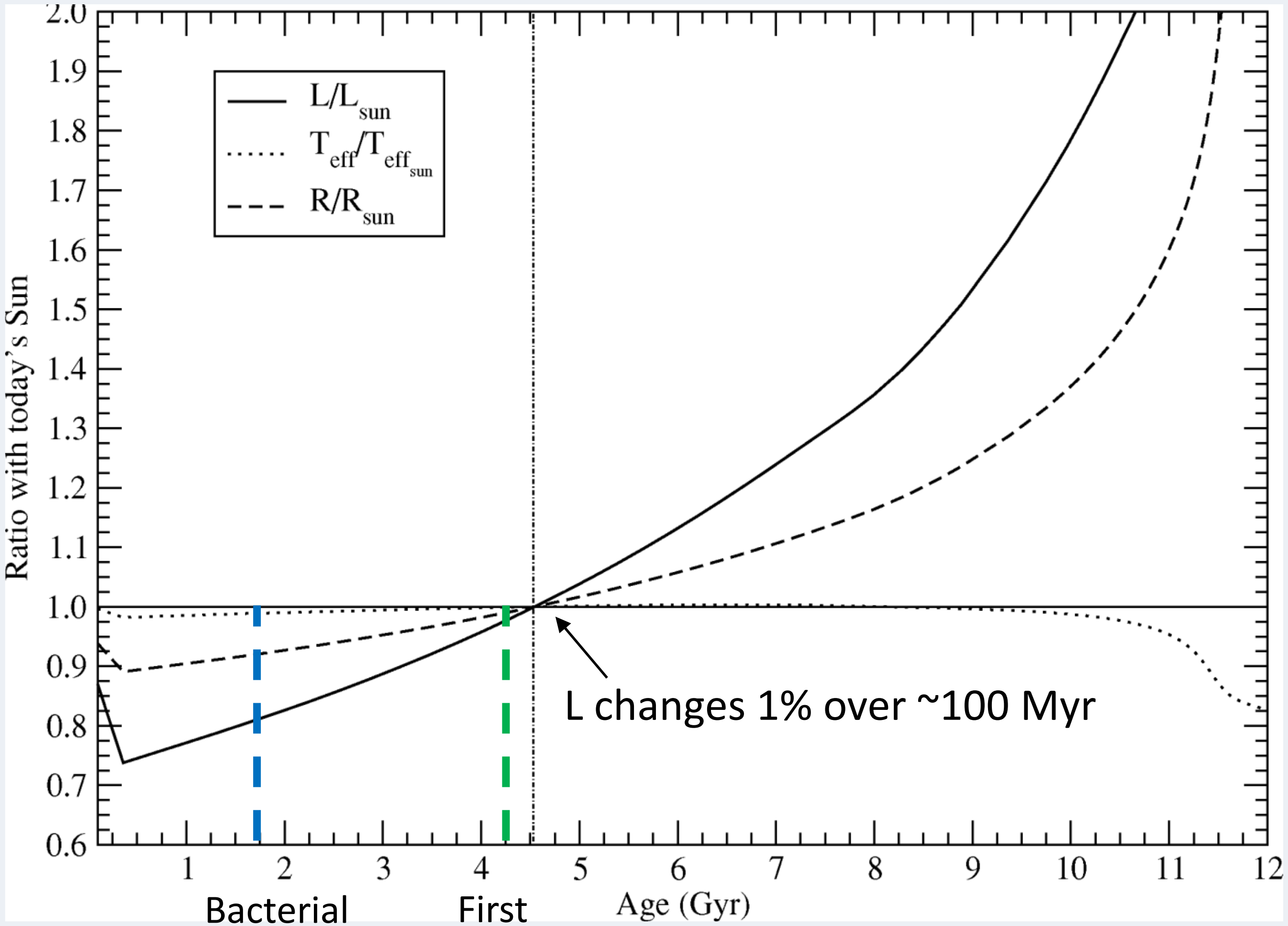
NSF's National Solar Observatory

Long-term solar activity

ALEXEI A. PEVTSOV

NATIONAL SOLAR OBSERVATORY

By its luminosity, Sun is a stable star, but …

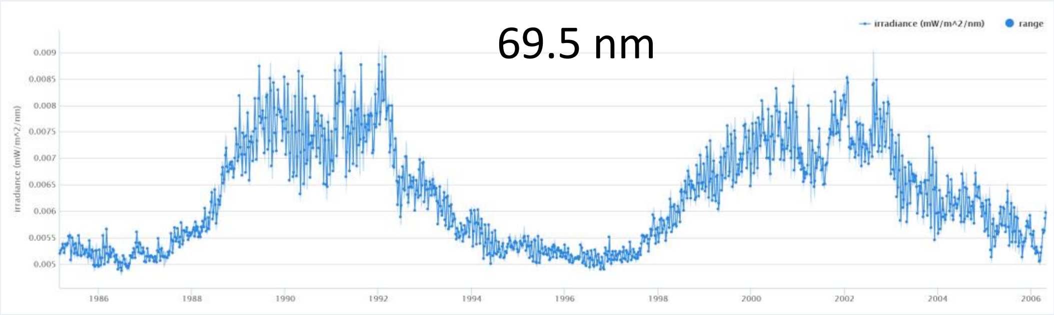


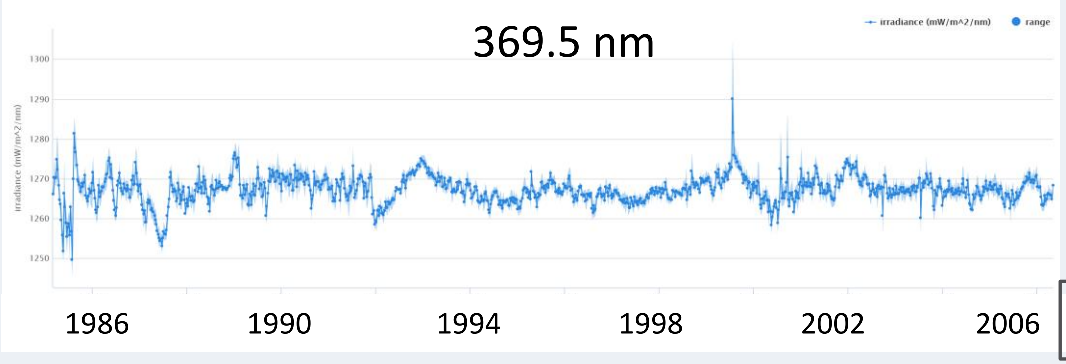
Bacterial life on land

First dinosaur

Ribas, 2009

LASP GSFC Composite Solar Spectral Irradiance

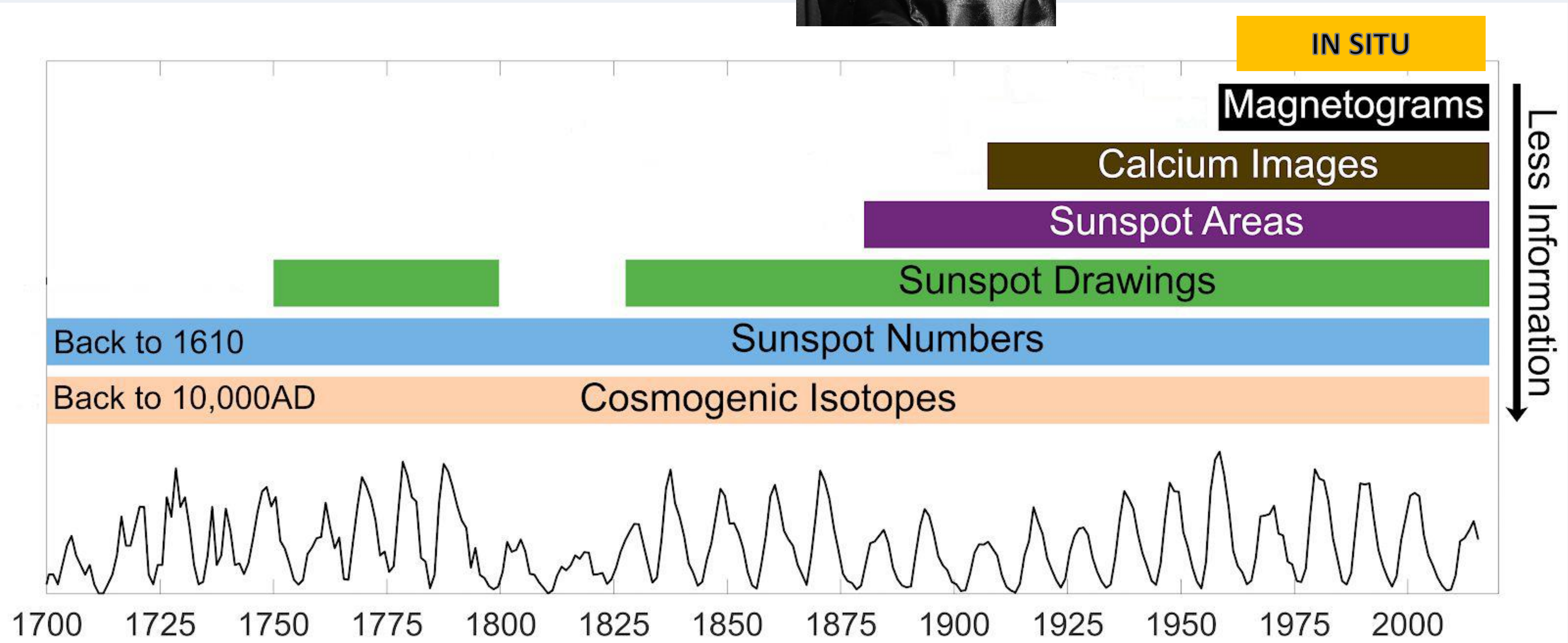




TSI cycle variations – 0.1%; EUV ~ 1.5x, X-ray >10x

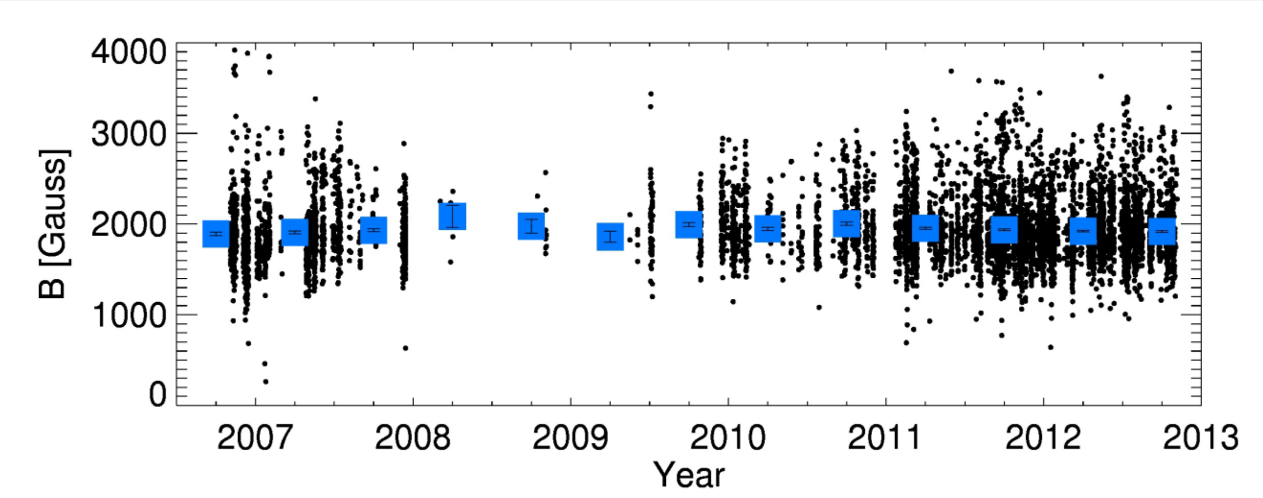
Solar activity in time

- Direct observations → proxies → analogies →



Property of sunspots

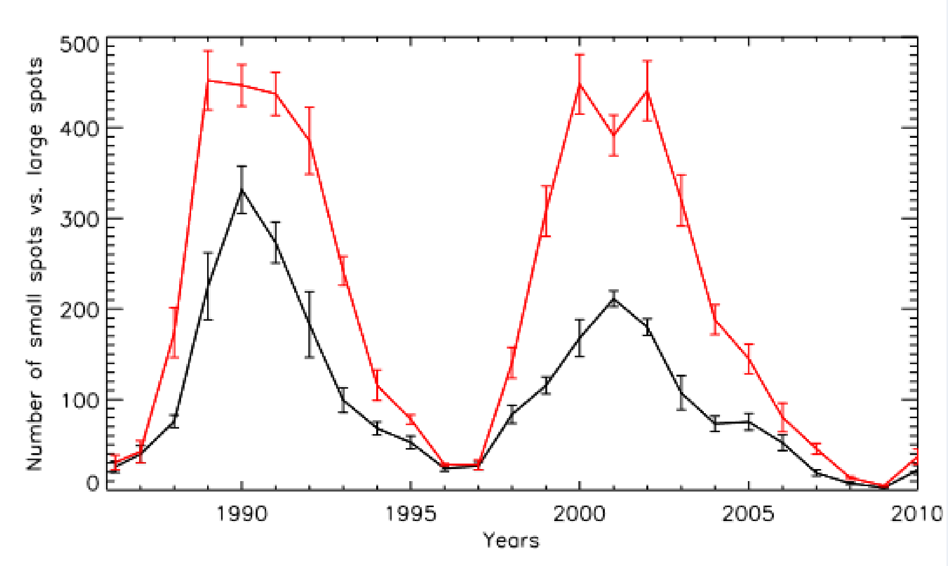
