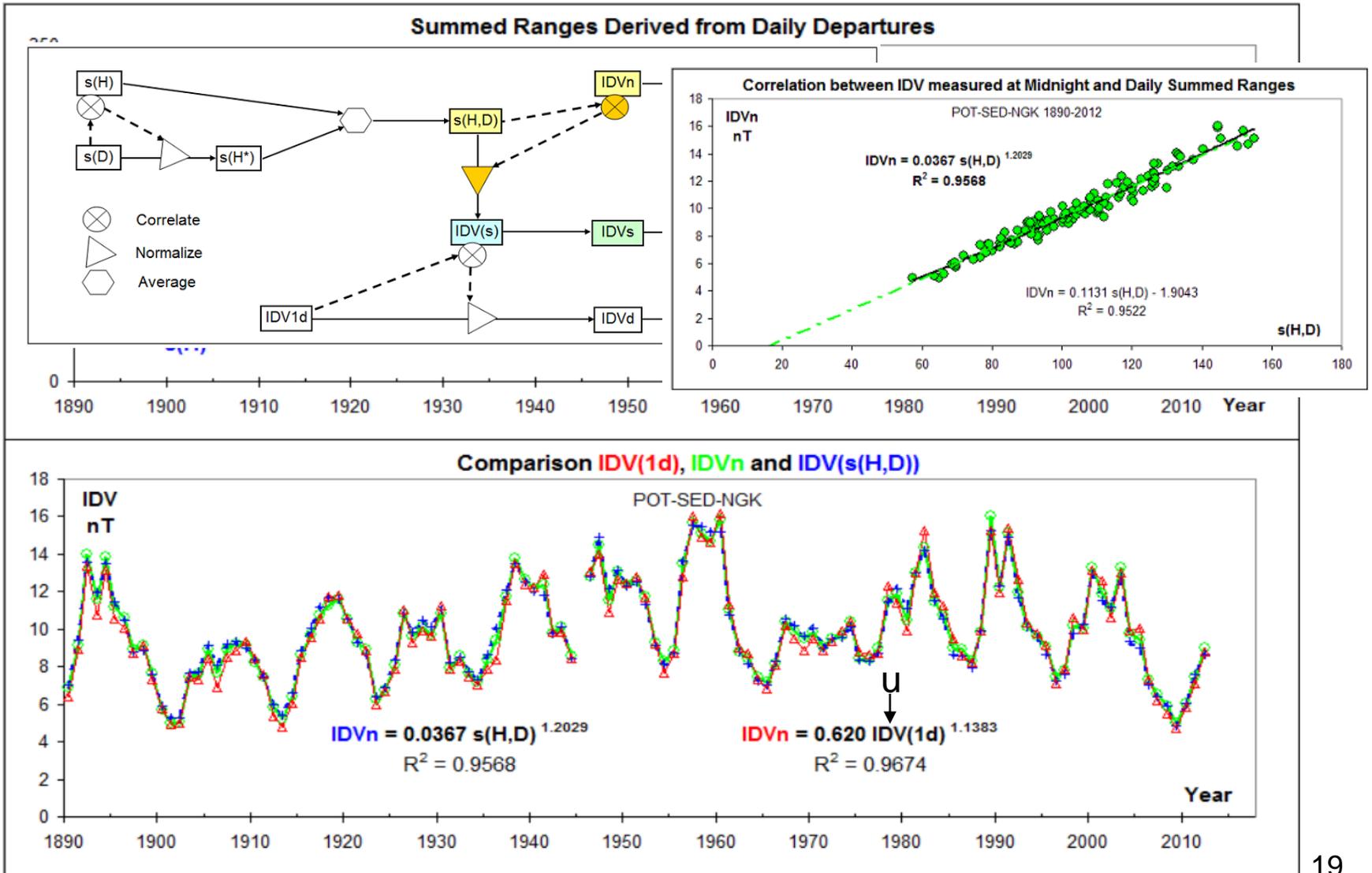
Moos introduced the concept of 'Summed Ranges'. Today we wouldn't do it that way, but much of the early data and discussions center around concepts they used back then, so we go along.

For each day, calculate the mean [of the data you have even if some hours are missing], the sum over all data points the absolute differences from that mean.

