The Sun at the Source

COLLAGE 2023
ASEN-5519:
Space Weather Overview

Lecture #1
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The Sun is an enormous cascade of processes converting different types of energy:

- **Gravitational (Potential)** – collapse of interstellar cloud
- **Thermal** – heating of plasma
- **Nuclear** – fusion in core
- **Kinetic** – convective flows, waves
- **Electromagnetic** – magnetic energy, waves
- **Atomic** – energy level transition, ionization
Key Concept: Density

There is a continuous outward density gradient in the Sun. For reference, compare the density profile of the Earth.

Density of Earth’s Interior with radius
Note linear scale
1 order of magnitude change

Density of Earth’s Atmosphere with height
Note logarithmic scale
12 orders of magnitude change

https://www.researchgate.net/publication/346576248_Earth_tomography_with_atmospheric_neutrino_oscillations
https://www.researchgate.net/publication/248866118_Vita_brevis_of_antibubbles
Solar Interior

This instead is the density gradient in the Sun.

6 order of magnitude decrease from core to surface

Outer half of Sun (85% of volume) is less dense than water.

Solar matter density

(Data Source: http://www.sns.ias.edu/~jnbs/SDdata/Export/BP2004/bp2004stdmodel.dat)

Solar matter density $\rho$ [g/cm$^3$]

<table>
<thead>
<tr>
<th>Relative radius $r = R/R_{Sun}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>1.0</td>
</tr>
</tbody>
</table>

Core Radiative Zone Convective Zone

Standard Solar Model BP2004
J. N. Bahcall and M. H. Pinsonneault

Liquid water
Solar Structure

Different energy transport mechanisms at work as energy moves outward
Solar “Surface”

Called **Photosphere**

Radiative escape carries away most of solar energy as electromagnetic waves
Granulation covers surface, with occasional sunspots

240 arcseconds = 170 Mm = 1/8th solar diameter

Photosphere
Small-scale magnetic fields (bright points) confined by granular flows.
Black Body

Continuum spectrum of Sun is an approximate blackbody spectrum
Magnetic Field Generation

Differential rotation of Sun (higher latitudes rotate more slowly) twists up poloidal magnetic field.
Magnetic Field Generation

- Pole
- Pressure gradient
- Magnetic curvature force
- Buoyancy force
- Coriolis force
- Equator

(e)
Magnetic Field Emergence

Nelson, et al., 2013,
https://arxiv.org/abs/1211.3129
Solar spectrum through the years

In addition to the blackbody spectrum, many dark spectral lines
Magnetic Field Measurements (Zeeman)

Properties of atomic transitions of certain spectral lines allow us to diagnose magnetic field in solar atmosphere (where line is formed).

Easiest measurement is the field strength along the line of sight.

Penn, 2014, Living Review Solar Physics
Sunspots, and the surrounding area (the active region) harbor strong magnetic fields of opposite polarities. Sometimes these magnetic field are complex and intertwined.
Sunspots and Magnetic Fields

Another example, with magnetic field polarities shown as red and blue. Notice sharp line between two polarities in some parts of the active region.
Polarity Inversion Lines (PIL) aka Neutral Lines

There can be strong, sheared horizontal magnetic fields at the locations where the polarity changes.

Dec.13, 1251UT
Magnetic Field Measurements (Transverse)

We can also measure the horizontal field with the Zeeman effect, but it is harder, noisier.
Penumbra can be seen surrounding dark sunspot umbra – these are sites of complicated, predominantly horizontal fields.
We can derive multiple parameters about the solar atmosphere with spectral lines.

- Temperature
- Magnetic Field Strength
- Inclination
- Azimuth

Note azimuth only goes from +/- 90°
Mt. Wilson Classification

Flaring and CME activity may be related to complexity of magnetic field. How do we characterize different active regions?

Table 4. Mount Wilson Magnetic Classification Codes

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>Unipolar (single magnetic pole) sunspot groups</td>
</tr>
<tr>
<td>Beta</td>
<td>Bipolar sunspot groups with a simple and distinct division between areas of opposite polarity</td>
</tr>
<tr>
<td>Beta-Gamma</td>
<td>Bipolar sunspot groups with no easily discernible dividing line separating areas of opposite polarity</td>
</tr>
<tr>
<td>Gamma</td>
<td>Complex sunspot groups with areas of opposite polarity completely intermixed, preventing classification as a bipolar group</td>
</tr>
<tr>
<td><em>Delta</em></td>
<td>Denotes sunspot groups consisting of opposite polarity umbrae within the same penumbra</td>
</tr>
</tbody>
</table>

*Note that the classification code ‘Delta’ is not a standalone magnetic classification. It is simply a descriptor that can be affixed to the end of the ‘Beta’, ‘Beta-Gamma’, and ‘Gamma’ classification codes, allowing for a total of seven unique magnetic codes.
McIntosh Classifications

This classification scheme just uses distribution of sunspots, not magnetic field measurements.

