What the SORCE SIM observations tell about solar spectral irradiance

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**Topic Outline**

- The unexpected nature of solar spectral variability
- Interpretation of variability in term of the Solar Radiation Physical Modeling (SRPM)
  - Image decomposition using the Precision Photometric Solar Telescope (PSPT)
    - Mauna Loa Solar Observatory & Rome Observatory
- Impacts of these findings on the Earth atmosphere
- Conclusions & the Future
Instrument Overview

- **Instrument Type:** Féry Prism Spectrometer
- **Wavelength Range:** 200-2400 nm
- **Wavelength Resolution:** 0.24-34 nm
- **Detector:** ESR, n-p silicon, InGaAs
- **Absolute Accuracy:** 2-8%
- **Relative Accuracy:** >0.1%
- **Long-term Accuracy:** 0.015%/yr

- **Field of View:** 1.5x2.5° total
- **Pointing Accuracy/Knowledge:** 0.016°/0.008°
- **Mass:** 21.9 kg
- **Dimensions:** 88 x 40 x 19 cm
- **Orbit Average Power:** 17.5 W
- **Orbit Average Data Rate:** 1.5 kbits/s
- **Redundancy:** 2 Redundant Channels

\[
\lambda = 2423 \\
\int E(\lambda) d\lambda \approx 1324.6 \text{ Wm}^{-2} \\
\lambda = 200 \approx 97.3\% \text{ of TSI}
\]

The Solar Atmosphere

Pressure (dynes cm$^{-2}$)

Corona ($T > 10^6 K$)

Transition Region

Upper Chromosphere

Lower Chromosphere

Photosphere

Convection Zone

Altitude (km)

Temperature (K)
What the SORCE SIM observations tell about solar spectral irradiance
The unexpected nature of solar spectral variability

200-300 nm, 300-400 nm
- decreasing trend with decreasing solar activity

400-691 nm
- increasing trend with decreasing solar activity
- affected by passage of active regions

691-972 nm, 972-1629 nm, 1629-2423 nm
- very TSI-like
- increasing trend with decreasing solar activity
- neutral by ~2000 nm

from the Stefan-Boltzman Eqn:
\[
\sigma T_{\text{eff}}^4 \Omega_{\text{sun}} \approx 1361 \text{ W m}^{-2}
\]
• SIM observations consistent with an overall decrease in the temperature gradient in the active (magnetic) solar photosphere
• Crossing point occurs in the solar atmospheric layers that are close to the $T_{\text{eff}}$ value
• The photospheres crossing point occurs at a temperature roughly designed to match the Topka et al. observations (ApJ, 484, 1997).
SRPM Modeling of SIM Observations

- Root causes of solar variability originates in changes in the magnetic and thermal structure of the solar atmosphere.
- The SRPM combines solar feature information with physics-based solar atmospheric spectral models at high spectral resolution to compute the emergent intensity spectrum.

What are Faculae?

- **Faculae** = plural of *facula*-Latin for “small torch”
- **History of observations:**
  - Originally discovered near the limb in full-disk images of the Sun, faculae are the small, bright, patterns around dark sunspots and in the “photospheric network”.
- **Facular brightness is difficult to model**
  - Depends sensitively on wavelength, size, and disk position.
  - Small-scale magnetic flux ranges in angular size from 1-to-2 arc-seconds (micro-pores) down to less than 0.1 arc-seconds (“flux tubes”) – very hard to observe.
  - Hardest thing to measure/model: the Center-to-Limb Variation (CLV) in brightness of faculae as a function of size and/or magnetic field strength.
TRACE White Light Image

Tickmarks = 10 Mm

T. Berger, 2004 SORCE Science Meeting
SRPM Spectrum

- SRPM calculates the solar spectrum at full spectral resolution (already reduced here).
- Spectrum is calculated for each model.
- High resolution spectrum can be convolved to any resolution for comparison with observations.

SRPM brightness temperatures reflect the cross-over point near $T_{\text{eff}}$. 
PSPT Solar Feature Identification

- Feature area determined from intensity analysis of PSPT images
- Analysis done as a function of disk position and time
- Full disk Irradiance determined from disk position and emitted intensity from each atmospheric model

Ca IIk
393.45 nm, 0.273 FWHM
Identify Active Regions

Red Continuum
607.095 nm, 0.458 FWHM
Identify Umbra & Penumbra

SRPM Mask Image
Identify 7 solar Features

Ca II k Intensity Histogram, Disk Center

Distribution becomes steeper with lower solar activity
SRPM Decomposition of Solar Cycle changes

- Clear indication of the rise of Solar Cycle 24 both in sunspot area and bright active regions.
- ~160 days separate the minimum in the longitudinal B-field (HMI) from the minimum active region Area (PSPT).
- Disk fractions for bright active regions are already approaching 2005 values.
Atmospheric Models Center-to-Limb Variability

- $\mu = \cos(\theta)$, $\theta =$ heliocentric angle
- $I_{\text{model}}$ defined relative to the internetwork model (B or 1001)
- **No solar cycle variation assumed in Model B**
- Applicable to continuum wavelengths
- ‘Cross-over’ is the location on the solar disk where solar features go from bright to dim at a given wavelength
- The specific intensity at $\mu = 0.66 \approx \text{flux (Eddington approximation)}$
- SIM-like solar cycle variability is observed in the behavior at $\mu = 0.66$:

![Graph showing center-to-limb contrast for different wavelengths and disk positions.](image)

*What the SORCE SIM observations tell about solar spectral irradiance*
Time Series Comparison of SIM to SRPM/PSPT

Trends in the near-UV match the observations within the noise constraints of both instruments.