- Penn & Livingston (2011), Livingston et al (2012) found a steady decrease in sunspot field strength and made prediction that sunspots will disappear by 2022-2024.
- Later studies did not confirm this (e.g., Watson et al, 2011, Pevtsov et al 2011, Rezaei et al. 2012, 2015, Schad 2014).
- Nagovitsyn et al (2012) explained P&L trend by a larger fraction of small spots at the end of cycle 23.



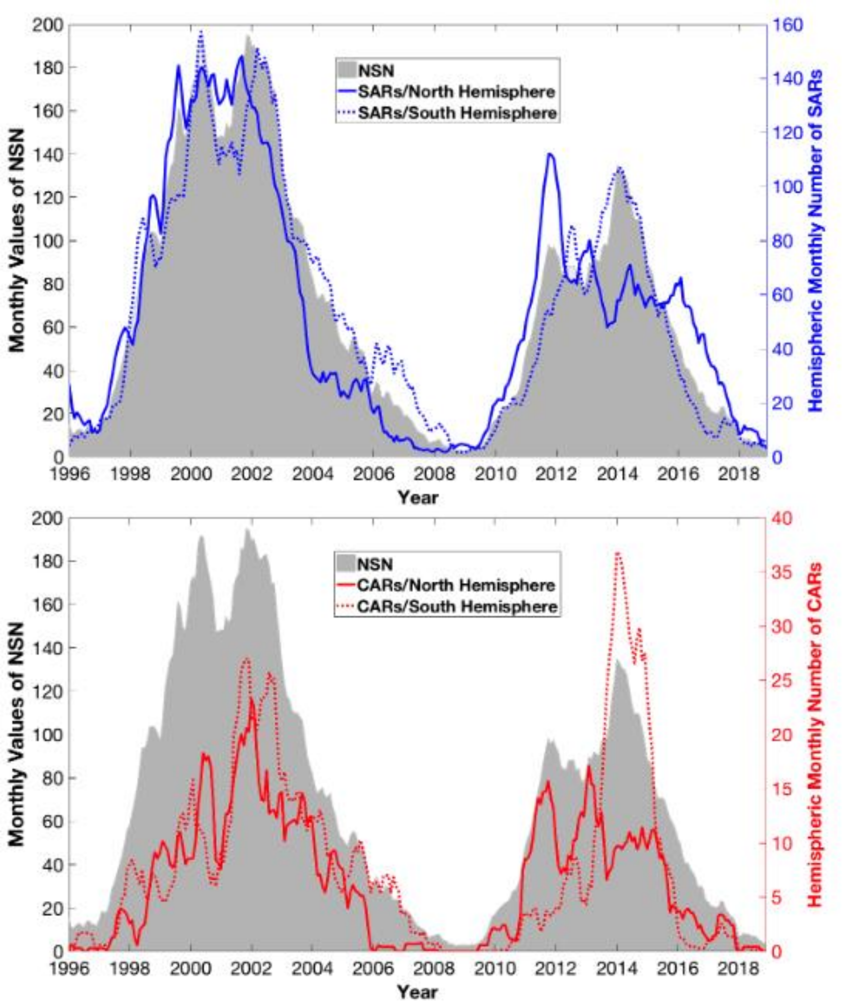
Schad, 2014)

AR complexity

- Lefèvre and F. Clette (2011), Nagovitsyn et al (2012) – small and larger regions may originate at different depths in the CZ.
- Cycle variation in simple and complex active regions (Jaeggli & Norton, 2016 (collision), Nikbakhsh et al. 2019 (local dynamo), Gao & Xie 2022 (local dynamo)).



