Solar Group Seminar

‘Analysis & Modelling of Solar Irradiance Variations’

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The 11-year activity cycle.

Figure 1: The Sun in the extreme ultraviolet (SoHO EIT, ESA/NASA).
### What do we want to answer?

How has the brightness of the Sun been changing? What is driving these changes?

### Key quantities.

- **Total flux → Total Solar Irradiance, TSI (Wm\(^{-2}\))**
- **Spectrum → Spectral Solar Irradiance, SSI (Wm\(^{-2}\)nm\(^{-1}\))**

### TSI/SSI describes the radiative output of the Earth-facing side of the Sun.

- Measured from space.
- Normalized to 1 AU.
Monitored from space since 1978. **Clear correlation with solar cycle.**

- Instruments degrade with time/exposure & not straightforward to calibrate. → Uncertainty in absolute level & overall trend.
- Composites exhibit divergent solar cycle amplitudes & secular trends.

Figure 2: TSI & sunspot number (spot.colorado.edu/~koppg/TSI/).

Figure 3: TSI composites (Fröhlich 2012).
Measuring solar irradiance - SSI

Figure 4: UV SSI (Deland & Cebula 2008).

Figure 5: Solar cycle amplitude.

- Also monitored (at least in the ultraviolet) from space since 1978.
- Similar issues as TSI.
- Instrumental effects vary with wavelength. → Uncertainty in wavelength-dependence of solar cycle amplitude.
Modelling solar irradiance - Why? How?

Direct observation NOT straightforward.
- Radiometry & stability issues.
- Only cover 4 solar cycles.
- Need to augment measurements with models aimed at reconstructing solar irradiance from other solar measurements.

What drives the variation in solar irradiance?

- \textit{p}-modes: Minutes
- Convection: Minutes to hours
- Magnetic: Days to cycles (& possibly secular)
- Thermal: $10^5$ years
- Chemical: $10^6$ years
Modelling solar irradiance - Mechanism

How does solar magnetism modulate solar irradiance?

- Cyclic emergence & evolution of kG magnetic concentrations on the solar surface.
- Affects temperature structure (radiant behaviour) of the solar surface & atmosphere.
- Photospheric magnetism prime candidate driver of variations in solar irradiance (at timescales greater than a day).

Figure 6: Active region NOAA 11520, 11 July 2012.
Modelling solar irradiance - SATIRE-S

Spectral And Total Irradiance REconstruction for the Satellite era

Figure 7: Identifying faculae and sunspots by the magnetic flux density & intensity (Fligge et al. 2000).

- One of the more established in the literature.
- Solar surface = Quiet Sun (Q) + Faculae (F) + Sunspots (S)
- Surface coverage of Q/F/S from full-disc intensity images and magnetograms.
- Intensity spectra of Q/F/S from semi-empirical model atmospheres & radiative transfer code (Unruh et al. 1999).
- Solar spectrum given by surface coverage-weighted sum of Q/F/S intensity spectra.
Previously...

Reconstruct TSI/SSI between 1974 and 2009 using KPVT and MDI data. **Cannot be extended to the present** (MDI was decommissioned in 2011).

This thesis...

- Extend to the present with HMI data.
- Modify how data from the various instruments are combined.
SATIRE-S reconstruction of TSI/SSI since 1974.

Combining data from the various instruments not straightforward due to instrumental differences.

Previous effort with SATIRE-S introduced empirical corrections to reconstructed SSI.

We rescaled KPVT & MDI magnetograms (w.r.t. HMI) and modified how faculae are identified.

This yielded a consistent solar irradiance time series WITHOUT the need for any empirical correction of reconstructed SSI.
SATIRE-S reconstruction of TSI/SSI since 1974.

Figure 9: SATIRE-S TSI
SATIRE-S reconstruction of TSI/SSI since 1974.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Observation</th>
<th>Period</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSI</td>
<td>PMO6V</td>
<td>1996-2013</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>PMOD</td>
<td>1978-2013</td>
<td>0.96</td>
</tr>
<tr>
<td>Lyman-α irradiance</td>
<td>LASP</td>
<td>1974-2013</td>
<td>0.97</td>
</tr>
<tr>
<td>Mg II index</td>
<td>IUP</td>
<td>1978-2013</td>
<td>0.98</td>
</tr>
<tr>
<td>SSI (120 to 180 nm)</td>
<td>SORCE/SOLSTICE</td>
<td>2003-2013</td>
<td>0.98</td>
</tr>
<tr>
<td>SSI (180 to 240 nm)</td>
<td>UARS/SUSIM</td>
<td>1991-2005</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Replicates most of the variability in multiple independent records.
SATIRE-S reconstruction of TSI/SSI since 1974.

Figure 10: SATIRE-S TSI (black) versus ACRIM, IRMB & PMOD composites (red).
SATIRE-S reconstruction of TSI/SSI since 1974.

Figure 11: SATIRE-S Lyman-\(\alpha\) irradiance (black) versus LASP composite (red).

Replicates the overall trend in the PMOD TSI composite and the LASP Lyman-\(\alpha\) irradiance composite.
SATIRE-S reconstruction of TSI/SSI since 1974.

Figure 12: SATIRE-S SSI (black) versus UARS & SORCE SSI (colour-coded).

Figure 13: Solar cycle amplitude as a function of wavelength in SATIRE-S (black) and Morrill et al. (2011) model (red).

Wavelength-dependence of solar cycle amplitude consistent with SUSIM measurements and Morrill et al. (2011) model.
SATIRE-S reconstruction of TSI/SSI since 1974.

Key results.
- Replicate, by a model based on photospheric magnetism alone, observed variability, including the cyclic & secular trend, in multiple independent records.
- No preceding model has demonstrated the same, at least not to the same extent.
- One of the longest daily reconstruction of TSI/SSI available.

Conclusions.
- Support the hypothesis that photospheric magnetism is the key driver of variations in solar irradiance.
- Represent a reliable data set for climate & solar irradiance studies.
Can we do better?

Reconstruction of the solar spectrum given by surface coverage-weighted sum of the intensity spectra of magnetic features.

1. Based on 1-D model atmospheres.
2. Spectral synthesis assumed Local Thermodynamic Equilibrium.
3. Spectra from single faculae model atmosphere empirically scaled by magnetogram signal to all bright magnetic features.

Possible solution to 1 & 3?

Employ 3-D magnetohydrodynamic (MHD) simulations of the solar atmosphere as model atmospheres, in so doing include 3-D effects and generate spectra corresponding to a range of magnetic flux densities.

What is standing in our way?

- Are 3-D MHD simulations realistic?
- How do we relate spectra calculated from such simulations to measured magnetic flux densities?
Examined the **intensity contrast of network & faculae** in HMI data as a function of magnetogram signal and disc position.

- **These results can be employed to constrain 3-D MHD simulations and relate spectra calculated from such simulations to measured magnetic flux densities.**

- **But that’s not all...**

Derived the **point spread function of HMI** from observations of Venus in transit.
Greater accuracy, detail and scope compared to earlier studies due to unprecedented quality of HMI data, allowing us to confirm...

- Scatter in results from earlier studies likely (mainly) due to differences in spatial resolution.
- Network have a greater heating efficiency than faculae.
- Intensity contrast exhibit opposite centre-to-limb variation in the continuum and within spectral lines.

Variations in solar irradiance is strongly driven by both continuum excess and spectral line changes.

Figure 14: Measured TSI (red). Continuum (dot), line core (dash) and hybrid (blue) models.
Figure 15: HMI data before (top) and after (bottom) stray light correction.

This allows us to correct HMI data for stray light, enhancing the quality.
Thank you for your attention!