What happens during a Gleissberg cycle and why ?

Kalevi Mursula

Space Climate Group, Space Physics and Astronomy Research Unit, University of Oulu, Oulu, Finland (kalevi.mursula@oulu.fi)

Thanks to:
Timo Asikainen, Alexei Pevtsov, Timo Qvick, Ismo Tähtinen, Anthony Yeates

Contents

- Gleissberg cycle (GC)
- Sunspots and weaker magnetic elements
- Sunspots and radio fluxes
- rY: Longer-term EUV proxy from Sq currents
- Correlating rY with other EUV proxies
- eEUV: rY-extensions of solar EUV proxies
- Implications to ionospheric driving
- What may happen in the Sun: Implications to solar atmosphere
- What happened to the Sun: Relation to solar stellar evolution
- Gleissberg cycle and solar relic field
- Conclusions

Main message

Sunspots give a limited view of the long-term evolution of solar magnetism

There are important systematic differences between solar parameters over the Gleissberg cycle

These differences have interesting consequences to the Earth

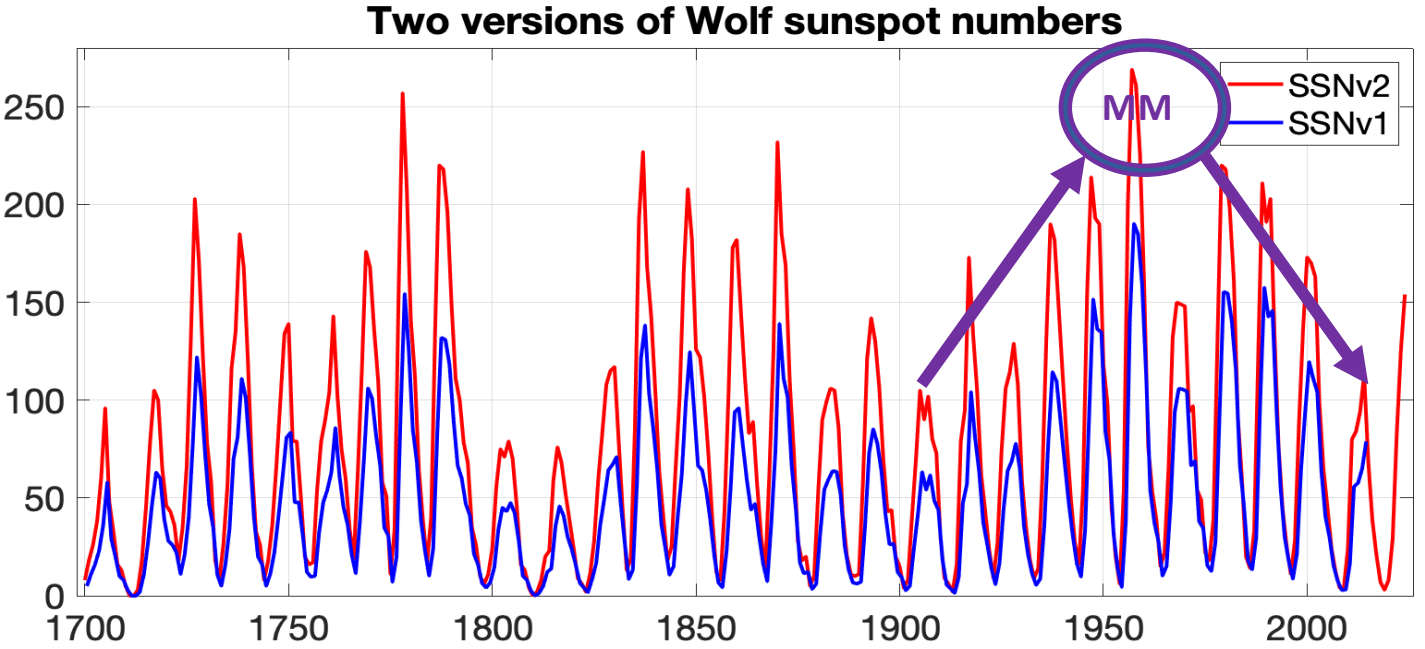
Ultimate explanation may be the existence of relic fields

Gleissberg cycle (GC)

Modern Maximum and two earlier GCs

Main features of sunspot activity:

- 11-year solar cycle (Schwabe cycle): Current cycle is number 25.
- Roughly 100-year Gleissberg cycle (GC)
- Latest GC maximum during solar cycle 19: Modern Maximum (MM)



Rise of MM from cycle 14 to cycle 19 and its decay to cycle 24 by factor of 2.5 in cycle height.

Red: Version 1 Wolf numbers
Blue: Version 2 Wolf numbers

Many effects from increasing sunspot activity

- Increases solar eruptions (CMEs, SEPs, flares,..)
  => more severe Space weather

- Increases solar total and spectral irradiances (at least until.. ?)
  => Increases global temperature

- Modifies solar surface magnetic field and strengthens polar fields
  => Enlarges polar coronal holes
  => Increases high-speed solar winds

- Enhances the interplanetary magnetic field but thins the heliospheric current sheet.

- Reduces galactic cosmic ray flux

- ...

How does this happen in detail?

- Do sunspots and the weaker magnetic field elements evolve in the same way over the Gleissberg cycle ?

- Do the many solar parameters (like solar spectral emissions) evolve synchronously over the Gleissberg cycle ?

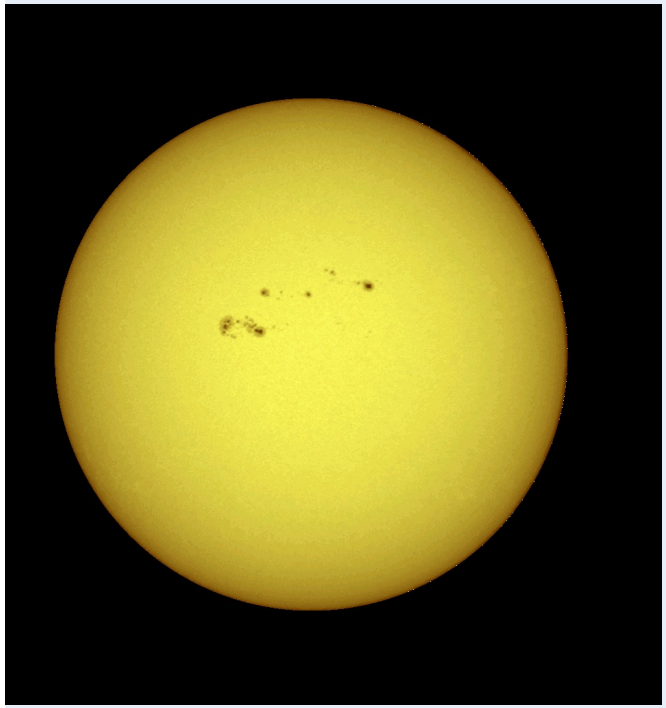
- Are their relations stable at all activity levels ?

- => In general:
  How does solar photosphere (e.g. sunspots) and chromosphere (e.g. EUV) evolve with respect to each other?

- What information can this give us ?

Sunspots and weaker magnetic elements

Sunspots: Only one form of solar magnetic field



Sunspots appear on the solar photosphere (¨solar surface¨).

Sunspots are measures of the strongest magnetic fields (B > 1400G)

However, sunspots form **only a small fraction** of total magnetic field on the solar surface.

Other proxies are needed to have information on the **long-term evolution of magnetic fields of lower intensity** !

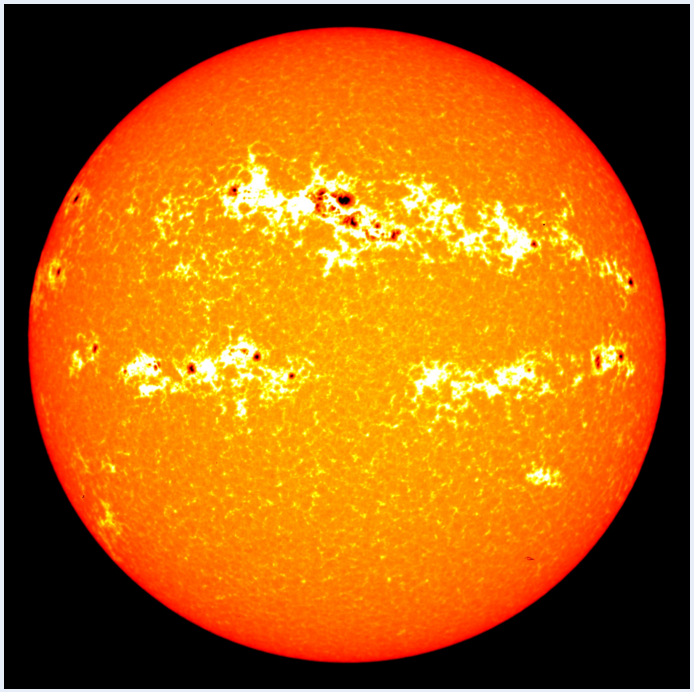
Radio and EUV emissions mainly come from plages

Most (>60%) of solar radio emissions are produced in **non-sunspot active regions (faculae, plages)** in solar chromosphere and lower corona via bremsstrahlung.

Non-sunspot active regions have less intense magnetic fields (50G-800G) but much larger areas than sunspots.

A small fraction of radio emissions is produced in sunspots via gyroresonance.

HERE: Radio and EUV emissions used as a proxy of plages (chromosphere)

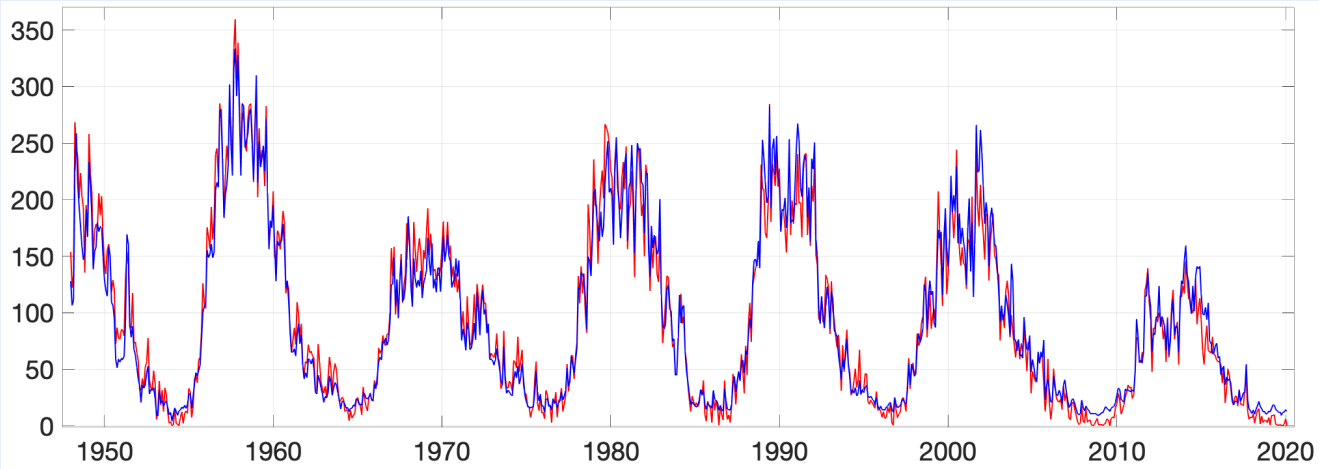


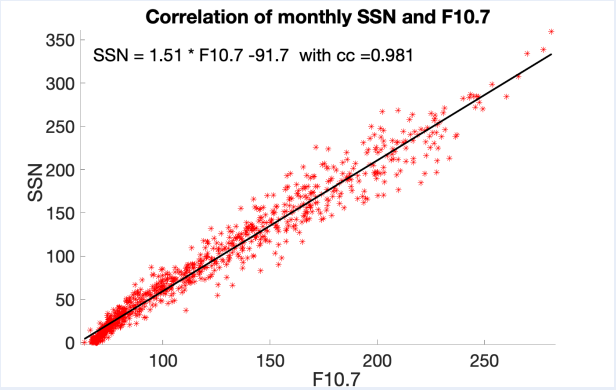
Large active regions (faculae) may also include some sunspots.