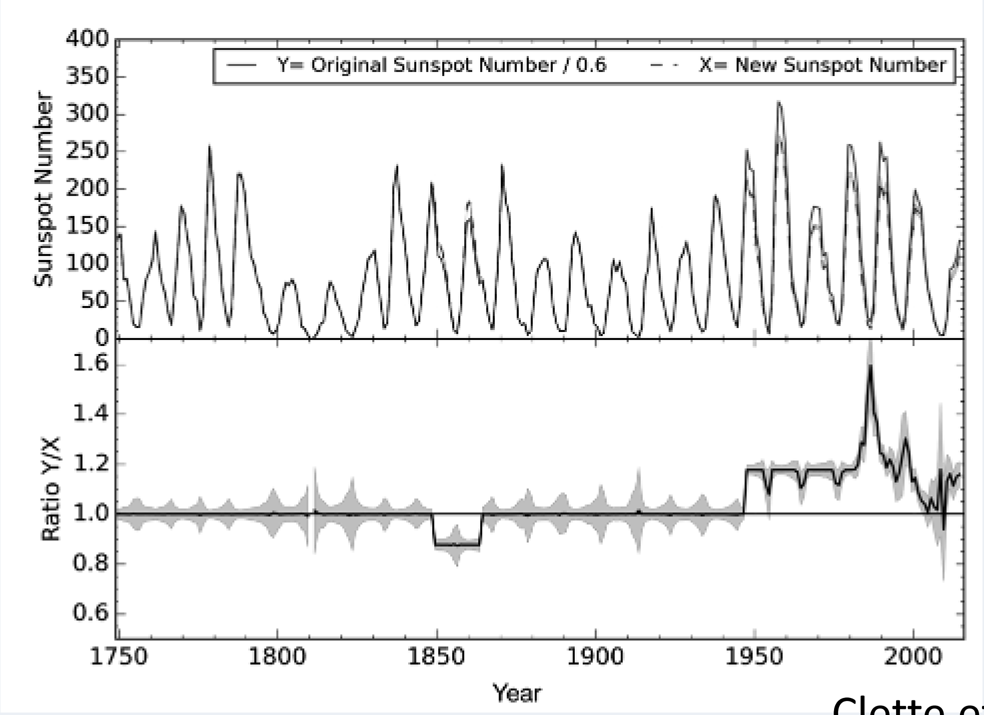
Lefèvre and Clette (2011)



Nikbakhsh et al. (2019)

Recalibrating sunspot number

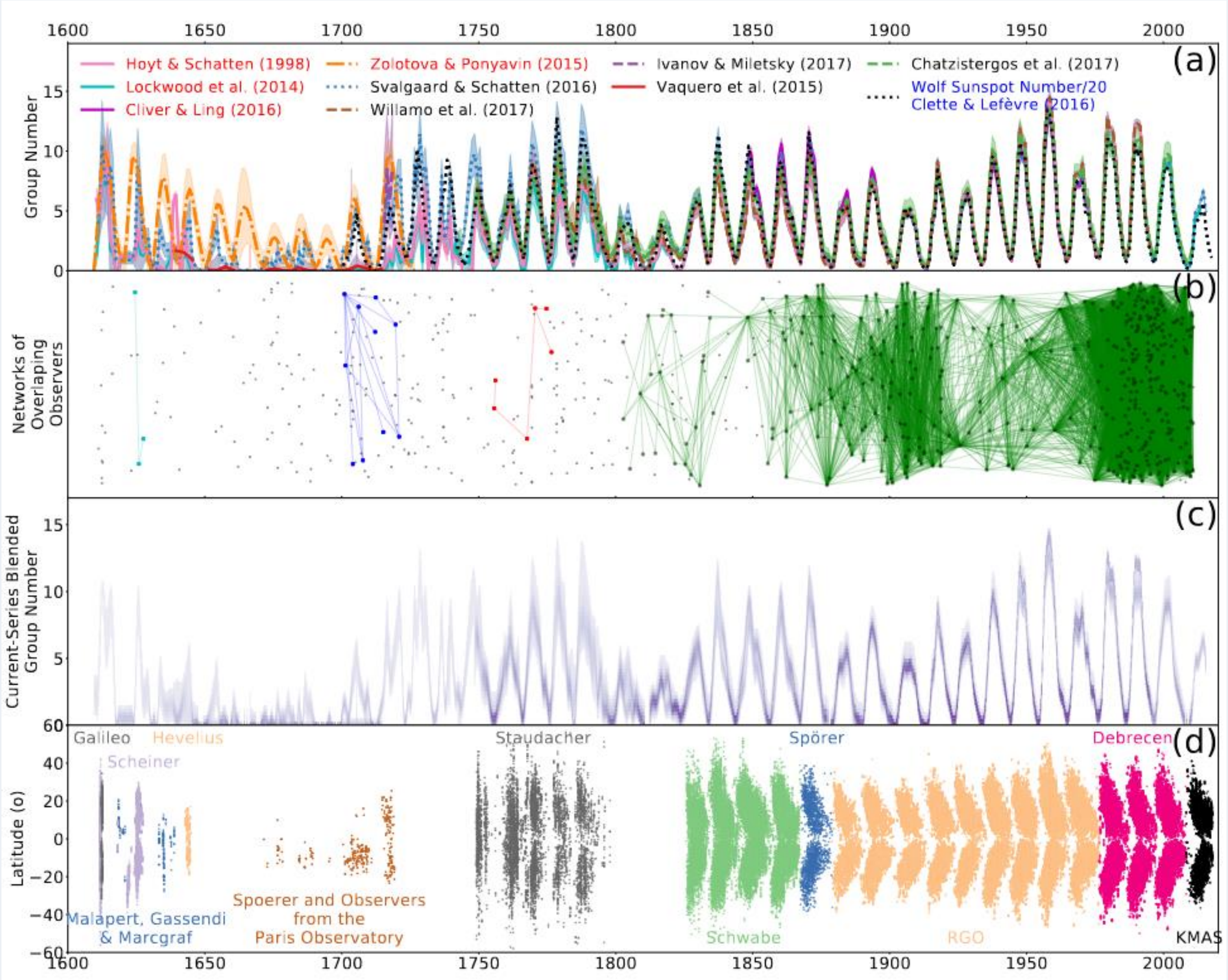
- Sunspot number WG (see papers by F. Clette, Solar Physics topical issue on Sunspot Number recalibration, v. 291).
- Discovery/addition of new sunspot records (see, papers by J. Vaquero, R. Arlt and their teams)
- Estimation of uncertainties (e.g., Dudok de Wit et al, 2016)

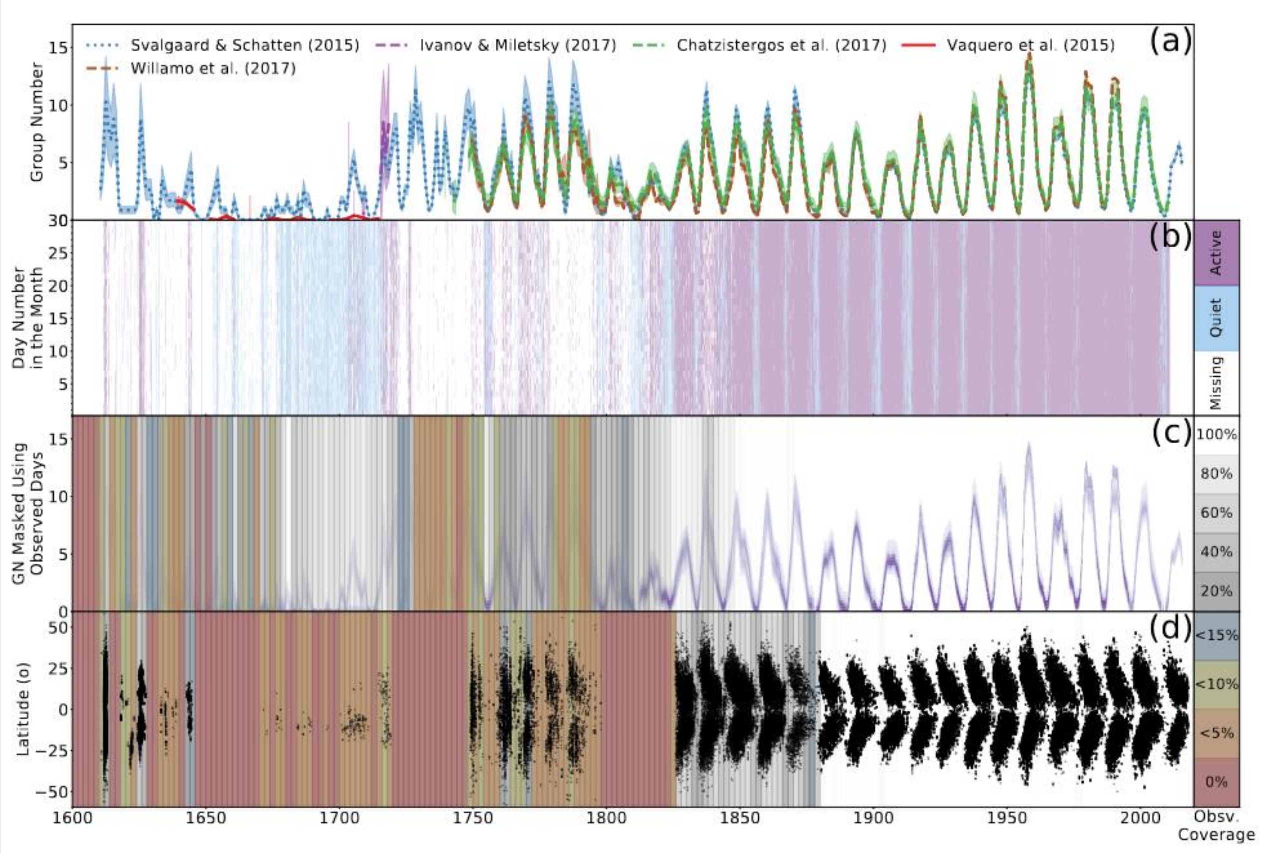


Clette et al (2016)

