Solar spectral irradiance and wind over time scales up to a decade

Karel Schrijver

schrijver@lmsal.com

Heliophysics Summer School 2013
Topics

• **Solar Spectral Irradiance:**
  • Atmospheric structure
    • Static atmosphere
    • Waves
    • Magnetic field
      • Photosphere
      • Corona
      • Chromosphere
  • Gradual changes: solar cycle
  • Impulsive changes: flares/eruptions
  • Integration: solar spectral irradiance

• **Solar Wind:**
  • Background wind:
    • Basics of the solar wind
    • Multi-fluid effects
    • Magnetic field, and angular momentum loss
  • Impulsive/eruptive events and the solar wind
  • Integration: solar wind
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A hypothetical static “Sun”

- In case of no dynamics (and thus no magnetic field)
- \( \frac{dX}{dt} = 0 \)
A hypothetical static “Sun”

- In case of no dynamics (and thus no magnetic field)
- $dX/dt=0$

Why is the disk darker towards the limb?
A hypothetical static “Sun”

- In case of no dynamics (and thus no magnetic field)
- $\frac{dX}{dt}=0$

Why is the disk darker towards the limb?

- Limb darkening is caused by the thermal gradient
A dynamic “Sun”

- Opacity unavoidably leads to (noisy) convection
A dynamic “Sun”

- Opacity unavoidably leads to (noisy) convection
• Opacity unavoidably leads to (noisy) convection
A dynamic “Sun”

- Opacity unavoidably leads to (noisy) convection
Solar oscillations in TSI

• Full-disk signal:

![Power spectrum graph]

**Fig. 2.** Power spectra of disk-integrated photometric fluctuations for the Sun: the predicted background signal of model Sun1 (green/grey solid line) and observational data from SOHO/VIRGO (black solid line). Note the steep decline in power towards high frequencies.
Solar oscillations in TSI

- Full-disk signal:

**Fig. 2.** Power spectra of disk-integrated photometric fluctuations for the Sun: the predicted background signal of model Sun1 (green/grey solid line) and observational data from SOHO/VIRGO (black solid line). Note the steep decline in power towards high frequencies.
Solar oscillations in TSI

Full-disk signal:

- Total solar irradiance
- Full-disk signal:

Fig. 2. Power spectra of disk-integrated photometric fluctuations for the Sun: the predicted background signal of model Sun1 (green/grey solid line) and observational data from SOHO/VIRGO (black solid line). Note the steep decline in power towards high frequencies.

Assumed model radius:
- Sun1: 1.0 R_Sun

Fig. 2. Power spectrum (in ppm^2/μHz) of the IPHIR data for the entire 155-day interval. Shown is the average result for the red and green channels (weighting the red channel by a factor of 1.25 relative to the green – see Sect. 4.1). The FFT algorithm used 2^19 points, oversampling by a factor of 1.7. The spectrum was smoothed over 4 points, and the average noise level was subtracted.
Visible/near-IR solar spectrum (SSI)

- To model irradiance of a non-magnetic Sun: include all dynamics, & radiative transfer

- To validate irradiance modeling: remove Earth-atmospheric effects.
Visible solar spectrum
Visible solar spectrum
Simulated magnetoconvection

Movie: Emergent continuum intensity (left) and vertical magnetic field at (right) from simulation with initial/boundary condition of convective inflows advecting 1 kG uniform, untwisted, horizontal field into the computational domain at 20 Mm depth. The intensity range is and the magnetic field range is ± 3.5 kG. The pores may form spontaneously in vertical flux tubes from magnetic loops that have reached the surface and opened out through top boundary. Compare this with Figure 14 for the rise of a coherent twisted flux tube. (Movie shows the initial “pepper and salt” emergence, the horizontal advection of the field, its concentration into unipolar regions with cancellation where opposite polarities meet and merging of like polarities to form pores. Resolution was increased from 48 km to 24 km horizontally at time 51.7 hrs.)