Sunspots and radio fluxes

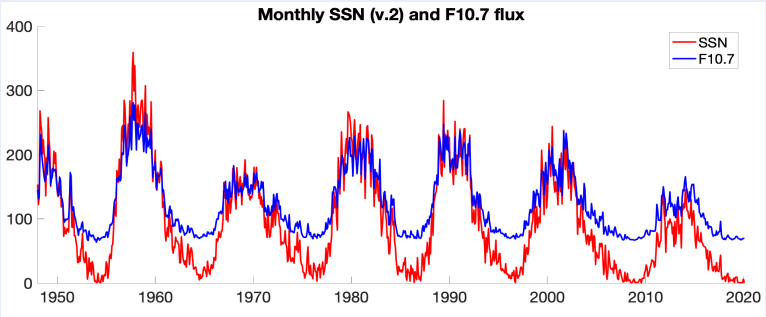
Two long proxies: Radio 10.7cm flux and sunspots

F10.7 index and sunspot numbers correlate very well, especially at monthly resolution and longer.. **But is this relation stable in time ?**





Monthly sunspots (version 2; red line) and correlated F10.7 cm flux (blue line) in 1947-2019.



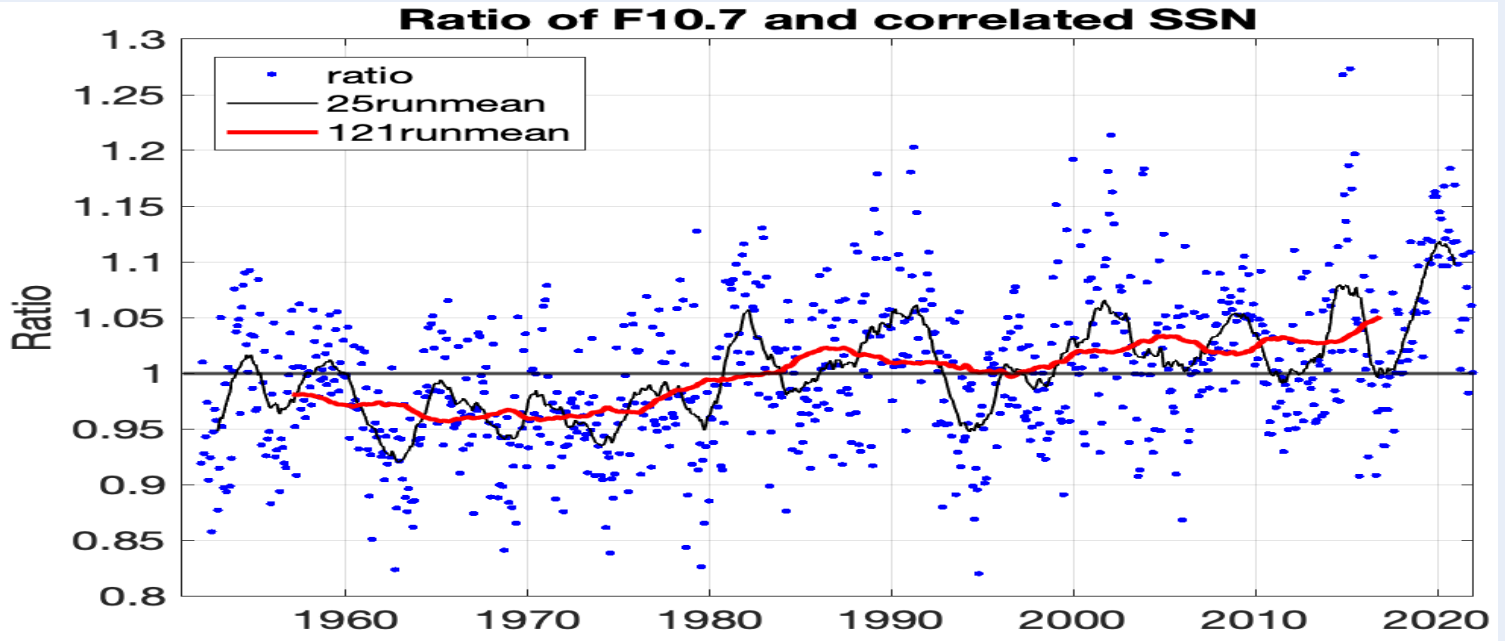
Reanalysis of monthly F10.7/corrSSN ratio

Clette (2021): F10.7 is inhomogeneous due to an abrupt level change in 1980

BUT: F10.7/SSN ratio increases from 1970s until 2010s. **What is the truth?**

Several short (1-2 year) ¨humps¨ seen, mostly around solar maxima.

Monthly ratios of F10.7 and correlated SSN for 1952-2021 (blue dots).
Black and red curves denote the 25-month and 121-month running means of monthly ratios.



Long-term EUV proxies: Radio fluxes

Long-term measurements of solar radio fluxes in Canada since 1947 and Japan since 1950s.

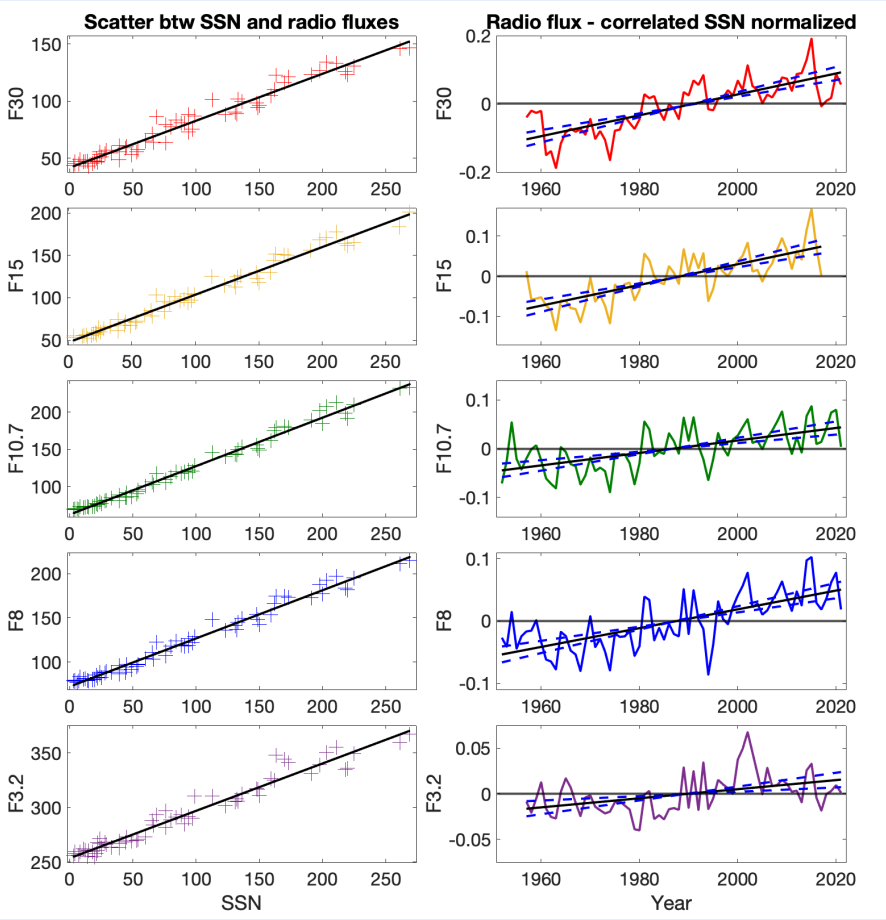
All five radio fluxes **increase** with respect to SSN from 1960/1970s to 2010s.

This confirms the long-term drift between SSN and EUV irradiance.

Relative increase varies from 3% to 20%.
The higher the origin of the radio flux is, the larger the difference to SSN !

This indicates height-dependent changes.

Five wavelengths: 30cm, 15cm, 10.7cm, 8cm, 3.2cm.

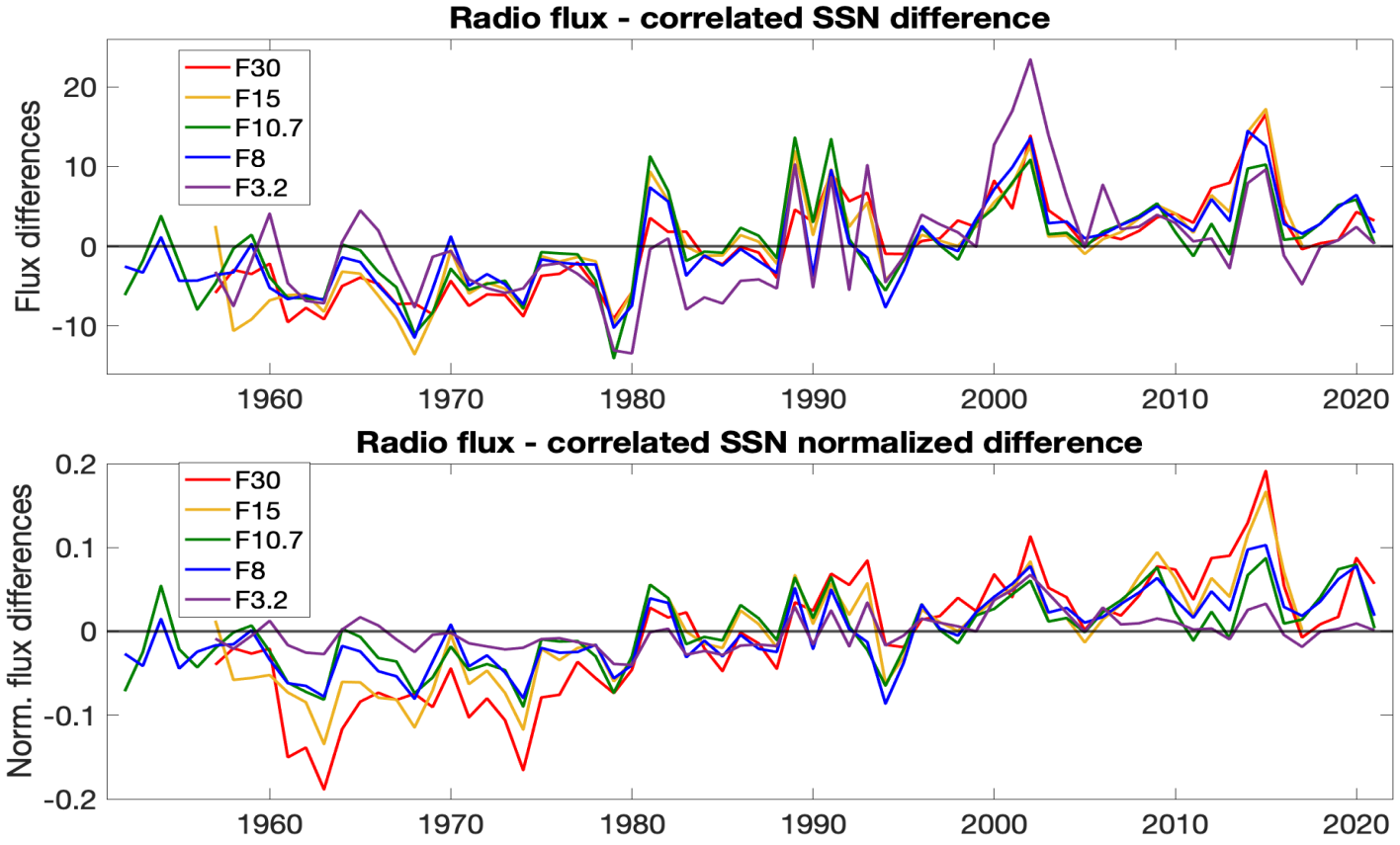


Mursula et al., A&A, 2024

Five radio fluxes: Residuals of correlation

Relatively more sunspots than radio flux in 1960s-1970s.