S_N is used extensively for reconstruction of solar irradiance, solar magnetic activity, and even in stellar research

“Goodness” of S_N (G_N) time series

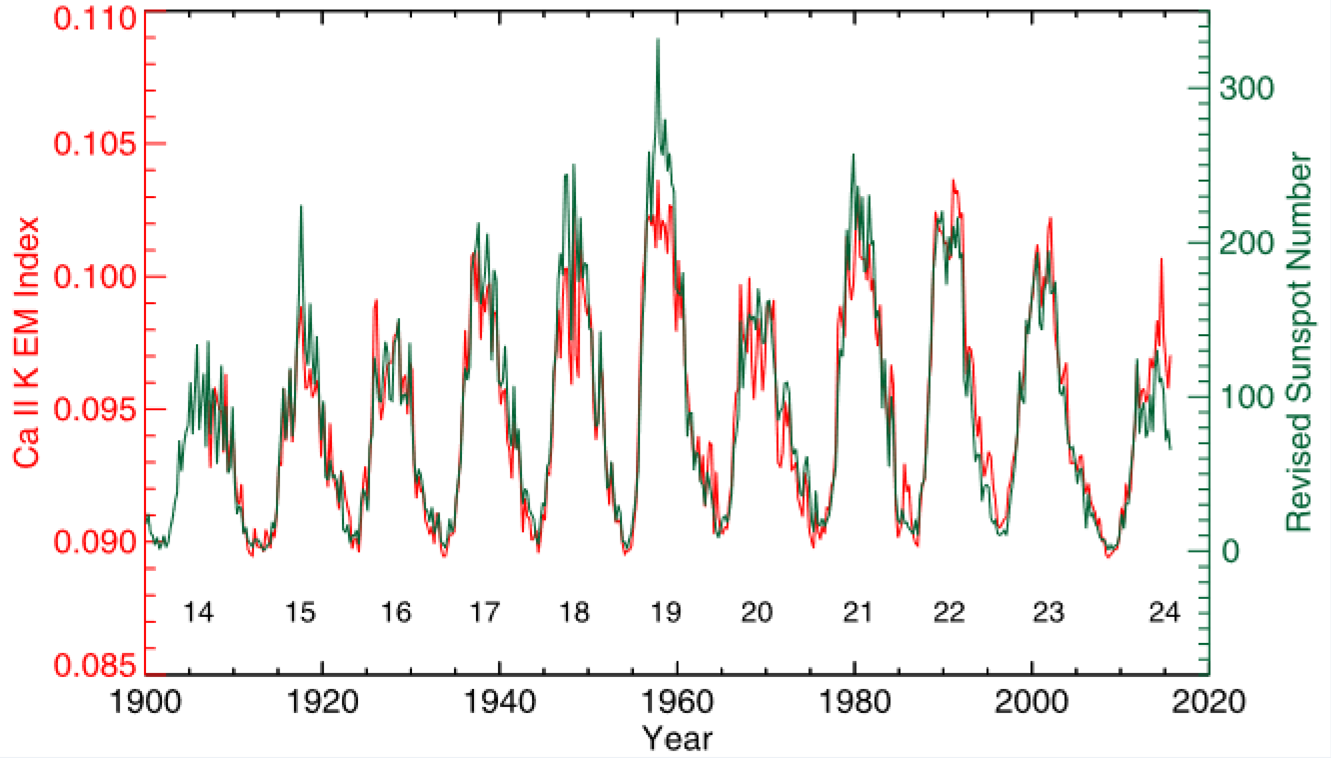


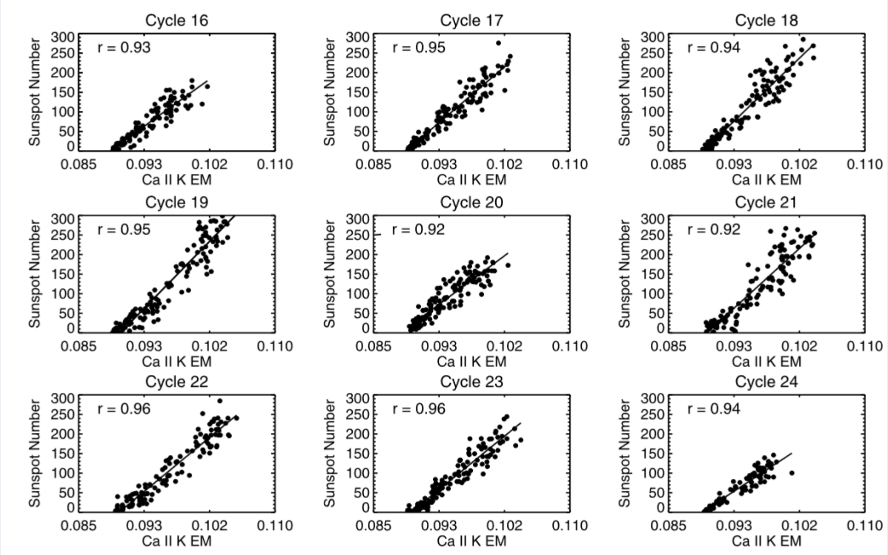


Muñoz-Jaramillo & Vaquero (2019)

Ca K line time series

- Long-term observations from Kodaikanal (India, 1906-) and Mount Wilson Observatories (USA, 1915-1985)