<table>
<thead>
<tr>
<th>McIntosh type</th>
<th>Number of occurrences</th>
<th>Number of class M flares</th>
<th>Number of class X flares</th>
<th>Flares/occurrence per 24 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M</td>
</tr>
<tr>
<td>H3e</td>
<td>1963</td>
<td>99</td>
<td>6</td>
<td>0.05</td>
</tr>
<tr>
<td>D3p</td>
<td>553</td>
<td>51</td>
<td>6</td>
<td>0.09</td>
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<tr>
<td>D3i</td>
<td>324</td>
<td>58</td>
<td>7</td>
<td>0.18</td>
</tr>
<tr>
<td>D3c</td>
<td>100</td>
<td>72</td>
<td>10</td>
<td>0.72</td>
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<tr>
<td>E3i</td>
<td>81</td>
<td>103</td>
<td>11</td>
<td>1.27</td>
</tr>
<tr>
<td>E3c</td>
<td>63</td>
<td>149</td>
<td>21</td>
<td>2.36</td>
</tr>
<tr>
<td>F3i</td>
<td>47</td>
<td>106</td>
<td>17</td>
<td>2.26</td>
</tr>
<tr>
<td>F3c</td>
<td>27</td>
<td>39</td>
<td>13</td>
<td>1.44</td>
</tr>
</tbody>
</table>
What happens higher in the solar atmosphere?

- **Core**
- **Solar “Surface”**
- **interior (opaque)**
- **Photosphere**
- **Chromosphere**
- **prominences**
- **active regions & flares**
- **ions in solar wind?**
- **most solar wind**

- Why so diverse?
  - Different wavelengths see hot gas (plasma) over a range of temperatures…
  - prominences
  - active regions & flares
  - most solar wind ions in solar wind?
  - interior (opaque)
  - Photosphere
  - Chromosphere
  - prominences
What happens higher in the solar atmosphere?

- **Terrestrial atmosphere**: $1.2 \times 10^{-3}$ g/cm$^3$
- **Martian atmosphere**: $1.5 \times 10^{-5}$ g/cm$^3$

**Density**

- $10^{-9}$ g/cm$^3$
- $10^{-13}$ g/cm$^3$
Solar (Stellar) Atmosphere

### Photosphere
- Thickness: ~500 km
- Density: \( \rho_{ph} = 2 \times 10^{-5} \text{ gr/cm}^3 \)
- Energy requirements: \( F_{ph} = 6 \text{ kW/cm}^2 \)
- Mass: \( 4 \times 10^{20} \text{ kg} \)

### Chromosphere
- Thickness: ~2000 km
- Density: \( 10^{-3} - 10^{-6} \times \rho_{ph} \)
- Energy requirements: \( 10^{-4} \times F_{ph} \)
- Mass: \( 2 \times 10^{18} \text{ kg} \)

### Corona
- Thickness: > 10^6 km
- Density: \( 10^{-8} \times \rho_{ph} \)
- Energy requirements: < \( 10^{-5} \times F_{ph} \)
- Mass: \( 6 \times 10^{15} \text{ kg} \)
Chromospheric Radiation

Radiation from chromosphere comes in the form of continuum radiation (in the UV and millimeter wavelengths) and many emission lines in the visible and UV.

- Ca II H & K
- Hγ
- Hβ
- Fe X1V 5303
- Na D1,D2
- He D3
- Hα

flash spectrum courtesy Dr. Manfred Rudolf
Magnetic Field Dominance

plasma $\beta = \frac{\text{plasma pressure}}{\text{magnetic pressure}}$

In the chromosphere and corona, because of the steep drop in density, the magnetic field begins to dominate the plasma motions.
Filaments and Prominences

This creates neat things like prominences (seen at the limb) and filaments (same structures, but seen on the disk)
A view of how structures connect up through different regions of the atmosphere.
The corona, the outermost layer of the solar atmosphere
Again we also use spectral lines to diagnose the conditions in the corona – different ionization states indicate different ambient temperatures.
SDO EUV Images

171 Å
Fe IX
105.8 K

171 Å
Fe XIV
106.3 K

171 Å
Fe XX, XXIII
10^7 K
XRT X-ray Images

Al-Mesh
$10^{6.9}$ K

Be-Thin
$10^{7.1}$ K

171 Å
Fe XX, XXIII
$10^{7}$ K
Magnetic Energy Storage

Driven by the plasma motions in the photosphere, the magnetic field in the photosphere can become intertwined and store energy in an unstable state.
Magnetic Energy Release

The magnetic energy can then be impulsively released, resulting in the release of high-energy photons, heating of the solar chromosphere, and outward flux of high-energy particle and mass ejections (CME).
Example Flare (movie)
Chromospheric Response

Flares generate energy propagation down to loops of magnetic loops, heating their footpoints in the chromosphere, which tend to fall on either side of the polarity inversion line.
Activity Indicators

Integrated, full-sun X-ray flux shows solar flare activity, with the flares showing up as sharp rises and slower decays.