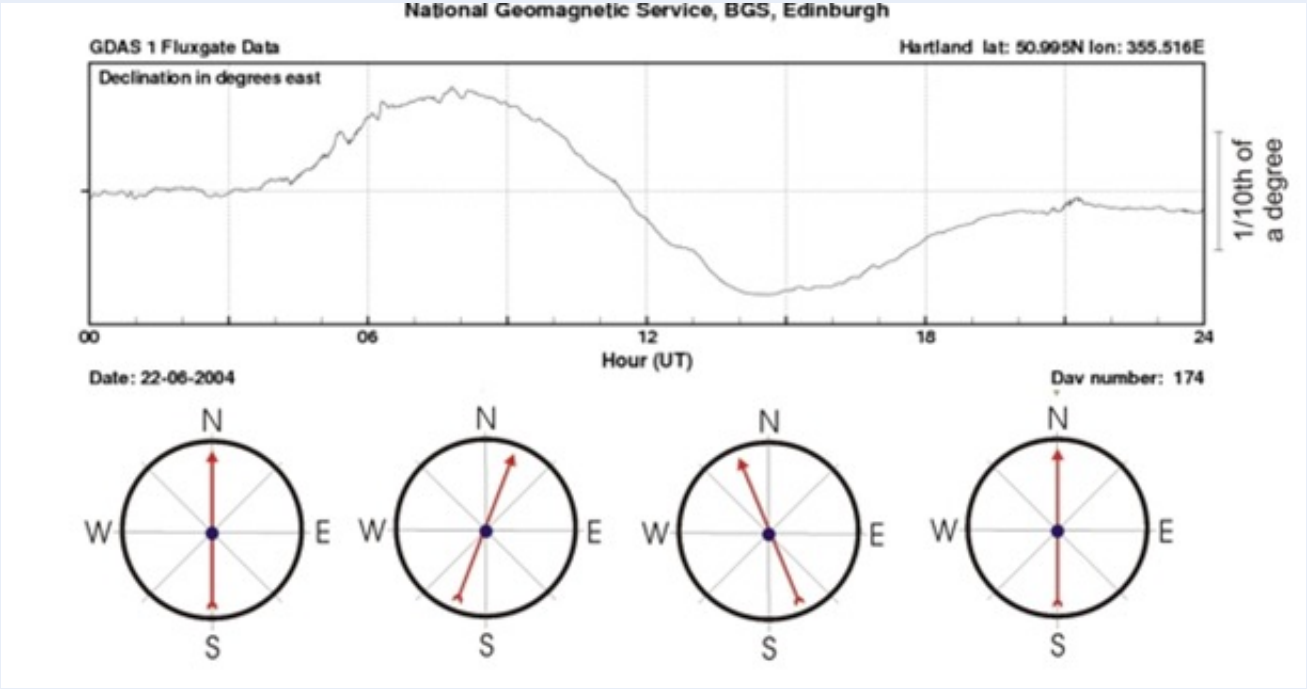
Relatively more radio flux than sunspots 1990s-2010s.



Residual of correlation between 5 solar radio fluxes and sunspot number.

rY: Longer-term EUV proxy from Sq currents

Daily variation of declination found in 1722





'honest' George Graham

Declination or the magnetic Y (East)-component shows a systematic daily variation.

Sunspot connection found in 1851-52



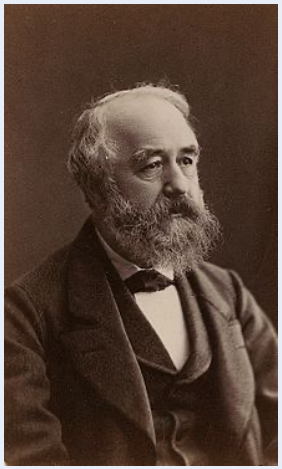
Johann von Lamont



Sir Edward Sabine



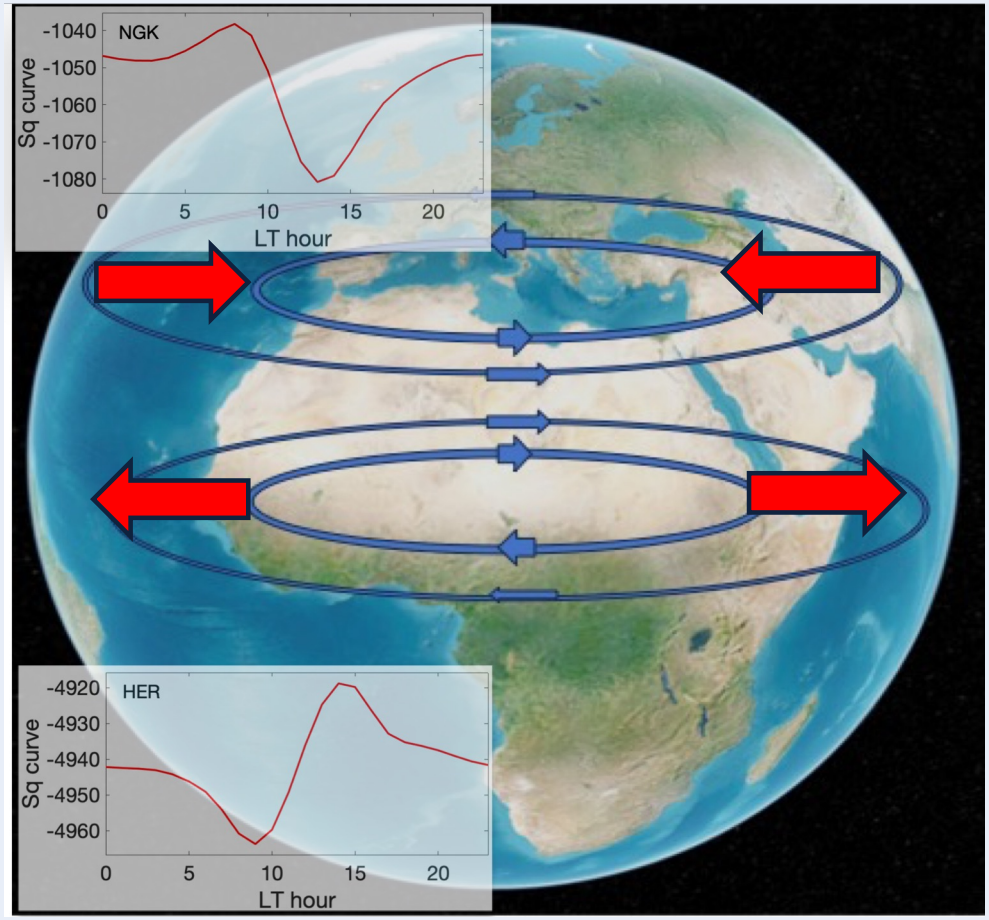
Jean-Alfred Gautier



J. Rudolf Wolf

Von Lamont, Sabine, Gautier and Wolf in 1851-52 found that the amplitude of the daily declination variation follows the occurrence of sunspots over the recently detected (by H. Schwabe) sunspot cycle.

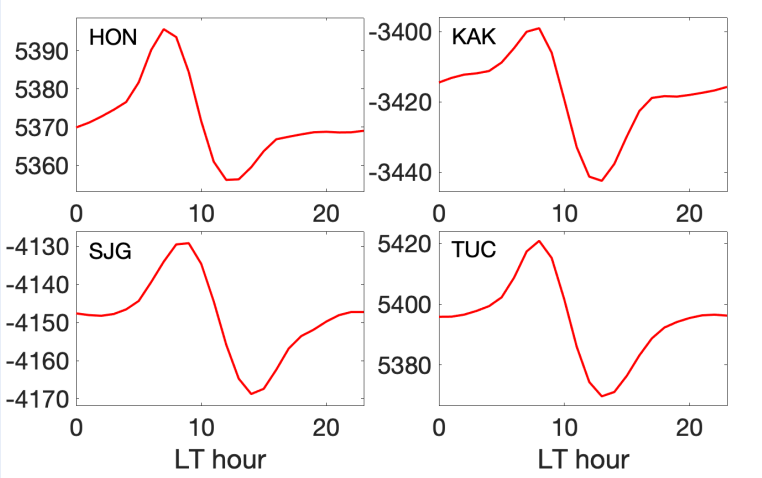
S_R (also called S_q) current system



Dayside ionospheric S_R current system produced by **solar EUV radiation** and Earth rotation.

S_R causes a systematic daily variation in declination.

This bipolar-type variation is fixed at local time and opposite in the two hemispheres.



Daily Y-component at 4 other low/mid-latitude stations

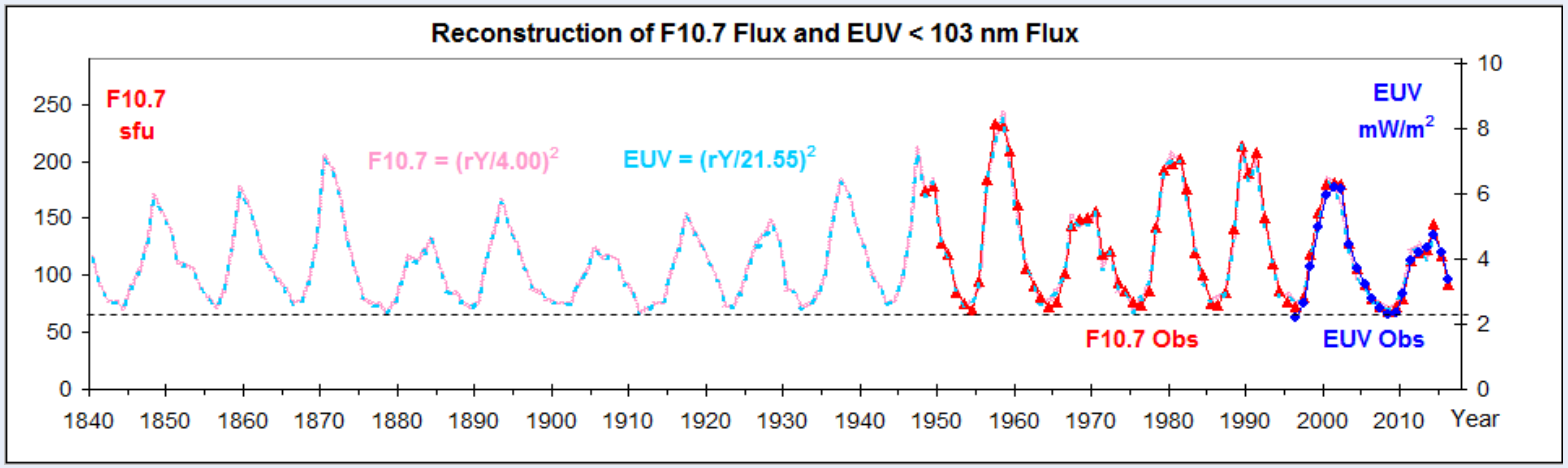
rY index

rY index: the daily range (amplitude) of the magnetic Y (East)-component

In 1850s Wolf used rY values to fill in data gaps when constructing the new sunspot number series (=>Wolf numbers are not purely solar !)

=> **rY depends of solar EUV irradiance**

Leif Svalgaard re-invented this method in 2000s.