From http://solarphysics.livingreviews.org/Articles/lrsp-2012-4/
Pervasive magnetic field

- Dynamic, hierarchy of scales, electrical currents, reconnection, non-thermal/non-radiative energy

~700km
Processes in the solar atmosphere

- corona
- transition region
- chromosphere
- ~1.5 Mm
- ~1 Mm
- ~0.5 Mm
- classical temperature minimum
- photosphere
- 0 Mm
- convection zone
- network
- canopy domain
- fibril wave guiding
- sub-canopy domain fluctosphere
- current sheets
- weak fields
- small-scale canopies / HIFs
- reversed granulation
- granulation
- p-modes / g-waves
- internetwork
- supergranulation

Wedemeyer-Böhm et al. (2008)
Processes in the solar atmosphere

- Actual aspect ratio:
Processes in the solar atmosphere

What happens to sound waves in the solar atmosphere?

- Actual aspect ratio:
Processes in the solar atmosphere

- Density and gradient cause sound to dampen & shock
- Actual aspect ratio:

? What happens to sound waves in the solar atmosphere?
Terminology/definitions

- Solar (and stellar) atmospheric domains

Table 8.1. Basic parameters for domains in the solar atmosphere, and their definitions. Note that all regions of the solar atmosphere are very inhomogeneous and that these values are only meant to give a rough idea of their magnitudes.

<table>
<thead>
<tr>
<th>Region</th>
<th>$n$ [m$^{-3}$]</th>
<th>$n_e/n_H$</th>
<th>$T$ [K]</th>
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<td>Photosphere$^1$</td>
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<td>$10 - 0.1$</td>
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<td>$1$</td>
<td>$10^4 - 10^6$</td>
<td>$1 - 10$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Corona$^4$</td>
<td>$10^{14}$</td>
<td>$1$</td>
<td>$10^6$</td>
<td>$1 - 10$</td>
<td>$10^{-2} - 1$</td>
</tr>
</tbody>
</table>

Definitions: 1 the photosphere is the layer from which the bulk of the electromagnetic radiation leaves the Sun. This layer has an optical thickness $\tau_{\nu} \lesssim 1$ in the near-UV, visible, and near-IR spectral continua, but it is optically thick in all but the weakest spectral lines; 2 the chromosphere is optically thin in the near-UV, visible, and near-IR continua, but optically thick in strong spectral lines - it is often associated with temperatures around $10,000 - 20,000$ K; 3 the transition region is a thermal domain between chromosphere and corona in which thermal conduction leads to a steep temperature gradient; 4 the corona is optically very thin over the entire EM spectrum except for the radio waves a a few spectral lines - it is often used to describe the solar outer atmosphere out to a few solar radii with temperatures exceeding $\sim 1$ MK.
Line of sight magnetic field

- Active region
- Sunspot
- Mixed-polarity
- "Quiet Sun"
- Decayed active region
- Long-decayed active region
- Filament
- Coronal hole

2010/08/01 23UT

Saturday, July 13, 2013
Line of sight magnetic field

? How is the magnetic field measured?

Active region
Decayed active region
Long-decayed active region
Sunspot
Filament
Coronal hole
Mixed-polarity “Quiet Sun”

2010/08/01 23UT
Line of sight magnetic field

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- Sunspot
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- Long-decayed active region
- Decayed active region

• Magnetic field is derived from polarization signals
  2010/08/01 23UT

? How is the magnetic field measured?
The dynamic magnetic field

“Carrington map”

Obs. magnetogram
The dynamic magnetic field

“Carrington map”

Obs. magnetogram

Why does the field disperse?
The dynamic magnetic field

“Carrington map”

Why does the field disperse?

Obs. magnetogram

Random walk >> resistive diffusion: scales!

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Line of sight magnetic field

2010/08/01 23UT
Visible light; photosphere

Active region
Sunspot
Mixed-polarity “Quiet Sun”
Filament
Long-decayed active region
Decayed active region
Coronal hole

2010/08/01 23UT
Visible light; photosphere

Why do we see only spots?

Active region

Long-decayed active region

Decayed active region

Sunspot

Filament

Mixed-polarity

“Quiet Sun”

Coronal hole

SDO/AIA-4500 20100801_230008

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Saturday, July 13, 2013
Visible light; photosphere

Why do we see only spots?