Rotational modulation well-matched in model and data.

Positive solar cycle trend not strong enough in model, photodiode degradation in SIM might influence comparison.

Rotational modulation well matched but intensity of the long term trend in the model weaker than observed.
Rotational Variability

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Chemistry Climate Models Need SSI
GISS GCM [Rind et al., 2004; Shindell et al., 2006]
NCAR WACCM [Marsh et al., 2007]
HAMMONIA [Schmidt and Brasseur, 2006]
CMAM [Beagley et al., 1997]

Near UV, visible, near infrared radiation affect surface and ocean processes

Ultraviolet (UV) radiation drives many atmospheric processes

Solar Forcing and Response Mechanisms are Wavelength Dependent

Solar Forcing and Earth Atmospheric Response

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- **Sensitivity studies are starting to address SIM observations in climate models:**
  - Cahalan *et al.*, *GRL*, 2010 (GISS ModelE)
  - Haigh *et al.*, *Nature*, submitted March 2010
  - Merkel *et al.*, in preparation, (WACCM)
Spectra differences 2004-2007

1σ errors ≤ 0.5 mW m⁻² nm⁻¹

Courtesy of Joanna Haigh, Imperial College London, SORCE 2010 meeting
What the SORCE SIM observations tell about solar spectral irradiance

Equatorial mean (25ºS to 25ºN)

1mb summary
Lean: +0.5%
SIM: -2%
What the SORCE SIM observations tell about solar spectral irradiance

1mb summary
Lean: -1%
SIM: -5%

Equatorial mean
(25°S to 25°N)

Unshaded area
Significant to 95% level
Conclusions at 1mb at Equator:
Solar Max compared to Solar min for Zonal Annual Mean

With SIM spectra:
- Less $O_3$ (2%)
- More $O^{1}D$ (4%)
- Level $O_2$ (no change)
- More $O$ (5%)
- More $HO_x$ (3%)
- Less $NO_x$ (-1%)
- More $CL$ (5%)
- Warmer $T$ (+1.5K)
- More cooling $QRL$ (-0.3 K/day)
- More Heating $QRS$ (0.3 K/day)
- Level $Qtot$ ($QRS+QRL$=no change)
- Net heating above 1mb (0.05 K/day)

With Lean Spectra:
- More $O_3$ (0.5%)
- More $O^{1}D$ (0.5%)
- Level $O_2$ (no change)
- More $O$ (1%)
- More $HO_x$ (1%)
- Less $NO_x$ (-1%)
- Level $CL$ (~0.2%)
- Warmer $T$ (0.25K)
- More Cooling $QRL$ (-0.05 K/day)
- More Heating $QRS$ (0.05 K/day)
- Level $Qtot$ ($QRS+QRL$ = no change)
- Net cooling above 1mb (-0.05 K/day)
Continuity for SSI measurements

- **With dissolution of NPOESS, TSIS no longer manifested on C1.**
  - Various options under review to fly TSIS within the same time frame (2013-2014 launch) and maintain TSI continuity with Glory.
  - SSI gap virtually assured under any scenario.

- **The SORCE SIM solar spectral irradiance is a ‘stand alone’ source of information about the variability of the solar spectrum.**
  - Data set available May 2003 and may extend to 2012 depending spacecraft/instrument health.
    - At the end of mission SORCE will not have a full solar cycle

![Probability of SSI Data Acquisition](image)

Analysis by G. Kopp

*Aspen Global Change Institute*
*Aspen, Colorado June 15, 2010*
The Future

• The SIM observations still require validation and a break in the record obfuscates the trends.
  – Degradation corrections on SORCE are delicate and sensitive, but our methodology remains stable over time {see GRL auxiliary material}
  – TSIS SIM eliminates a number of short comings in the current instrument
    – Pre-flight calibration based on NIST SIRCUS – gives traceability to SI
    – Ultra-clean spectrometer cavity - reduces prism degradation
    – 3 independent SIM channels – improves degradation corrections
    – 21-bit analog-to-digital converter – improves radiometric precision
  – Will SORCE last long enough to overlap with TSIS? Probably not…
    • Progress using physics-based approaches such as SRPM are needed to fill this gap

• At this point in time, we need to consider building a second generation space-based PSPT imager that can provide radiometric information, i.e. replace the notion of contrast with an absolute pixel intensity.
Conclusions

• The combined SIM, SRPM, and PSPT image analysis provide a effective method to analyze solar variability
  – SIM indicates irradiance trends that are larger than solar modulation that compensate to produce the TSI trend.
  – SRPM analysis is able to capture offsetting trends observed by SIM, but refinements are still needed.
  – Active region evolution by itself is not sufficient to account for the observations – suggestive of changes in the internetwork/network radiance.

• In-depth Earth atmospheric modeling is progressing
  – Both direct SIM observations and SRPM model output are applicable

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Model Work by Joanna Haigh
Lesley Gray & Jerry Harder
Major question: are we using the correct estimates of UV variations in our models?

SIM Spectra differences 2004 - 2007

Harder et al. 2009
**Stratospheric temperature responses using different spectra (2004-2007)**

Haigh et al. 2010  December

**Lean**

Cahalan et al. 2010

**Harder** / SIM

x4-5 difference

Harder: 0.9K

Lean: 0.18K

*Note: The plots illustrate the temperature changes in the stratosphere due to different solar spectral irradiance models. The plots show temperature differences over time and across latitude and pressure levels.*
2D model O₃ differences in December (%) 
2004-2007

Lean

SIM

0.8%

2.0%