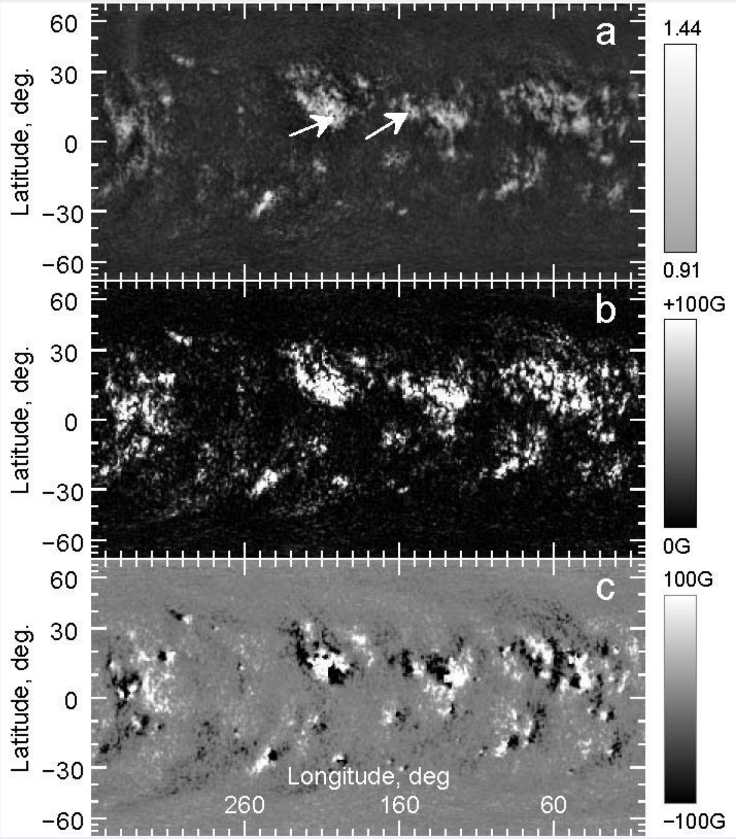


S-index - CaK EM ~ S_N

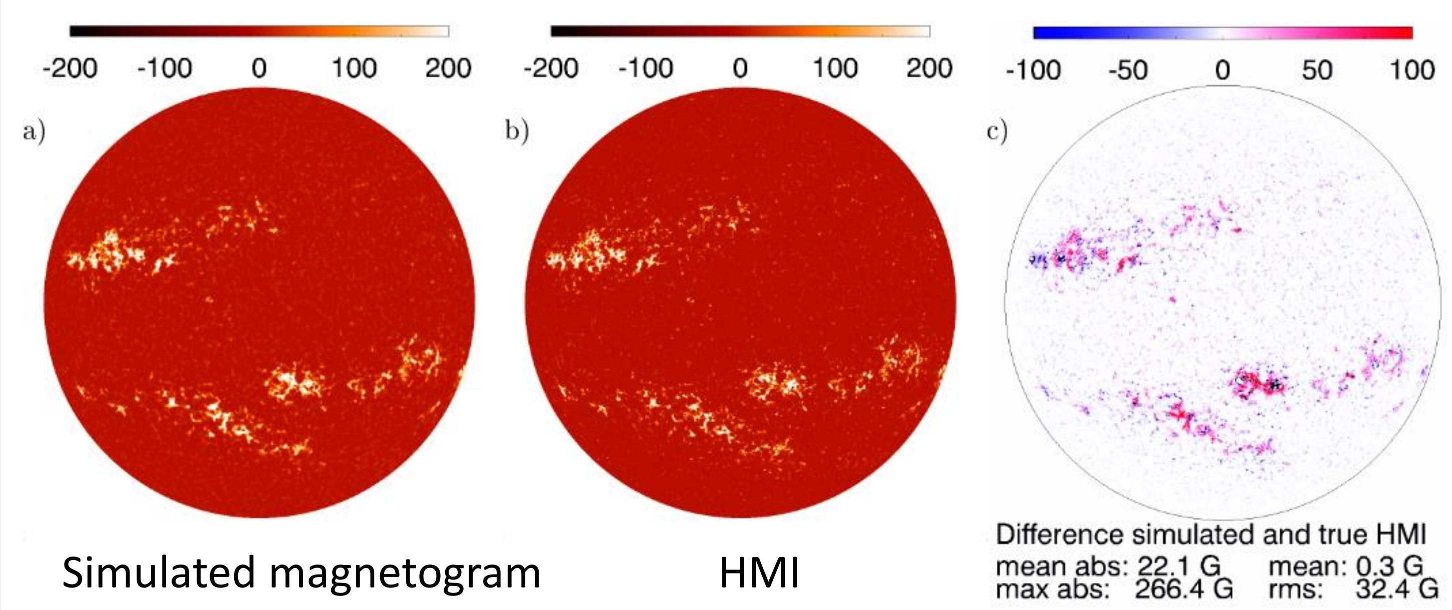
Bertello et al (2016)

Ca K line time series

- There is a strong correlation between spectroheliograms and unsigned magnetic flux (Babcock & Babcock 1955, see references in Chatzistergos et al (2019).



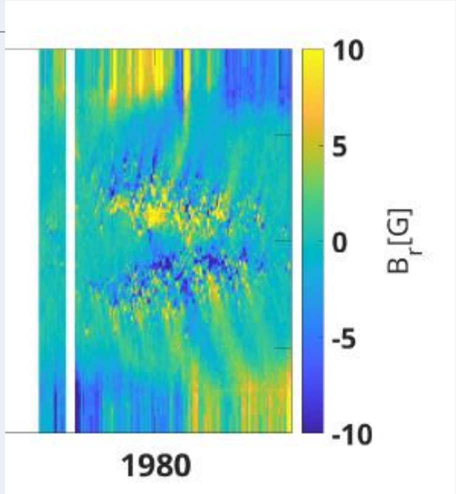
Pevtsov et al (2016)

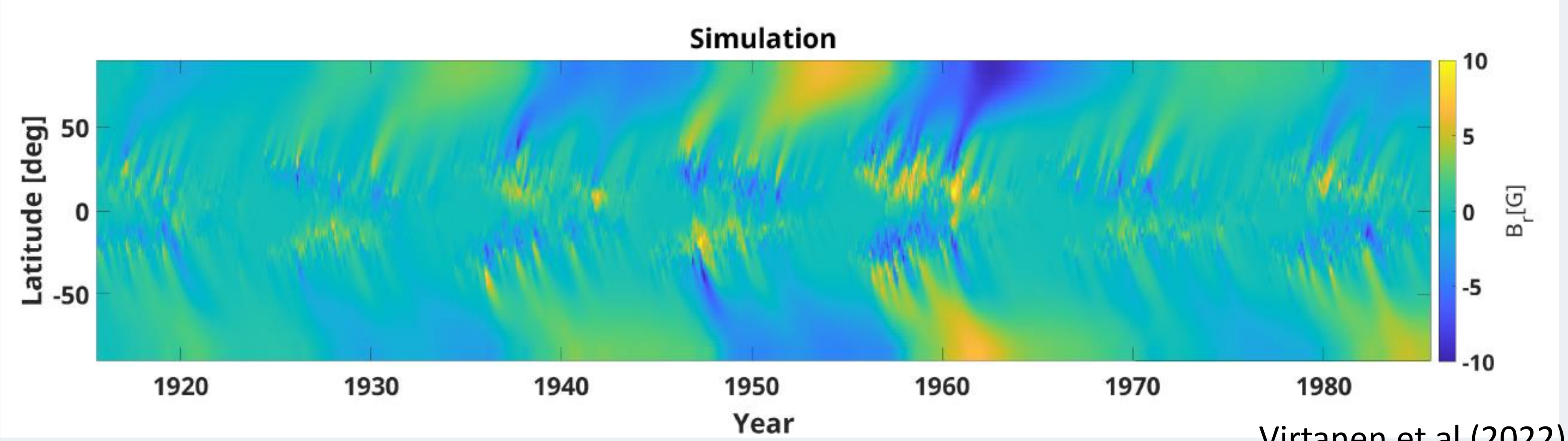


Chatzistergos et al (2019)

Extending “magnetogram” period by 100 years

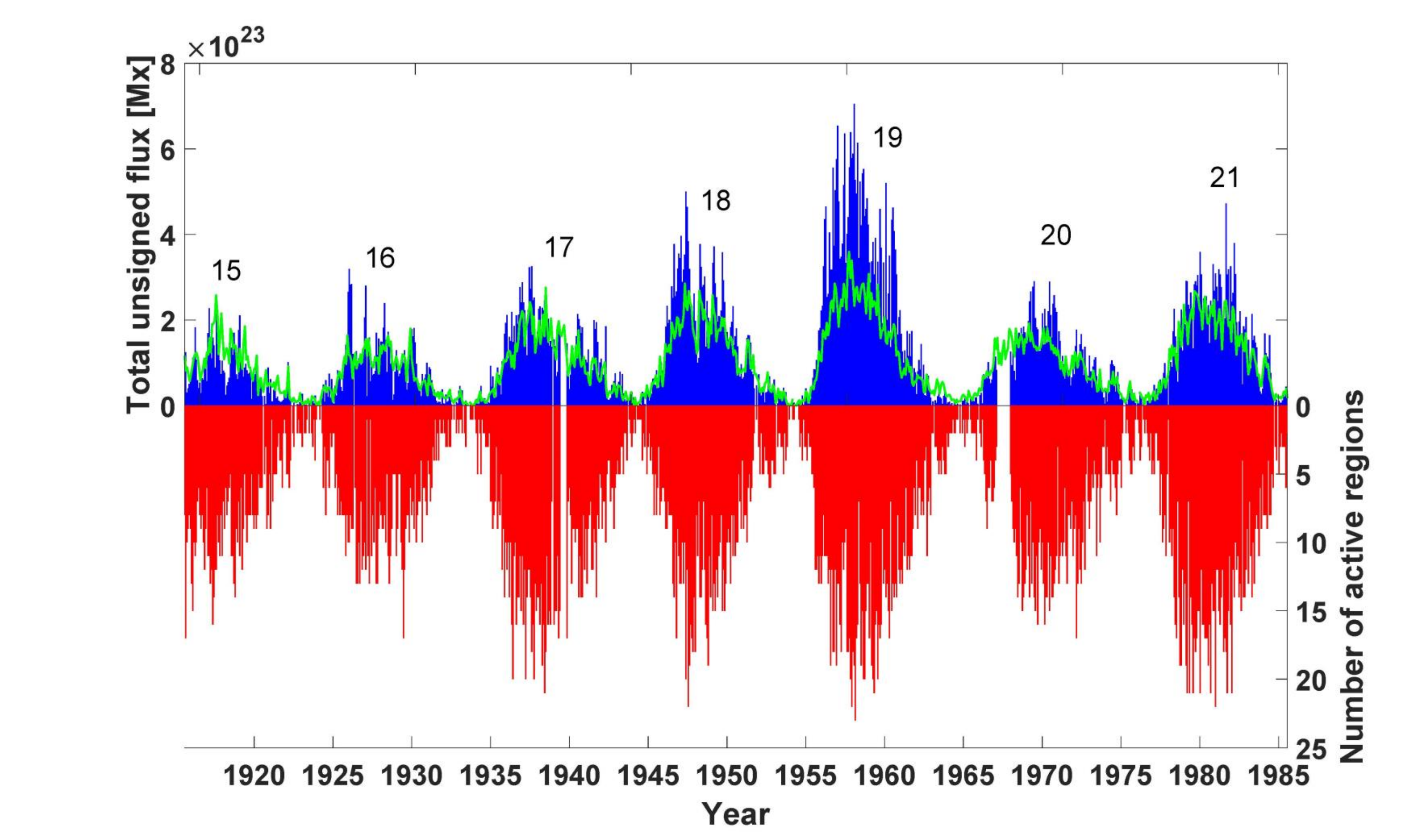
- Identify plages in Ca K spectroheliograms
- Assign polarity of magnetic field to plage pixels (MWO sunspot measurements)
- Determine field strength based on intensity in CaK spectroheliograms
- Evolve this primitive magnetograms using surface-flux transport models





Virtanen et al (2022)