B-field invisible in intensity, unless it changes the atmosphere

Saturday, July 13, 2013
Dark-bright: function of size
Figure 4.5: Concept of the magnetohydrostatic flux-tube model. One level of constant optical depth in the continuum, $\tau_0 = 2/3$, is shown, with the Wilson depression $\Delta z$. The hatched arrows $F_i$ and $F_o$ stand for the flux densities in the (nonradiative) energy flows inside and outside the flux tubes, respectively. The horizontal arrows indicate the influx of radiation into the transparent top part of the tube. The resulting bright walls are best seen in observations toward the solar limb (as seen along the oblique wavy arrow; figure adapted from Zwaan and Cram, 1989).
Figure 4.5: Concept of the magnetohydrostatic flux-tube model. One level of constant optical depth in the continuum, $\tau_0 = 2/3$, is shown, with the Wilson depression $\Delta z$. The hatched arrows $F_l$ and $F_o$ stand for the flux densities in the (nonradiative) energy flows inside and outside the flux tubes, respectively. The horizontal arrows indicate the influx of radiation into the transparent top part of the tube. The resulting bright walls are best seen in observations toward the solar limb (as seen along the oblique wavy arrow; figure adapted from Zwaan and Cram, 1989).
Spots, pores, faculea, ... and TSI
Visible light; photosphere
Line of sight magnetic field

2010/08/01 23UT
Line of sight B with “PFSS field lines”

http://sdowww.lmsal.com/suntoday_v2/

2010/08/01 23UT
UV $\sim$1600$\lambda$; high photosphere, low chromosphere

2010/08/01 23UT
He II 304Å; chromosphere

- Filament
- Active region
- Sunspot
- Mixed-polarity “Quiet Sun”
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2010/08/01 23UT
He II 304Å; chromosphere

2010/08/01 23UT
The low solar atmosphere
The low solar atmosphere
The low solar atmosphere

Dime at ten miles
He II 304Å; chromosphere

2010/08/01 23UT
EUV 193Å; corona

- Filament
- Active region
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2010/08/01 23UT

Saturday, July 13, 2013
EUV 193Å; corona

Filament

Active region

Sunspot

Long-decayed active region

Decayed active region

Mixed-polarity

“Quiet Sun”

Coronal hole

2010/08/01 23UT

? Why do we see “loops”??
Why do we see “loops”? 

- “Frozen in”: diffusion is negligible
- 2010/08/01 23UT

EUV 193Å; corona

- Filament
- Active region
- Sunspot
- Mixed-polarity “Quiet Sun”
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- Coronal hole

Saturday, July 13, 2013
Coronal loop atmospheres

In quasi-static models, only three terms are involved in the energy balance at any point at a distance $s$ above the base, measured along the loop: the local volume energy deposition, $\epsilon_{\text{heat}}$, the conductive flux density, $F_c$, along the loop, and the radiative losses per unit volume $\epsilon_{\text{rad}} = n_e n_H \mathcal{P}(T, \ldots)$ for radiative losses from an optically thin plasma [Eq. (2.59)]. Then:

$$\epsilon_{\text{heat}}(T, n_e, s, \ldots) = \frac{1}{A(s)} \frac{d}{ds} \left[ A(s) \kappa_c \frac{dT(s)}{ds} \right] + n_e n_H \mathcal{P}(T, n_e, A_i, \ldots). \quad (8.20)$$

In general, the loop cross section $A(s)$ is expected to change along the loop. The classical heat conductivity $\kappa_c$ equals $8 \times 10^{-7}$ erg cm$^{-1}$ s$^{-1}$ K$^{-7/2}$ (Spitzer, 1962).
Solar atmosphere > size

Mercury transit observed with TRACE on 15 Nov 1999

<table>
<thead>
<tr>
<th>171A</th>
<th>Time (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 19 48</td>
<td>21 26 10</td>
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<table>
<thead>
<tr>
<th>1600A</th>
<th>Time (UT)</th>
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<tbody>
<tr>
<td>21 19 19</td>
<td>21 26 19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>white light</th>
<th>Time (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 19 21</td>
<td>21 26 22</td>
</tr>
</tbody>
</table>
Why is the Sun's size color dependent?
Solar atmosphere > size

Mercury transit observed with TRACE on 15 Nov 1999

171A
Time (UT) 21 19 48 21 26 10 21 33 48 21 41 27 21 48 26

1600A
Time (UT) 21 19 19 21 26 19 21 33 57 21 42 14 21 48 36

Why is the Sun’s size color dependent?