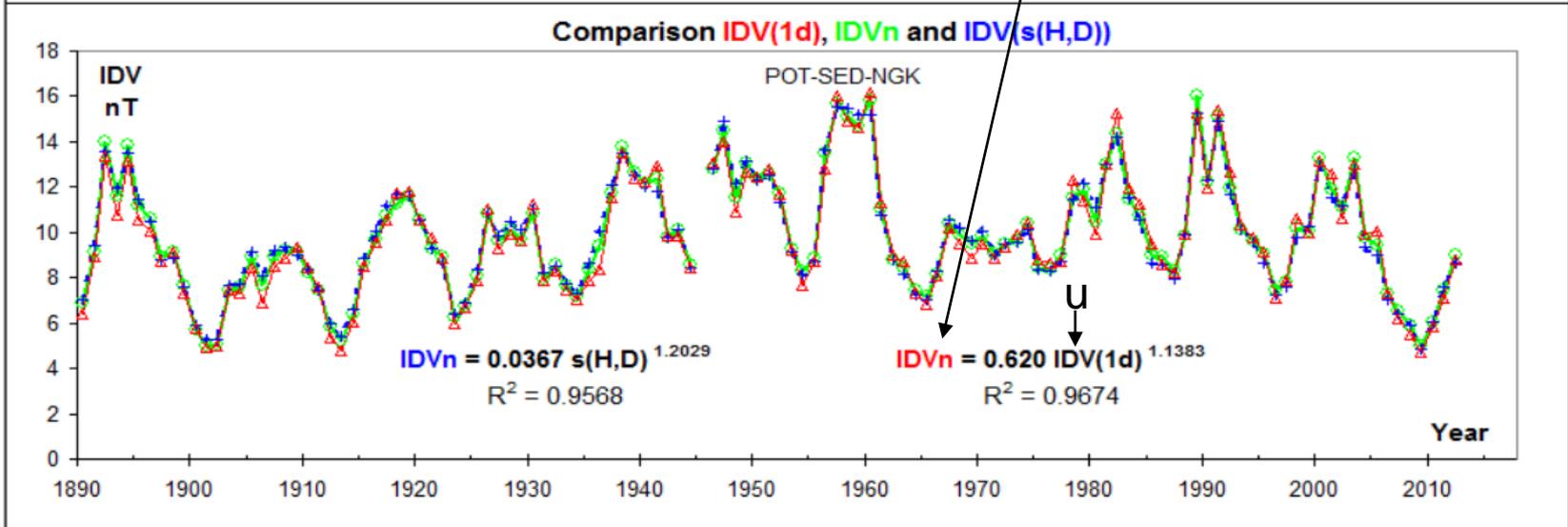
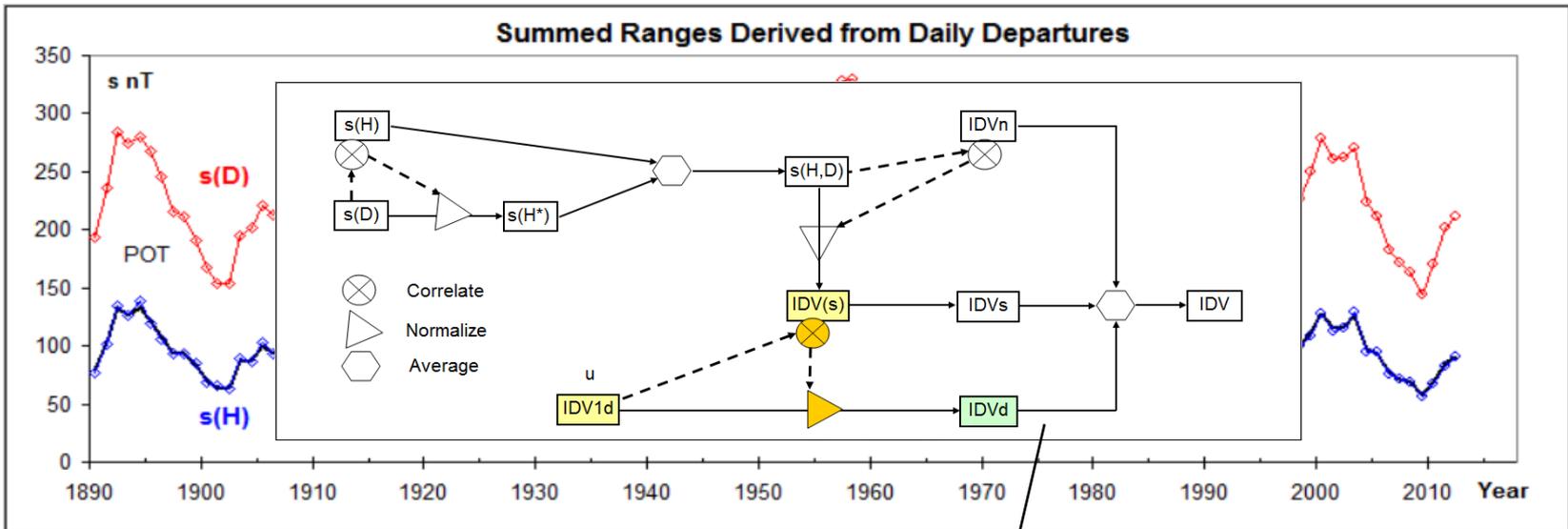
# The Summed Ranges can give us IDV



