Towards a more reliable reconstruction of the historical solar variability: A more realistic description of solar ephemeral magnetic regions

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Total solar irradiance and magnetic activity

- The **total solar irradiance** (TSI) is the spectrally-integrated energy flux per unit area at 1 AU.
- Direct satellite measurements are available since 1978. They show that TSI varies on various timescales.
- This variability is important for climate models. Due to the short time series reconstructions are needed.
- On climate relevant timescales the variability is driven by surface magnetism. **Sunspots** cause darkening of the Sun while **faculae** lead to its brightening.

➔ TSI is reconstructed from proxies of solar activity, the longest direct proxy is the **sunpot number** (SN).

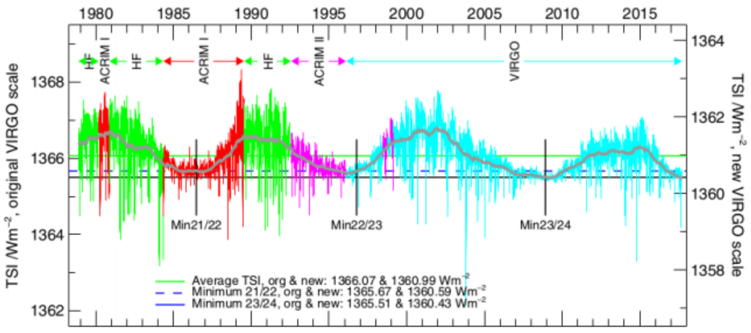
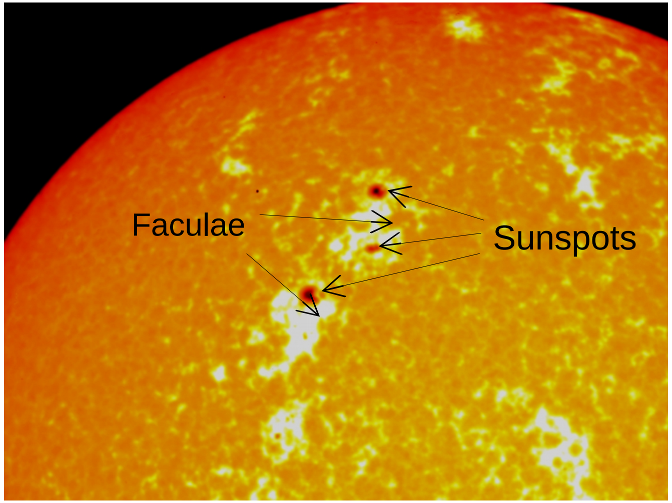


Figure is courtesy of the VIRGO team (From: https://www.pmodwrc.ch)



Adapted from: NASA/Goddard Space Flight Center Scientific Visualization Studio (From: https://svs.gsfc.nasa.gov/2656)

The role of ephemeral regions

- **Ephemeral regions** (ERs; *red circles*) are small-scale bipolar magnetic regions believed to be the main source of long-term TSI variations. Contrary to the much larger **active regions** (ARs; *blue circle*) they are too small to feature sunspots.

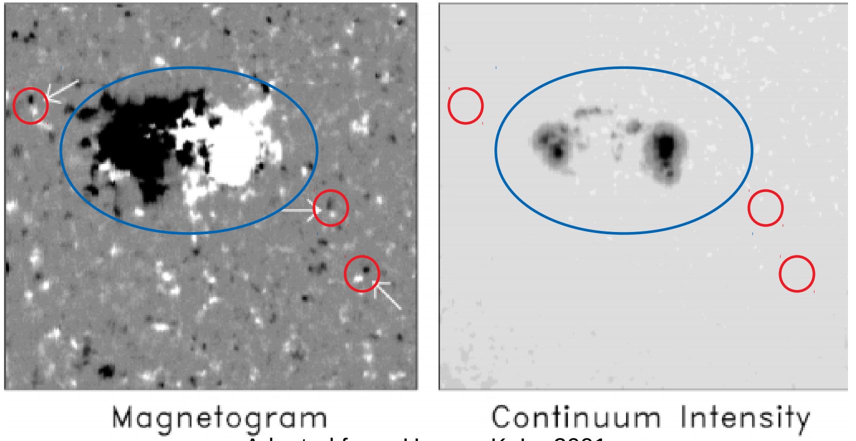
➔ ***ERs are missed completely by SN records!***

- While crucial for the long-term variability, most models ignore them. In the SATIRE-T model (Wu et al. 2018) the emergence of ERs is linearly linked to the SN.

