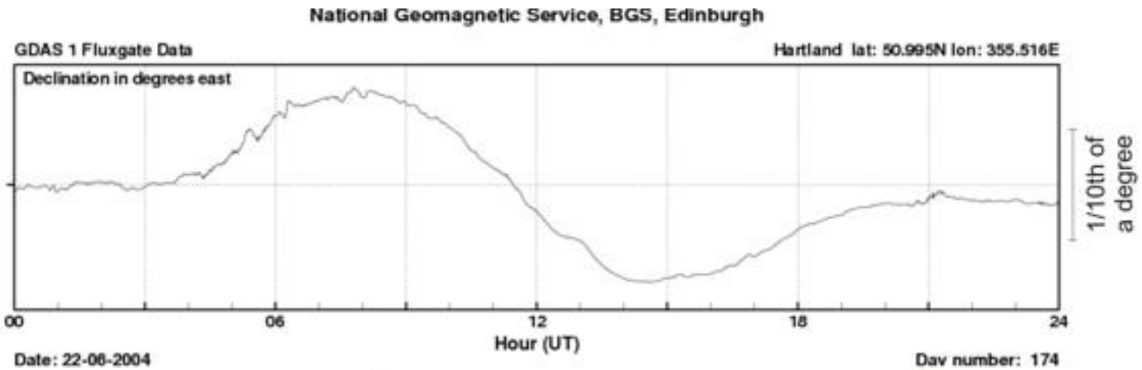
Reconstruction of Solar EUV Flux 1781-2014

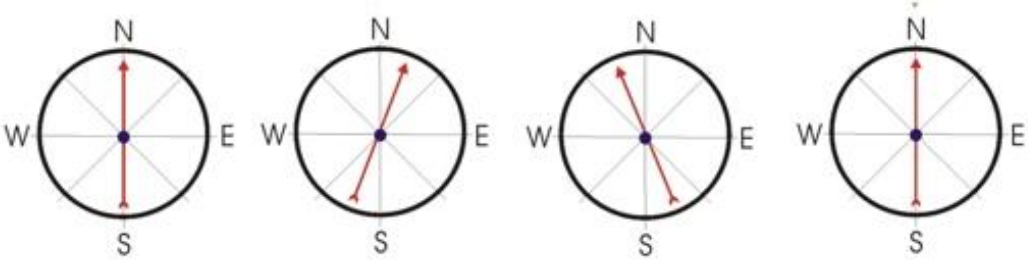
Leif Svalgaard

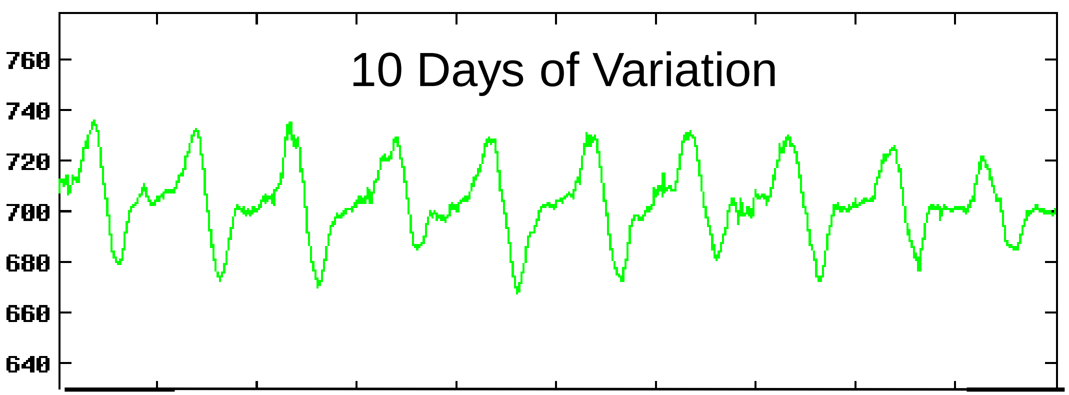
Stanford University

EGU, Vienna, April 2015

The Diurnal Variation of the Direction of the Magnetic Needle



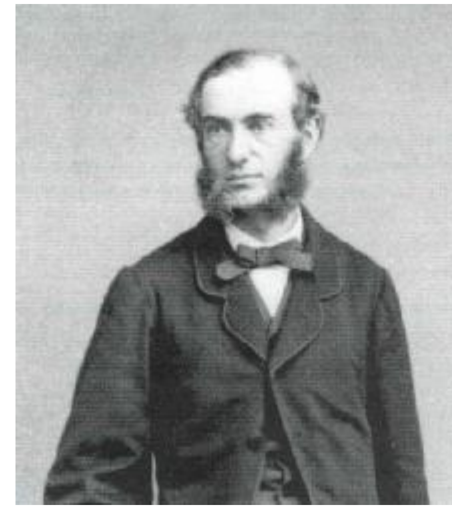




George Graham [London] discovered [1722] that the geomagnetic field varied during the day in a regular manner.

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

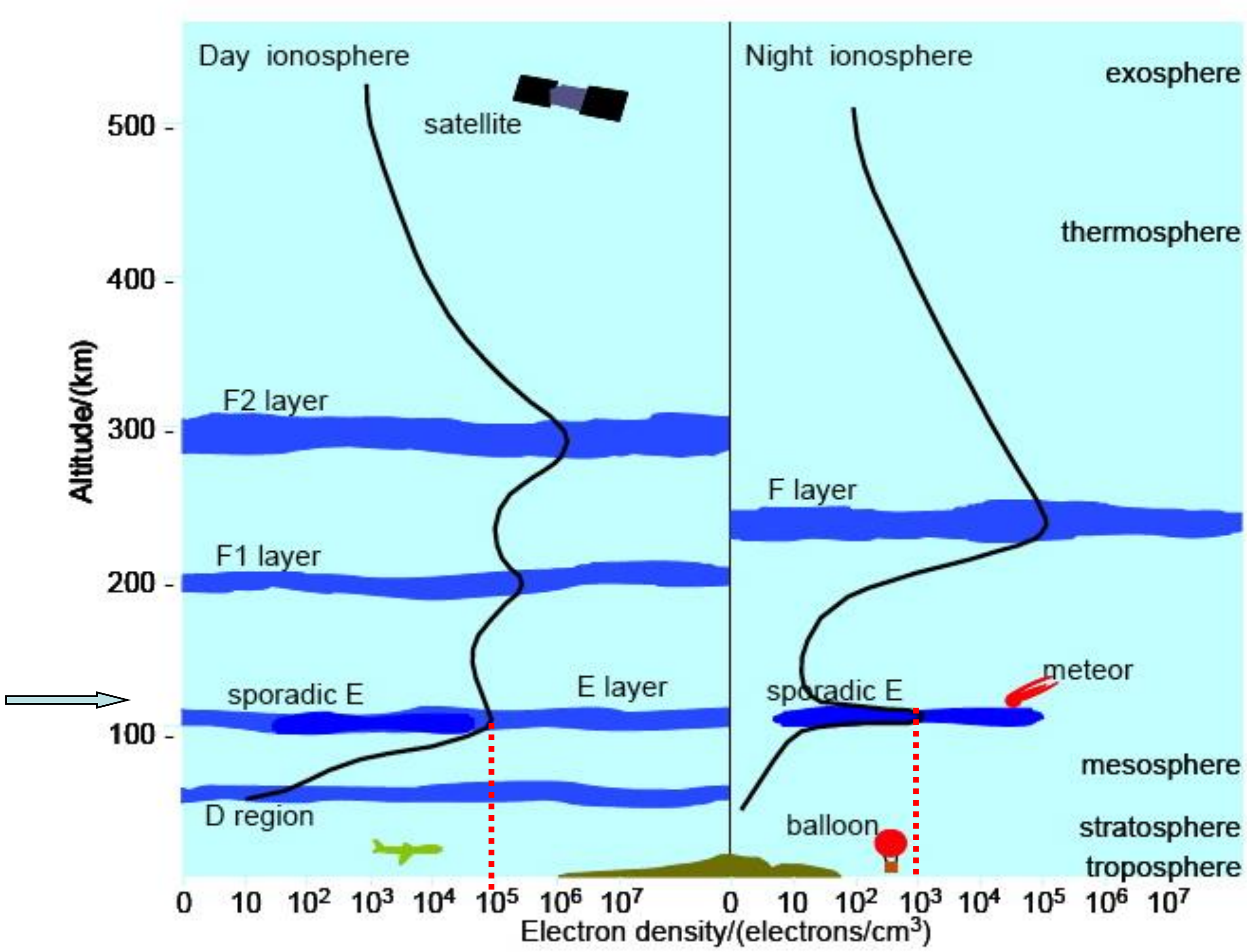
"The various speculations on the cause of these phenomena [daily variation of the geomagnetic field] have ranged over the whole field of likely explanations. (1) […], (2) It has been imagined that convection currents established by the sun's heating influence in the **upper regions of the atmosphere are to be regarded as conductors moving across lines of magnetic force, and are thus the vehicle of electric currents which act upon the magnet**, (3) […], (4) […].



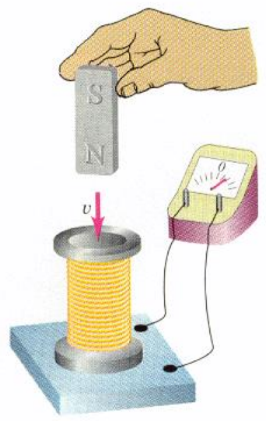
Balfour Stewart
1828-1887

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

Ionospheric Layers



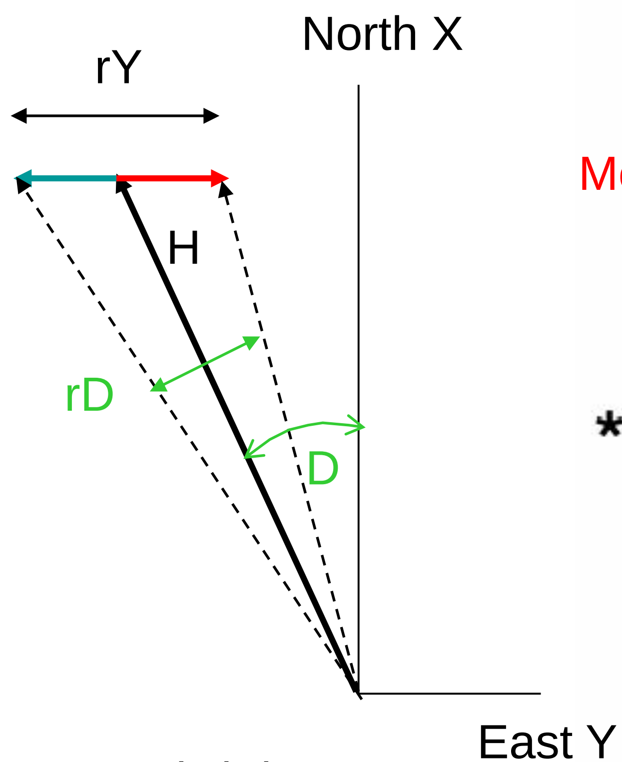
Dynamo



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

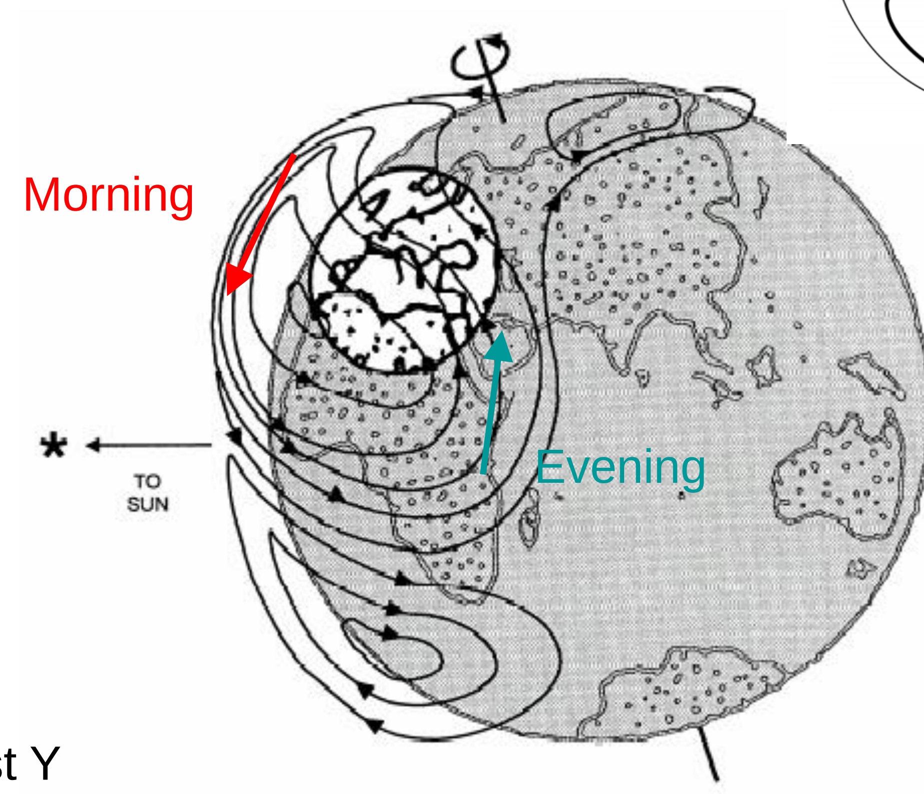
We thus expect the geomagnetic response due to electric currents induced in the E-layer.

