Solar Atmosphere

Photosphere

Chromosphere

Corona

highly ionised gas: plasma
Observing Sun’s Atmosphere

- Visible light
- Ultra-violet
- X-rays
- Gamma rays
The Many Faces of the Sun

SOLAR ATMOSPHERE
10 JAN 92

Corona
EUV, Xrays

(Hα), UV, EUV
Chromosphere

Near UV, VIS, IR

Photosphere

Temperature (K)
Height (km)
The Solar Atmosphere

- Only visible during solar eclipses
- Apparent surface of the sun

Heat Flow

- Chromosphere
- Photosphere
- Solar interior

Temp. incr. inward

Temperature (K)
Temperature and Density Variation

-Log Temperature (K)
-Height above visible limb (Mm)

Thomas Neukirch
The **Surface** of the Sun…

- The rapid decrease of the density within a short distance is the reason that we see a sharp edge…
- The surface layer is where sunlight is generated. It is referred to as the **Photosphere**.
Photosphere

- $H \sim 500 \text{ km}$
- Visible light images reveal sunspots, granulation, faculae
Photospheric Features: Granulation

- Size of granulation cell \( \sim 1000 \text{km} \)
- manifestation of convection

(bubbling up and down...)
Photospheric Features: Supergranulation

- Size of super granulation cell ~ 30000 km = 30 Mm
- convection cells (red=downflow, blue=upflow)
- related to chromospheric network
Photospheric features: Sunspots

- strong magnetic fields (several kGauss)
- dark because lower T
- in active regions
- most obvious signature of solar cycle
Photosphere

- Magnetograms reveal surface magnetic fields
  - Field into Sun – black
  - Field out of Sun - white

2005/02/07 01:36
The Chromosphere is a thin, irregular layer above the photosphere in which the temperature rises up from 5,800 K to about 20,000 K. This layer is usually observed in the red wavelength of the Hydrogen line. It is therefore termed Chromosphere, meaning *color*-sphere. (Halpha in emission from the hotter part of chromosphere)

Bright patches (the Plages) and dark spots (sunspots) are related to higher magnetic field regions.
Composition:
Photosphere and Chromosphere
Analyzing the Fraunhofer absorption lines from the different elements in various stages of excitation and ionization.
Spectral line formation
The Chromosphere

- Region of sun’s atmosphere just above the photosphere.

- Temperature increases gradually from $\approx 4500 \, ^oK$ to $\approx 10,000 \, ^oK$, then jumps to $\approx 1$ million $^oK$
The Chromosphere

Spicules: Filaments of cooler gas from the photosphere, rising up into the chromosphere.

Visible in Hα emission.

Each one lasting about 5 – 15 min.
Filaments and prominences are cool and dense gas suspended high in the solar atmosphere, and embedded in the very hot solar corona.

- When they are observed on the solar surface, they appear as dark absorption features…filaments!
- When they are observed outside of the solar limb, they appear as bright features because they reflect sunlight toward us…prominences!

A huge solar prominence observed in 1946

The Grand Daddy Prominence
The gas in prominences may be 60,000 to 80,000 K, quite cold compared with the low-density gas in the corona, which may be as hot as a million Kelvin.
Prominences

- Observed in chromospheric lines, but located in corona
- Cool, dense plasma confined in vertical sheets
- Lifetimes: hours-months
Chromospheric features: Spicules

- jets of material moving upward
- height \( \sim 5000 \text{ km} \)
- width \( \sim 500 \text{ km} \)
- \( T \sim 10^4 \text{ K} \)
- velocity \( \sim 25 \text{ km/s} \)
- well-correlated with network
- Physical mechanism still a matter of some debate

spicules (mottles)
Corona

- $T > 10^6 \text{ K}$
- $n < 10^{15} \text{ m}^{-3}$
- extends to Earth & beyond!