Evolution of magnetic flux over last 100 years

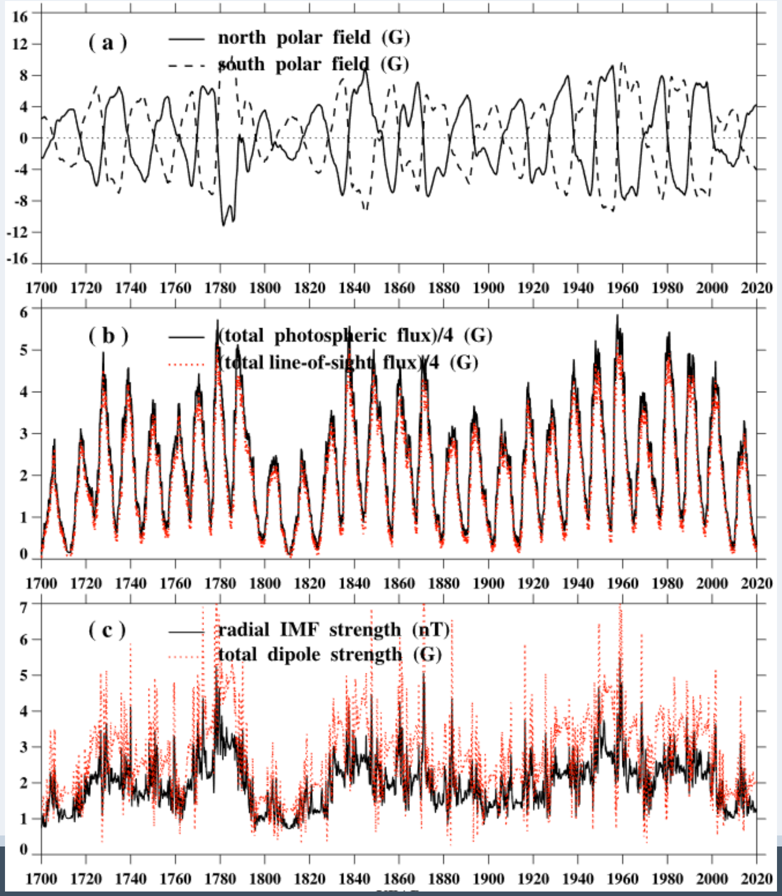


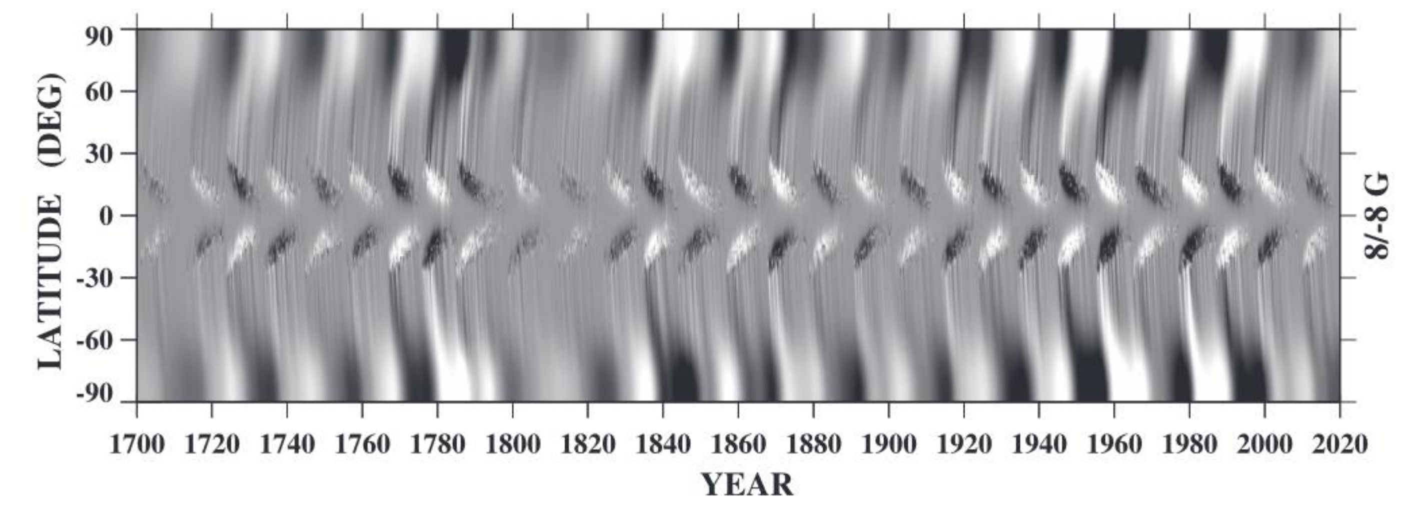
- Good correlation between total magnetic flux and monthly $S_N x10^{22}$ Mx (green line), agrees with Wang and Lean (2021)

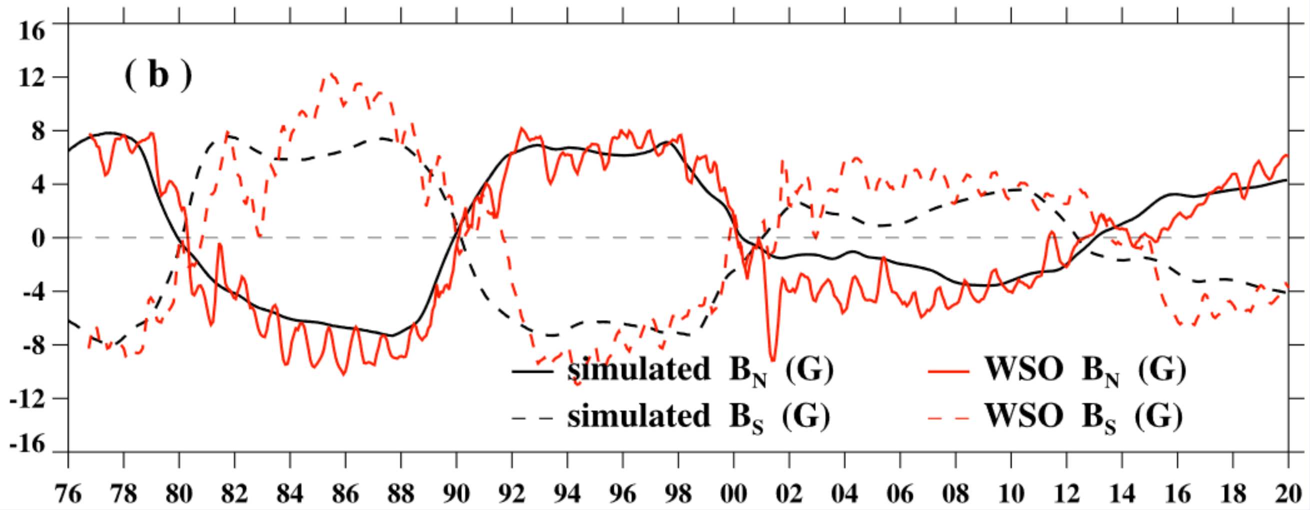
Virtanen et al (2022)

Modeling long-term evolution of polar field

- Wang & Lean (2021). Random bipoles, Hale-polarity oriented, Joy-law tilted, injected within 10 deg latitude.