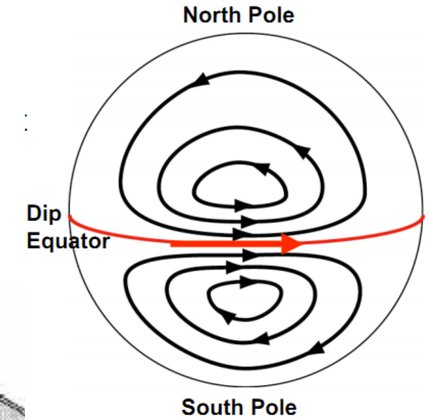
The E-layer Current System



$Y = H \sin(D)$

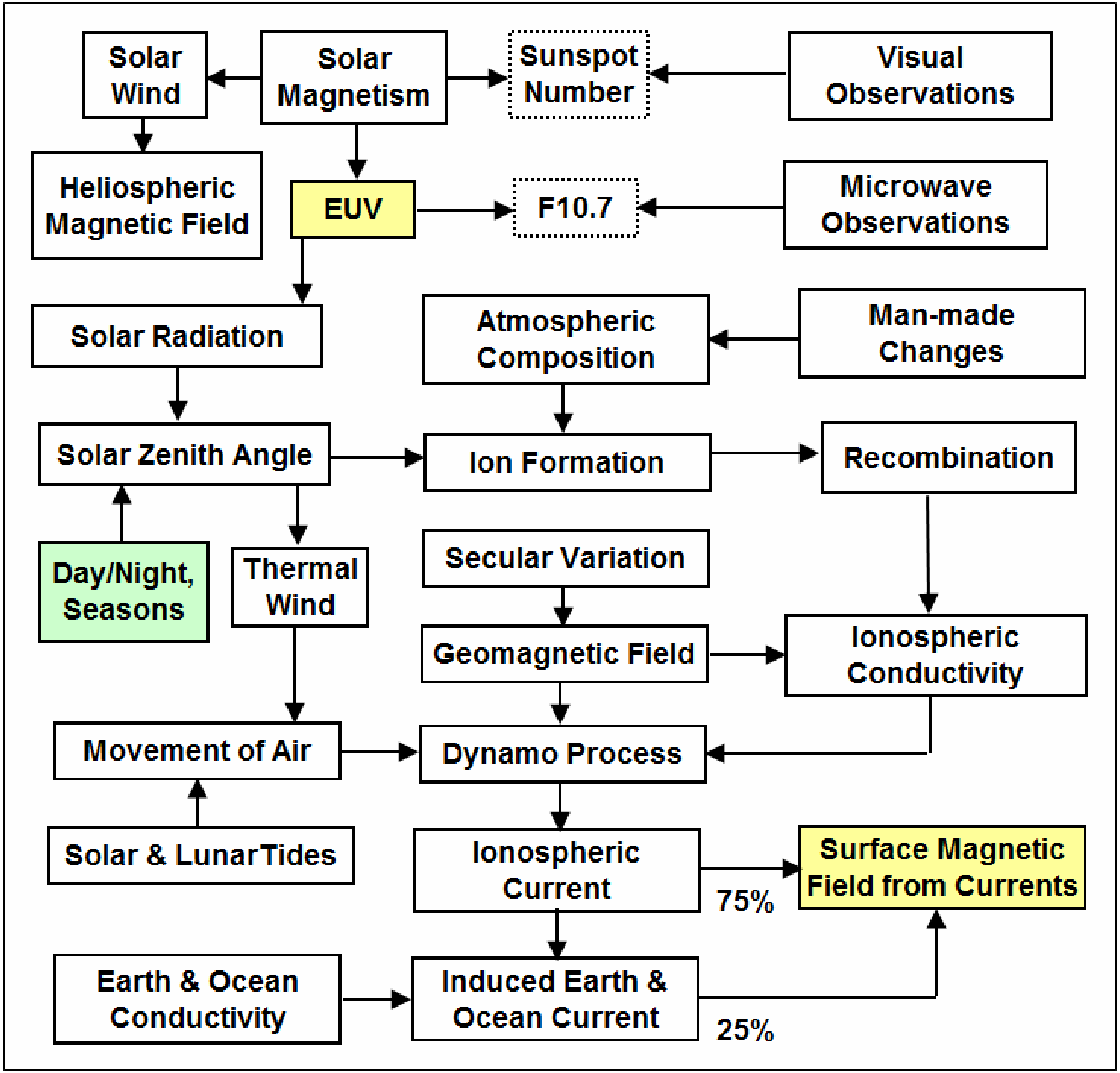
$dY = H \cos(D)\, dD$ For small dD





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

The magnetic effect of this system was what George Graham discovered



The Physics

With the possible exception of the 'solar boxes' the physics of the rest of the boxes is well-understood

We'll be concerned with deriving the EUV flux from the observed diurnal variation of the geomagnetic field

Electron Density due to EUV

< 102.7 nm

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

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

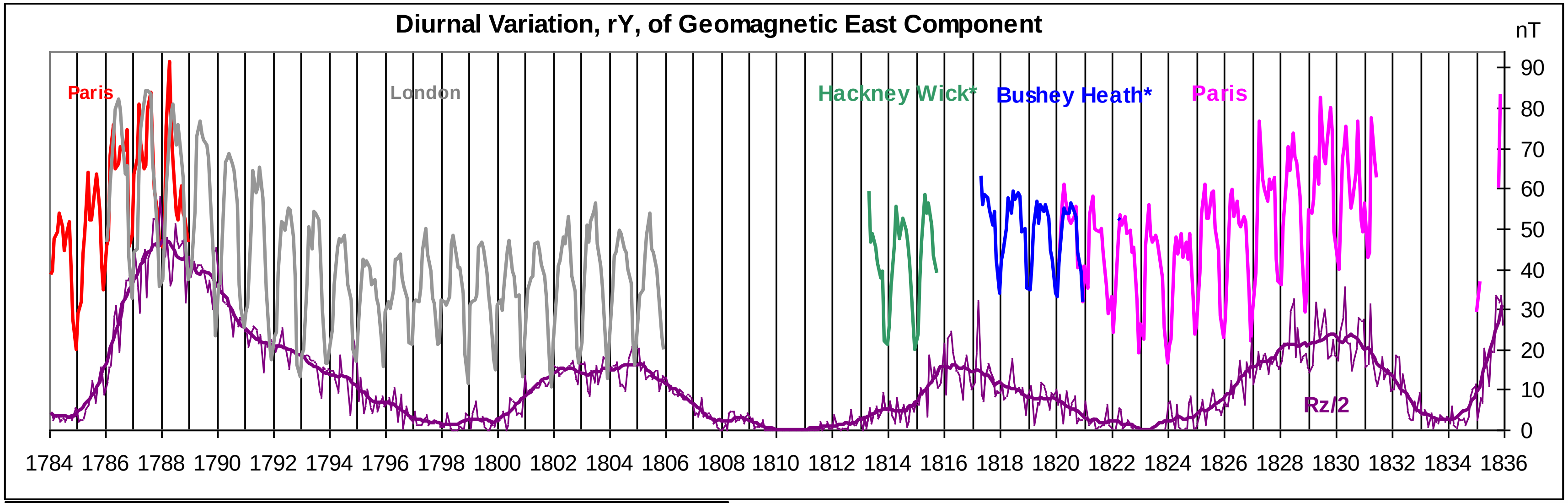
The conductivity at a given height is proportional to the electron number density N_e. In the dynamo region the ionospheric plasma is largely in photochemical equilibrium. The dominant plasma species is $O^+{}_2$, which is produced by photo ionization at a rate J (s^{-1}) and lost through recombination with electrons at a rate α (s^{-1}), producing the Airglow.

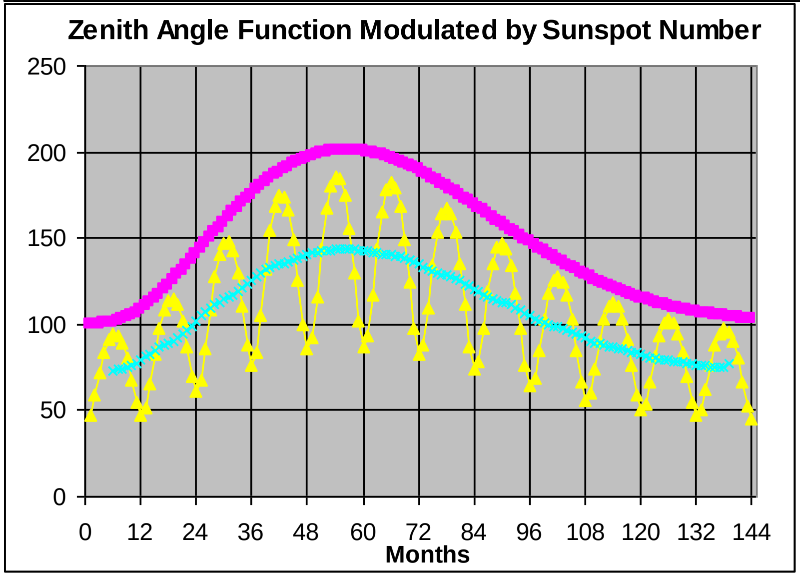
The rate of change of the number of ions N_i, dN_i/dt and in the number of electrons N_e, dN_e/dt are given by $dN_i/dt = J \cos(\chi) - \alpha N_i N_e$ and $dN_e/dt = J \cos(\chi) - \alpha N_e N_i$. Because the Zenith angle χ changes slowly we have a quasi steady-state, in which there is no net electric charge, so $N_i = N_e = N$. In a steady-state $dN/dt = 0$, so the equations can be written $0 = J \cos(\chi) - \alpha N^2$, and so finally

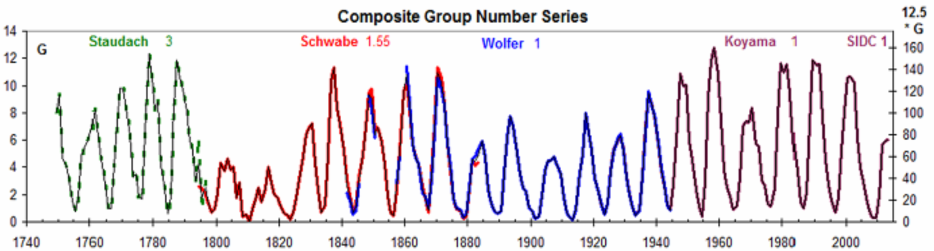
$$N = \sqrt{(J \alpha^{-1} \cos(\chi))}$$

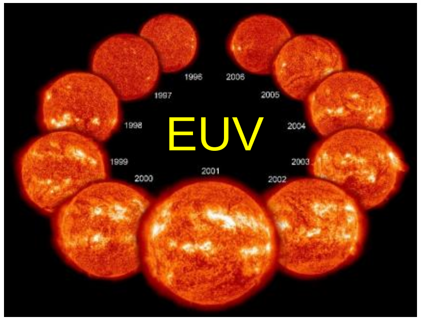
Since the conductivity, Σ, depends on the number of electrons N, we expect that Σ scales with the square root $\sqrt{(\boldsymbol{J})}$ of the overhead EUV flux with $\lambda < 102.7$ nm.