- Radius differences: opacity

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The dynamic Sun
Fig. 10.1. Comparison of the solar spectrum and the black body spectrum for radiation at 5770 K (the approximate temperature of the Sun’s visible surface).
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What is the color of sunlight? What is the color of sunlight?

- Color of sunlight: white

Fig. 10.1. Comparison of the solar spectrum and the black body spectrum for radiation at 5770 K (the approximate temperature of the Sun’s visible surface).
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16-y of magnetogram assimilation, viewed as Solar Orbiter may see it

Lat. +30°; Carr. long. 0°

Lat. -30°; Carr. long. 180°

Lat. -60° – +60° assimilated; high-latitude field advected by transport code
The solar cycle
The solar cycle
TSI(t)
$\text{TSI}(t)$

![Graph showing TSI(t) with PMOD, ACRIM, and SARR data with trend lines and unit changes per decade.](image)
Spots, pores, faculae, ... and TSI(t)

Irradiance Variability Components

- facular brightening
- sunspot darkening

W m^-2

Fig. 10.1. Comparison of the solar spectrum and the black body spectrum for radiation at 5770 K (the approximate temperature of the Sun’s visible surface). Also shown is an estimate of the variability of the solar spectrum during the 11-y solar cycle, inferred from measurements (at wavelength below 400 nm) and models (at longer wavelengths) and, for reference (dashed line), the solar cycle 0.1% change in the total solar irradiance.
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Dynamic atmosphere

Time: 2011-02-14T17:59:50.062Z, dt=300.0s
aia_20110214T180000_211-193-171-blos_1k.prgb
channel=211, 193, 171, source=AIA,AIA,AIA,HMI
X-ray flaring: rapid, high contrast
Flare evolution over the spectrum
Long-range disturbances

“Running-ratio composites
Long-range disturbances

“Running-ratio composites

AIA ratio [RGB]=[211,193,171] 2012-03-06 23:42:37
Flare energy: mostly WL and kinetic

From Emslie et al. (2012): values for X3, X3, X4, X7, X8, X10 flares.
Flare energy: mostly WL and kinetic

From Emslie et al. (2012): values for X3, X3, X4, X7, X8, X10 flares.
Chameleon behavior of solar storms

- GOES class provides a very uncertain measure of the energy in a solar coronal storm event.

- Example: GOES classes for an active-region flare and quiet-Sun filament eruption differ by factor of ~250 for comparable ‘bolometric’ energies in the X-ray/(E)UV domain.
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Solar spectral/total irradiance

- TSI(t) in phase with sunspot cycle: faculae outshine sunspots (on average, not when spots are near disk center).
- TSI(t)/SSI(t) variations attributable to atmospheric magnetic field, with little/no effect of internal changes.
- Long-term trends in TSI(t) and SSI(t) in visible light: to be determined.
- Explosive events: at short wavelengths very strong contrasts but small contributions to TSI; most energy emitted in visible light, where that hardly makes a difference.
- (X)(E)UV changes associated with “closed field”: reconstructing (T)(S)SI(t) by terrestrial proxies remains uncertain, debated, and to be explored.
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Comet C/1995 O1 (Hale-Bopp), March 1997

Early indicator of a solar wind

Ion-Gas tail

Nucleus (1-10 km)

To Sun

Coma

Dust tail

33,000,000 km
 (~0.2 Earth-Sun Distance)