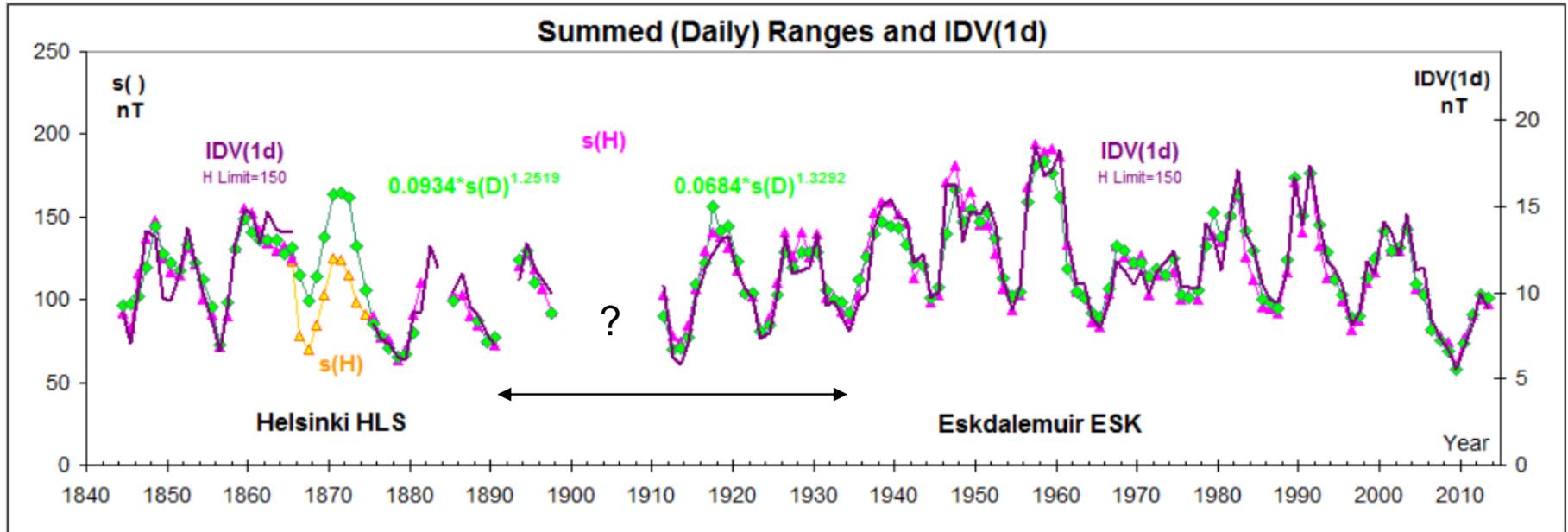
# The Summed Ranges can give us IDV



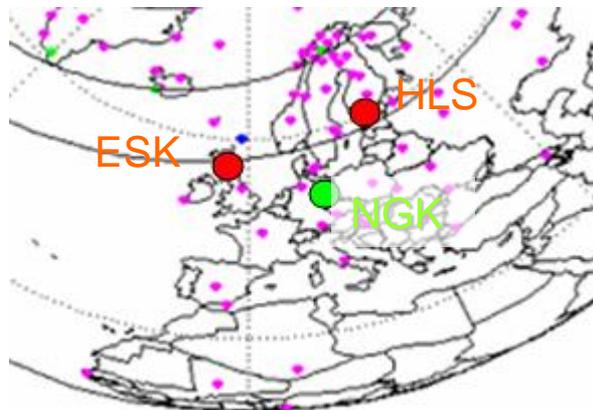
# The Summed Ranges can give us IDV



# Lockwood et al. attempt to use the u-measure from HLS and ESK

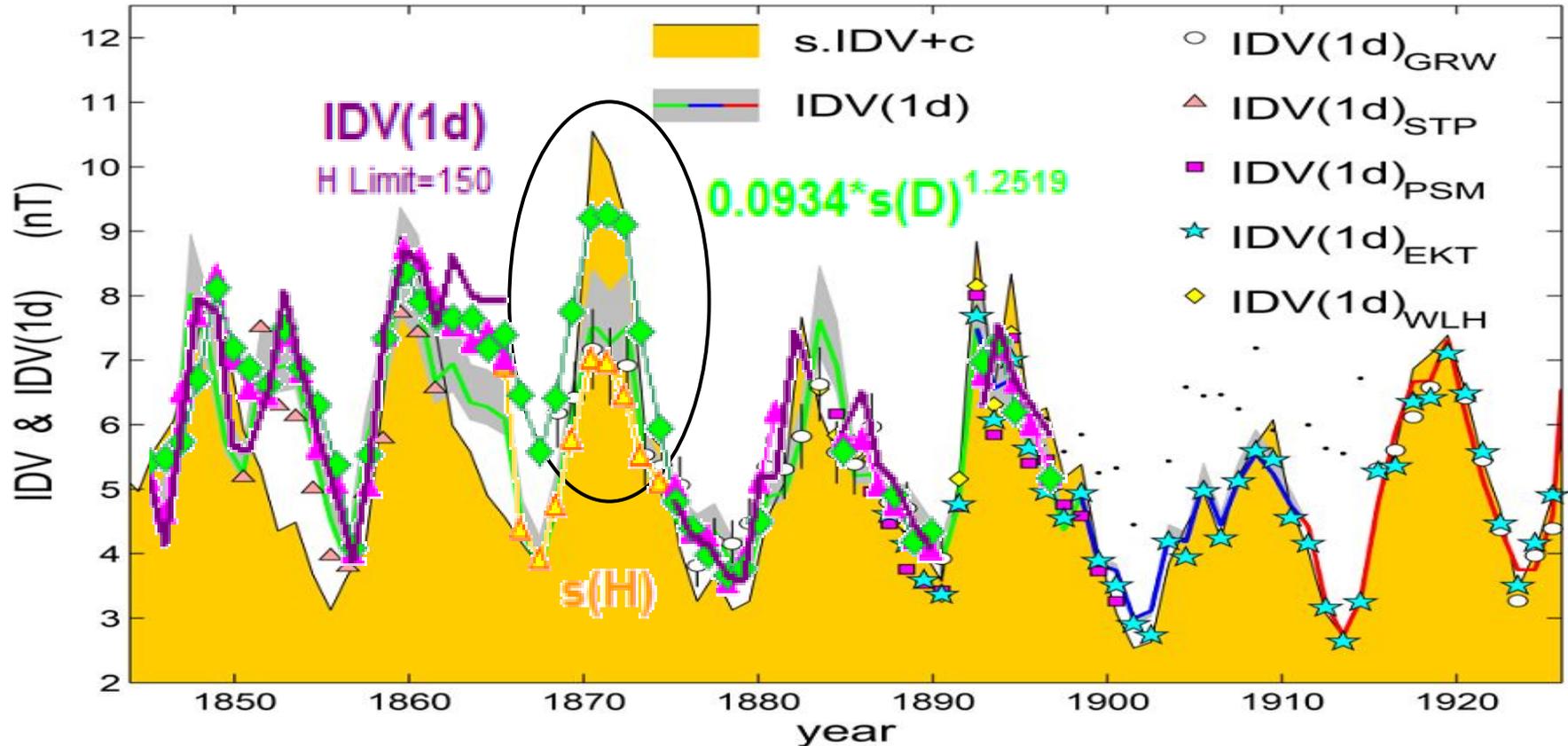


HLS Helsinki



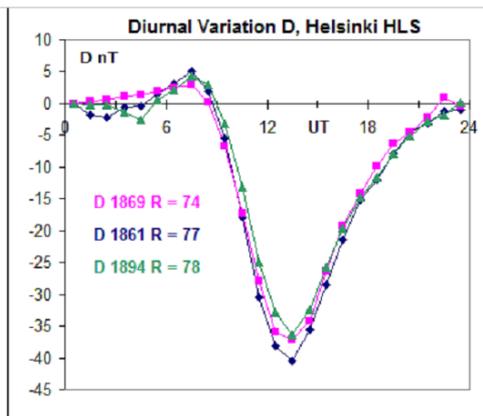
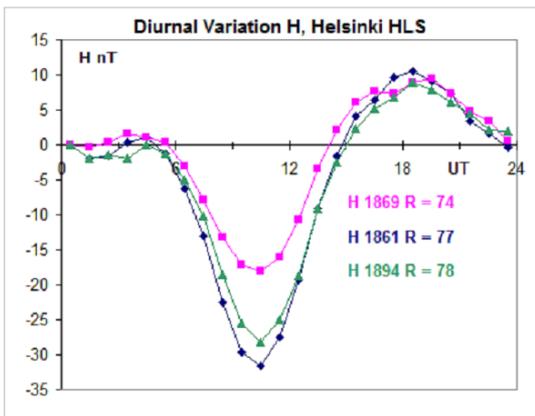