Solar Cycle and Zenith Angle Control





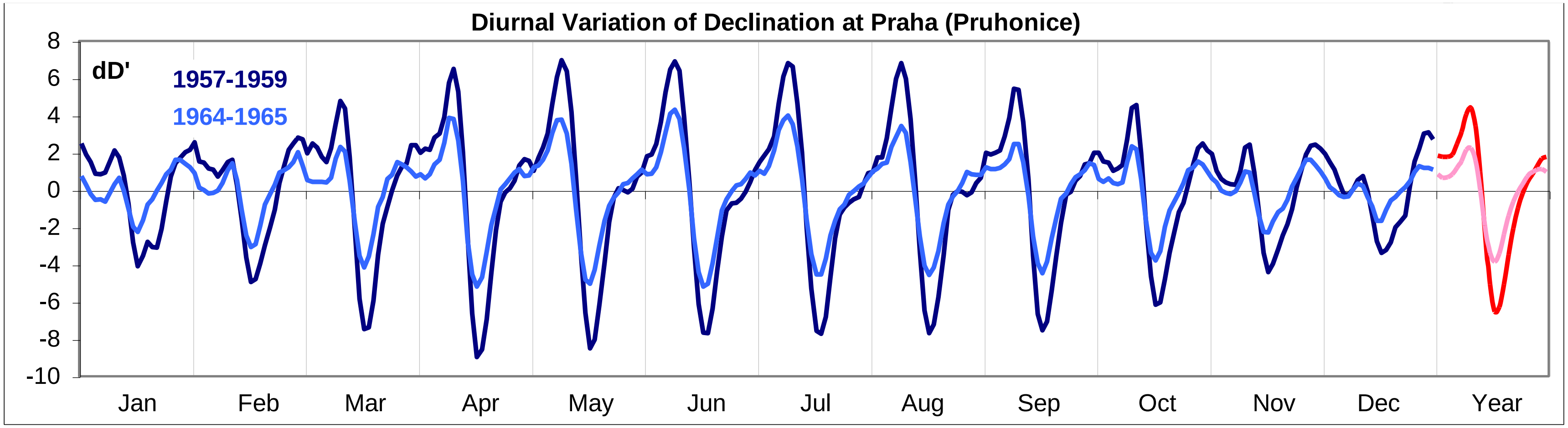


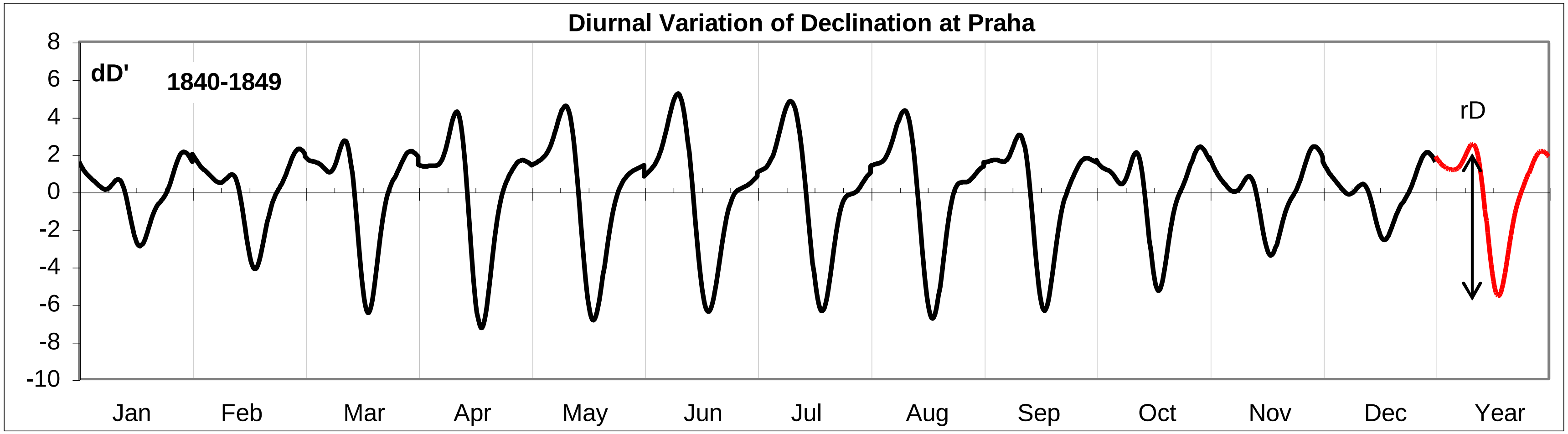


Johann Rudolf Wolf, 1852

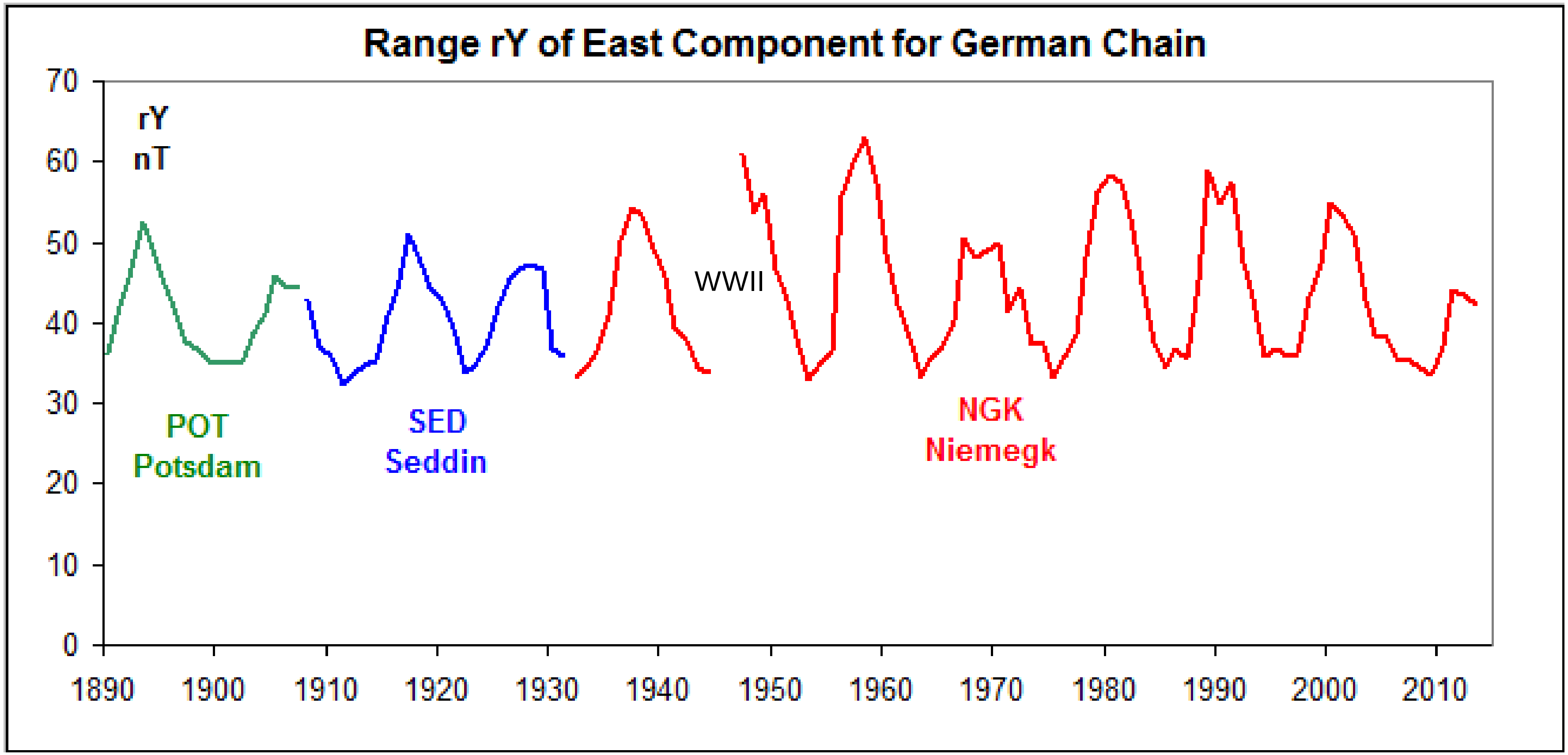
+ J-A. Gautier

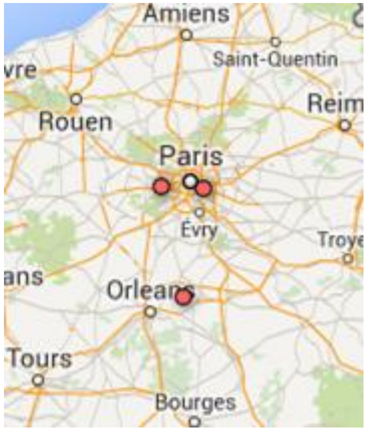
The Diurnal Variation of the Declination for Low, Medium, and High Solar Activity



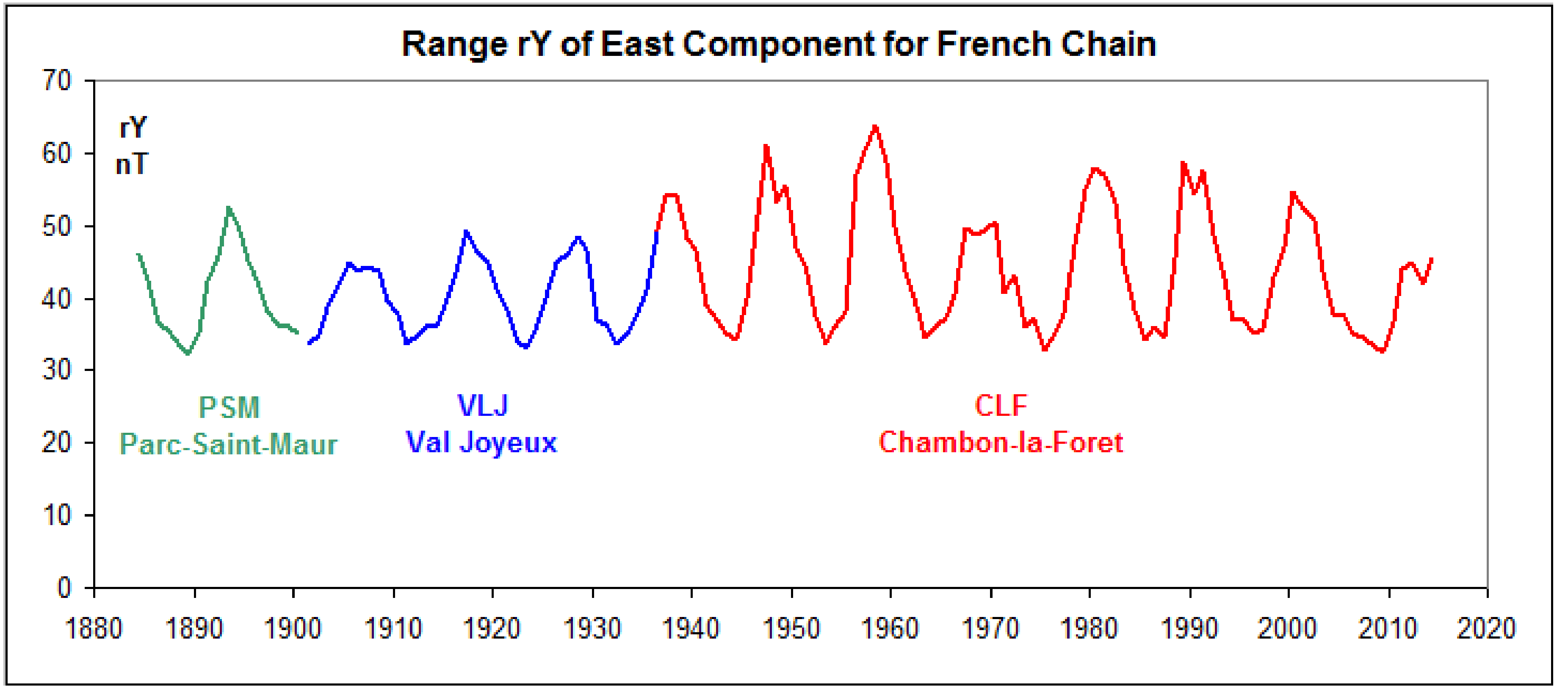


POT-SED-NGK 1890-2013

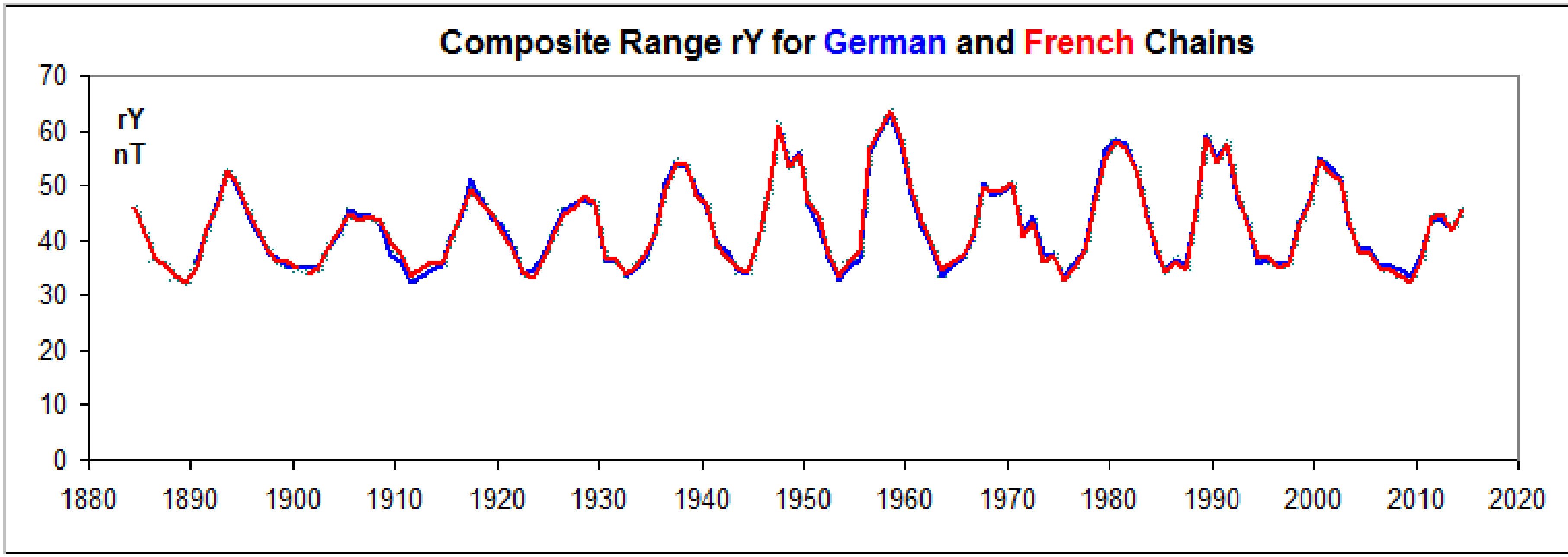




PSM-VLJ-CLF
1884-2014

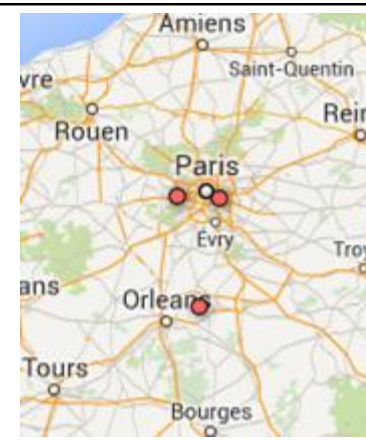


PSM-POT-VLJ-SED-CLF-NGK

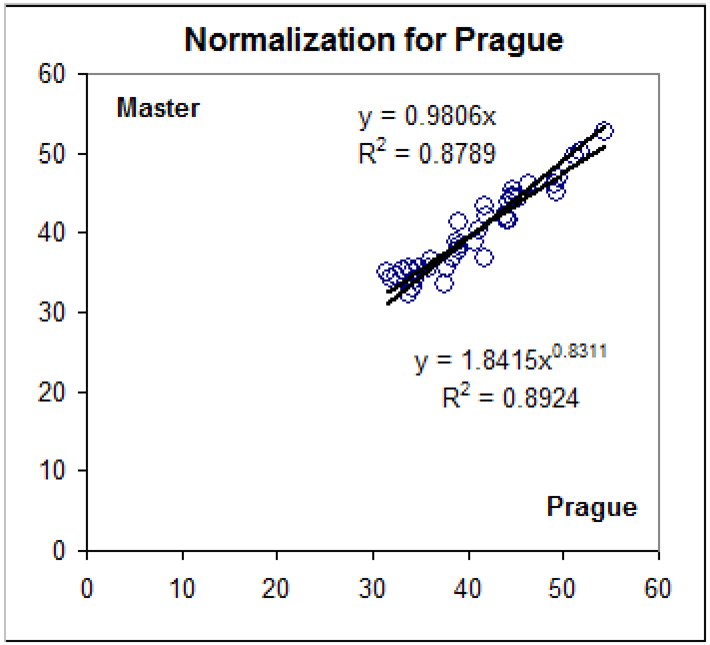


A 'Master' record can now be build by averaging the German and French chains.

