Long-Term Solar Activity Reconstruction: Grand Minima and Maxima

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Solar activity variations: telescopic sunspot number record

- 11-year solar cycle (Christian Horrebow 1770s; Schwabe 1843)
- Variable amplitude/envelope (Gleissberg 1944);
- Maunder minimum (Hivelius; Eddy 1976);
- The contemporary level is high
Solar activity in the past

- Electronic
- Photographic data
- Geomagnetic measurements
- Sunspot counts and drawings
- Aurora sightings
- Naked eye sunspot observations
- Cosmogenic isotopes

Years before present
Proxy of SA: Cosmogenic isotopes

• Variable solar activity expands to the Heliosphere: solar wind, interplanetary magnetic field, interplanetary transients (CME, corotation regions), etc.
• Galactic cosmic rays are modulated by IMF, magnetic inhomogeneities, solar wind;
• Geomagnetic field partly shields the Earth (mid- and low-latitude regions) from incoming cosmic rays;
SN reconstruction from $^{14}\text{C}$ or $^{10}\text{Be}$

- *e.g. Model by Solanki et al. (2002)*

- Sunspot number $\leftrightarrow$ open magn. flux

- *e.g. Model by Usoskin et al. (2002a)*

- Modul. strength $\leftrightarrow$ CR intens. variations

- Deposition models, paleomagnetic models
  - $^{10}\text{Be}$: *Webber & Higbie*, $^{14}\text{C}$: *Usoskin & Kromer*
  - $B_\oplus$: *Yang et al. (2000), Korte & Constable (2005)*

- *Usoskin et al. (2002b)*

- *Solanki et al. (2004), Usoskin et al. (2004, 2007)*

- Sunspot numbers $\downarrow$ Heliospheric params $\uparrow$

- CR intensity $\downarrow$ CR intensity $\uparrow$

- Cosmogenic isotopes in natural archives $\downarrow$
Sunspot number reconstructed from $^{14}\text{C}$

Smoothed Sunspot number over 11400 yr

27 Grand minima
19 Grand maxima can be identified.

Minima cover 1880 yr $\approx$ 17% of time
Maxima cover 1030 yr $\approx$ 9% of time

Sunspot number statistics

Red curve: best-fit normal distribution
Waiting time distribution

Grand minima

Grand maxima

Closer to power law (red lines) than to exponential (dotted yellow lines) \(\rightarrow\) waiting time tends to show clustering of Min and Max
Durations of Minima & Maxima

Grand minima

Grand maxima

Maunder

Spoerer

Quasi-Bimodal

Exponential
Conclusions

- The Sun spends 17% of the time in **grand minima**, 9% in **grand maxima**. Currently the Sun is in a grand maximum.

- Grand **minima/maxima** are not due to long-term cyclic variations but rather to stochastic/chaotic processes.

- Waiting time distribution of occurrence of **grand minima** and **maxima** deviates from an exponential distribution \(\Rightarrow\) typical of non-Poisson processes with, e.g., self-organized criticality or processes related to accumulation and release of energy.

- **Grand minima** can be classified into two different types: short minima of **Maunder type** and long minima of **Spörer type**.

- Duration of **grand maxima** exponentially distributed \(\Rightarrow\) leaving a **grand maximum** is a random process, unlike for **grand minima**
Ti-44 activity: measurements vs. model

Preliminary results!
New data are currently being finalized and analyzed