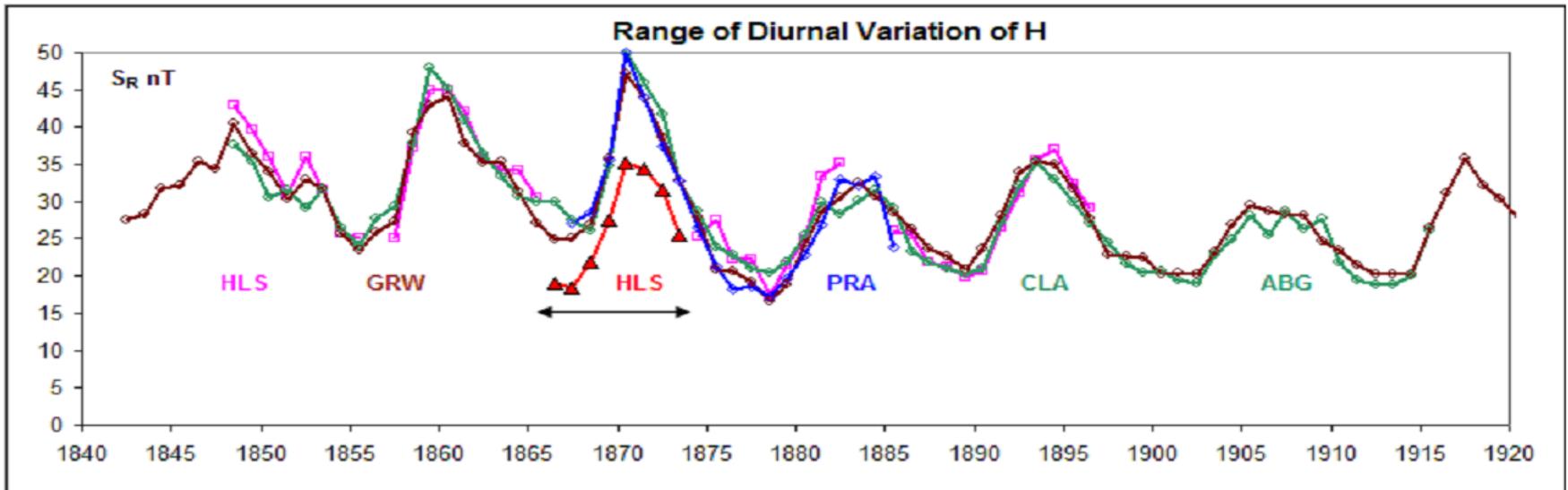
ESK Eskdalemuir 21

Lockwood et al. have also tried to derive IDV or rather  $u$ -measure which they call IDV(1d)



Suitably scaled their reconstruction agrees well with ours, except for solar cycle 11 [oval]. This is due to an error ( $\sim 30\%$ ) in the calibration of H at Helsinki.