Kalevi Mursula at the First Workshop on Sun and Space Weather, Antalya, Türkiye, 28/9/2026

Data from 8 long-operating stations

Use magnetic data from the following 8 reliable long-term or early stations:

- 4 Dst stations: Hermanus (HER), Honolulu (HON), Kakioka (KAK), San Juan (SJG)
- Niemegk (NGK): standard station for Kp/Ap (and other) geomagnetic indices
- Cheltenham-Fredericksburg (CLH)
- Ekaterinburg (EKT)
- Tucson (TUC)

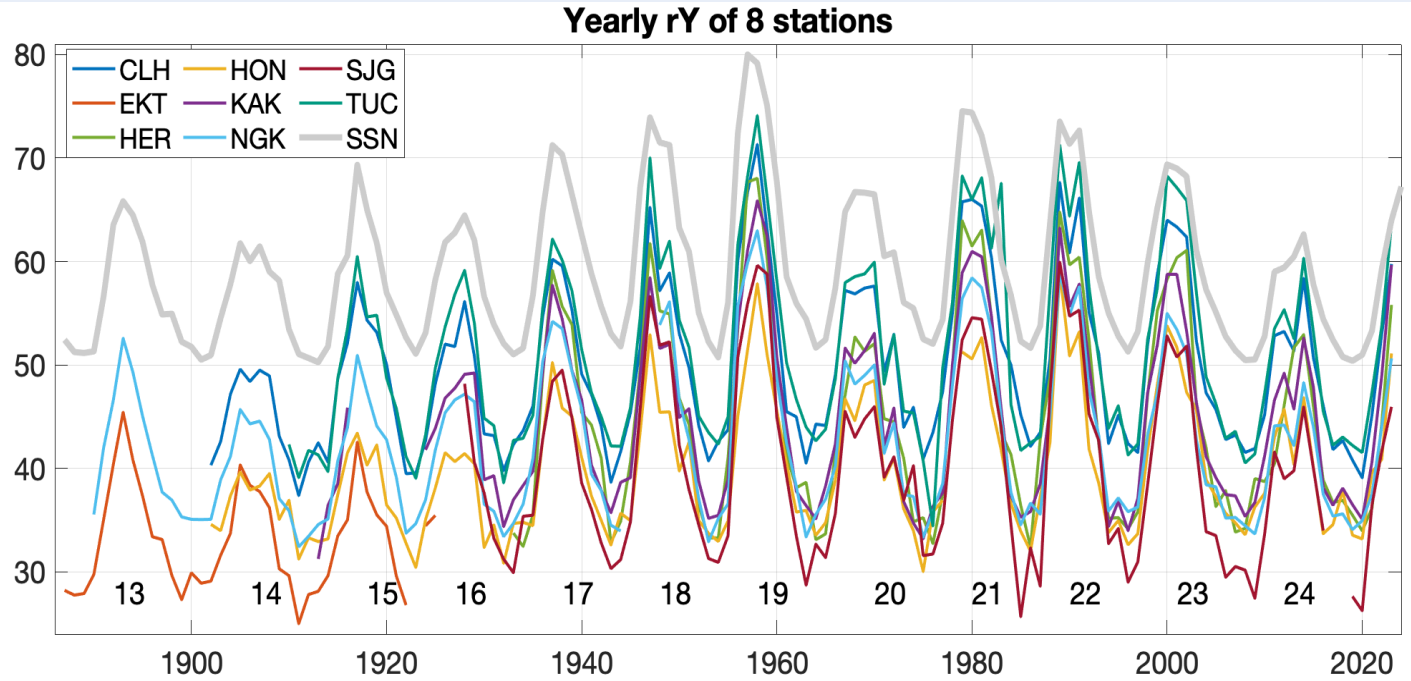
Station	GGlat	GGLong	MiUT	Start	End	Omitted
CLH	38.73	1-76.84	5	1902	2023	1901
EKT	56.83	60.63	20	1887	1925	1923
HER	-34.43	19.23	23	1933	2023	1932
HON	21.32	-158	11	1902	2023	1978
KAK	36.23	140.18	15	1913	2023	1917-1923
NGK	52.07	12.68	23	1890	2023	1945-1947
SJG	18.38	-66.12	4	1926	2023	1927,2017,2018
TUC	32.17	-110.73	7	1910	2023	1909

Mursula, JASTP, 2025

Yearly rY indices of 8 stations

Despite very different secular variations, the overall scale and temporal evolution of all 8 station-based rY indices are very similar.

A standardised **centennial rY index, a new measure of EUV irradiance,** can be reconstructed from these station-based rY indices **from 1890 onward.**



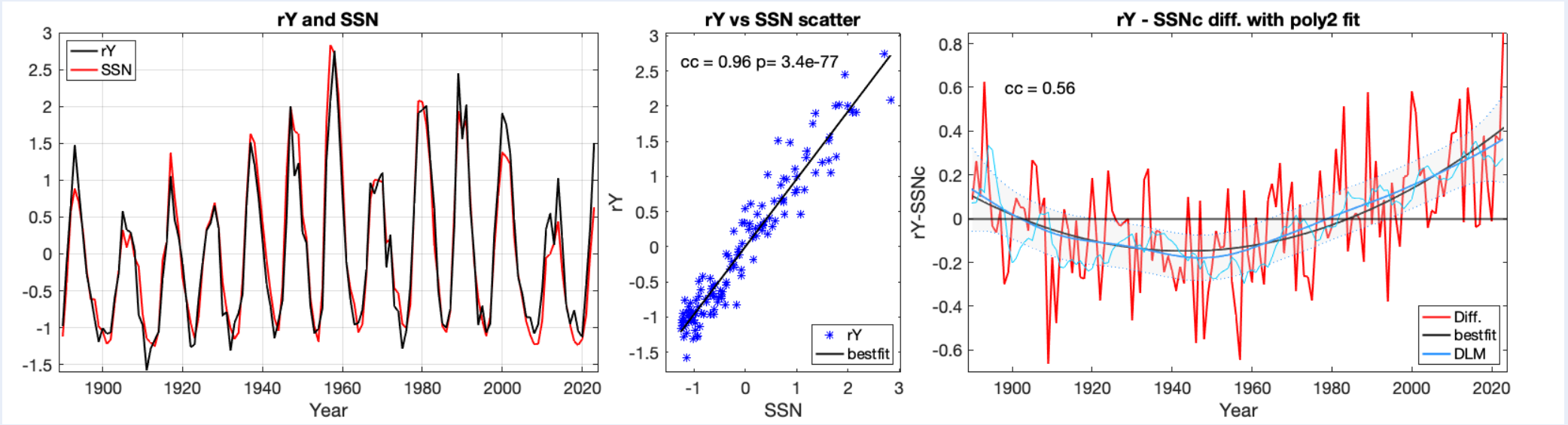
Mursula, JASTP, 2025

Centennial rY index of EUV vs. SSN

rY shows a significant quadratic evolution with SSN over the last 130 years.

SSN is relatively larger than rY in 1940s-1960s. (More SSN than EUV)
rY is relatively larger than SSN in 1890s and since 1990s. (More EUV than SSN)

Relation between SSN and EUV oscillates with the Gleissberg cycle.



Mursula, JASTP, 2025

Correlating rY with other EUV proxies

EUV proxies to be extended by rY

SSN

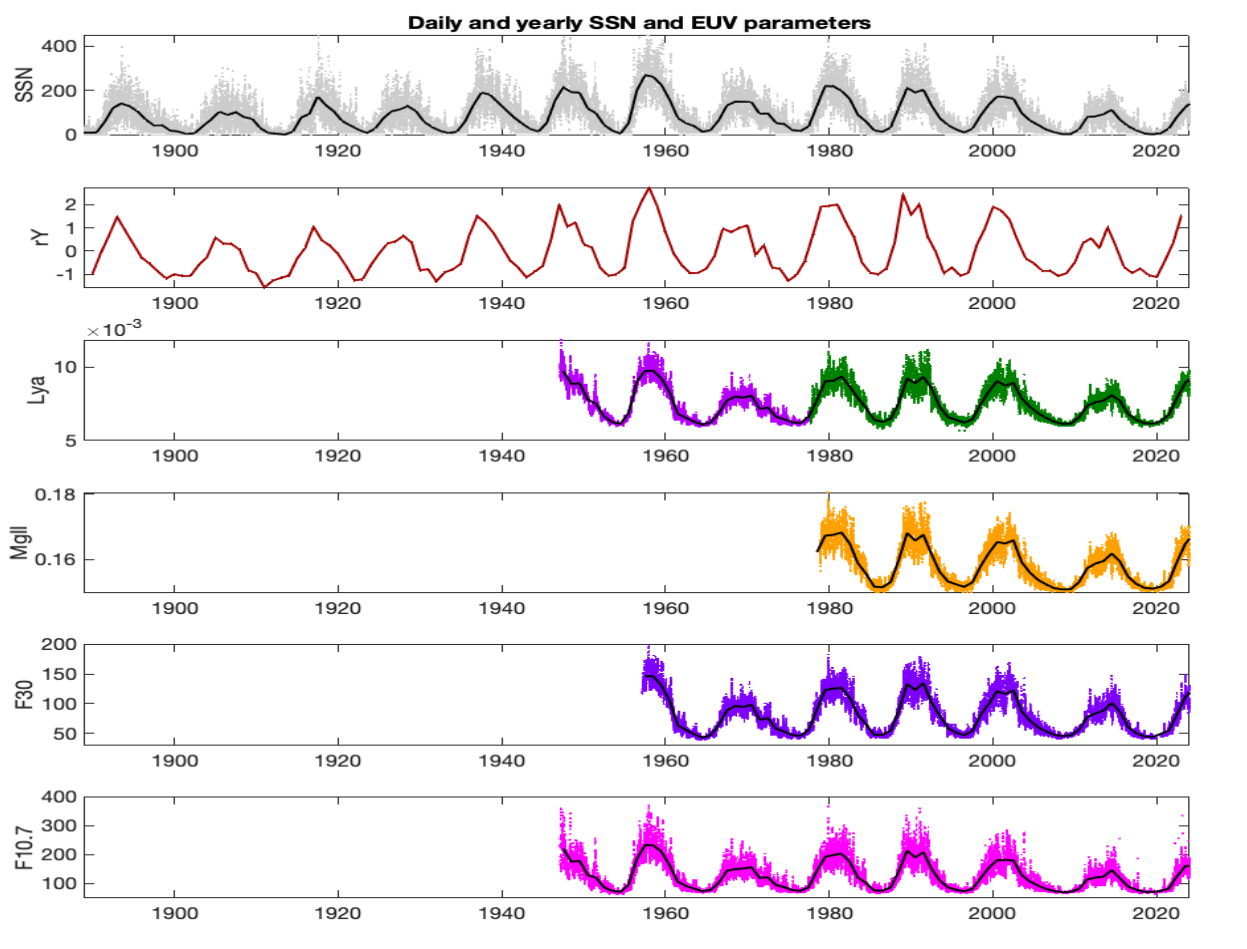
rY

Ly-alpha

MgII index

F30

F107

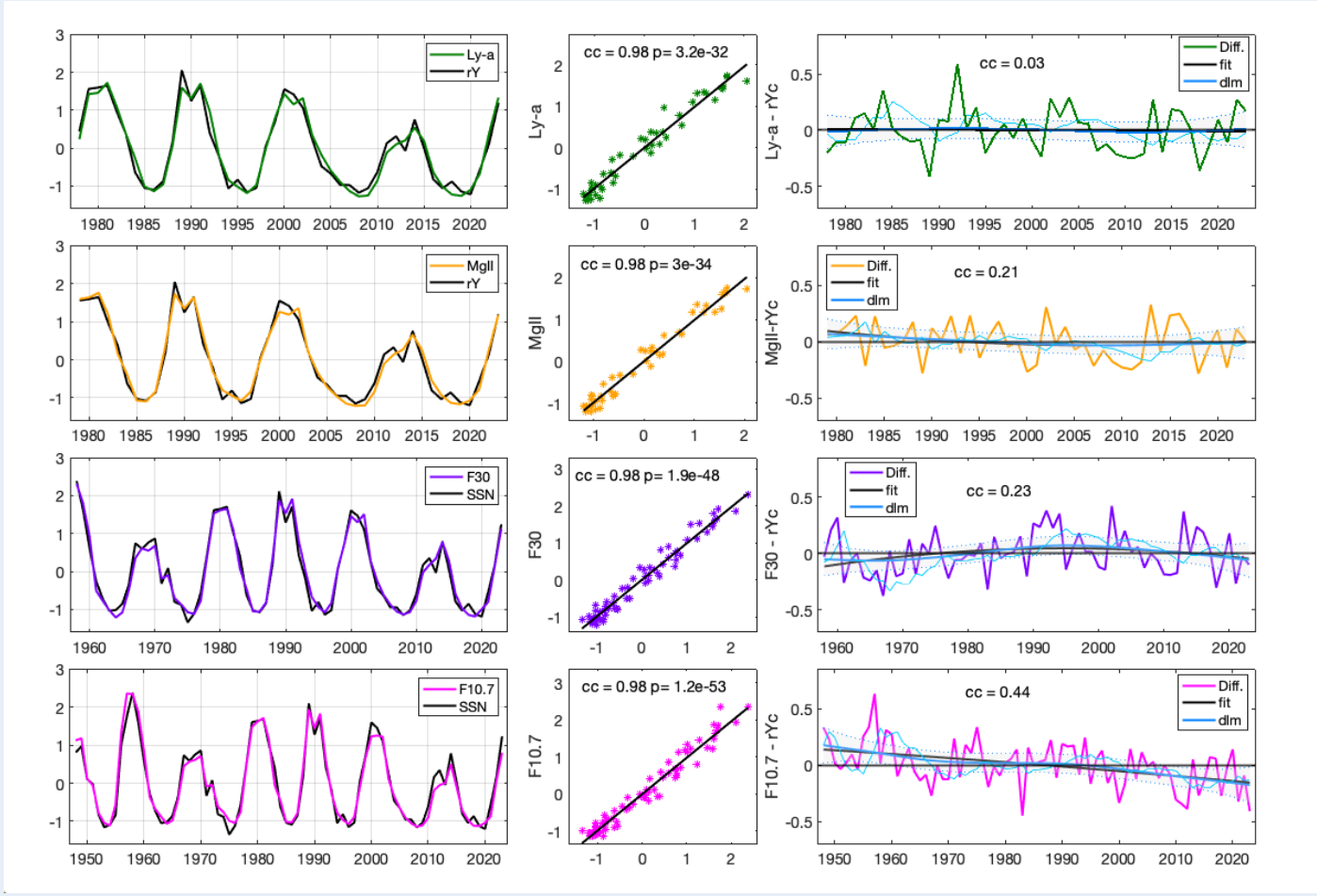


Correlating rY with other EUV proxies

rY index is long-term **stable** with respect to
- Ly-alpha
- MgII index
- F30

This shows that rY is indeed a reliable long-term EUV proxy since late 1950s.