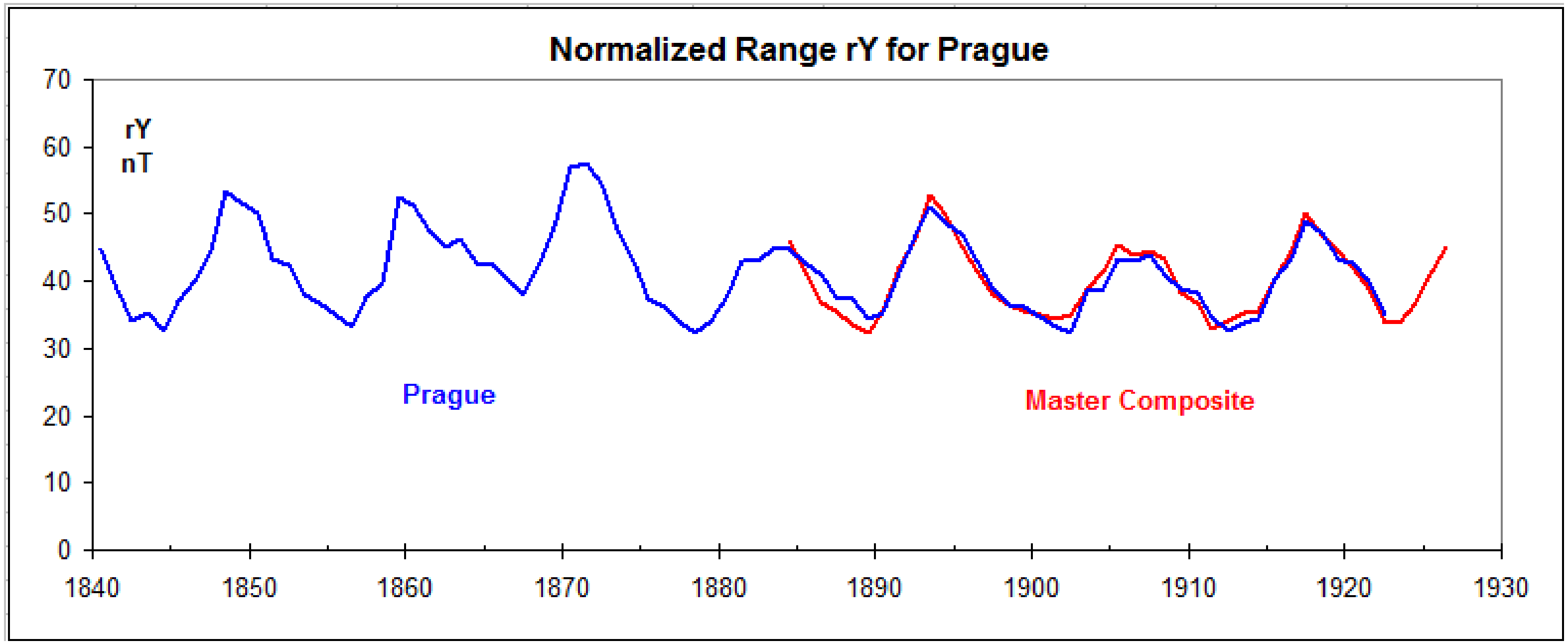
We shall normalize all other stations to this Master record.

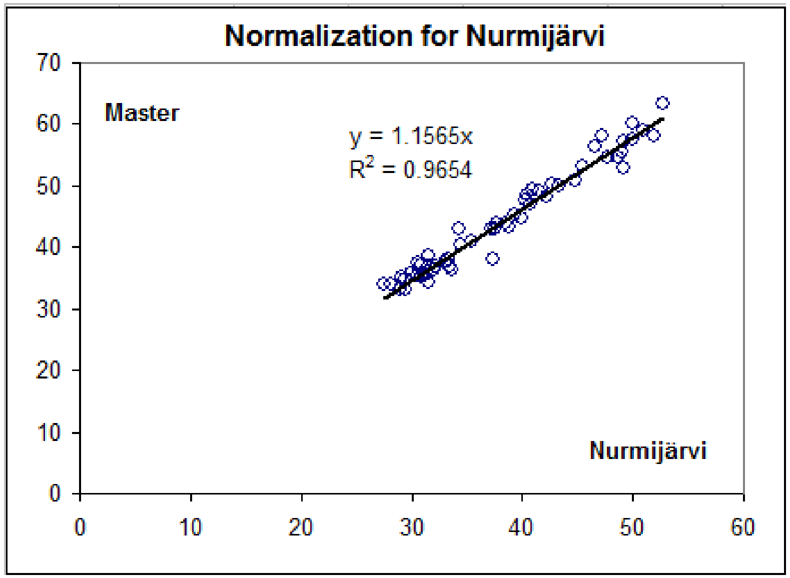


Adding Prague back to 1840

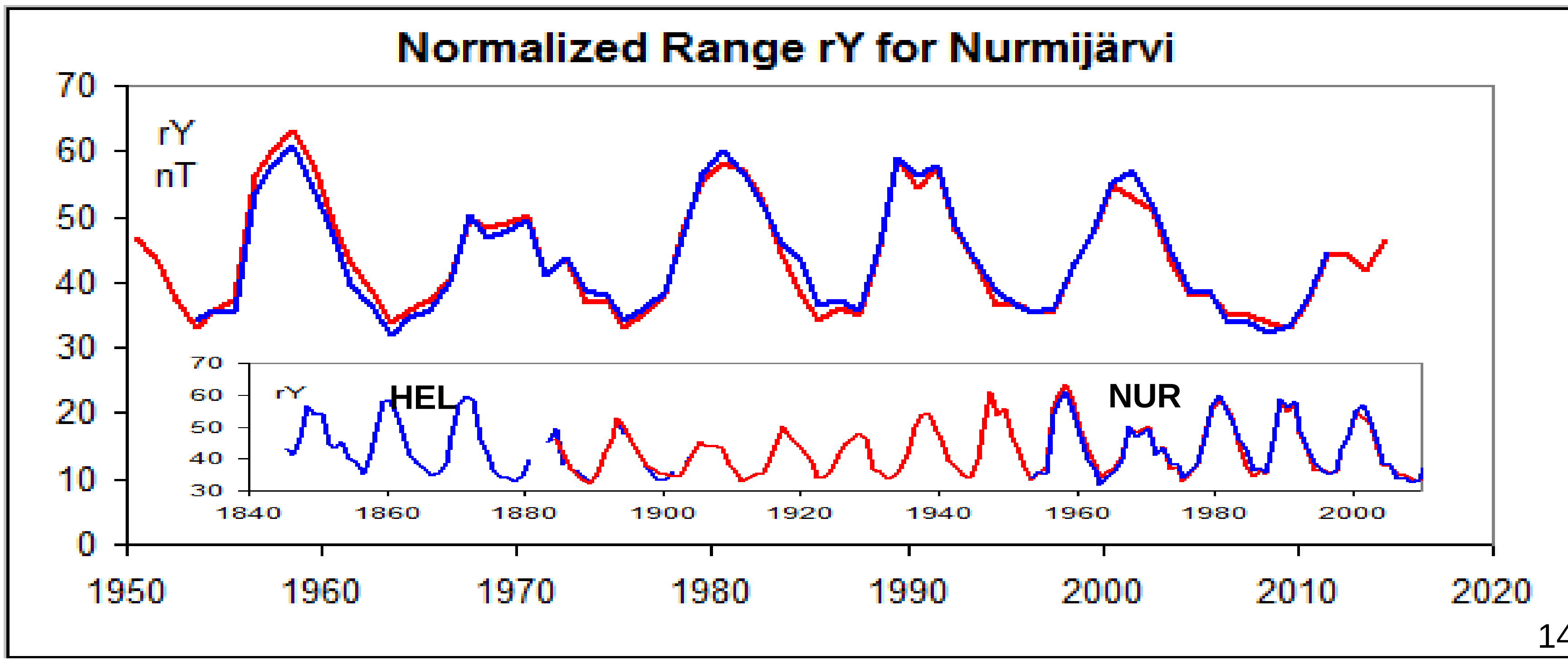


If the regression against the Master record is not quite linear, a power law is used.



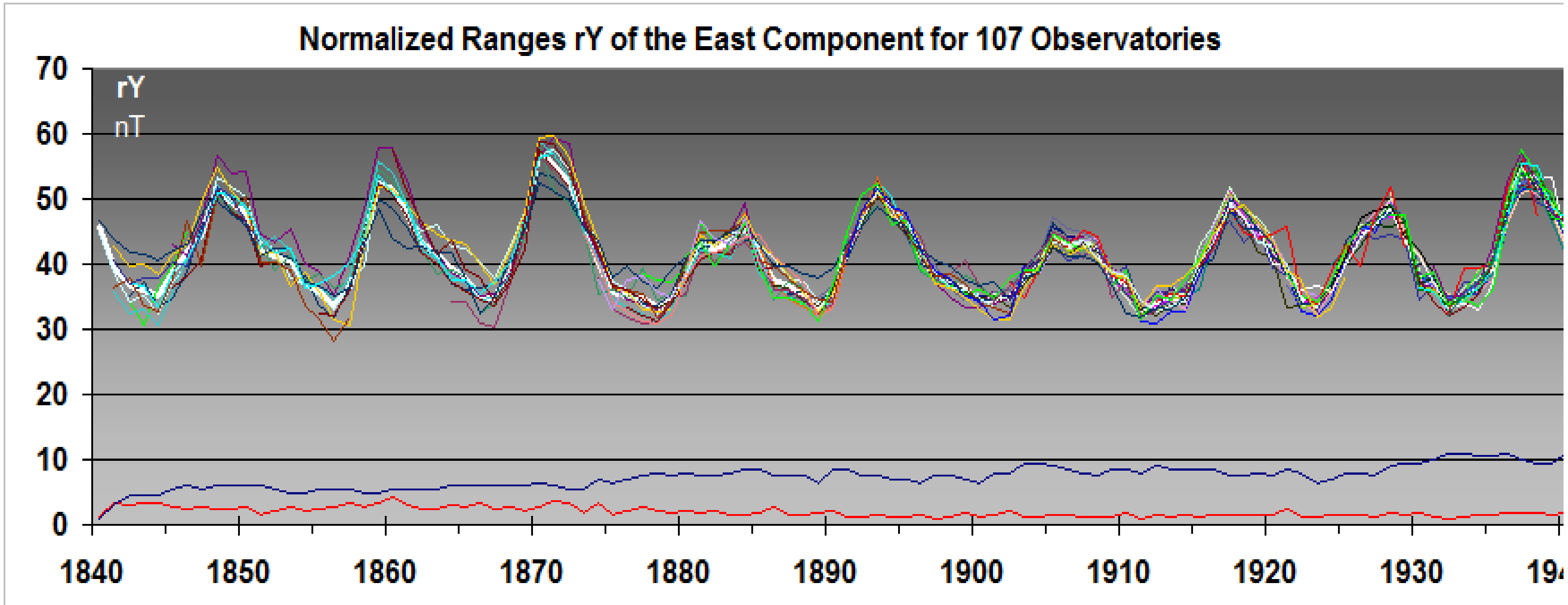


Adding Helsinki replacement observatory Nurmijärvi

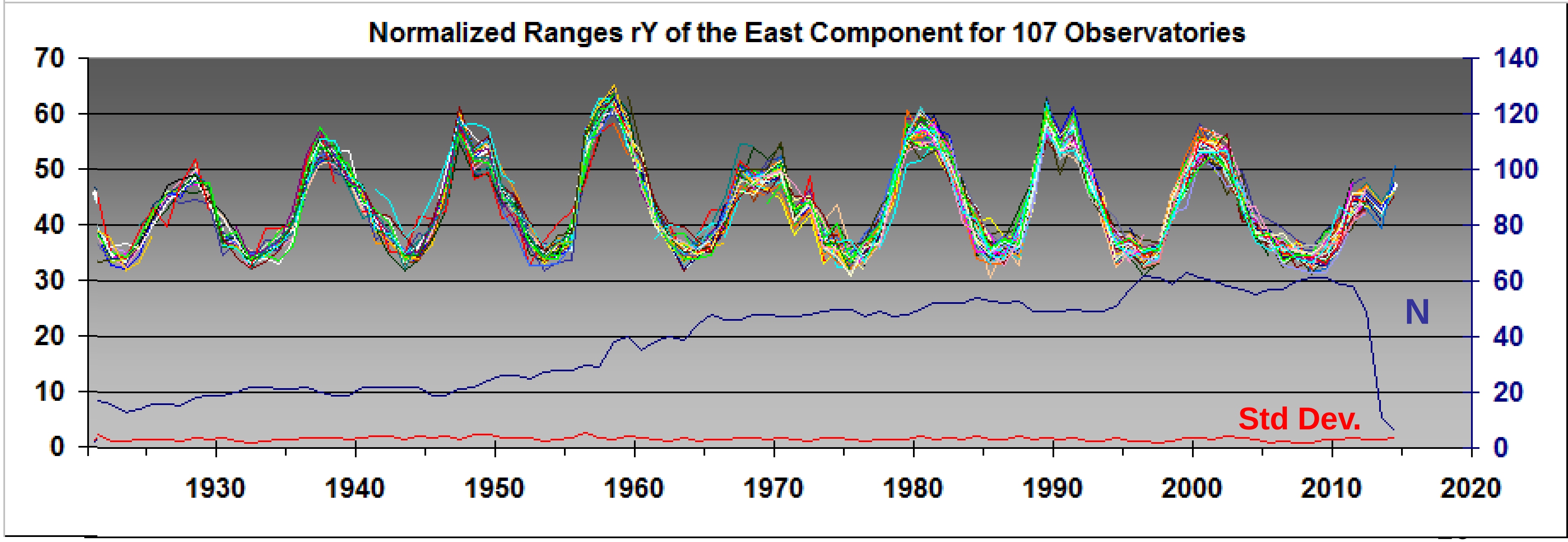


And So On: For 107 Geomagnetic Observatories with Good Data

POT	COI	WIK	BSL	DBN	VAL
SED	WNG	AAA	TOR	WIT	VIC
NGK	TOK	ARS	MON	FUR	YAK
PSM	HRB	ASP	AML	WLH	SPE
VLJ	TOO	BDV	AQU	EKT	MIL
CLF	WAT	BEL	BTV	BAL	BER
KAK	SIT	BJI	PET	OSL	TFS
ESK	SSH	BOU	ROM	CLA	MBO
HLS	PIL	BOX	EYR	ABG	CBI
NUR	LOV	SFS	FRN	WIE	LRM
CLH	RSV	CDP	GNA	GRW	NVS
FRD	BFE	CNB	HLP	MNH	PAG
HON	HER	CTA	EBR	KLT	PPT
TUC	SVD	HBK	MIZ	GEN	PST
VQS	AGN	ISK	GCK	MNK	THY
SJG	OTT	LNN	IRT	KNZ	STJ
ABN	HBT	TAM	JAI	DOU	CZT
HAD	PRA	MMB	LER	LVV	