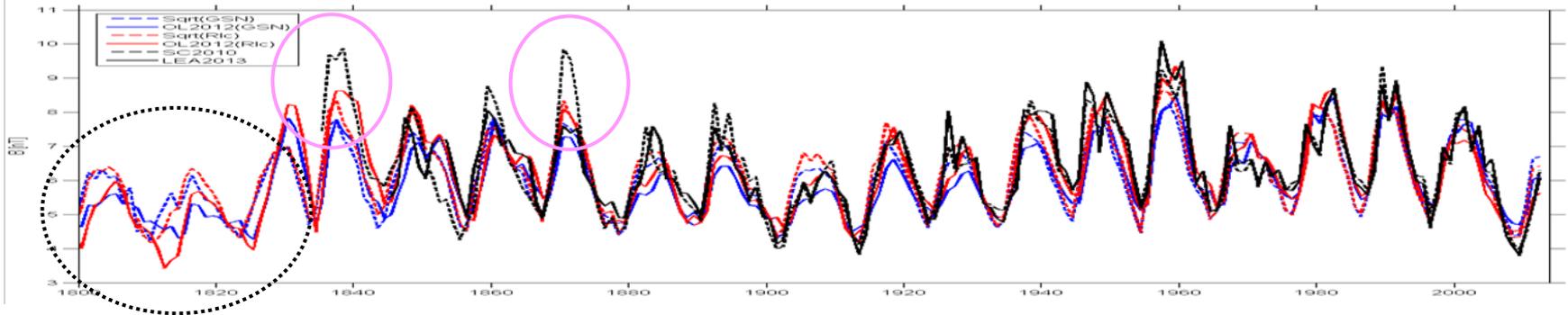
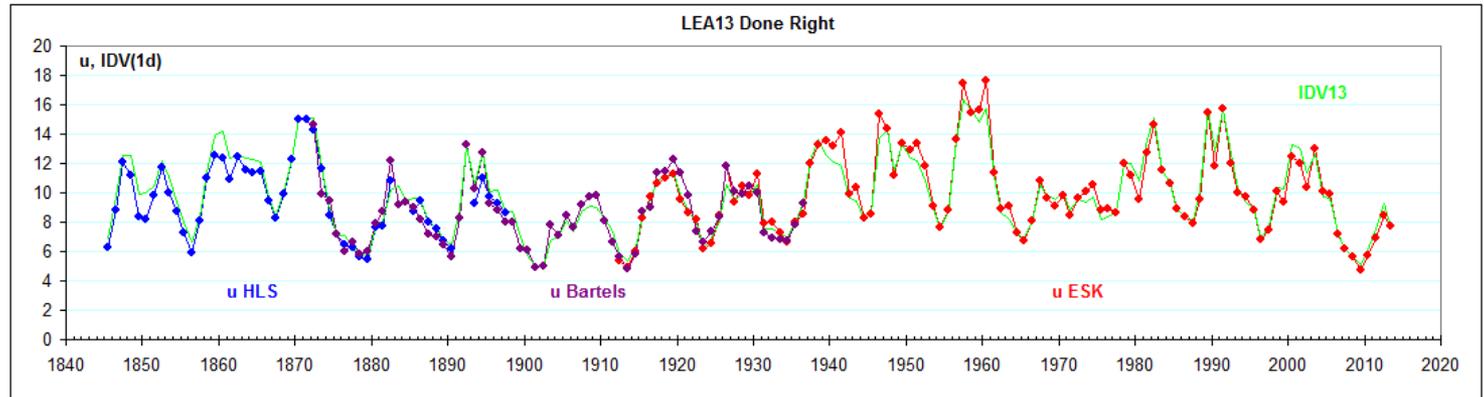
# The Helsinki Calibration Error



Several lines of evidence show that the scale value for H at Helsinki during 1866.0-1874.5 is 32% too small. Perhaps the simplest is comparison with data from other stations.

# The Lockwood et al. construction done Right

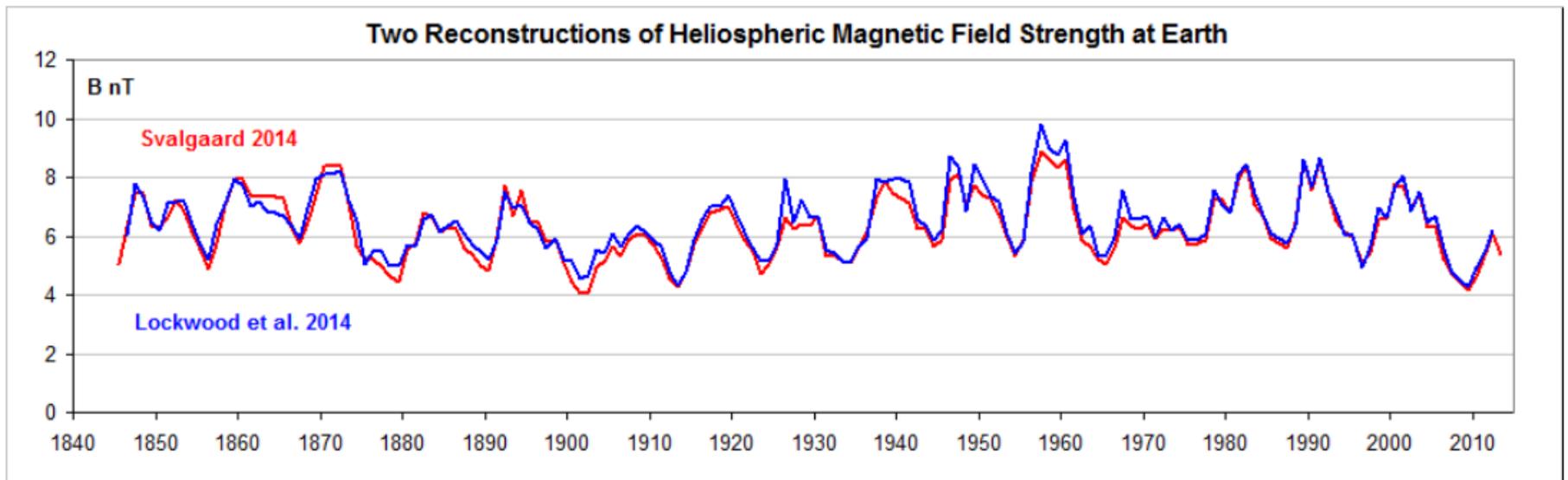
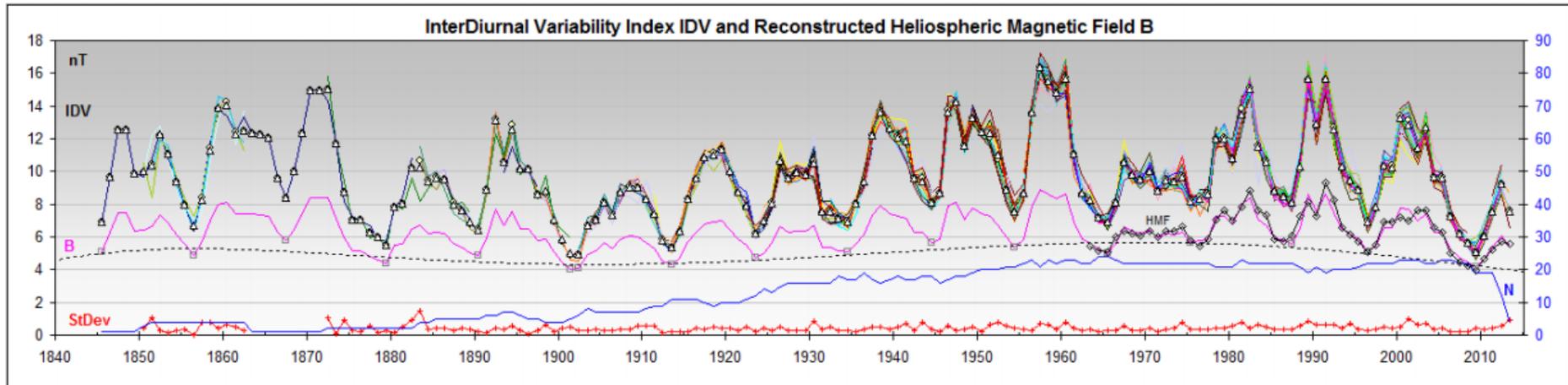
Correcting H  
and making  
the bridge  
using the well-  
determined u-  
measure  
1872-1936