~100,000 km

~100,000 km
Solar wind parameters

<table>
<thead>
<tr>
<th>Property (1 AU)</th>
<th>Slow wind</th>
<th>Fast wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>430 ± 100 km/s</td>
<td>700 – 900 km/s</td>
</tr>
<tr>
<td>Density</td>
<td>≈ 10 cm⁻³</td>
<td>≈ 3 cm⁻³</td>
</tr>
<tr>
<td>Flux</td>
<td>(3.5 ± 2.5) × 10^8 cm⁻² s⁻¹</td>
<td>(2 ± 0.5) × 10^8 cm⁻² s⁻¹</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>6 ± 3 nT</td>
<td>6 ± 3 nT</td>
</tr>
<tr>
<td>Temperatures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>T_p = (4 ± 2) × 10^4 K</td>
<td>T_p = (2.4 ± 0.6) × 10^5 K</td>
</tr>
<tr>
<td>E</td>
<td>T_e = (1.3 ± 0.5) × 10^5 K &gt; T_p</td>
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</tr>
<tr>
<td>Anisotropies</td>
<td>P isotropic</td>
<td>P⁺ &gt; P⁻</td>
</tr>
<tr>
<td>Structure</td>
<td>filamentary, highly variable</td>
<td>uniform, slow changes</td>
</tr>
<tr>
<td>Composition</td>
<td>He/H ≈ 1 – 30%</td>
<td>He/H ≈ 5%</td>
</tr>
<tr>
<td>Minor species</td>
<td>n_i/n_p variable</td>
<td>n_i/n_p constant</td>
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<tr>
<td></td>
<td>T_i ≈ T_p</td>
<td>T_i ≈ (m_i/m_p)T_p</td>
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<tr>
<td></td>
<td>v_i ≈ v_p</td>
<td>v_i ≈ v_p + v_A</td>
</tr>
<tr>
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~0.06 G
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Closed / open field; 2-fluid
Closed / open field; 2-fluid
Closed / open field; 3-fluid

- Heat: 60% into H, 40% into He
Solar wind “opens” magnetic field
Solar wind “opens” magnetic field
MHD-lite: magnetofrictional model
MHD-lite: magnetofrictional model
Fig. 9.3. The heliospheric current sheet forms a warped, undulating structure extending from the top ridge of the helmet streamer belt (cf., Figs. 1.3 [top] and 8.1) that sweeps by the Earth as the Sun rotates once per 27 days (synodic period). The magnetic field changes direction across the current sheet. (From Alfvén, 1977)
Potential-field simulation

- Heliospheric field base over a full cycle

$t = 0.0 \text{ y} \quad (27\text{-day synodic reference frame}) \quad \phi = 0.00$
Elements of the solar wind

Temporal
Elements of the solar wind

Temporal

Geometrical
“Air brake”

Present-day Sun ($P = 24 \, d$) vs. Young Sun ($P = 1.2 \, d$)

- $u_r/a_0$, $u_r/A_r$, $A_r/a_0$
- $a$

- Pressure
- Gravity
- Magnetic
- Centrifugal
- TOTAL

 accel. [cm s$^{-2}$]

$r/r_0$

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“Air brake”
“Air brake”

- Spin down because of magnetic “arm” in the wind
Topics

• Solar Spectral Irradiance:
  • Atmospheric structure
    • Static atmosphere
    • Waves
    • Magnetic field
      • Photosphere
      • Corona
      • Chromosphere
  • Gradual changes: solar cycle
  • Impulsive changes: flares/eruptions
  • Integration: solar spectral irradiance

• Solar Wind:
  • Background wind:
    • Basics of the solar wind
    • Multi-fluid effects
    • Magnetic field, and angular momentum loss
  • Impulsive/eruptive events and the solar wind
  • Integration: solar wind
Pulse in the wind: model, propagating
Pulse in the wind: model, propagating
Pulse in the wind: real, at Earth

![Graph showing various parameters over time](image-url)
Pulse in the wind: real, at Earth

Temporal
Geometrical
Stream interactions

[Diagram showing stream interactions with labels for origins, forward and reverse shocks, stream interface, fast stream, slow stream, forward shock, reverse shock, leading and trailing unshocked layers, and distances marked as 1 AU and 5 AU.]
Topics

• Solar Spectral Irradiance:
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Solar wind over a sunspot cycle

Ulysses First Orbit
Ulysses Second Orbit
Ulysses Third Orbit

SWOOPS
Speed [km s\(^{-1}\)]

Outward IMF
Inward IMF

Smoothed Sunspot Number

Current Sheet Tilt [deg]

WSO Radial

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Solar wind over a sunspot cycle

What causes the pattern change in the solar wind speed over the years?
What causes the pattern change in the solar wind speed over the years?

- Dipole tilt and CMEs involved in wind pattern