The “size” of a flare is defined by the maximum value of the emission, and labeled by letters (B, C, X, M) indicating order of magnitude changes in flare emission.
Radio flux (10.7 cm wavelength) provides a good proxy for solar activity, and can be obtained from the ground, resulting in a long, continuous series of observations.
**Sun In Time: 2023-01-18**

**Image Channels**

- **1K** 4K PFSS No Lines
- 304 | 4500 | 1600 | 1700 | 304-211-171
- 094-335-193 | 094 | 335 | 131
- 211-193-171 | 211 | 193 | 171
- HMI cont | HMI B红线 | 171-B红线

Tip: Hover over the wavelength labels underneath the set of images to change the thumbnail image.

FITS files (for planning purposes): 4500 | 1700 | 1600 | 335 | 304 | 211 | 193 | 171 | 131 | 64 | B红线

**Movie links:**
- Daily movies: *Not Yet Available*
- 304-171 movies: *Not Yet Available*
- 211-193-171 movies: *Not Yet Available*
- 211-193-171 running-ratio movies: *Not Yet Available*
- AIA and STEREO/EUVI-A+B movies: *Not Yet Available*

**Other resources:**
- Image data request forms: [click here]
- SolarMonitor for this date: [click here]
- IRIS pointing summary for this date: [click here]
- Interactive PFSS model for this date: [click here]
- STEREO Science Center daily browse data for this date: [click here]
- AIA emission measure data: [click here](image) or [click here](movie) or [click here](image cube) or [click here](source code)
Welcome to the GONG Data Archive.
Use this page to access most GONG data products from 1995* to present.
* Note that observations from before February-July 2001 (depending on the site) were made with lower-resolution 236x256 pixel camera.

Data Access Steps:
- Step 1: Choose Product Set
  Select one of the links below to proceed to step 2:
  | Full Calibration Products: | M Image Data: | Vorticity & Intensity: | Global Helioseismology: | Local Helioseismology: | Magnetic Field Products: |
  | Daily Reduced New | Daily Reduced New | Daily Reduced New | Daily Reduced New | Daily Reduced New |
  | Real Time Products: | M Image Data: | Vorticity & Intensity: | Global Helioseismology: | Local Helioseismology: | Magnetic Field Products: |
  | Daily Reduced New | Daily Reduced New | Daily Reduced New | Daily Reduced New | Daily Reduced New |

Step 2: Select Data From Product Set And Select Time Period
Products for H-Alpha Product Set:
Instructions: Click the calendar button below for a quick view of availability. OR: Select a product and date range to search. The search results page will appear along with directions for storing and downloading your data request.

GONG Network H-Alpha Images
These options will search all GONG sites for a given time.
- GONG Network (un-merged) H-Alpha FITS Data
- GONG Network (un-merged) H-Alpha JAS Preview

GONG Site-specific H-Alpha Images
- Big Bear Reduced H-Alpha FITS Data
- Cerro Tololo Reduced H-Alpha FITS Data
- Learmonth Reduced H-Alpha FITS Data
- Mauna Loa Reduced H-Alpha FITS Data
- Teide Reduced H-Alpha FITS Data
- Udaipur Reduced H-Alpha FITS Data
- Big Bear Reduced H-Alpha JPG Preview
- Cerro Tololo Reduced H-Alpha JPG Preview
- Learmonth Reduced H-Alpha JPG Preview
- Mauna Loa Reduced H-Alpha JPG Preview
- Teide Reduced H-Alpha JPG Preview
- Udaipur Reduced H-Alpha JPG Preview

Select Date: (YYMMDD HHMM)
[Note: Date ranges should not cross the 1999-2000 boundary.]
Data Start: 230101 0000 Data Stop: 230101 0000

Search
solarMonitor.org
Virtual Solar Observatory

Search for Solar Physics Data Products:

If you're new to the VSO, see How To Search, the FAQ or click the ? icons for online help.

Please select which values you wish to use to search for data products:

- **Time**
  - Search by time interval.
  - Derive time intervals from event catalogs
- **Observable**
  - Search based on physical observables
- **Instrument / Source / Provider**
  - Search based on instruments or data archives
    - Compact listing
    - Instrument / Source (not provider dependent)
    - Instrument Only (not source or provider dependent)
- **Spectral Range**
  - Search based on a spectral range
- **Nicknames**
  - Search based on common terms used to describe data products
  - Note: Nicknames generate an intersection with other search terms, so searching for a nickname, and a physical observable (or other parameter) when a nickname defines other physical observables will result in no matches.
    - Show Nickname Definitions

Searching against current VSO Instances

Generate VSO Search Form

VSO Documentation

- Documentation for Scientists, Programmers and Data Providers, including Changes, FAQs, and contact info.

Help us improve VSO

- Tell us what features you would like to see.
- Other suggestions / comments / criticism
- Contact information for VSO team members

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