However, rY increases with respect to F10.7.
(See F30 vs F10.7)



Implications to ionospheric driving

Unstable solar driving of ionosphere

Solar driving of ionosphere by certain solar EUV proxies is temporally variable.

Laštovička (GRL, 2019):

- foF2 relation with F10.7 is different in 1976-1995 and in 1996-2014

Laštovička & Burešová (SpW, 2023):

- F30 and Mg II outperform F10.7 and sunspot number in temporal consistency of ionospheric driving

- Recommended F30 and Mg II as best EUV proxies for ionospheric climatology and trend studies

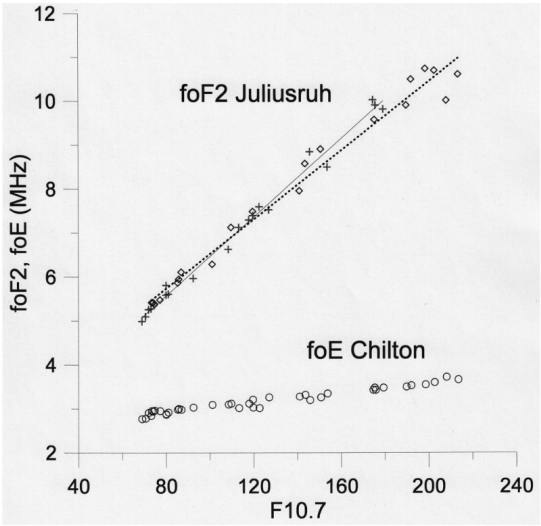


Figure 1. Dependence of fo*F*2 (Juliusruh) and fo*E* (Chilton) on solar activity (*F*10.7), 1976–2014. Empty squares, dotted line—fo*F*2, 1976–1995. Crosses, full line—fo*F*2, 1996–2014.

NOW: rY is likely the best long-term driver for the ionosphere.

No wonder: It is constructed from the ionosphere.

It applies during low and high solar activity.

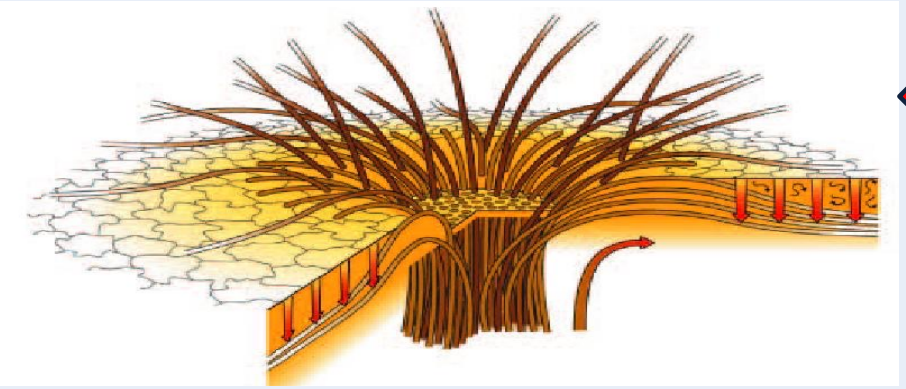
What may happen in the Sun: Implications to solar atmosphere

Different evolution in sunspots and plages/faculae

Magnetic elements of different intensity evolve differently over the Modern Maximum.

- Sunspots grow relatively larger than weaker-field faculae/plages when long-term solar activity is increasing/high.
- Faculae/plages grow relatively larger than sunspots when long-term solar activity is subsiding/low.

This suggest a **change in the (canopy) structure and/or the intensity distribution of solar magnetic fields** over the Modern Maximum.



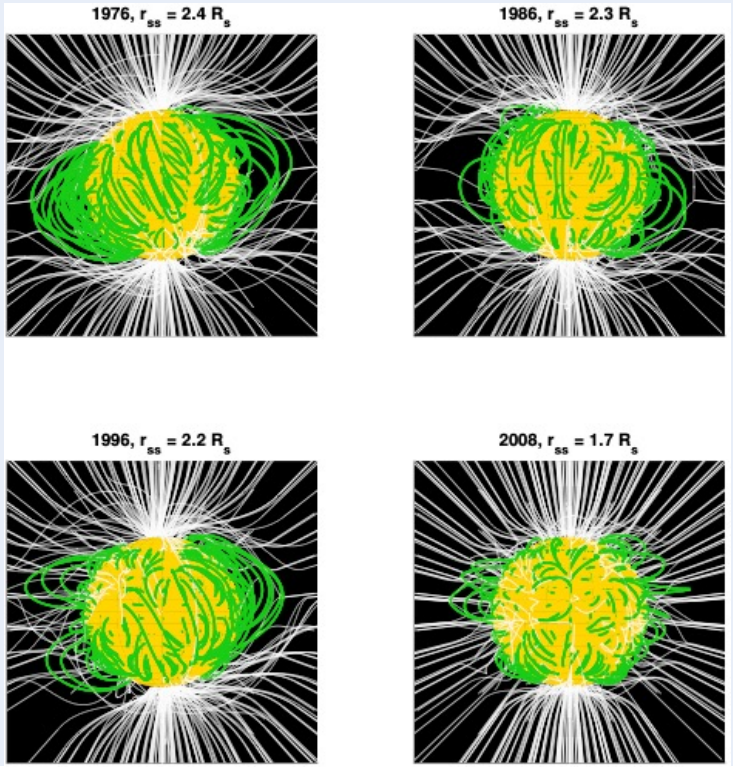
Plages / Chromosphere+low corona

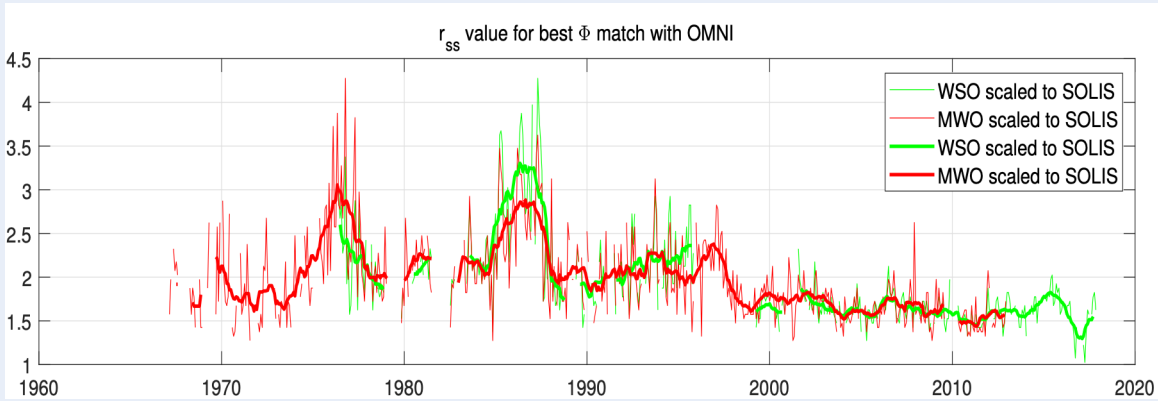
Sunspots / Photosphere

Long-term change in solar magnetic structure

A change in solar magnetic field structure from 1970/1980s to 2010s:
Solar coronal field lines become shorter and connect more locally: Corona shrinks !

=> => This brings plasma lower in the solar atmosphere !





Virtanen, J. Koskela, and K. Mursula, Abrupt shrinking of solar corona in the late 1990s, ApJ. Lett., 2020

What may happen to the Sun: Relation to solar stellar evolution

Stellar implications: Evolution of solar brightness

- Early, very active Sun was dominated by sunspots (spot-dominated Sun), and increased activity reduced solar brightness (dark sunspots decrease irradiance).
- NOW (and later), the Sun is plage/facula-dominated, and increased activity increases solar brightness (faculae are brighter than mean surface).
- **The Sun is now relatively close to the turn from a spot-dominated to facula-dominated phase**.

Our results suggest:

- This turn is not sharp and its evolution is affected by overall magnetic activity.
- **Gleissberg cycles cause variations in spot to facula -ratio around this turn.**
- Stellar brightness studies need revision.

Gleissberg cycle and solar relic field

Relic field can persist in the Sun

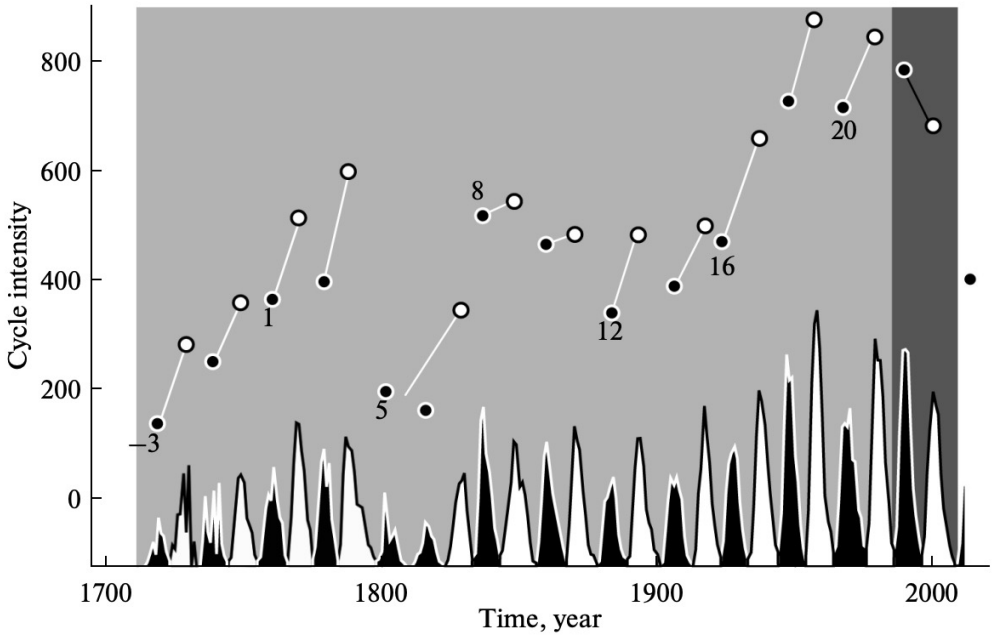
Relic electric current and magnetic field CAN PERSIST in the Sun from the times of solar system formation because of a very long diffusion time (plasma is a perfect conductor; Cowling, 1945).

Relic magnetic field was suggested to explain the long-held **Gnevyshev – Ohl rule:**
An odd solar cycle is more intense than the previous even cycle.

Valid for 200 years, until broken in SC24.

Odd cycles are **higher =>**

- Relic magnetic field is **northward oriented**
- Relic electric currents flow in the direction of solar rotation.