This resolves the problem of cycle 11 making it on par with cycles 21-23.

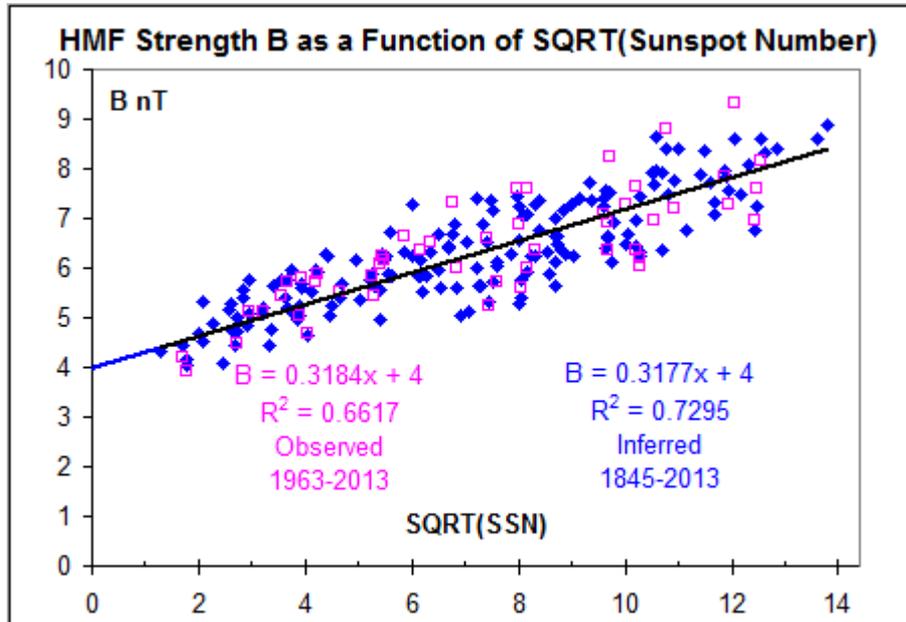
Where do we get the data 1810-1835 from? Next Slide!

# Applying the methods described above we can reconstruct HMF B with Confidence:

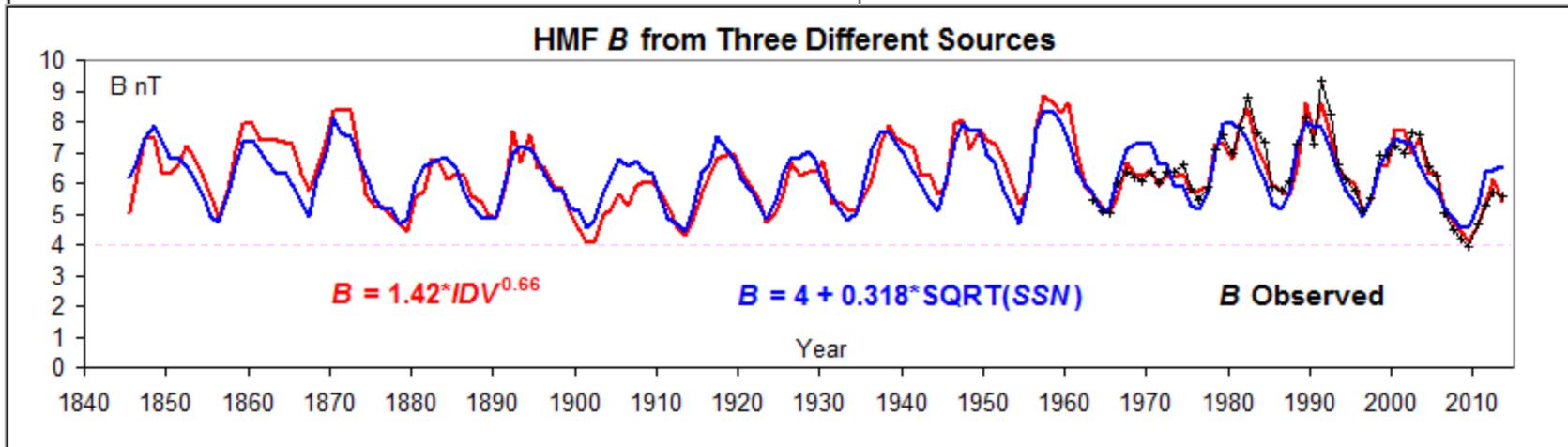


Lockwood et al. have conceded that their finding should be corrected and everybody now agree.