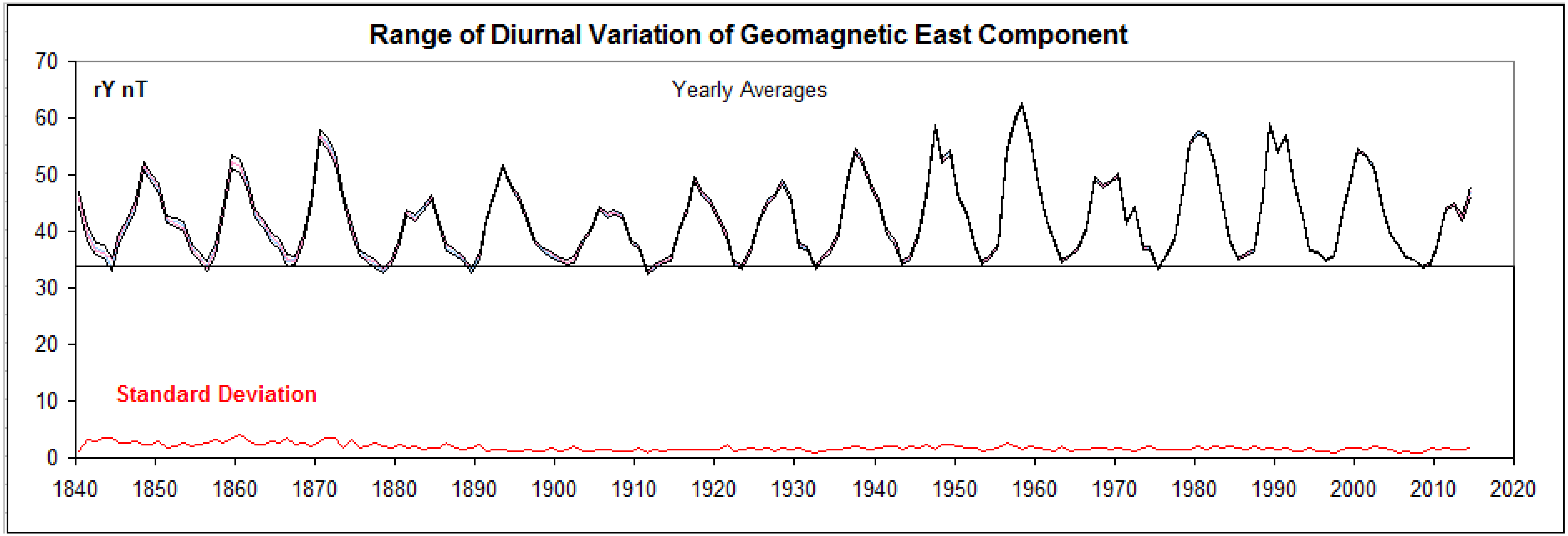


Normalized Ranges rY of the East Component for 107 Observatories
rY
nT
70
60
50
40
30
20
10
0
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930



Normalized Ranges rY of the East Component for 107 Observatories
70
60
50
40
30
20
10
0
140
120
100
80
60
40
20
0
N
Std Dev.
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

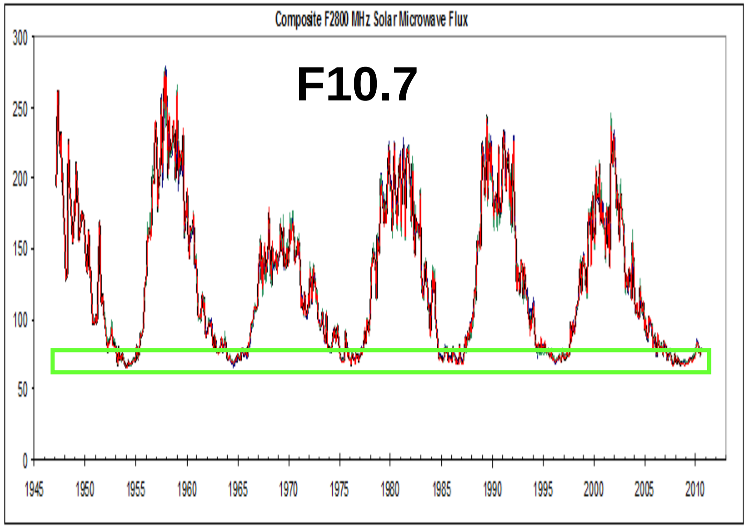
Composite *rY* Series 1840-2014



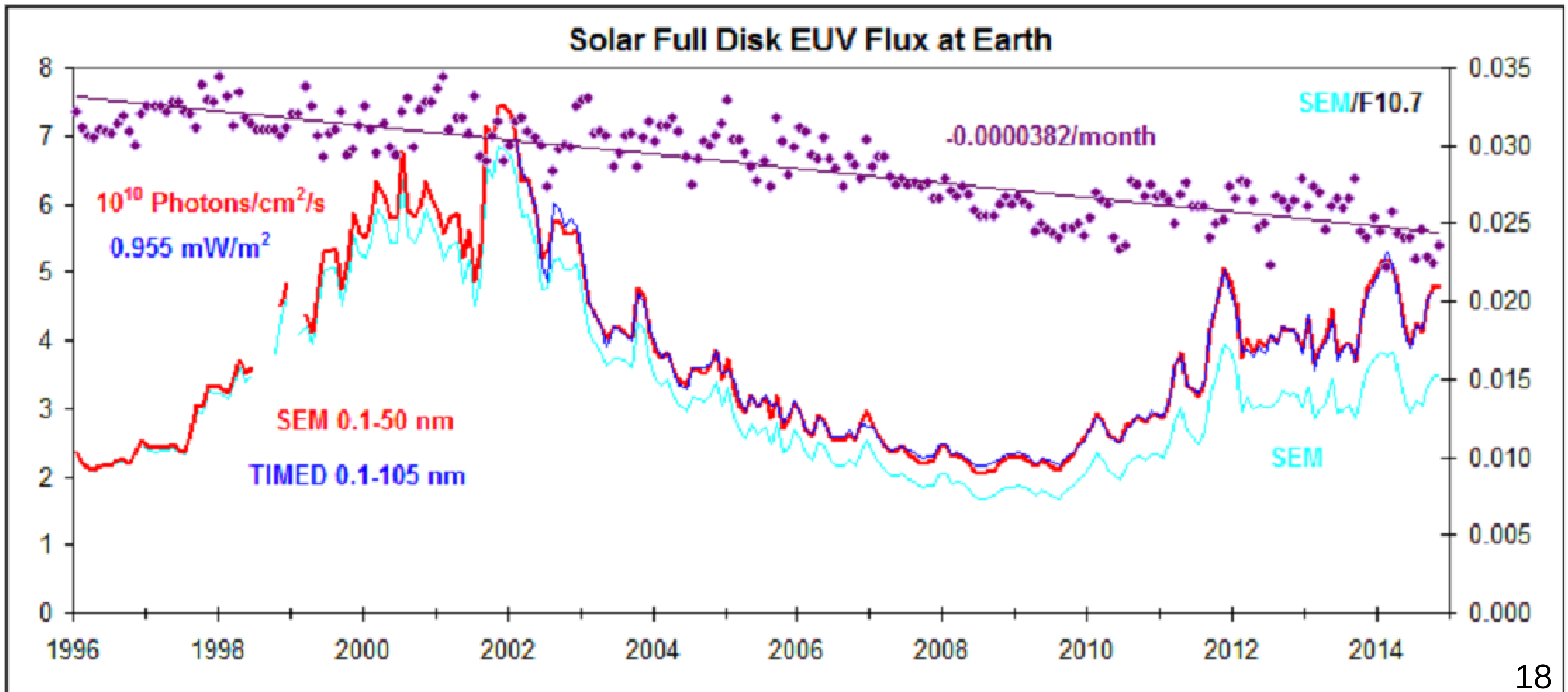
From the Standard Deviation and the Number of Station in each Year we can compute the Standard Error of the Mean and plot the ±1-sigma envelope.

Of note is the constancy of the range at every sunspot minimum

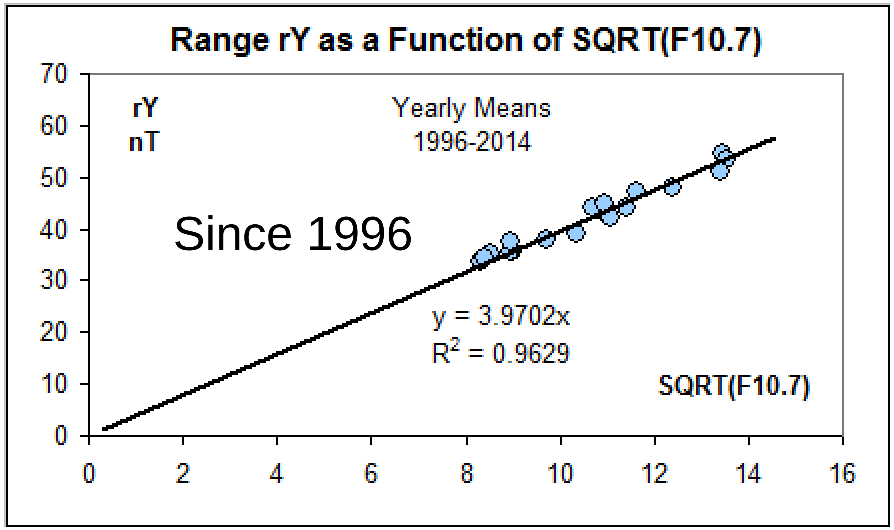
EUV and its proxy: F10.7 Microwave Flux

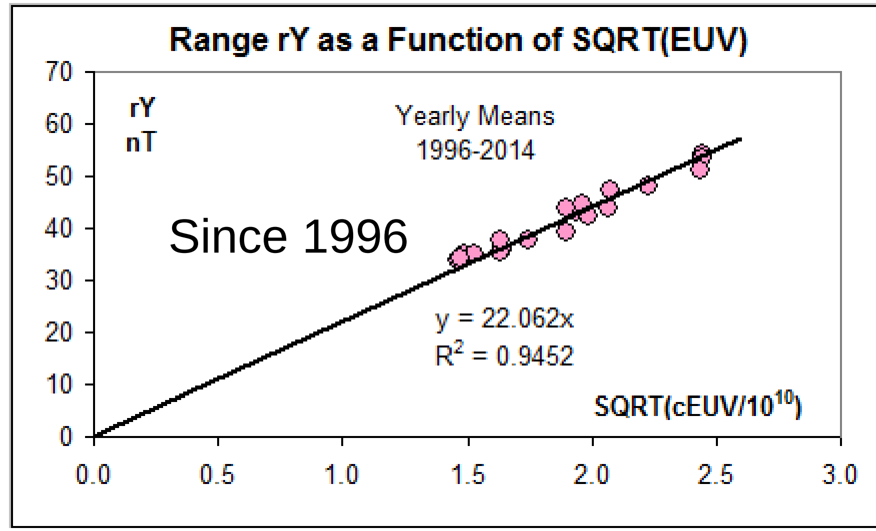


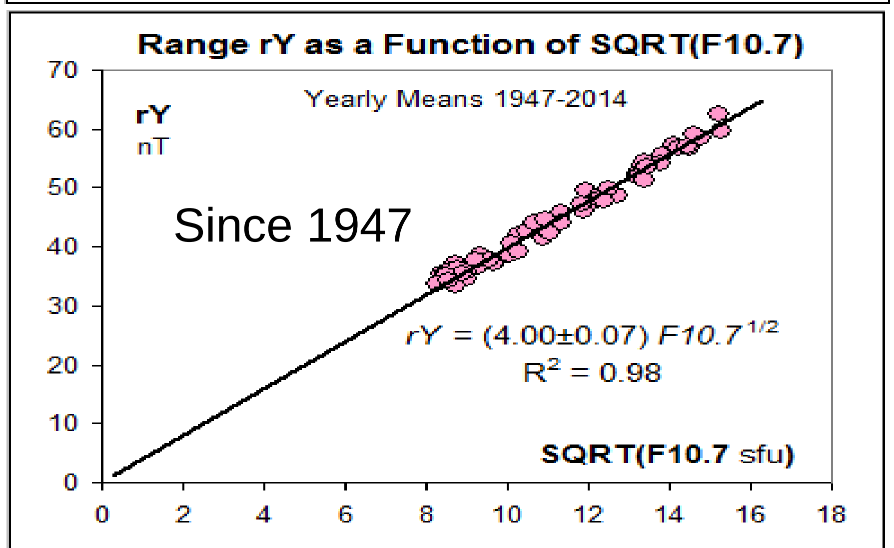
Space is a harsh environment:
Sensor Degradation

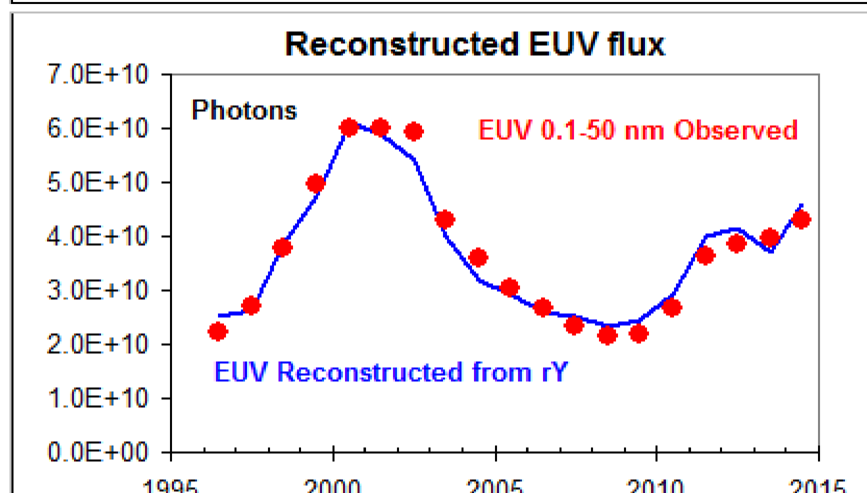


rY and F10.7$^{1/2}$ and EUV$^{1/2}$ √(*J*)

