Surface magnetic field-based irradiance models

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Why bother? To answer the most pressing questions raised in the media!
Measured total irradiance: sunspots

C. Fröhlich, PMOD
Importance of faculae

Irradiance

Sunspots

TSI (Wm⁻²)


Year

Rz

0 50 100 150 200


Year
Influence of magnetic features in photosphere on energy flux

- **Sunspots**: B in spot blocks energy transport. Blocked energy is distributed over CZ on convective time scale (≈month). Stored energy is released over $10^5$ years on thermal equilibrium time scale (Spruit 1982) ➔ only weak bright rings around spots (Waldmeier 1938; Rast et al. 01)

- **Faculae**: Faculae increase solar surface area (via Wilson depression) ➔ enhanced emission. Excess flux taken from CZ on convective time scale (Spruit 1976; Deinzer et al. 1984)
MHD simulations: from quiet Sun to strong plage

Radiation MHD simulations of solar surface layers. Open lower boundary with fixed value of entropy for bottom inflow (i.e. assume irradiance changes in surface layers)

Vögler et al. 2005
6000x6000x1400 km box, 20km grid
MHD simulations: from quiet Sun to strong plage
Vertical cut through a sheet-like structure

Radiation flux vectors & temperature

- partial evacuation leads to a depression of the $\tau=1$ level
- lateral heating from hot walls (Spruit 1976)
- Brightness enhancement of small structures
B<sub>0</sub>=200 G: CLV of wavelength-integrated brightness

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<th>μ</th>
<th>1.0</th>
<th>0.9</th>
<th>0.8</th>
<th>0.7</th>
<th>0.6</th>
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panels separately normalized
**Facular brightening**

Facula: narrow layer of hot material on side and top of adjacent granule

Dark lane: - cool & tenuous material in adjacent flux concentration
- cool & dense material above neighbouring granule

(Keller et al. 2004)
From quiet Sun to strong plage

Photometric properties \textit{(normalized to case }B_0=0\text{)}

- Total emerging energy flux
- Mean disk center $\lambda$-integrated intensity
- Constant entropy of inflowing gas at the bottom
CLV of continuum intensity at 676.8 nm

Constant entropy of inflowing gas at bottom

Zakharov et al. 2008
Pore simulation: brightening near the limb

Pore appears brighter near limb due to Wilson depression: hot walls become visible, dark bottom is hidden.

\[ \mu = 1 \]

\[ \mu = 0.7 \]

\[ \mu = 0.5 \]

\[ \mu = 0.3 \]
SATIRE: Spectral And Total Irradiance REconstruction

Semi-empirical model with main assumption: B-field at solar surface causes TSI + SSI variations in UV, vis, IR

Components: Spots (contin. images), faculae + network (magnetograms), quiet Sun

Model atmospheres

1 free parameter
Filling Factors

\[ \alpha_s = 1 \ (\text{or } 0) \]

\[ \alpha_q = 1 - \alpha_s \cdot \alpha_f \]
>90% of solar irradiance variations on time scales days to solar cycle caused by surface magnetism.

Caveat: There is a free parameter in the model.

Wenzler et al. 2006, A&A
What about other TSI composites?

- 3 composites available: PMOD (Fröhlich), ACRIM (Willson), IRMB (DeWitte et al.).
- Differ in employed data sets + corrections: trends

SATIRE model gives best agreement with Fröhlich’s TSI composite. Thus, if another composite, e.g. of Willson, were to be correct, then the secular trend present in that composite cannot be caused by surface magnetic fields.
Further Applications of SATIRE

- SATIRE also reproduces, spectral irradiance changes over time (Krivova et al. 06, 08; Unruh et al. 99, 08), and variation of spectral lines over solar cycle (Danilovic et al. 2008) with same value of free parameter!

- Same model also reproduces the change from facular to spot dominated irradiance variations with increasing stellar activity (Knaack et al. 2008)
Short wavelengths: faculae dominate also on rotational timescales

Long wavelengths: spots dominate on rotational timescales

Same free parameter as obtained from fit to TSI composite: $\Phi_{\text{sat}} = 300\text{G}$
How strongly do different wavelengths contribute to TSI and TSI variations?