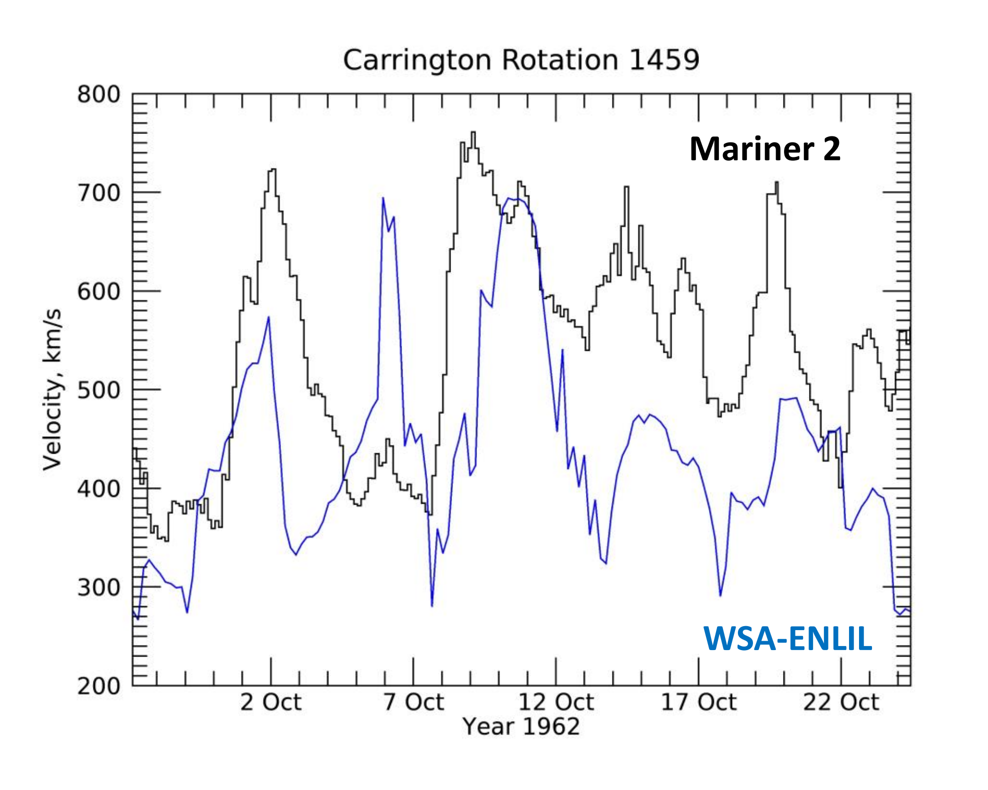


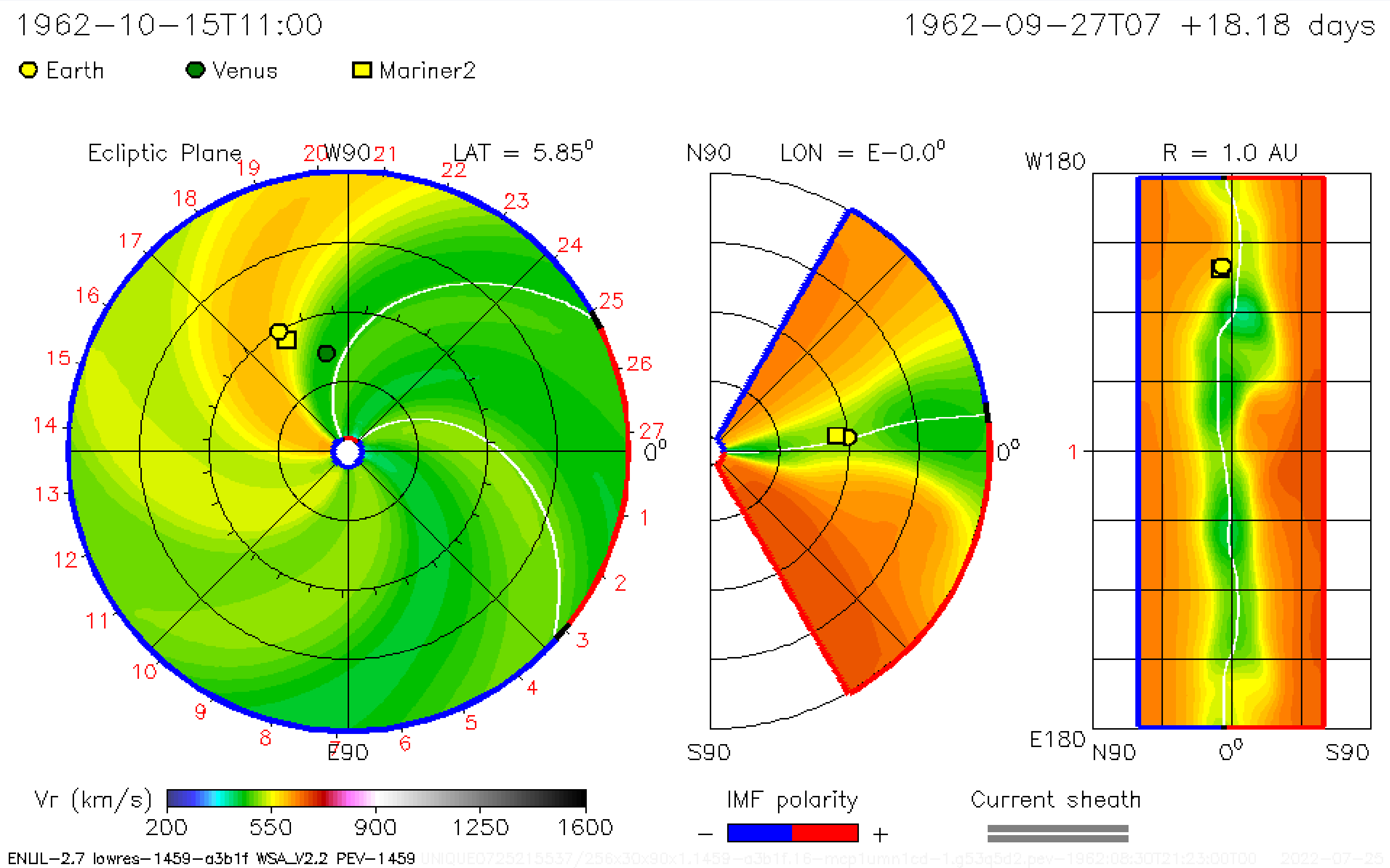




Variation of the north（BN） and south（BS） polar fields

Modeling solar wind in pre-magnetograph era

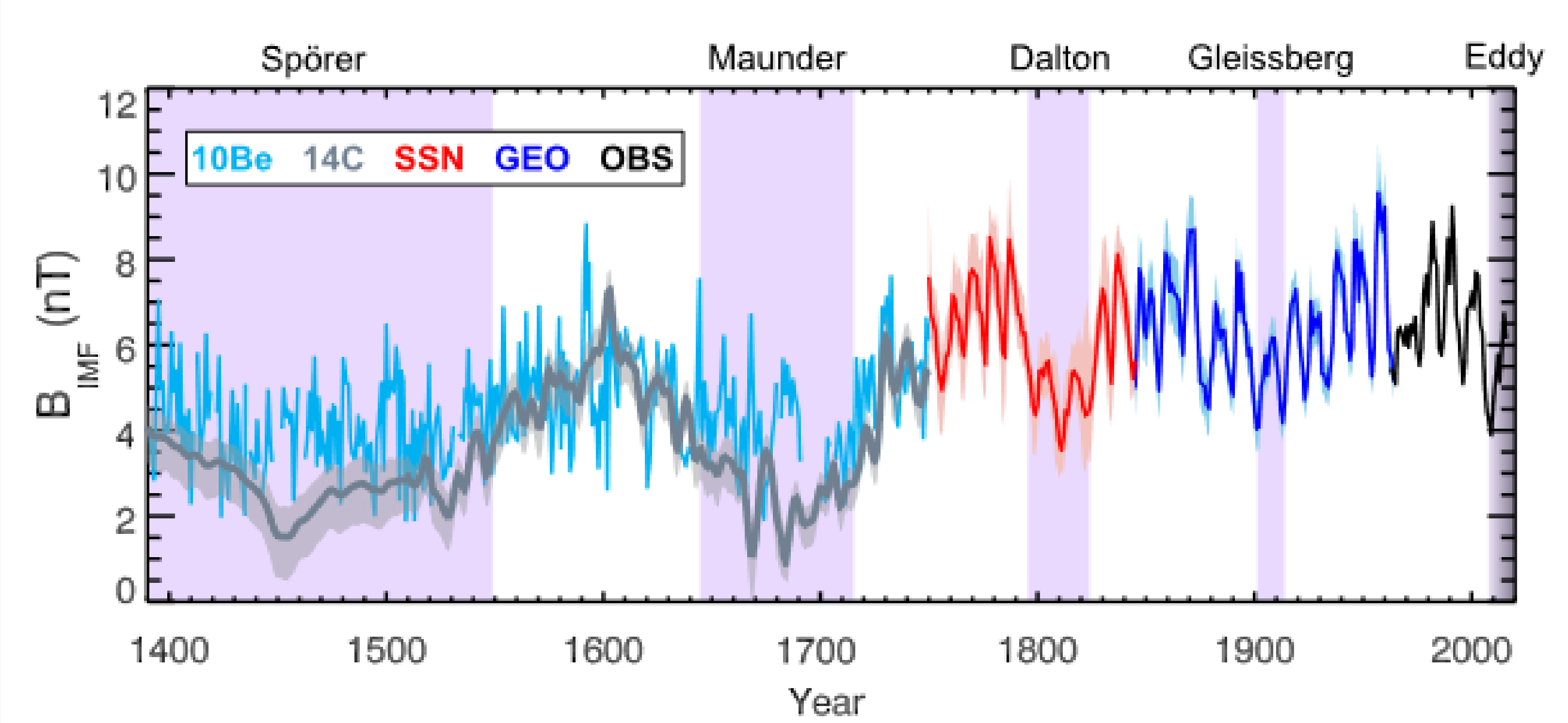




Using Virtanen et al (2022) pseudo-magnetograms

Modeling IMF field

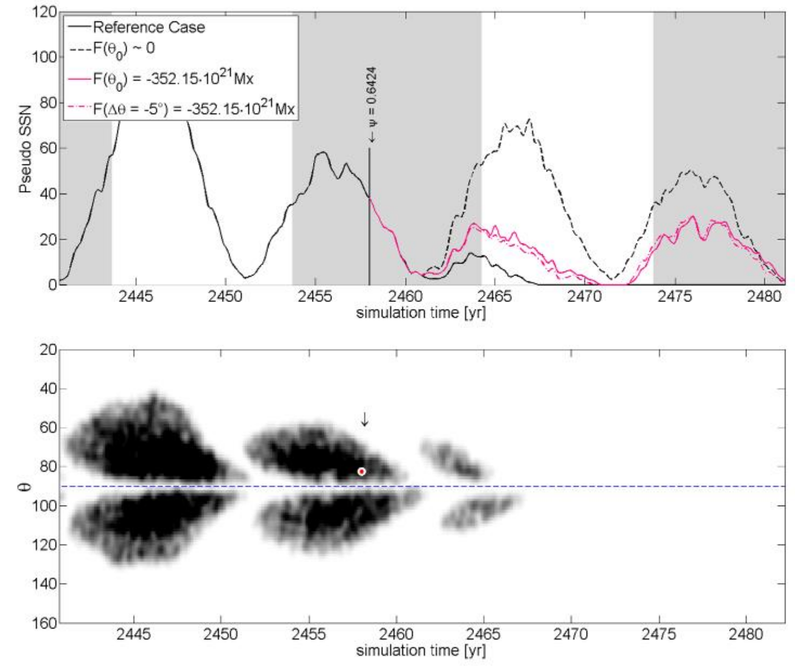
- Feynman & Crooker (1978) aa ~ Vx2B_S; Lockwood et al. (1999), Svalgaard et al. 2003; Svalgaard & Cliver 2005), McCracken & Beer (2015), Owens et al. 2016), Muscheler et al. (2016).