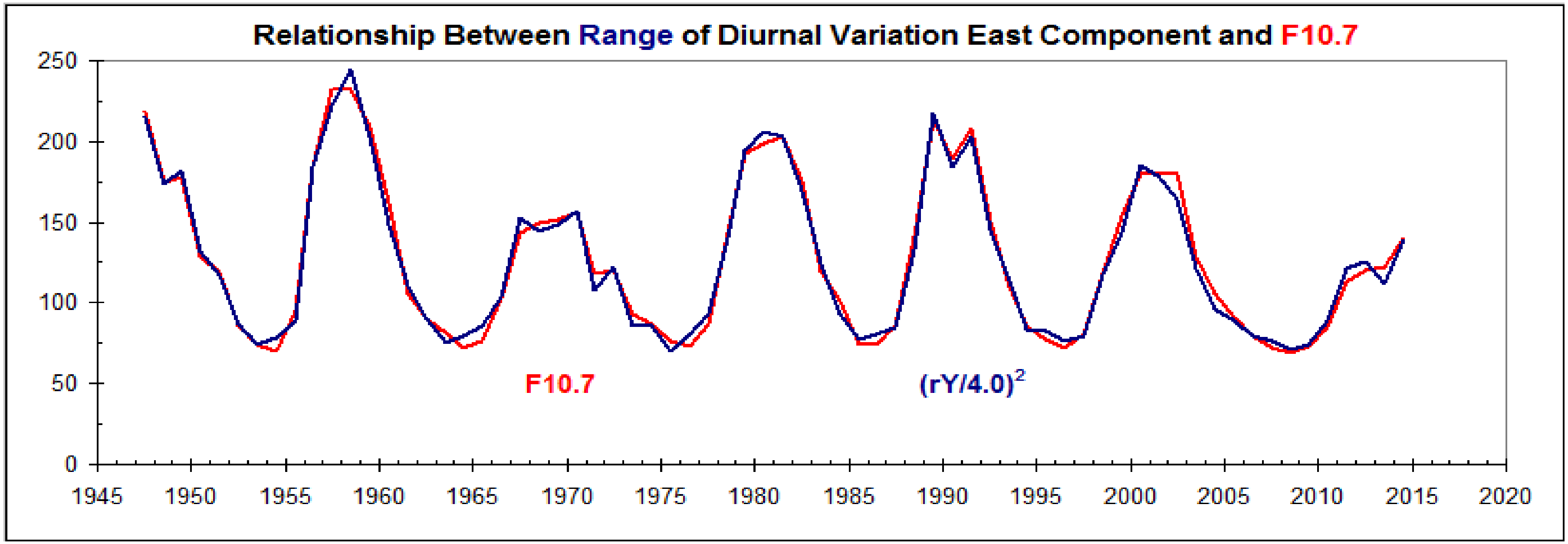


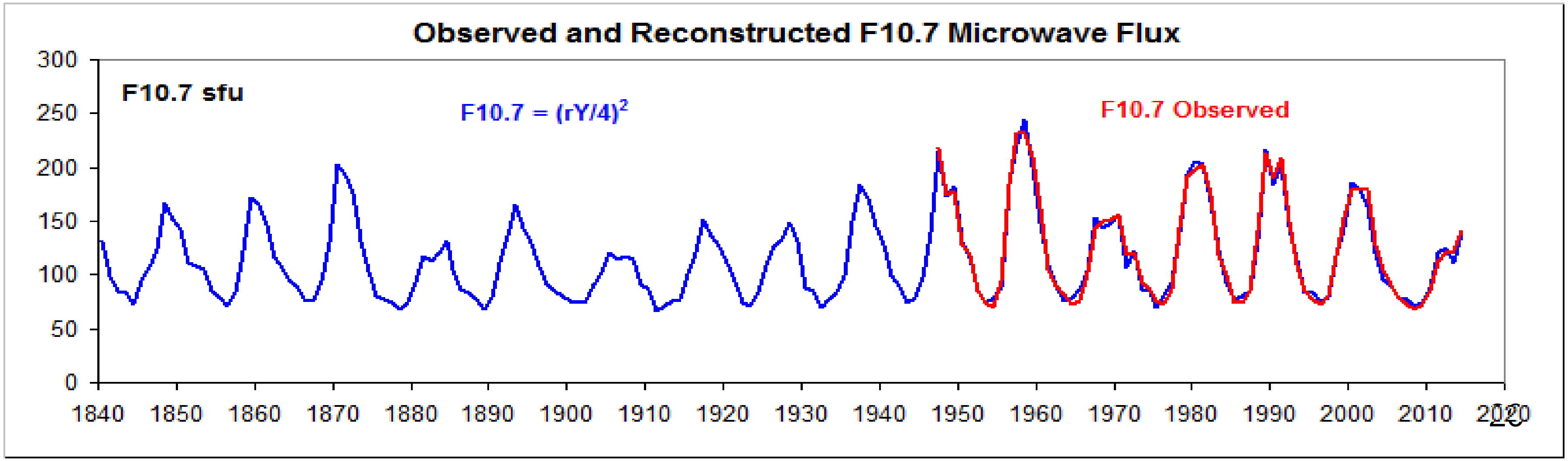




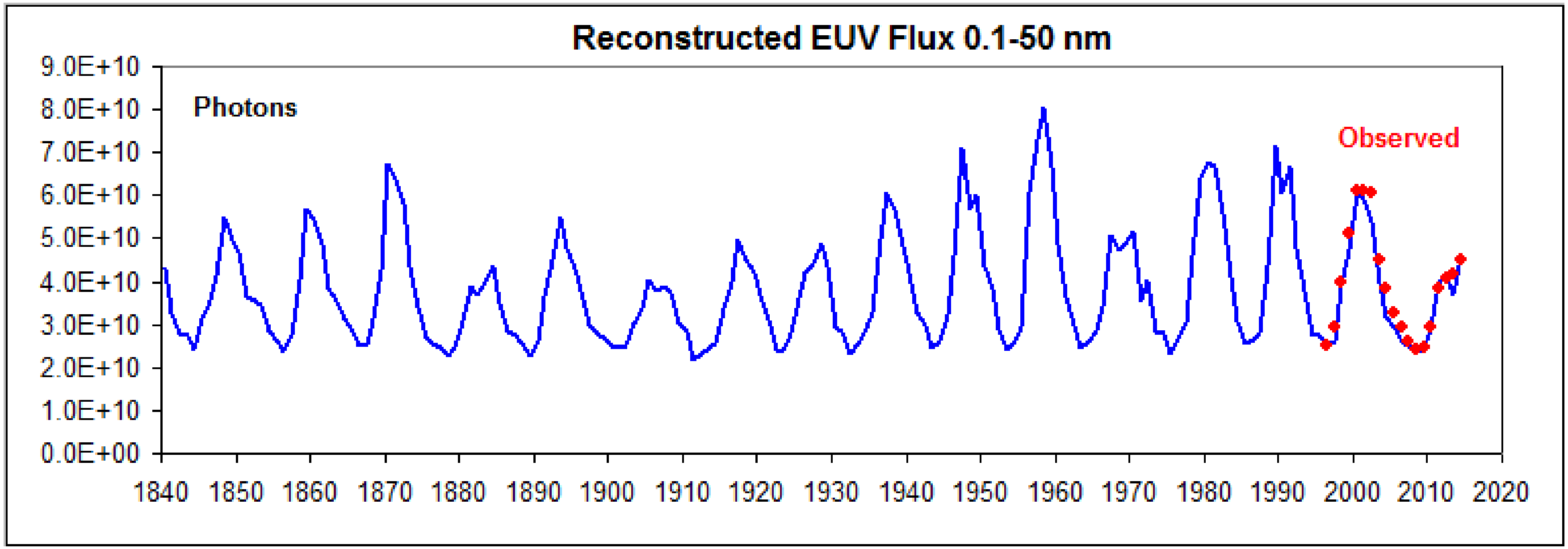


Reconstructed F10.7 [an EUV Proxy]



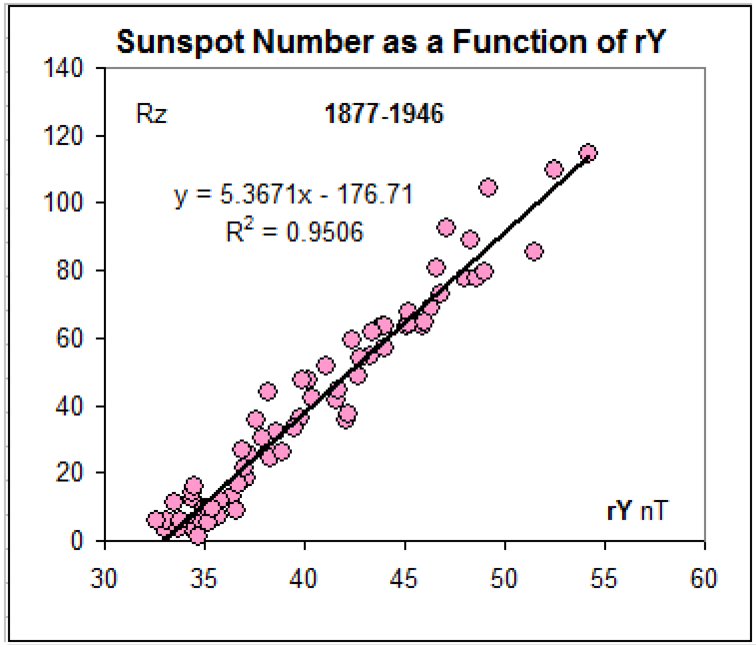


Reconstructed EUV Flux 1840-2014



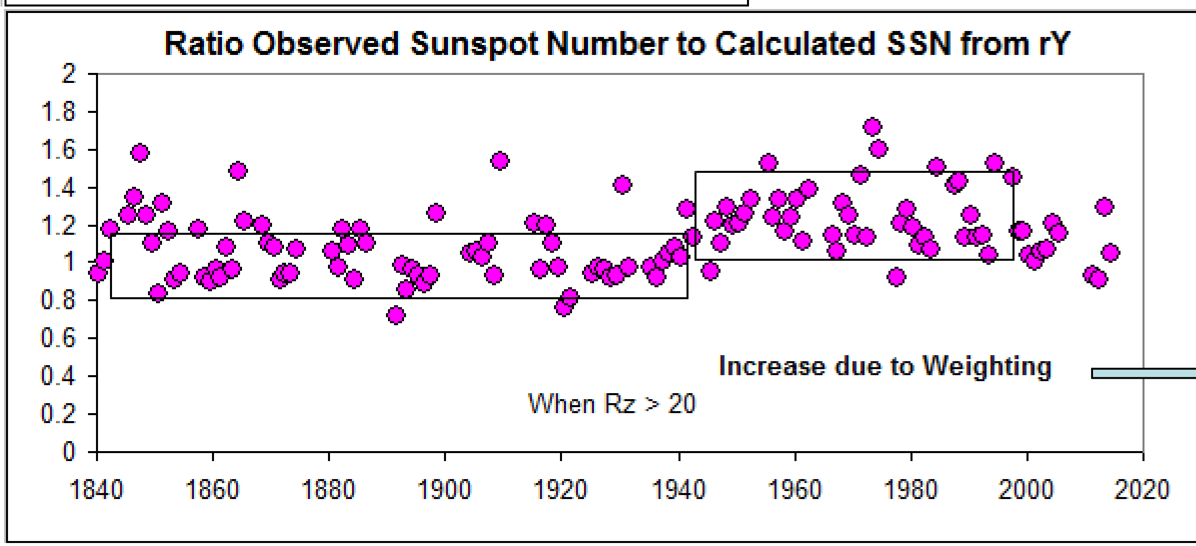
This is, I believe, an accurate depiction of true solar activity since 1840

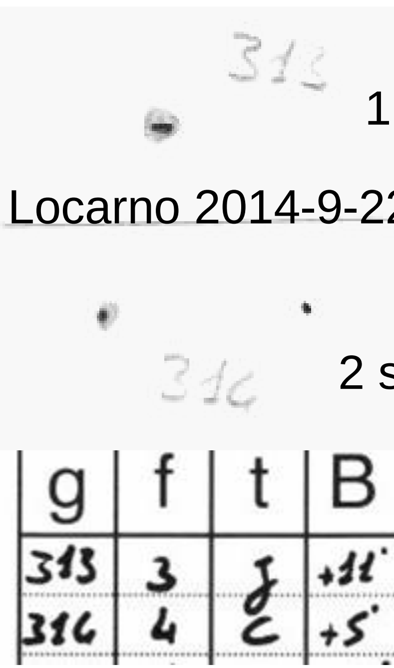
We can compare that with the Zurich Sunspot Number



	ratio
1840-1876	1.052
1877-1946	1.000
1947-1999	1.210

Wolfer & Brunner

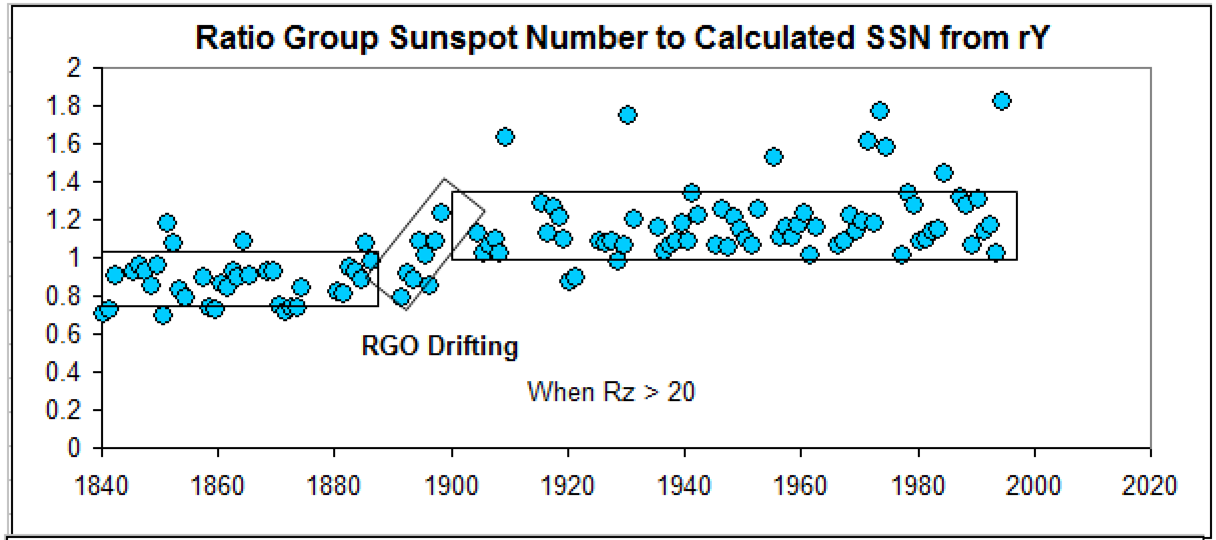


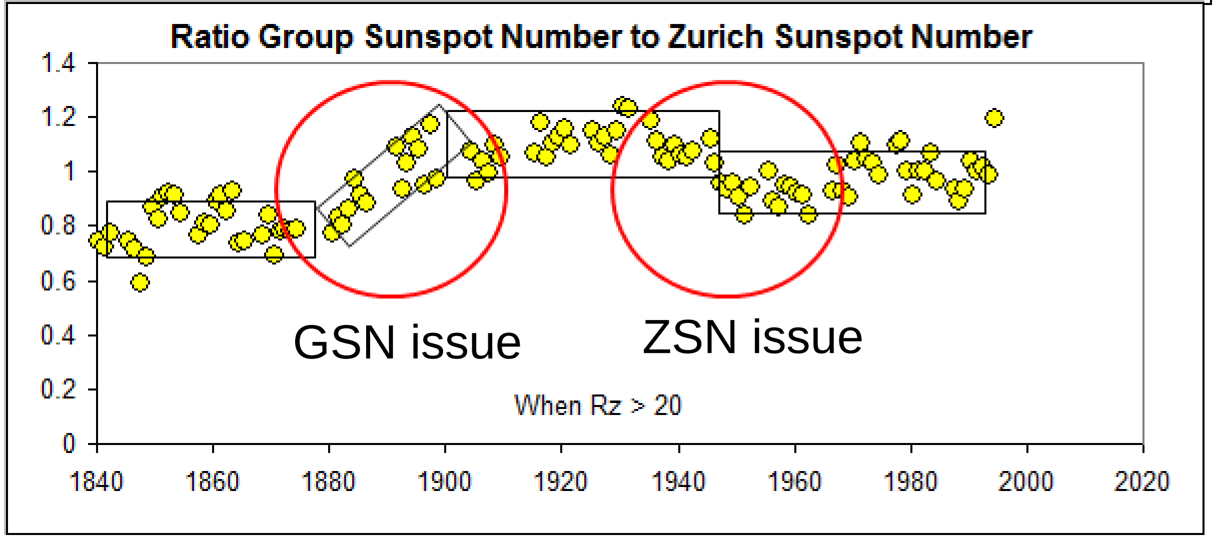


1 spot

2 spots

How About the Group Sunspot Number?