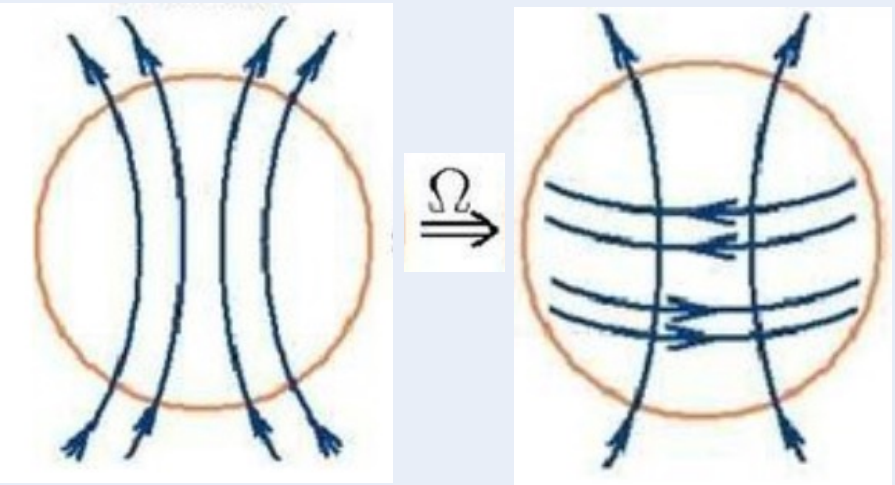


Dynamo + relic fields during positive minimum

Schematic of how a northward directed relic affects the dynamo fields during a positive minimum.

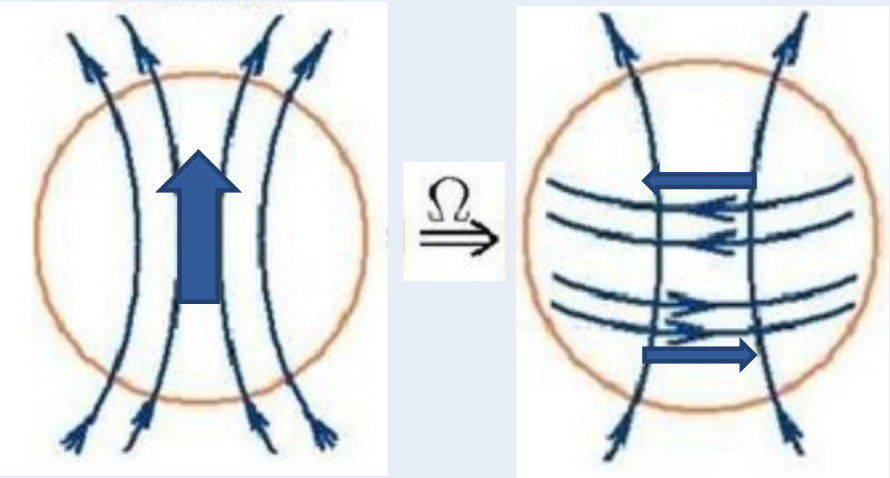
Regular dynamo mechanism

positive minimum **odd** cycle maximum



Relic + dynamo:

Relic enhances equally both hemispheres

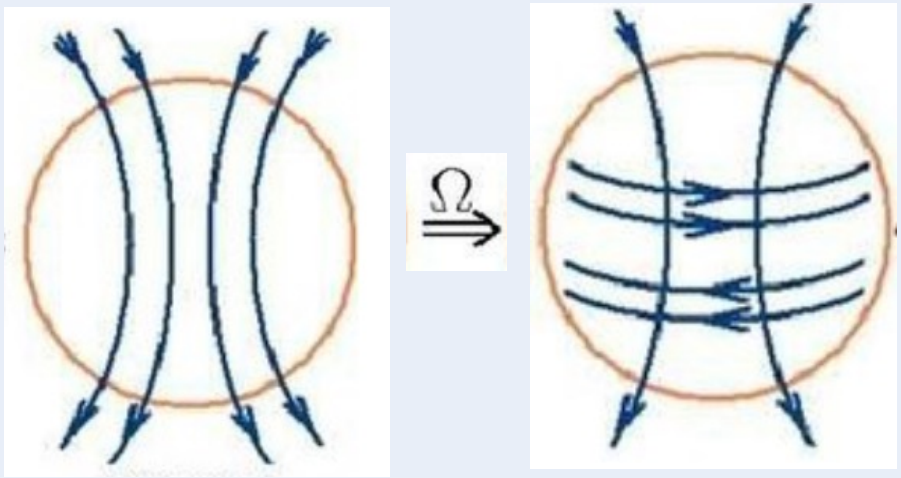


Dynamo + relic fields during negative minimum

Schematic of how a northward directed relic affects the dynamo fields during a negative minimum.

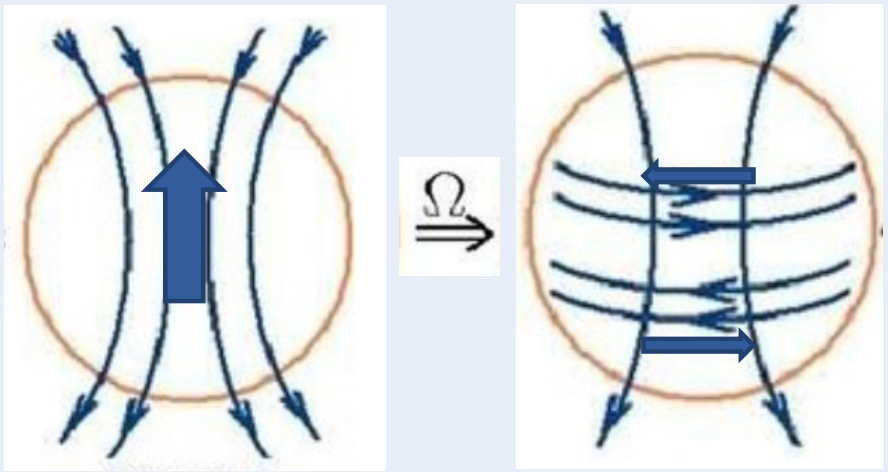
Regular dynamo mechanism

negative minimum **even** cycle maximum



Relic + dynamo:

Relic reduces equally both hemispheres

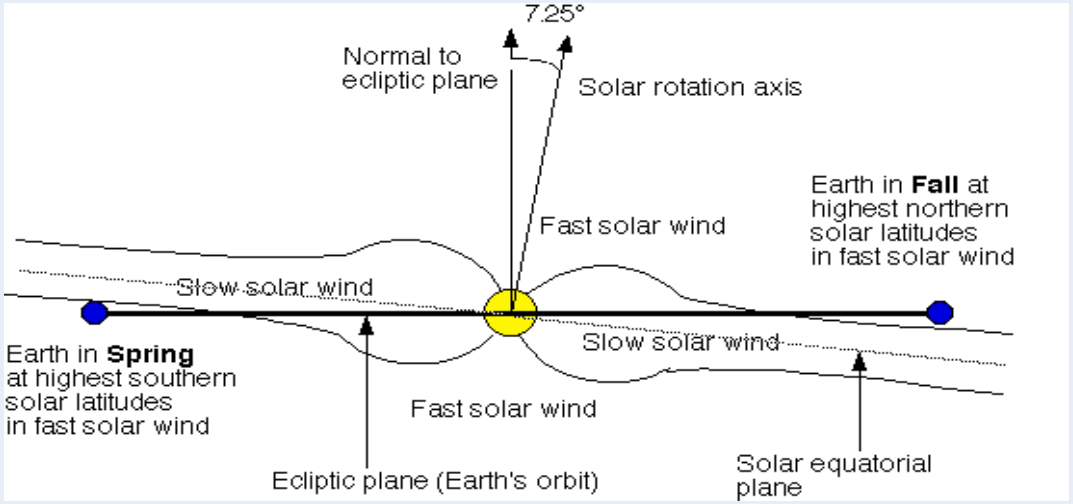


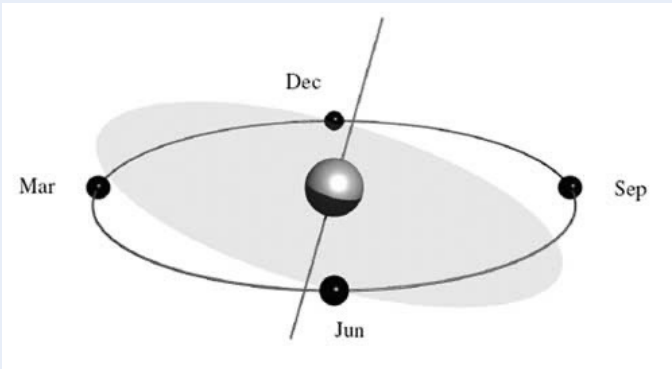
Radio flux at different heliolatitudes

HERE: Novel method to use the Earth´s annually varying heliolatitudinal vantage point to prefer the flux from the Northern hemisphere in Fall and from the South in Spring.

Solar rotation axis is tilted by 7.25° with respect to the ecliptic. Solar northern (southern) hemisphere is better visible in Fall (Spring) around the high heliolatitude times.

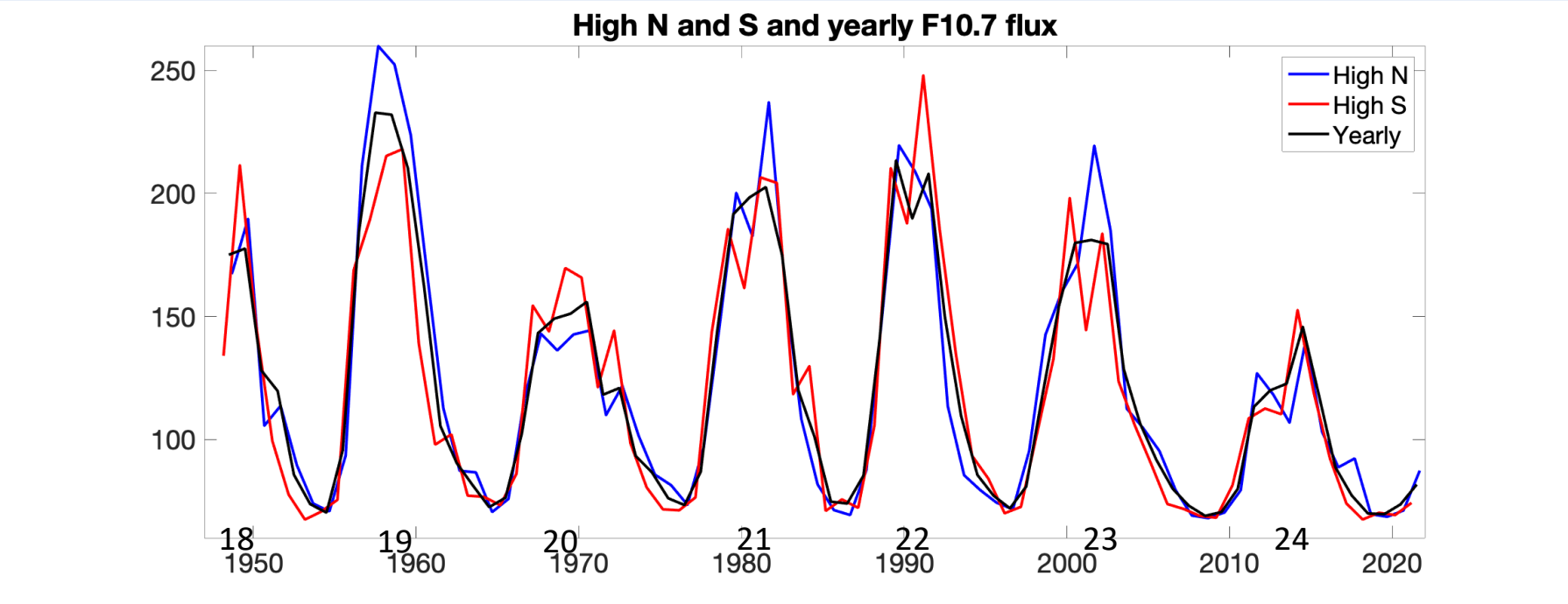
Earth has its highest northern (southern) heliolatitude on September 7 (March 6).