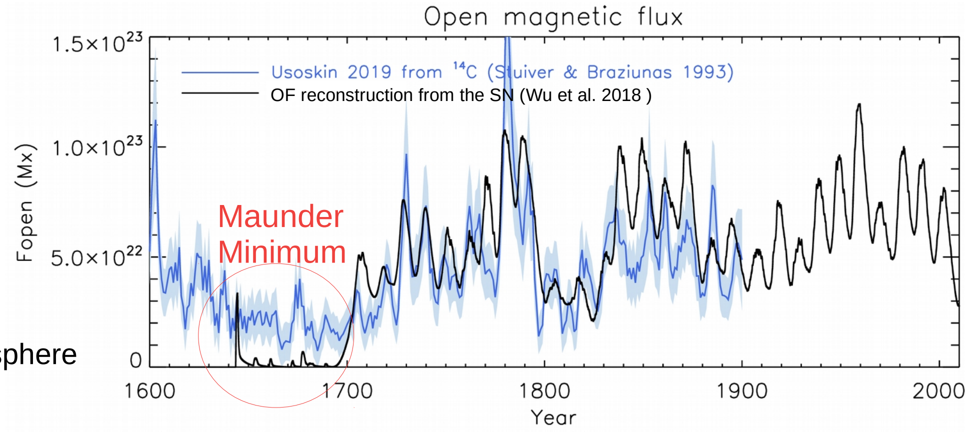
➔ **Problem**: No ERs emerge at **zero sunspots.**

- However, reconstructions from **cosmogenic isotopes** (Usoskin et al. 2019) suggest that the **open magnetic flux**[1] (OF) during the Maunder Minimum did **NOT** vanish. (contradicts our model (*black curve*))

➔ **New description of ERs is needed.**



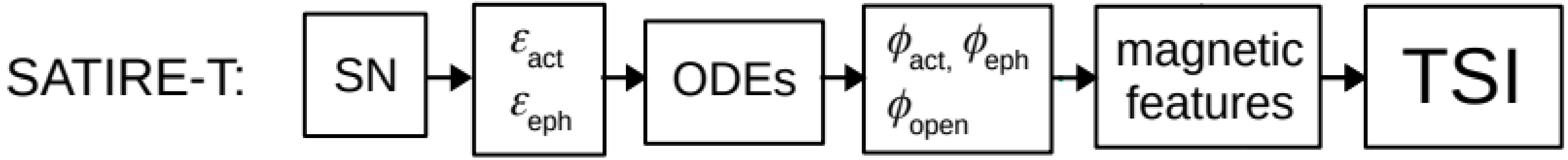
Adapted from: Harvey, K. L., 2001



[1] Open flux is part of the solar magnetic field reaching out into the heliosphere

SATIRE-Model

- We use the **S**pectral **A**nd **T**otal **I**rradiance **RE**construction (SATIRE) model; version T.
  (Wu et al. 2018)
- SATIRE differentiates between: **umbra**, **penumbra**, **faculae**, **network** and **quiet Sun**.
- The evolution of the magnetic field of ARs, ϕ_{act}, ERs, ϕ_{eph}, and the OF, ϕ_{open} is described by a set of ordinary differential equations (ODEs).
- Source terms: The emergence rates of ARs and ERs ε_{act} , ε_{eph}. In the original SATIRE-T model ε_{eph} is linked linearly to the SN.
- From the magnetic flux the fractional disc coverage by the magnetic features and the **TSI** is calculated.



New approach

- We describe the emergence of active and ephemeral regions by a single **powerlaw size distribution** (Thornthon&Parnell, 2012)

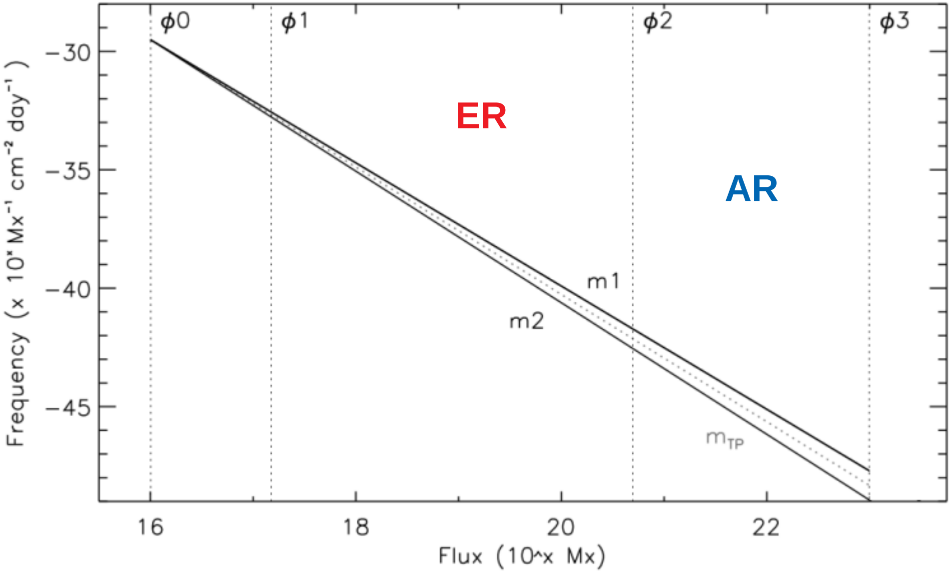
- The flux emergence varies with solar activity as described by exponent m_{SN} that varies with the SN

$$\frac{dN}{d\phi} = \kappa \frac{n_0}{\phi_0}\left(\frac{\phi}{\phi_0}\right)^{m_{SN}} \qquad m_{SN} \sim SN^{\alpha}$$