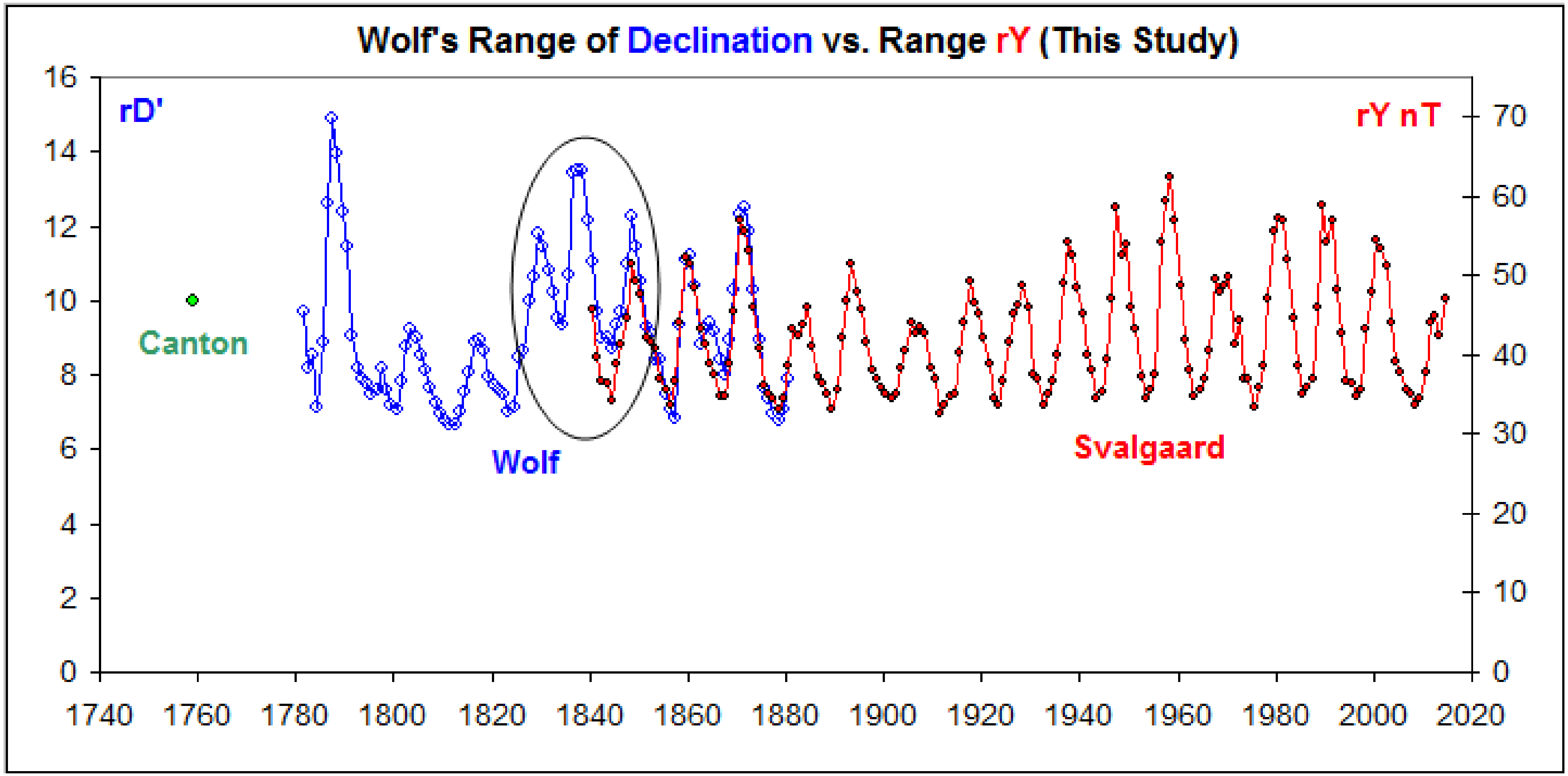




The main issue with the GSN is a change relative to the ZSN during 1880-1900. This is mainly caused by a drift in the reference count of the standard (Royal Greenwich Observatory)

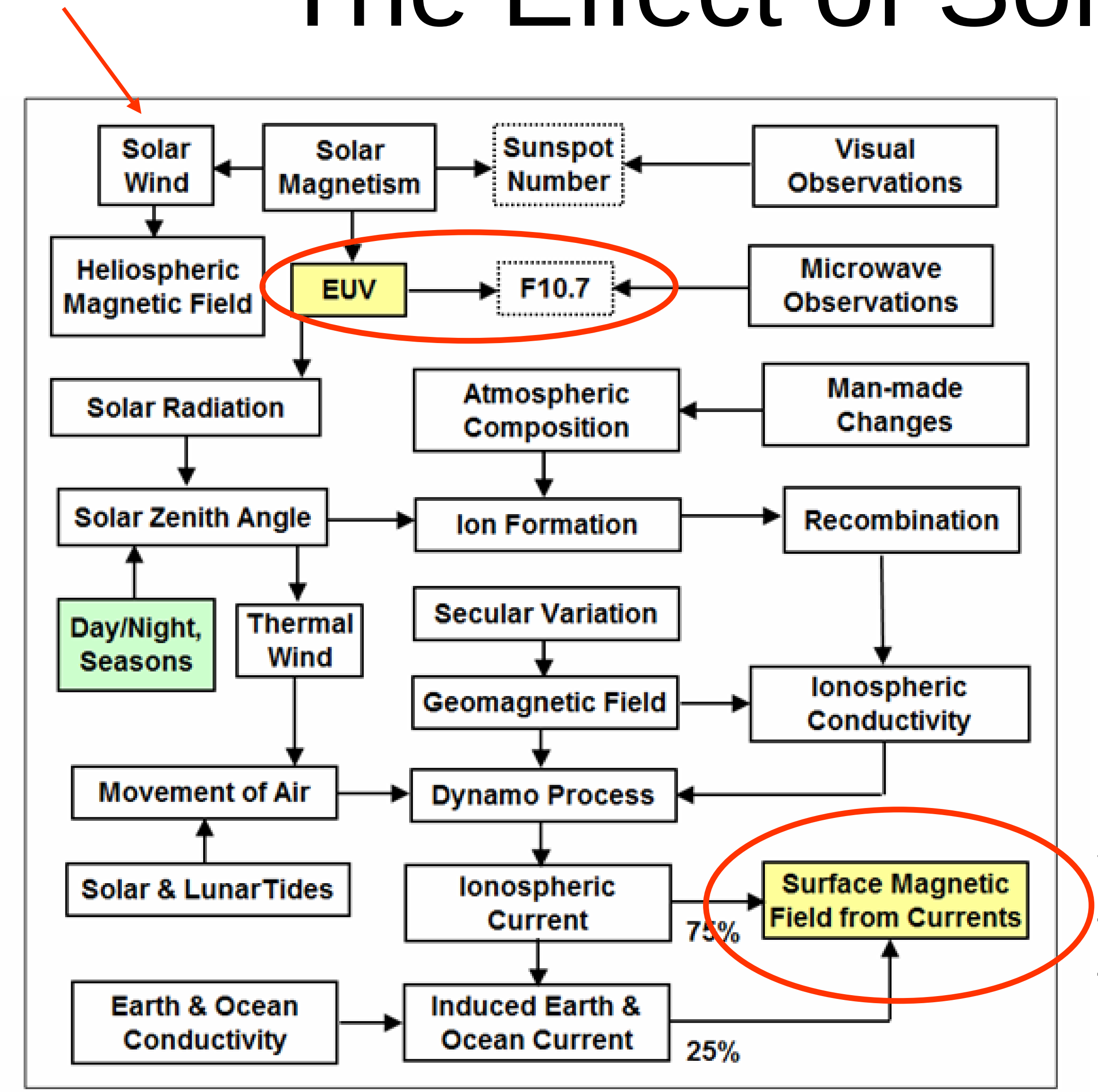
The ratio between the Group Sunspot Number reveals two major problem areas. We can now identify the cause of each

Wolf's Series of Declination Ranges



The discrepancy (in oval) is caused by Greenwich using absolute range rather than the morning-afternoon difference

The Effect of Solar EUV

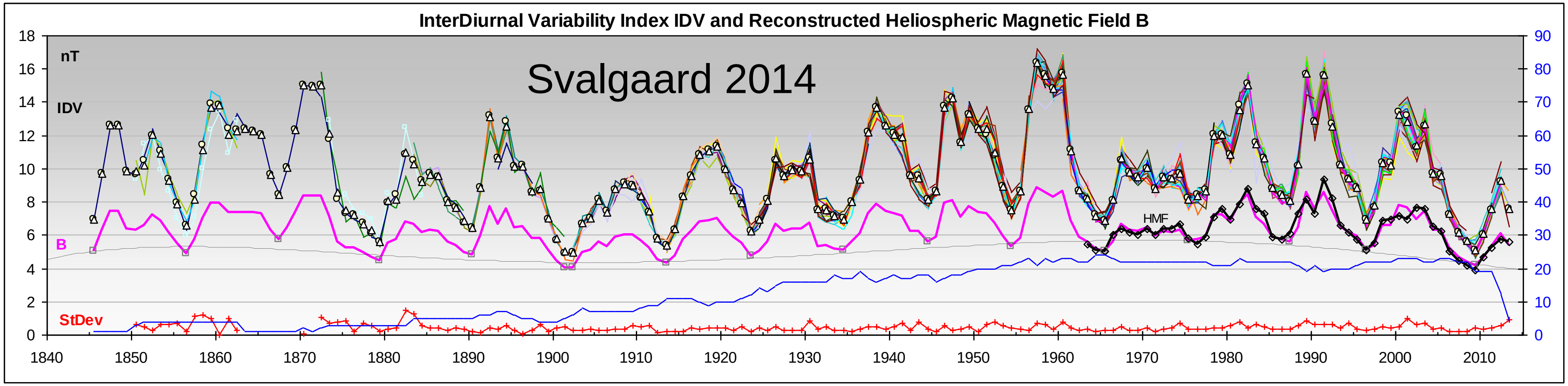


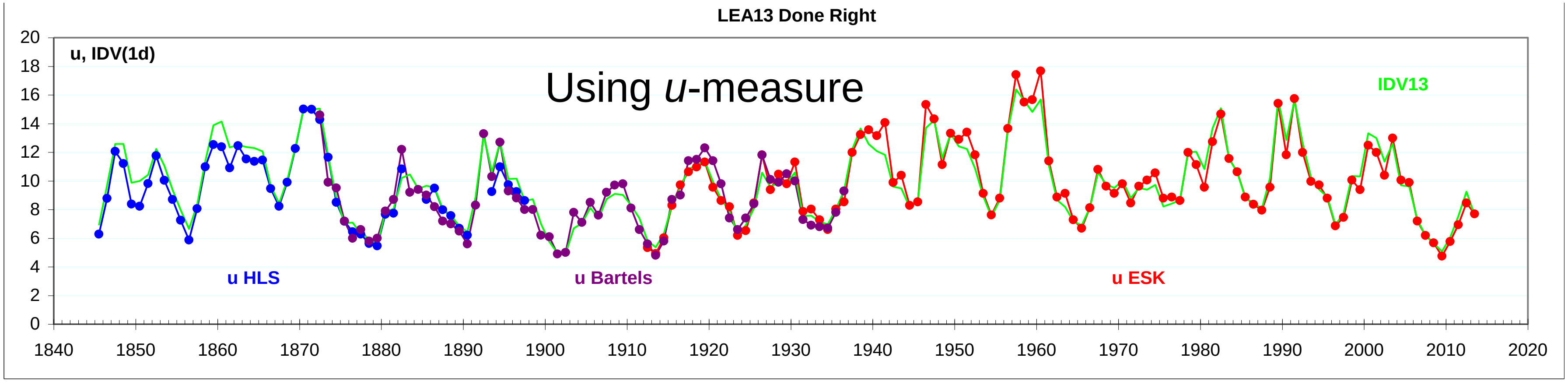
The EUV causes an observable variation of the geomagnetic field at the surface through a complex chain of physical connections.