High-latitude F10.7 radio flux

F10.7 index calculated above 7 degrees of northern and southern helio-latitude.
We call them high-latitude fluxes.
- High south from Feb 19 to March 23; High north from August 22 to Sep 26. (> one solar rotation)
Large differences between hemispheres. **Maxima clearly alternate from S in even to N in odd cycles.**



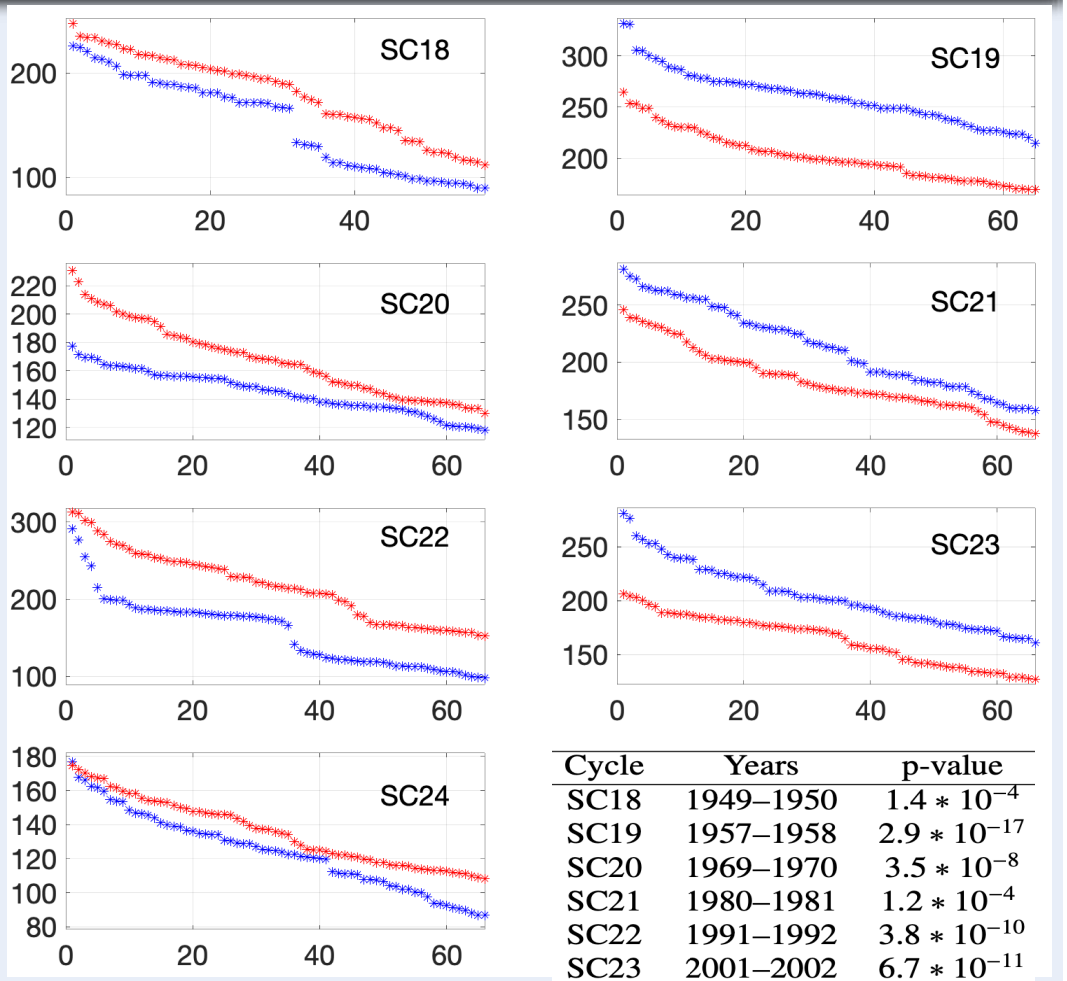
Rank order of high-latitude flux values

In even cycles (left column), southern (red) high-latitude daily flux values are systematically above the northern (blue) fluxes in descending rank order.

Opposite order is true for odd cycles (right column).

Two-sided Wilcoxon rank sum test with 99% confidence limit shows that, for **each cycle, the N and S populations are different**, with p-values given in Table.

This shows that differences between the fluxes of the dominant and recessive hemispheres and, thereby, the corresponding **hemispheric asymmetries, are not due to a small number of extreme events, like large flares,** but due to a **systematic difference** between the flux distributions around cycle maxima.

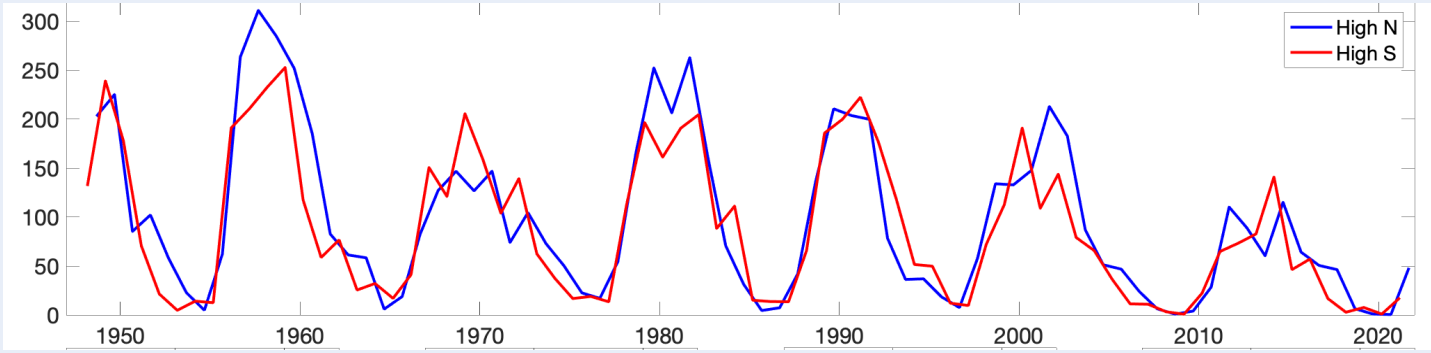


Cycle	Years	p-value
SC18	1949–1950	$1.4 * 10^{-4}$
SC19	1957–1958	$2.9 * 10^{-17}$
SC20	1969–1970	$3.5 * 10^{-8}$
SC21	1980–1981	$1.2 * 10^{-4}$
SC22	1991–1992	$3.8 * 10^{-10}$
SC23	2001–2002	$6.7 * 10^{-11}$
SC24	2014–2015	$8.2 * 10^{-4}$

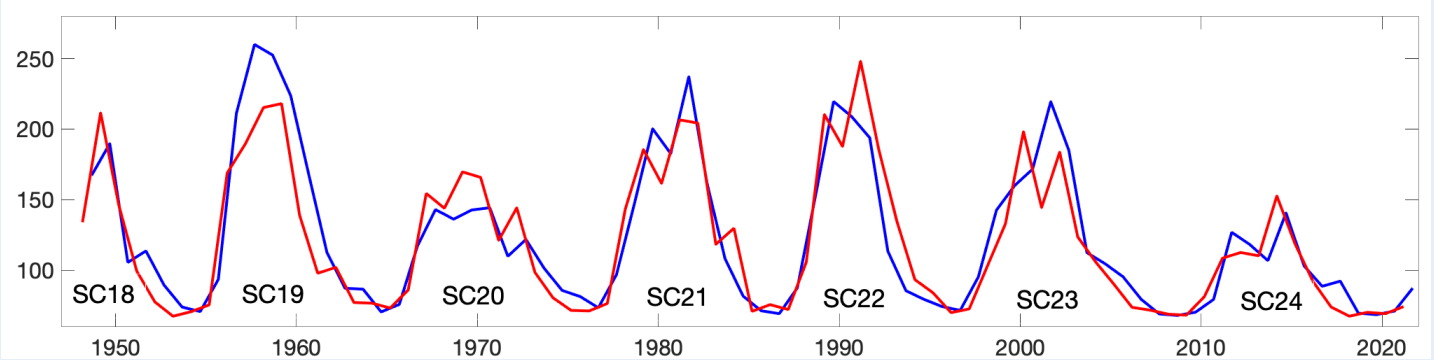
High-latitude radio fluxes and sunspot numbers

High heliolatitude **sunspot numbers depict the same pattern of alternating** hemispheric dominance.
This pattern is in overall **magnetic flux emergence**, and it is related to the **Hale cycle**.
Earlier studies of hemispheric asymmetry have not found this systematic pattern.

Sunspot numbers



Radio flux



Mursula,A&A, 2023

Relative asymmetry of high-latitude fluxes

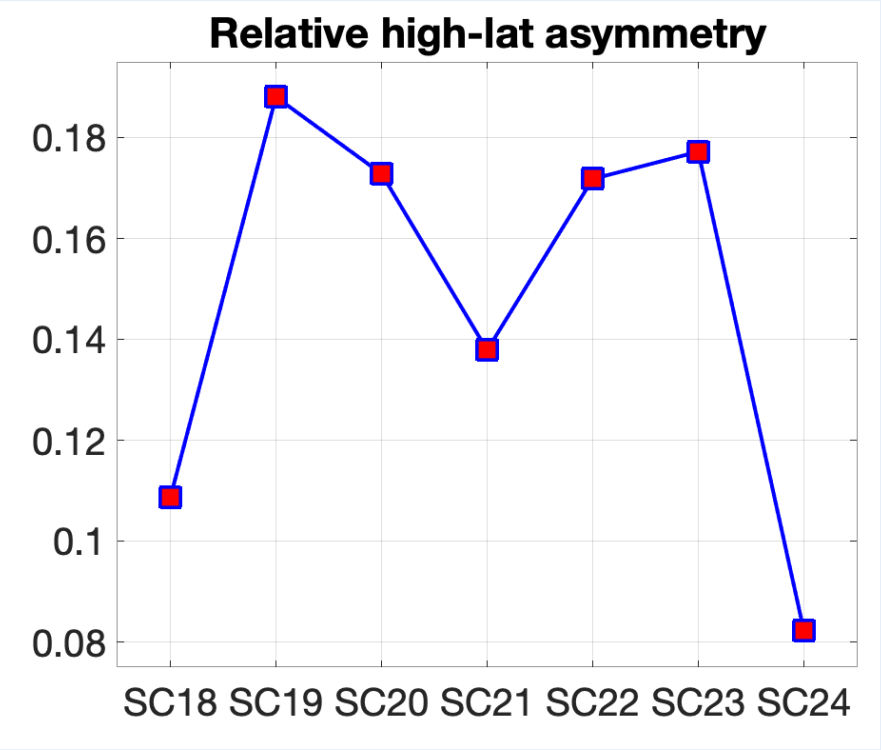
Relative asymmetry (difference of the two high-latitude fluxes divided by their mean) is about 15±4% for all cycles and about 17±1% for high cycl es 19-23.

This sets the scale for a **typical amount of relative hemispheric asymmetry.**

The rough constancy of the relative asymmetry of cycles 19-23 indicates that **asymmetry and cycle height roughly correlate** for these cycles.

Cycle 19 has a slightly overproportional asymmetry.

Cycle 24 asymmetry remains far smaller (by 5 stdev) than cycles 19-23.



However..

A relic field located symmetrically around solar equator makes no hemispheric asymmetry.

So, what about the systematic alternation of hemispheric dominance observed here ?

¿¿ Relic cannot explain observations ??

SOLUTION

The mean location (distribution) of the relic field
oscillates around the equator !

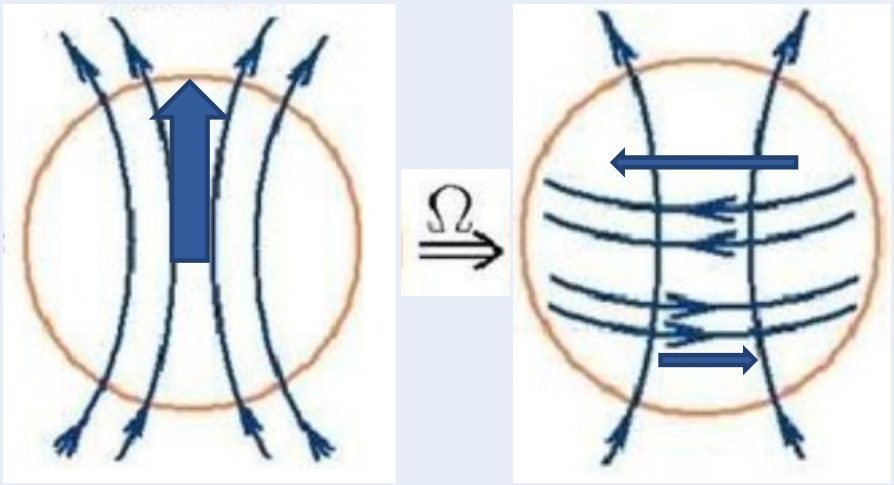
=>

Shifted relic field

Shifted relic field during positive minimum

Northward shifted relic during positive minimum **enhances more** the northern hemisphere than the southern.

