Solar Total and Spectral Irradiance Reconstruction Over the Last 9000 Years

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**Solar Irradiance**

![Solar Irradiance Diagram](image)

**Figure 1:** Solar irradiance

- TSI is \( \sim 1360 \text{ Wm}^{-2} \) with variability \( \sim 0.1\% \)
- UV/SSI contribute \( > 50\% \) TSI variability
- Effect of SSI on Earth’s climate through **top-down & bottom-up** mechanisms (**heights, wavelengths dependent**)

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**Earth Radiation Components**

- Solar Incident Energy
- Solar Reflected Energy
- Earth Emitted Energy
Why model solar irradiance

- Continuous observations only cover four decades

- Connection between solar variability & solar surface magnetism

- Various models use different indices/proxies of solar magnetic activity to reconstruct solar irradiance in the past
Spectral And Total Irradiance REconstruction

- Solar variability > 1 day caused by surface magnetism
- Solar surface composed by Faculae(f), Network(n), Umbra(u), Penumbra(p), Quiet Sun(q)
- Surface coverage $\alpha$ of component f,n,u,p,q
- Intensity spectra $I$ of component f,n,u,p,q from radiation transfer code + model atmosphere (spectrum spans 115 - 160000 nm)

Solar spectrum at any given time

$$F(\lambda, t) = \alpha_q(t)I_q(\lambda) + \alpha_u(t)I_u(\lambda) + \alpha_p(t)I_p(\lambda) + \alpha_f(t)I_f(\lambda) + \alpha_n(t)I_n(\lambda)$$
Spectral And Total Irradiance REconstruction

- SATIRE-S_{atellite}: Continuum Images & Magnetograms (back to 1974; Ball et al. 2014; Yeo et al. 2014, 2015)
- SATIRE-T_{elescope}: Group sunspot number (back to 1610; Krivova et al. 2007, 2010)
- SATIRE-T_{elescope v.2}: Synthesis sunspot number & simulated magnetograms (SFTM) (back to 1700; Dasi-Espuig 2014, 2015)
- SATIRE-M_{illennia}: Cosmogenic isotopes $^{14}$C & $^{10}$Be (prior to 1610; Vieira et al. 2011)

Other models
SRPM; back to cycle 23 [Fontenla et al. 1999 ]
NRLSSI; back to 1610 [Lean et al. 2001, Coddington et al. 2015]
Millennial TSI through linear correlation; [Steinhilber 2009, Shapiro et al. 2011]
- **Coupled ODEs**
  describing evolution of magnetic fields
- **Free parameters**
  describing relations between magnetic components, timescales of components

**Figure 3:** TSI reconstruction

\[
\begin{align*}
\frac{d\phi_{act}}{dt} &= \epsilon_{act} - \frac{\phi_{act}}{\tau_{act}^0} - \frac{\phi_{act}}{\tau_{act}^s} - \frac{\phi_{act}}{\tau_{act}^r} \\
\frac{d\phi_{eph}}{dt} &= \epsilon_{eph} - \frac{\phi_{eph}}{\tau_{eph}^0} - \frac{\phi_{eph}}{\tau_{eph}^s} \\
\frac{d\phi_{r\,open}}{dt} &= \frac{\phi_{act}}{\tau_{act}^r} - \frac{\phi_{r\,open}}{\tau_{open}^r} \\
\frac{d\phi_{s\,open}}{dt} &= \frac{\phi_{act}}{\tau_{act}^s} + \frac{\phi_{eph}}{\tau_{eph}^s} - \frac{\phi_{s\,open}}{\tau_{open}^s}
\end{align*}
\]
Proxies: Cosmogenic isotope concentration in natural archives

Figure 4: Solar activity vs. cosmic ray flux
Solar modulation potential
Open flux

Geomagnetic field model

Global carbon cycle model

Regional precipitation model
Solar modulation potential

Open flux

Geomagnetic field model

Global carbon cycle model

Regional precipitation model
SATIRE-M

1. Proxies: Cosmogenic isotope concentration in natural archives
2. Decadal average of SATIRE-T ODEs
3. Constrained parameters from SATIRE-T

\[
\langle R_g \rangle_j = a \langle \phi_{open} \rangle_j + b \langle \phi_{open} \rangle_{j+1}
\]

\( R_g \) (decadal) + each component’s \( I = \text{millennial SSI reconstruction} \)

Coefficients \( a \) & \( b \) are constrained from SATIRE-T

First SSI reconstruction with physics-based model
SATIRE-M is so far the only physics-based model reconstructs TSI/SSI on millennial timescale.

TSI has about 0.1% variability and UV/SSI (200-400 nm) contributes 51.8% variability on millennial timescale.

The relations between cosmogenic isotope abundances and TSI/SSI are non-linear. Linear assumption is not realistic.