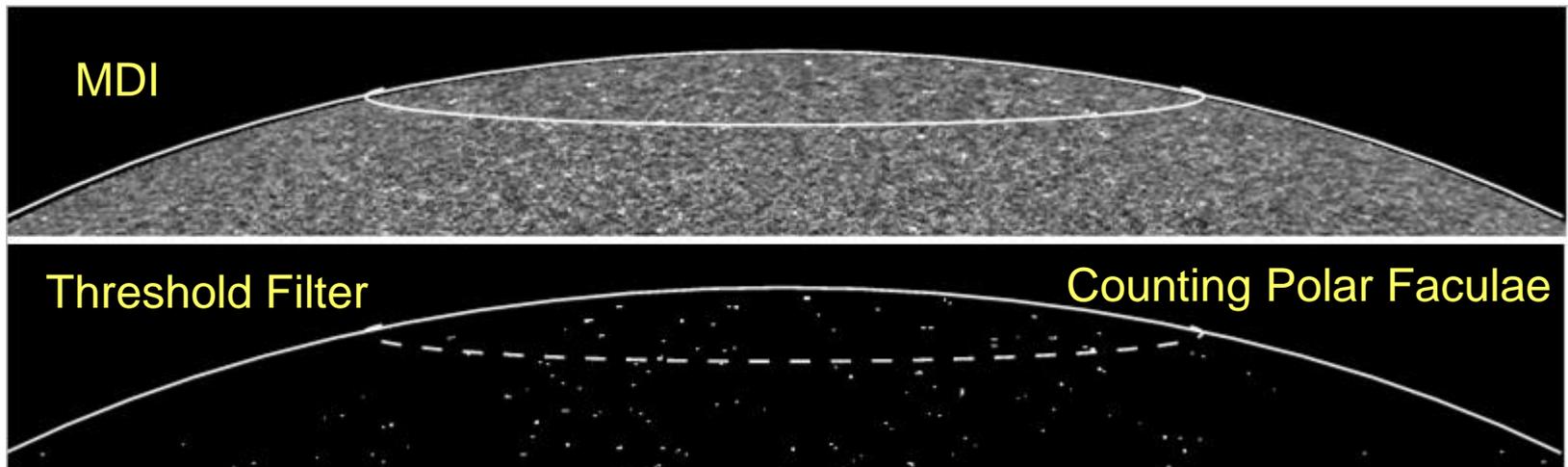
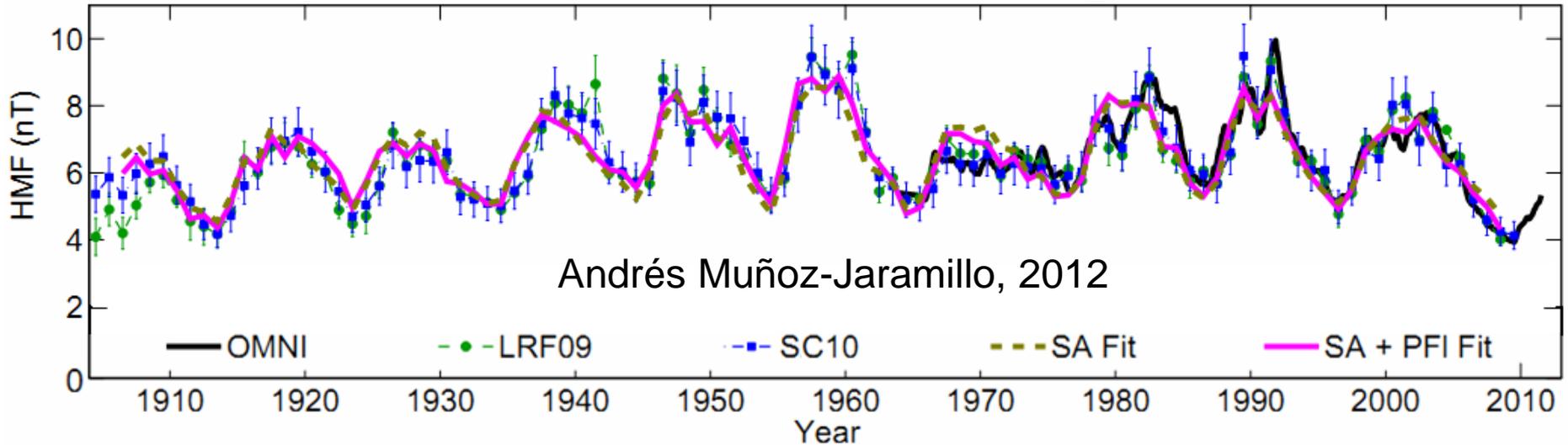
# HMF $B$ related to Sunspot Number