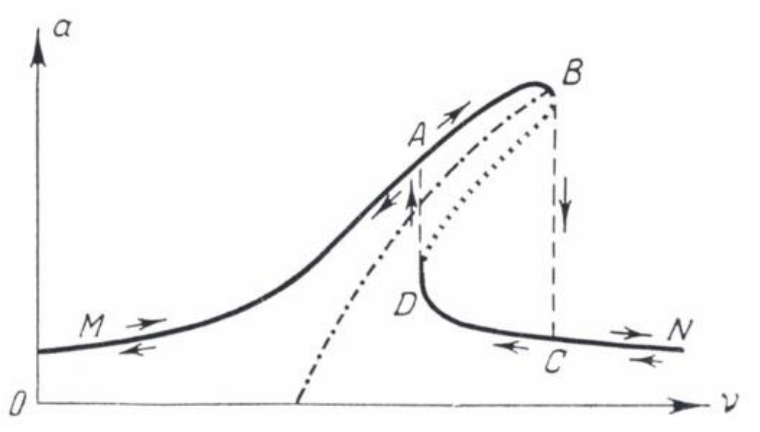


Cliver & Herbst (2018)

Grand minima

- Extended periods of extremely low sunspot numbers: Spörer (1460-1550), Maunder (1645-1715), Dalton (1796-1830), Gleissberg (1900–1910).
- MM: Sunspot activity was limited to Southern hemisphere (Ribes & Nesme-Ribes 1993). Cosmogenic isotopes still show solar cycle (Miyahara et al 2006), Poluianov et al (2014). Virtanen et al (2018) – activity in one hemisphere will maintain cycle.
- Chaotic component of dynamo, Karak & Choudhuri (2013, fluctuations in meridional circulation), Nagy et al (2017, rogue active region), Nagovitsyn & Pevtsov (2020, Duffing oscillator)
- Lubin et al (2012): 309 stars with near Sun metallicity and mass. Solar S-index was used as threshold for MM. About 11.1% are in MM.

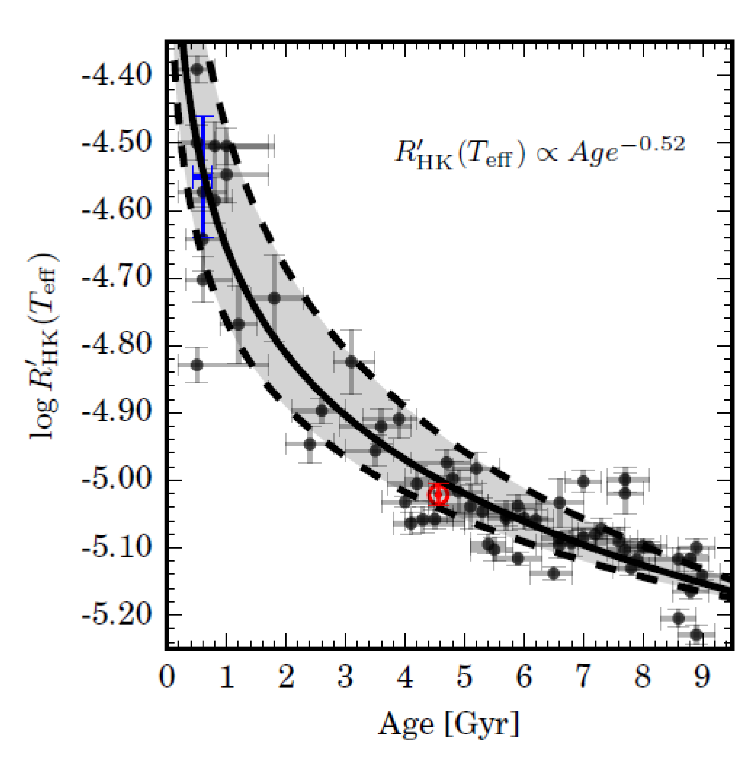




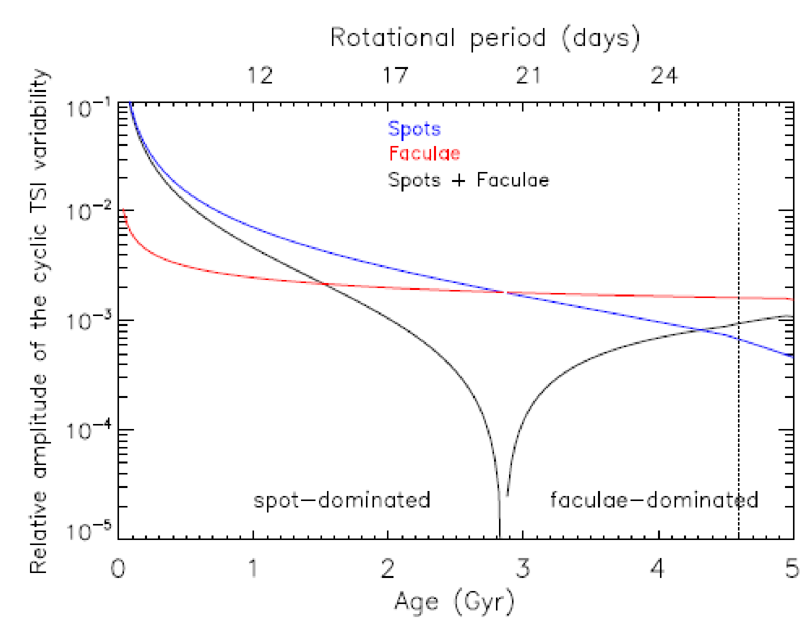
Amplitude–frequency response curve

Solar Irradiance over very long time-scales

- Lorenzo-Oliveira et al (2018): 82 solar twins (T_{eff} within 100K of the solar value, log g within 0.1 dex, and [Fe/H] within 0.1 dex); stellar rotation decreases with age and so the magnetic field. To increase sample, S-index – S_N correlation was used. S-index was found to be a good proxy for age.
- Shapiro et al (2020): S-index → plage and sunspot disk coverage, SATIRE model

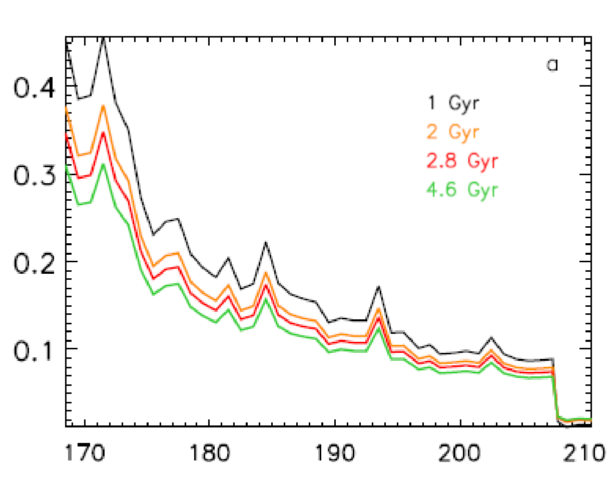


Lorenzo-Oliveira et al (2018)



Shapiro et al (2020)

Amplitude of solar cycle.



Wavelength, nm

Long-term solar activity - conclusions

- New approaches for extending data with “high information content” to past periods.
- Comparison with stellar analogues offers a glimpse to early sun and future solar activity.
- From stellar observations: younger Suns have stronger magnetic activity and larger cycle variations
- Sun’s activity is typical for its stellar age.
- In sun-like stars, after star (Sun) enters the main sequence, the (magnetic) activity gradually decreases until it is 6-7 Myr old (e.g., Lorenzo-Oliveira et al, 2018) – similar magnetic activity will continue for other 1-2 Myr?
- Cycle activity seems to be very regular over more recent period for which direct or proxy observations are available.
- Grand minima interruptions in cycle activity could be random (and thus, less predictable); some models could offer limited predictive capabilities.