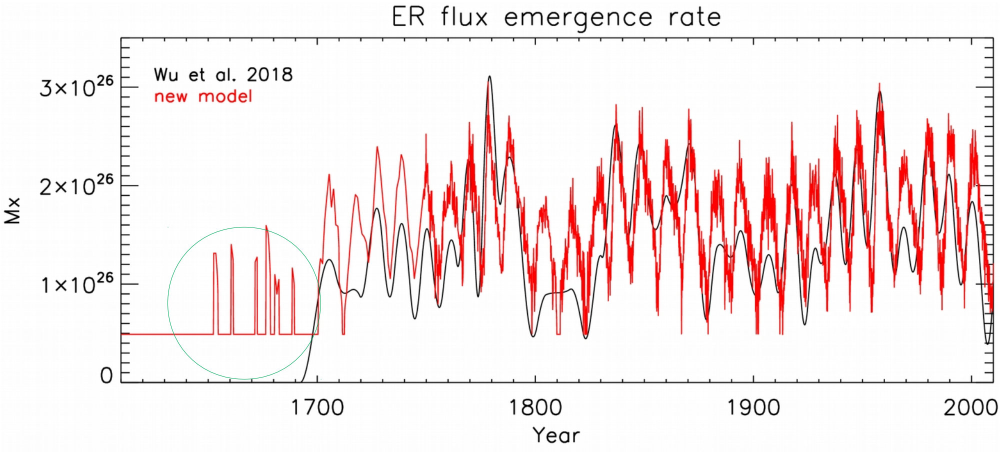
κ, n_0 and α: model parameters

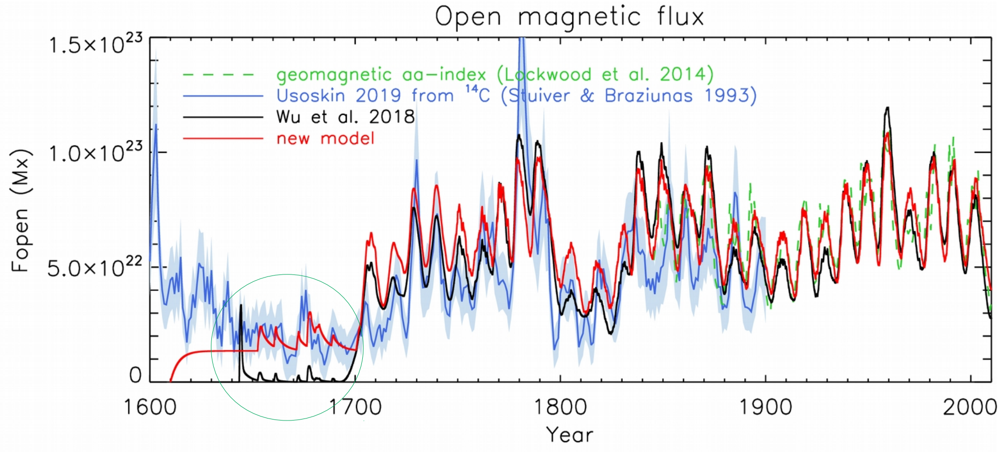
- The emergence rate of **ARs** varies stronger (factor **8**) between solar minimum and maximum than that of **ERs** (factor **2**) (Harvey, 1993)

- The new model agrees with the observations by Harvey and the **AR emergence rate** is consistent with the previous model



Results





- In original SATIRE-T (Wu et al. 2018) the ER emergence rate (*black*) drops to zero during the Maunder Minimum

➔ In the new model (*red*) it never falls below a minimum "**ground level**"

- OF of the new model (*red*) and the original model (*black*) are consistent with the reconstruction from the geomagnetic aa-index (*green*) (Lockwood et al. 2014)

➔ The new model successfully **reproduces the OF during the Maunder Minimum** reconstructed from cosmogenic isotopes (*blue*) (Usoskin et al. 2019)

Summary

- **ERs** are crucial for **long-term reconstructions** of solar irradiance variability, but they are not or not realistically accounted for by the existing models.

- We propose a new description of the ERs. The new model assumes that all magnetic regions emerging on the solar surface can be described by a single **power-law distribution**, with its slope varying with solar activity.

- The new model is **supported by various independent observations**, such as the solar cycle variability of ERs and ARs (Harvey, 1993) and independent reconstructions of the solar OF (Lockwood 2014, Usoskin 2019).

- It will help to reduce the uncertainty in the long-term irradiance variability and thus also in the **solar forcing in future scenarios**.

References

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