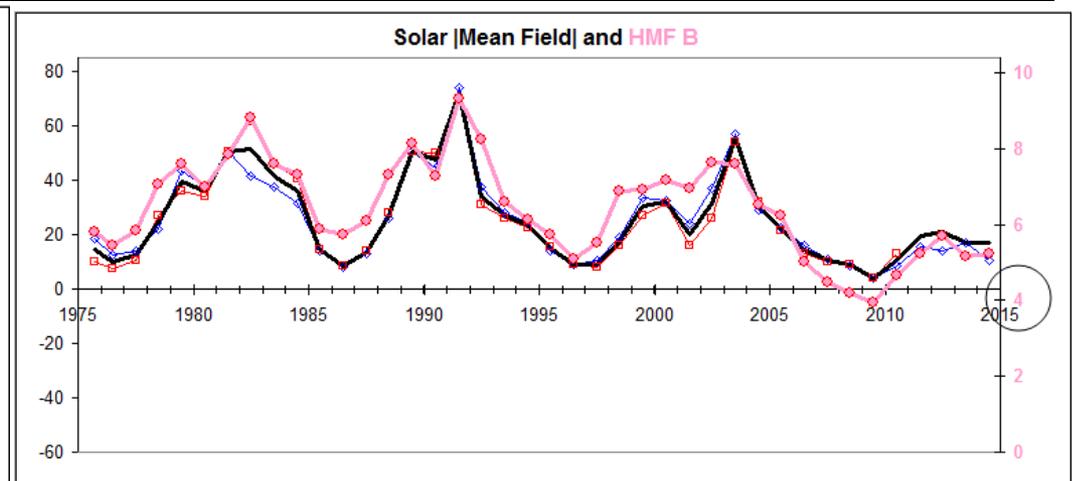
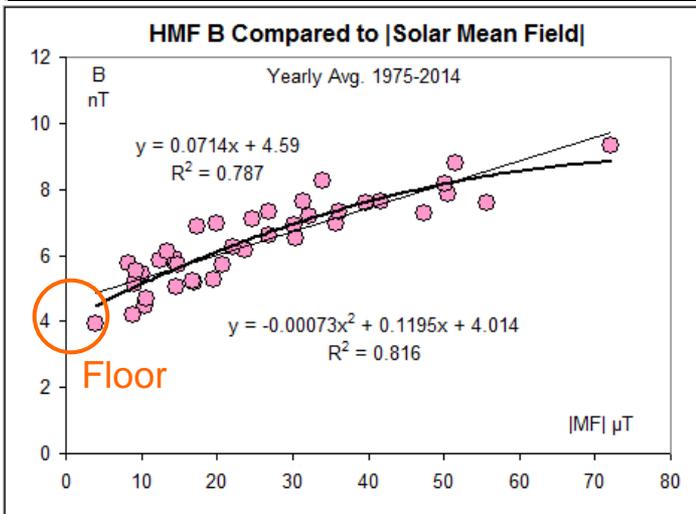
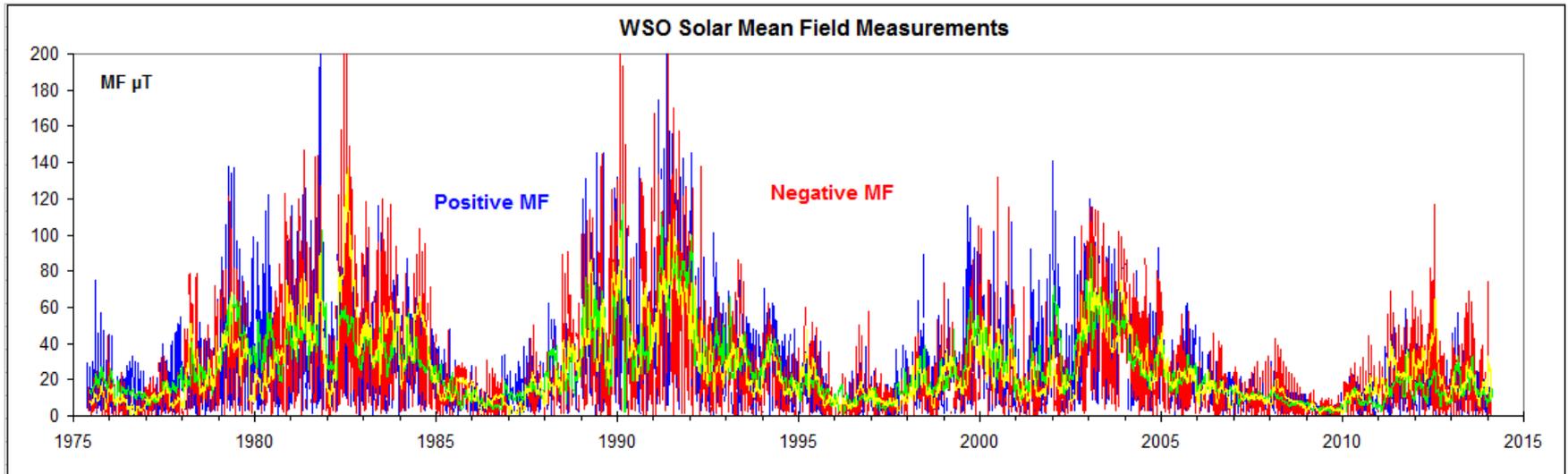
The main sources of the equatorial components of the Sun's large-scale magnetic field are large active regions. If these emerge at random longitudes, their net equatorial dipole moment will scale as the square root of their number. Thus their contribution to the average HMF strength will tend to increase as  $SSN^{1/2}$  (see: Wang and Sheeley [2003]; Wang et al. [2005]).



# Combining Polar Faculae and Sunspot Areas can also give HMF B



# Where does the 'Floor' in HMF B come from? Not from the Mean Field



# Some Conclusions and a Puzzle

- There is now consensus on HMF B back to 1845 with a standard deviation less than 0.5 nT [or 10%].
- B in the 19<sup>th</sup> century was on par with B in the 20<sup>th</sup>. No GRAND Modern maximum
- The 'Open Flux' would likely vary as B
- Solar Magnetism [and thus TSI and related measures] have varied simply as the square root of the Sunspot Number riding on top of a constant floor.
- The Solar Mean Field magnitude scales with the variation of HMF B which is above the Floor.
- Where does the Floor come from?

# Abstract

After C. F. Gauss and W. E. Weber's invention of the Magnetometer in 1833 systematic [e.g. hourly] measurements of the variation of the Earth's magnetic field were begun at several newly erected observatories around the World ["the Magnetic Crusade"]. These observations [greatly expanded] continue to this day. Magnetometers on the first spacecrafts to explore interplanetary space in 1962 showed that the, long hypothesized and then detected, solar wind carried a measurable magnetic field, which was soon identified as the main driver of disturbances of the magnetic fields observed at the Earth. Vigorous research during the last decade has shown that it is possible to 'invert' the causative effect of the magnetic field in near-Earth interplanetary space [the near-Earth Heliospheric Magnetic Field] and to infer with good accuracy the value of that field [and also of the solar wind speed and density] from the observed magnetic changes measured at the surface of the Earth. In this talk we describe the remarkable consensus reached by several researchers of the variation of the Heliospheric Magnetic Field (and thus of its source: the solar magnetic field) since the 1830s to today. We discuss solar cycle 24 in that long-term context.