Krivova et al. 2006
Irradiance butterfly diagram

**Statistics:**

Features with weaker flux tend to contribute more to the TSI variations on solar cycle timescales (but not on rotational time scales)

Rings of equal \( \Delta \mu \) contribute similar amounts to solar cycle TSI variations
Solar Irradiance Since 1610 Based on Magnetic Field Reconstruction

Model agrees with: obs. TSI, total & open magn. flux

→ estimates of secular rise in TSI since Maunder minimum

≈0.9-1.5 W/m²

A secular variation of total solar irradiance > 1.5 W/m² cannot be ruled out, but is not likely to be based on variations of solar surface magnetic flux

Krivova et al. 2007
Outlook: Improve sunspot models

- Incorporate new knowledge: sunspot intensity depends strongly on size (Mathew et al. 2007)
- Comparison with SORCE SIM & SCIAMACHY to improve facular model (Unruh et al. 2008)
Outlook: improved treatment of faculae, improved magnetograms

- Compute spectra from **3D radiation MHD simulations** and use these to determine total and spectral irradiance ➔ no free parameter needed anymore.

- Employ **lower noise magnetograms available from SOLIS** and hopefully from **SDO** (allow also brightening from weaker fields to be included, in particular also near the limb).
Outlook: Irradiance over 11 kyr

- Use SN obtained from $^{14}\text{C}$ data (cf. Usoskin et al. talk on wed) to reconstruct TSI over 11400 years
- Only cycle averages can be reconstructed with $^{14}\text{C}$ data
- Make use of near-linear relationship betw. 10-year avges. of SN and of reconstructed TSI since Maunder minimum

Vieira et al. in preparation
What about other composites?

- 3 composites available: PMOD (Fröhlich), ACRIM (Willson), IRMB (DeWitte).
- Differ in employed data sets + corrections: trends
SATIRE UV irradiance vs. SUSUM

Reconstruction of spectral irradiance based on the same model as for total irradiance, with same value of free parameter!
**Spectral Irradiance: SATIRE vs. SUSIM**

Relative difference between UV irradiance at activity max & min

Other models with more detailed radiative transfer have been and are being constructed by Haberreiter et al. 2005, Haberreiter 2006; Fontenla et al. 2004, 2006. They will eventually improve on these reconstructions.

Krivova and Solanki 2005
Although UV provides only a minor contribution to total irradiance, it produces ≈60% of TSI change over a solar cycle. Stratospheric chemistry.

See poster by Krivova et al. (cf. Usoskin et al. talk on wed)
New tests of SATIRE II: Livingston's line observations

Solar cycle variation is absent

Danilovic et al. 2006
New tests of SATIRE II: Livingston’s line observations

Significant solar cycle variation

Danilovic et al. 2006

Same free parameter as obtained from fit to TSI composite: $\Phi_{\text{sat}} = 300\text{G}$
Regimes of solar magnetoconvection

- horizontal scale of convection decreases
- convective energy transport decreases

G-band image: KIS/VTT, Tenerife
From quiet Sun to strong plage

Weak fields: exponential

Strong fields: Gaussian

Efficiency of convective field intensification decreases for small $B_0$
3D view of a thin flux sheet

- Quasi 2-dimensional above the surface
- Loss of coherence beneath the surface

Face-on view
Recent observations reveal:
(Lites et al. 2004)

- 3D appearance of faculae
- extension up to 0.5”
- narrow dark lanes centerward of faculae
Photospheric irradiance has both spot and facular contributions; chromospheric and coronal irradiance has mainly facular contribution.
Contrast of magnetic features

Chromosphere (Ca II K)

Photosphere (λ ≈ 5251Å, contin)

Frazier (1971)
Influence of magnetic features in chromosphere

- **Photosphere**: heat blocking & release at solar surface

- **Chromosphere**: release of excess energy stored in field or channelled by field to higher layers (e.g. MHD wave dissipation, or in current sheets).

- **Sunspots**: dark in photosph+lower chromo; neutral-bright in upper chromosphere + TR

SATIRE model discussed here is based on magnetic field at solar surface. It has 1 free parameter. 
Fligge et al. (2000); Krivova et al. (2003); Wenzler et al. (2004, 2005, 2006); Haberreiter et al. (2005); Unruh et al. (2006); Danilovic et al. (2006)