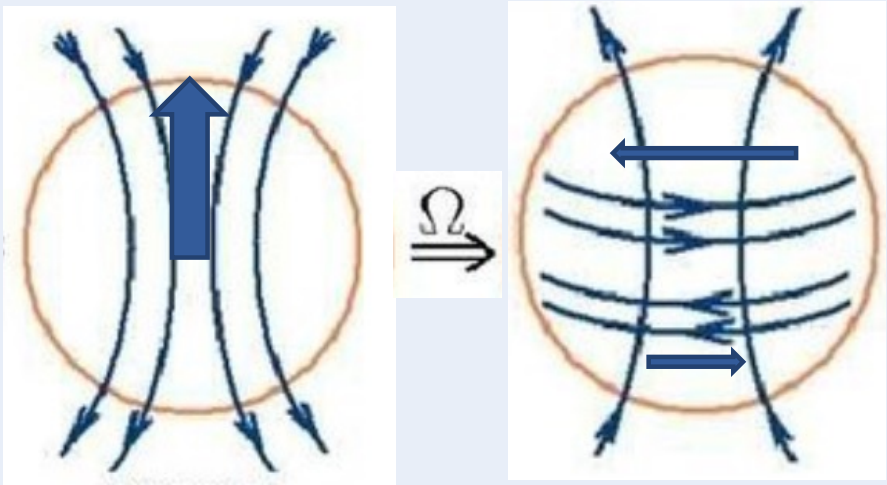
Produces the observed hemispheric asymmetry: **North dominates during odd cycles.**



Shifted relic field during negative minimum

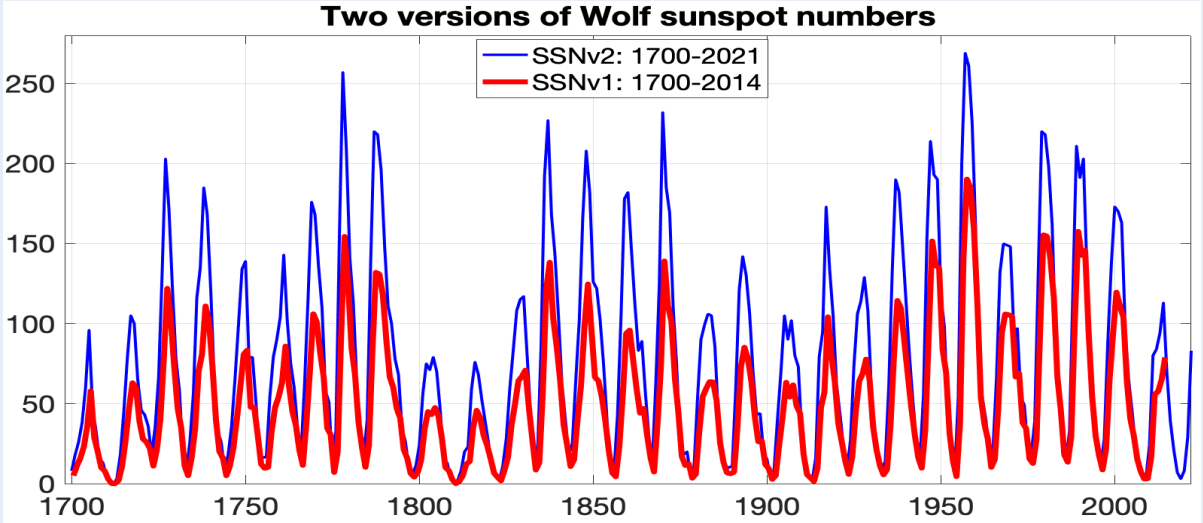
Northward shifted (and northward directed) relic during negative minimum **reduces** more the northern hemisphere than the southern.

Produces the observed hemispheric asymmetry: **South dominates during even cycles.**



Relic shift oscillates: Gleissberg and Suess/deVries cycles

We found that hemispheric asymmetry correlates with cycle height.



Cycle 19: Relic at its northernmost position
- maximum northern dominance
- maximum cycle height

Cycle 24: Relic around the equator
- Very weak northern dominance
- low cycle height

Time from SC19 to SC24:

Relic shift makes **one quarter** of the full relic oscillation cycle.

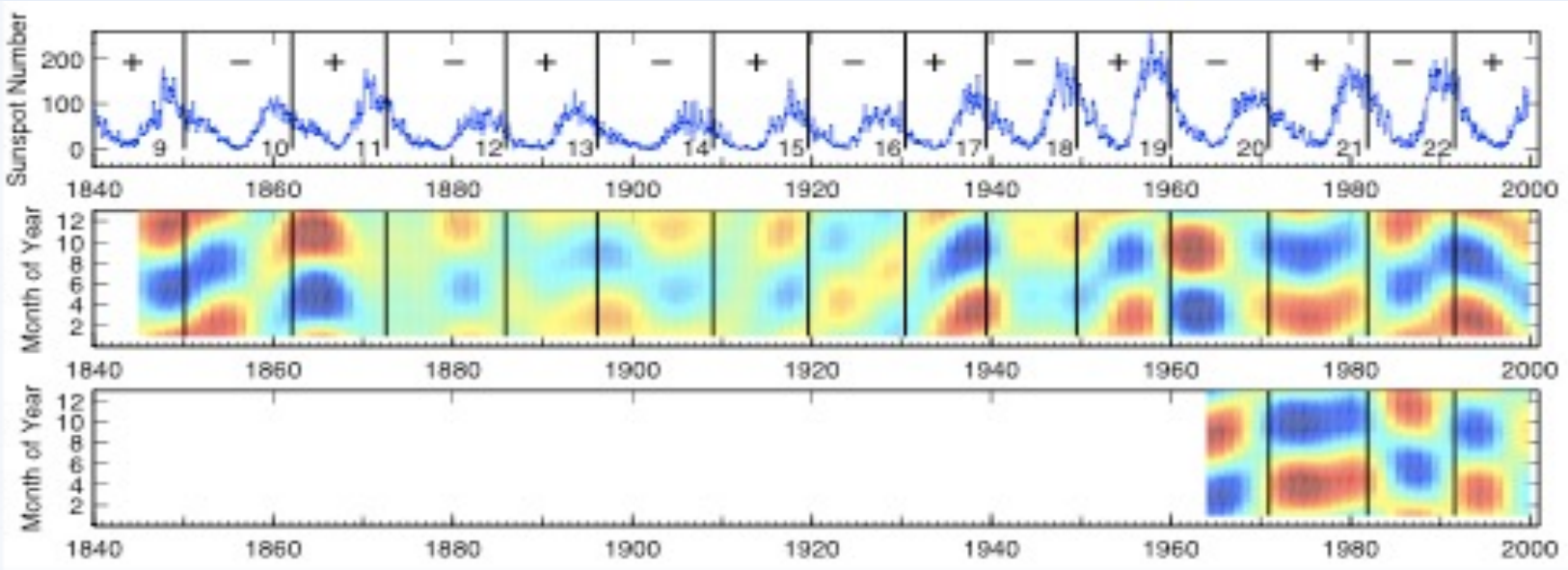
Gleissberg cycle explained: Relic makes one excursion away from equator and back.

210-year Suess/deVries cycle explained: Relic makes a full oscillation, once north and once south.

Additional evidence for oscillating shifted relic

There is earlier evidence for a 200yr-scale oscillation related to solar hemispheric asymmetry!
Streamer belt asymmetry experiences a long-term oscillation around the solar equator, roughly at the 210-year period of the Suess/deVries cycle.

Streamer belt asymmetry matches with the found alternation of hemispheric dominance!
Faster solar wind speed in the north during declining phase of odd cycles in 20th century.
Oppositely in the 19th century => Change in phase => Relic shift was southward in 19th century!



Annual variation of geomagnetic activity (upper) and solar wind speed (lower).

Mursula and Zieger, GRL, 2001.

Forecast for the starting Gleissberg cycle

SC26 will still remain rather small (maybe even smaller than SC25) because of G-O disfavor

SC27 will be much higher, probably above 200, because of large shift and G-O favor

SC28 will be rather high, but not the highest in century (maybe even lower than SC27)

SC29 will be the **21st century-high cycle** (corresponding to SC19 in 20th century).

Increasing **southern dominance** in the coming cycles, especially SC27 and SC29.

Cycles after SC29 will again start having lower heights and smaller asymmetries.

These properties will also have corresponding important affects to space weather, space climate and even climate via changes in irradiance, streamer location etc.

Conclusions

Conclusions

New Earth-based eEUV indices (eLya, eMgII, eF30, eF107) cover the whole latest Gleissberg cycle.

There is an oscillating relation between photospheric sunspots and chromospheric plages over the Gleissberg cycle:

Relatively more sunspots than EUV during Gleissberg growth+max phase
Relatively more EUV than sunspots during Gleissberg decay+min phase

The distribution of magnetic fields experiences an oscillating change over the Gleissberg cycle:

Relatively more sunspots than faculae/plages during Gleissberg growth+max phase
Relatively more faculae/plages than sunspots during Gleissberg decay+min phase

Conclusions: Consequences

This affects **solar/stellar brightness**:

Relatively less bright during Gleissberg growth+max phase
Relatively more bright during Gleissberg decay+min phase

Important changes in the solar atmosphere and magnetic structure over the Gleissberg cycle
Intensity distribution of magnetic fields and their canopy structure and connectivity change

These changes affect e.g., in the driving of ionosphere, geomagnetic activity and magnetic storms.

Suggested explanation for Gleissberg cycle: Oscillating, shifted relic magnetic field in the Sun !

Stellar implications: Varying spot/facula relation over the GC affects solar-stellar comparison

The Sun may be rather unique in its large variability due to a still rather strong relic field

Conclusions: Future

Opposite change (relatively more sunspots) may have started growing already (cycle 25 is higher than cycle 24), toward the next Gleissberg cycle, the Future Grand Maximum.

Sunspots will then increase with respect to faculae/plages and EUV irradiance.

Sun will become dimmer in EUV and less bright than estimated from sunspots (although activity does increase brightness).

Stellar (very long) future of the Sun:

- Faculae will slowly get relatively more and more abundant than sunspots.
- Amplitude of Gleissberg cycle variation will decrease.
- Sunspots will eventually disappear.

Philosophical Consequences

- ✓ Our view of the Sun may still be too stagnant.
- ✓ Sun is more variable in a more versatile way than we have been able to think or accept.
- ✓ We do not yet fully understand the long-term evolution of solar magnetism
- ✓ **Surprises are to come !**

Related papers

K. Mursula, Hale cycle in solar hemispheric radio flux and sunspots: Evidence for a northward shifted relic field, *Astron. Astrophys.*, **674**, A182, https://doi.org/10.1051/0004-6361/202345999, 2023.

K. Mursula, A. A. Pevtsov, T. Asikainen, I. Tähtinen, and A. Yeates, Transition to a weaker Sun: Changes in the solar atmosphere during the decay of the Modern Maximum, *Astron. Astrophys.,* **685**, A170, https://doi.org/10.1051/0004-6361/202449231, 2024.

K. Mursula, Centennial solar EUV irradiance from ionospheric currents: Varying sunspot-EUV irradiance relation and modified spot-facula ratio, *J. Atm. Solar-Terr. Phys.*, **227**, 106653, 19 pages, https://doi.org/10.1016/j.jastp.2025.1066532025, 2025,

K. Mursula, Relation between sunspots and solar EUV irradiance changes during the Gleissberg cycle, ArXiV, 2025.

K. Mursula et al., eEUV: Earth-based solar EUV irradiance proxies since 1890, to be submitted, 2026.

K. Mursula, T. Qvick, T. Asikainen, Different evolution of CME and HSS storms during the Gleissberg cycle: Evidence and implications, to be submitted, 2026.

More coming..

Thanks

That`s it, folks !