Coherency in the solar spectral irradiance

(a blind source separation approach)

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This work was supported by the FP7 SOTERIA and ATMOP projects
Dignity ?
Coherency!
6 years of observations (SORCE & TIMED)

sunspot nr

XUV (1-10 nm)
EUV (10-120 nm)
Lyα (120.5 nm)
FUV (120-200 nm)
MUV (200-300 nm)
NUV (300-400 nm)
VIS (400-700 nm)
NIR (700-1000 nm)
especially at short timescales

sunspot nr

- XUV (1-10 nm)
- EUV (10-120 nm)
- Lyα (120.5 nm)
- FUV (120-200 nm)
- MUV (200-300 nm)
- NUV (300-400 nm)
- VIS (400-700 nm)
- NIR (700-1000 nm)
Motivation

- **Commonalities**
  - likely same physical drivers
  - gives deeper insight into the physics

- **Departure from this coherency**
  - most likely due to instrumental noise or to particular processes
Model assumption

Decompose the SSI $I(\lambda, t)$ into elementary contributions

$$I(\lambda, t) = A_1(t) \cdot S_1(\lambda) + A_2(t) \cdot S_2(\lambda) + \ldots$$

Assume

- linear decomposition
- instantaneous decomposition

This is “blind source separation” because neither the sources nor their mixing coefficients are known beforehand.
Example from ECG
Key questions

- How many sources?
  - 3?
  - 42?
  - ... 

- Are they unique?

- Ill-posed problem: what physical constraints can we use?
Various approaches

\[ I(\lambda, t) = A_1(t) \cdot S_1(\lambda) + A_2(t) \cdot S_2(\lambda) + \ldots \]

1) Sources and mixing coefficients are orthogonal

\[
\begin{align*}
\langle S_k(\lambda) S_l(\lambda) \rangle &= 0 \\
\langle A_k(t) A_l(t) \rangle &= 0
\end{align*}
\] if \( k \neq l \)

The solution is given by the Singular Value Decomposition (SVD)

- Similar to principal component analysis
- Simple, unique solution, but not very realistic
Various approaches

2) Sources and mixing coefficients are independent

\[ P(S_k, S_l) = P(S_k)P(S_l) \]
\[ P(A_k, A_l) = P(A_k)P(A_l) \]

The solution is given by Independent Component Analysis (ICA)

- Computationally most costly, but also more realistic
- Very popular in acoustics & image processing
Various approaches

3) Sources and mixing coefficients are independent and positive

\[ S_k(\lambda) \geq 0 \quad A_k(t) \geq 0 \]

The solution is given by Bayesian Positive Source Separation

- Computationally costly, but also more realistic
- Recent but very active field of research (chemometrics, image processing, astrophysics, ...)
  
  [Kuruoglu, IEEE signal proc. magazine 87 (2010)]
First example
XUV to VIS (TIMED & SORCE)
Example 1: SVD analysis

- 7 years of daily observations from 0.6 - 600 nm (TIMED/SEE, SORCE/XPS-SOLSTICE-SIM)
Example 1: SVD analysis

 diferentes time scales = different physical processes

→ decompose the data beforehand into different time-scales

we focus here on time scales < 3 solar rotations

data are normalized to their solar cycle variability
Example 1: SVD analysis

Distributions of the weights

\[ I(\lambda, t) = W_1 A_1(t) S_1(\lambda) + W_2 A_2(t) S_2(\lambda) + \ldots \]
Mixing coefficients

<table>
<thead>
<tr>
<th>Year</th>
<th>$W_1A_1(t)$</th>
<th>$W_2A_2(t)$</th>
<th>$W_3A_3(t)$</th>
<th>$W_4A_4(t)$</th>
<th>$W_5A_5(t)$</th>
<th>$W_6A_6(t)$</th>
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<tr>
<td>2004</td>
<td>39%</td>
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<td></td>
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<td>2009</td>
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<td>2012</td>
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</tr>
</tbody>
</table>
Mixing coefficients

\[ W_1 A_1(t) \]
\[ W_2 A_2(t) \]
\[ W_3 A_3(t) \]
\[ W_4 A_4(t) \]
\[ W_5 A_5(t) \]
\[ W_6 A_6(t) \]

TSI

Mg II

year

Apr04 Jul04 Oct04 Jan05 Apr05 Jul05
Sources

![Graph showing spectral data for various sources.](image)

The graph illustrates the spectral data for different sources labeled as $S_1(\lambda)$ to $S_6(\lambda)$. Each source is plotted against wavelength, with the x-axis representing wavelength in nanometers (nm) and the y-axis representing source intensity in arbitrary units (a.u.). The spectrum is divided into five regions: XPS, SEE, FUV, MUV, and SIM, each with distinct features and patterns. The data points are marked with different colors for each source, allowing for comparison and analysis of the spectral characteristics across the different regions.
Most of the salient features are captured by sources 1 & 2 only

The similarity maps provides a very compact representation of the spectral variability

\[ W_2 S_2(\lambda) \]

\[ W_1 S_1(\lambda) \]
Similarity map

$W_2 S_2(\lambda)$

$W_1 S_1(\lambda)$

wavelength [nm]

0 100 200 300 400 500

T. Dudok de Wit (SORCE, 9/2011)
Similarity map

facular brightening

sunspot darkening

\[ W_2 S_2(\lambda) \]

\[ W_1 S_1(\lambda) \]

wavelength [nm]
Similarity map with proxies

$W_2 S_2(\lambda)$

$W_1 S_1(\lambda)$

wavelength [nm]

0
100
200
300
400
500

T. Dudok de Wit (SORCE, 9/2011)
Conclusion 1

- The variability is very coherent:
  - 2 sources capture the salient features
  - other ones contain a significant amount of instrumental artefacts

- Guidance for the choice of proxies

- Instrumental effects are omnipresent
  - be *very* careful in the interpretation of sources > 2
Second example

EUV & FUV (TIMED/SEE)
Example 2

Homogeneous data set:
- 8 years of daily observations by TIMED/SEE
- 28-195 nm, 0.1 nm resolution
- no flares

Now consider positive sources only (more realistic)
- use Bayesian Positive Source Separation
- 3 sources are statistically significant
Source nr 4 contains plain instrumental noise
Mixing coefficients

![Graph of mixing coefficients showing three curves labeled A1, A2, and A3, with data points from 2002 to 2011.](image-url)
Mixing coefficients (excerpt)
Superposed epoch analysis of mixing coefficients confirms limb (XUV-like) contribution of source 3
Sources

Coronal & transition region lines

Quiet Sun only

Hottest coronal lines
Positive source separation gives physically meaningful sources [Amblard et al., A&A 487 (2008)]

Given the instrumental noise level

- the variability in the EUV & FUV has 3 degrees of freedom only e.g. [Lean et al., JGR 87 (1982)]
- they correspond to different temperature layers of the solar atmosphere

Perspectives for reconstructing the EUV/FUV from proxy data
The remarkable coherency of the solar spectral irradiance also provides a means for:
- eliminating part of the instrumental noise
- filling gaps/stitching together records (see poster)