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

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

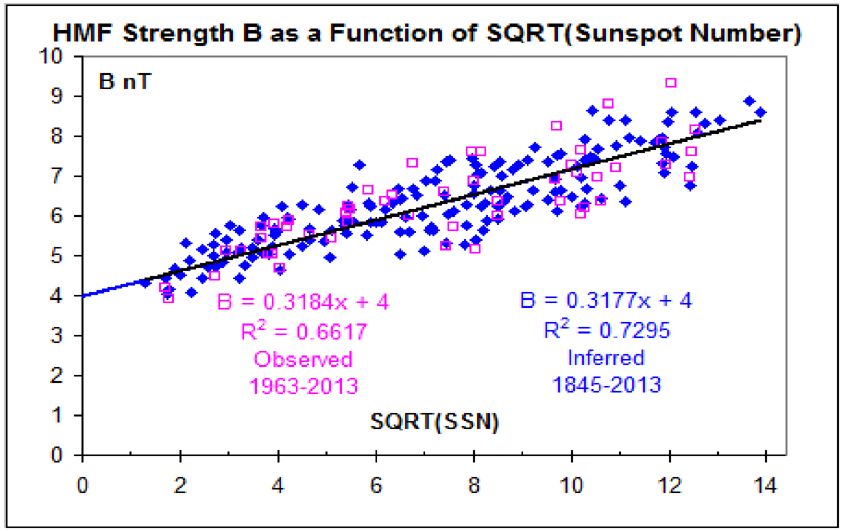
Progress in Reconstructing Solar Wind Magnetic Field back to 1840s

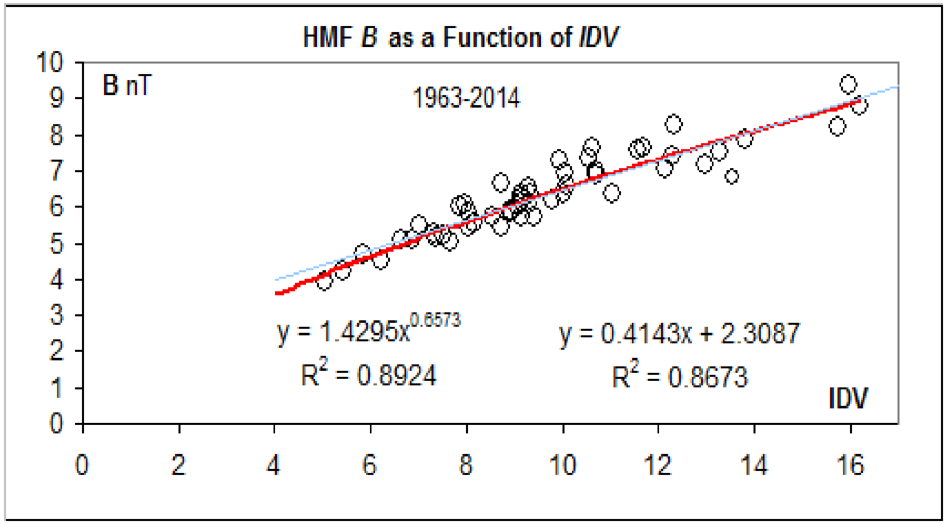


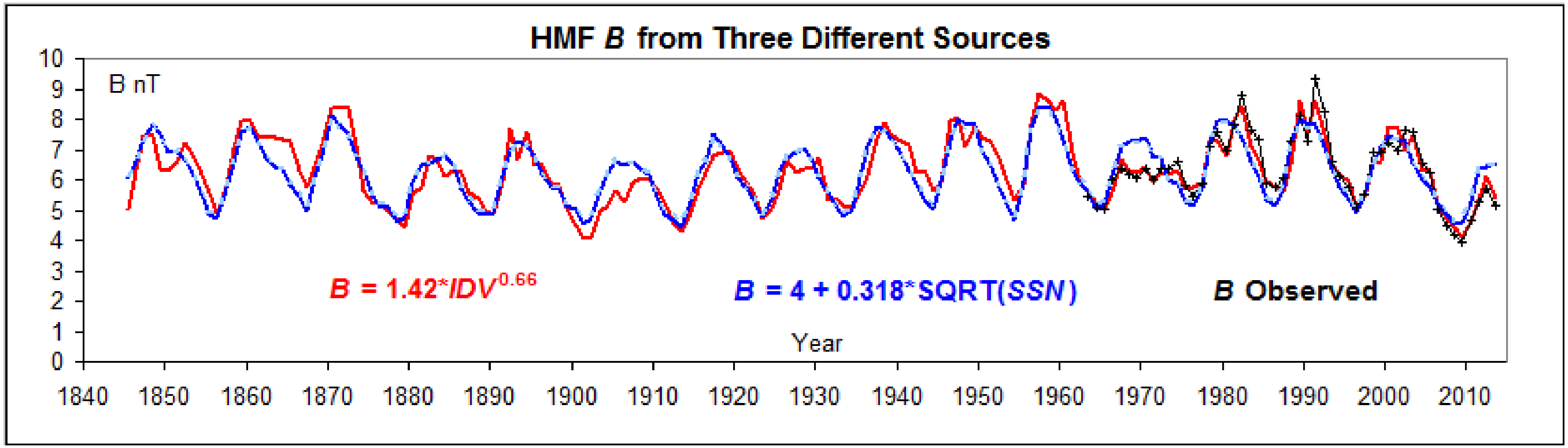


Even using only ONE station, the 'IDV' signature is strong enough to show the effect

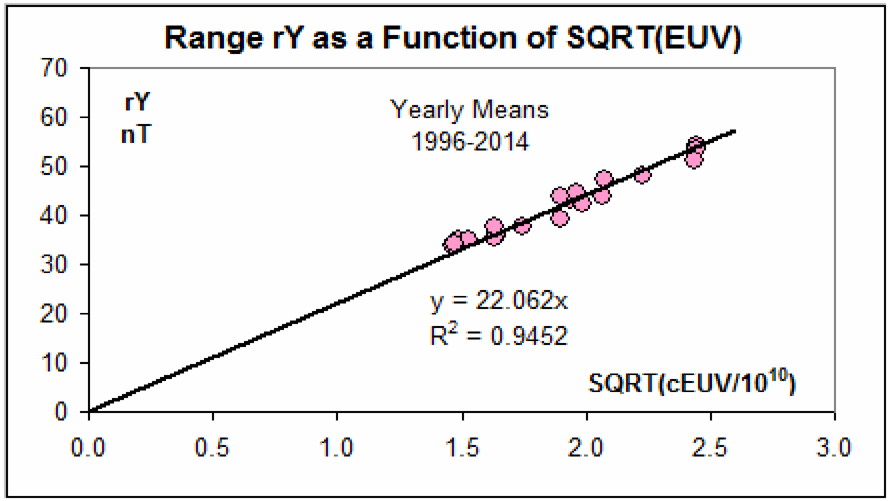
Different Ways of Reconstructing HMF B

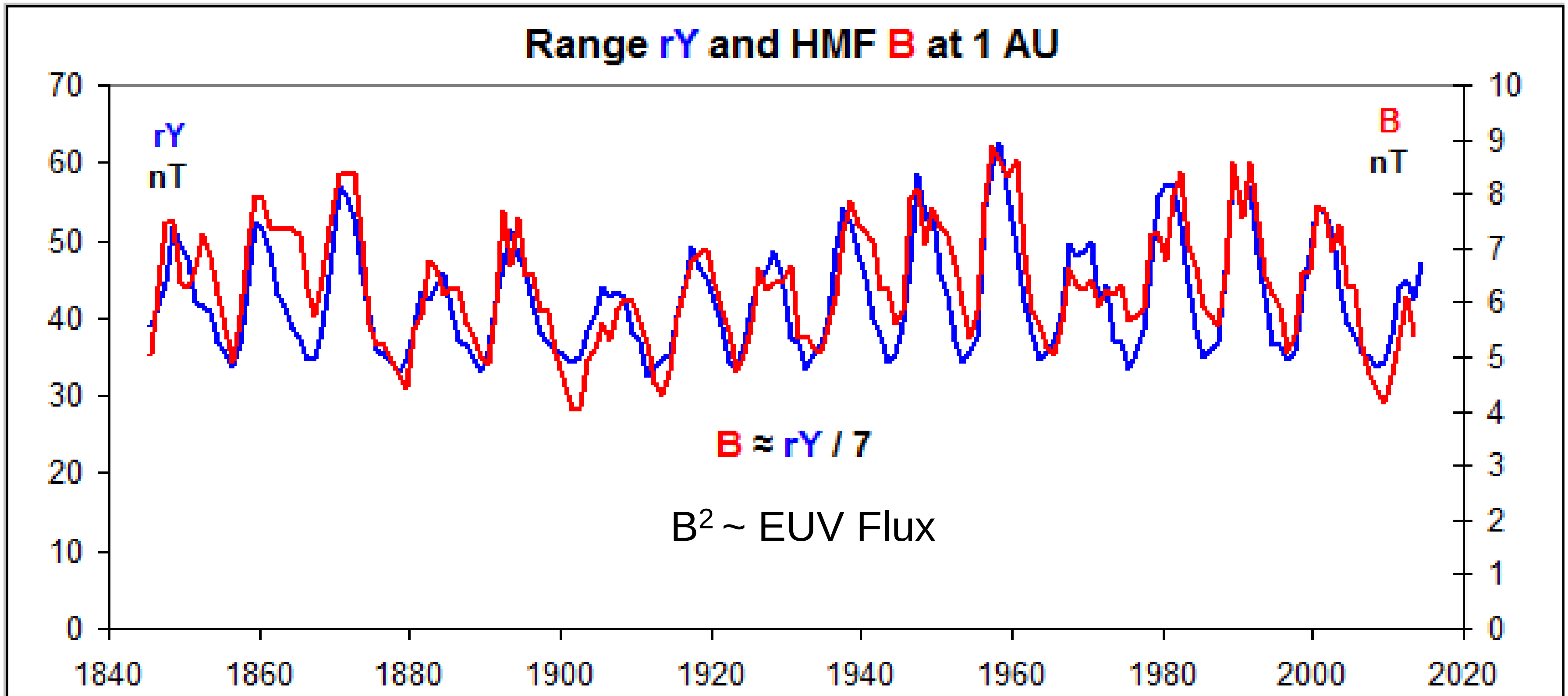






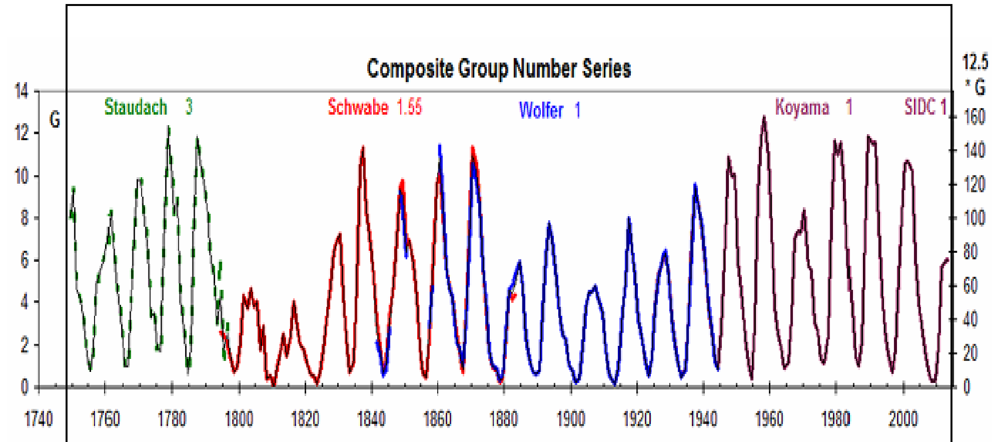
HMF B Scales with the Sqrt of the EUV flux





A New Picture of Solar Activity is Emerging

Number of Groups, Clette et al. 2014



Sunspot Number, Riley et al. 2015

THE ASTROPHYSICAL JOURNAL, 802:105 (14pp), 2015 April 1

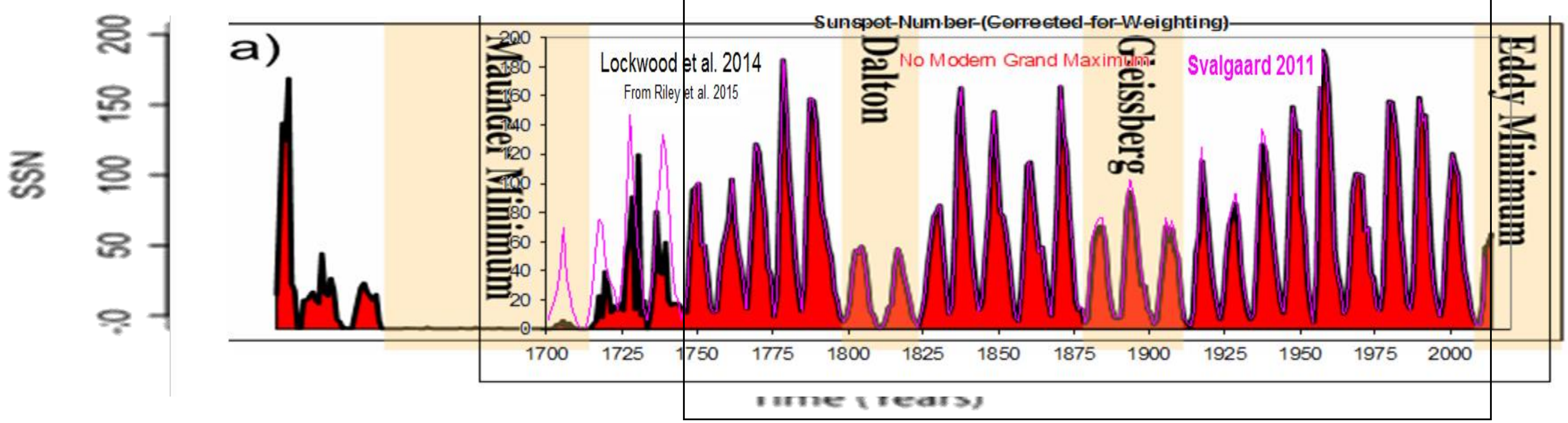


Figure 1. The evolution of various solar-related parameters from 1600 through 2012: (a) the yearly sunspot number (Lockwood et al. 2014a);

Abstract

Solar EUV creates the conducting E-layer of the ionosphere, mainly by photo ionization of molecular Oxygen. Solar heating of the ionosphere creates thermal winds which by dynamo action induce an electric field driving an electric current having a magnetic effect observable on the ground, as was discovered by G. Graham in 1722. The current rises and sets with the Sun and thus causes a readily observable diurnal variation of the geomagnetic field, allowing us the deduce the conductivity and thus the EUV flux as far back as reliable magnetic data reach. High quality data go back to the invention of the magnetometers by Gauss and Weber in 1834 and less reliable, but still usable, data are available sporadically for the hundred years before that. J. R. Wolf and, independently, J-A. Gautier discovered the dependence of the diurnal variation on solar activity, and today we understand and can invert that relationship to construct a reliable record of the EUV flux from the geomagnetic record. We compare that to the F10.7 flux and the sunspot number, and find that the reconstructed EUV flux reproduces the F10.7 flux with great accuracy and that the EUV flux clearly shows the discontinuities of the sunspot record identified by Clette et al, 2014.