- Observed in
  - EUV ($T \sim 10^6 \text{ K}$)
  - Soft X-ray ($T > 2 \times 10^6 \text{ K}$)
  - White light
Coronal Loops

High resolution image of the corona obtained by TRACE satellite.
Corona and coronal Holes

X-ray images of the sun reveal coronal holes. These arise at the foot points of open field lines and are the origin of the solar wind.
Solar wind velocity (ULYSSES)

Background = composite image of the Sun from SOHO

**FAST** Solar Wind
(700 km/s) in coronal holes

**SLOW** Solar Wind
(300 km/s) in equatorial regions

Red = inward field
Blue = outward field
The Solar Wind

Constant flow of particles from the sun.
Velocity $\approx 300 - 800$ km/s

$\Rightarrow$ Sun is constantly losing mass:

$10^7$ tons/year

$(\approx 10^{-14}$ of its mass per year)
Schematic of Global Corona (solar minimum):
The Solar Corona in ‘White Light’

This is an image of total solar eclipse.
- The radiation are reflection of sunlight by the electrons in the corona.
- The streamers are where *slow* solar wind leave the Sun.
- The coronal holes are where *fast* solar wind leave the Sun.
The Coronal Heating Problems

• The temperature of the Sun is the highest in its core, about 15 million degrees.
• The temperature decreases as we move outward toward the surface, dropping to 6,000 K at the photosphere.
• The temperature then rises to about 20,000 K in the chromosphere, just a few thousand km above the photosphere.
• The temperature rises rapidly to 1 to 2 million degrees in the corona.
• *We do not understand how the corona is heated, and this is one of the important unresolved questions of solar physics.*
The Many Faces of the Sun

MDI MAGNETOGRAM
01-May-2005 20:48 UT

MDI WHITE LIGHT
01-May-2005 20:48 UT

BBSO GHN H\(\alpha\)
01-May-2005 20:48 UT

EIT FeX 195 A
01-May-2005 20:48 UT

EIT FeXV 284 A
01-May-2005 20:48 UT

GOES SOFT X-RAY
01-May-2005 20:48 UT
Magnetic Field of the Whole Sun

- A magnetogram shows the magnetic field on the surface (the photosphere) of the Sun. The black and white patches show where the magnetic fields are strong.
  - **White** indicates magnetic field pointing toward us.
  - **Black** indicates magnetic fields pointed away from us.
  - The large patches of black and white are due to **sunspots** and active regions.
- The pepper-and-salt patterns outside of the active regions indicates that there are magnetic fields everywhere on the surface of the Sun.
Zeeman effect
Sun Spots

Magnetic field in sun spots is about 1000 times stronger than average.
Early Clues of Sunspot Magnetic Field

The brightness structure of a sunspot seen in the absorption line of hydrogen resemble the magnetic field lines surrounding a bar magnet.
Active Region Magnetic Fields at the Photosphere

• Active regions appear as bipoles, which implies they are the tops of large Omega-shaped loops which have risen through the solar convection zone and emerged into the photosphere.

• On average, bipoles are oriented nearly parallel to the E-W direction (Hale’s law 1919) indicating that the underlying field geometry is nearly toroidal.

• Hale’s law persists for years through a given solar cycle, thus the toroidal layer must lie deep in the interior in a region relatively free from convective turbulence.
Active regions (sunspot groups) are tilted so that the following spots are slightly poleward of the preceding spots. This tilt increases with latitude.
Sun Spots

 Cooler regions of the photosphere ($T \approx 4200$ K).

 Only appear dark against the bright sun. Would still be brighter than the full moon when placed on the night sky!
High-Resolution View of the Solar Surface

- Sunspot
  - Umbra
  - Penumbra
- Solar Granulation
Granulation

... is the visible consequence of convection
Internal Structure

Energy generation via nuclear fusion

Energy transport via radiation

Energy transport via convection

Flow of energy

Temperature, density and pressure decreasing

Basically the same structure for all stars with approx. 1 solar mass or less.
Energy Transport in the Sun-like stars

Energy generated in the star’s center must be transported to the surface.

Inner layers:
Radiative energy transport

Outer layers (including photosphere):
Convection

Gas particles of solar interior

γ-rays

Cool gas sinking down

Bubbles of hot gas rising up

Granule

Sinking gas

Rising gas
Solar Granulation

On the surface of the Sun, we can see the action of convection...

Image of solar granulation. The bright center of the cells are where hot gas rise to the surface. The narrow dark lanes are where cold gas sink to the ‘bottom’.

- Each cell is about 1,000 km in size
Mar. 29, 2006

Nov. 1994

Early 1996

Corona at solar minimum
Solar Cycle

Solar Maximum

Solar Minimum

Sunspot Number

Date

Magnetic Field and X-Ray Variation Through one Solar Cycle

The activities in the solar corona also follow the solar cycle. In fact, the level of almost every aspect of solar activities (flares, coronal mass ejections, etc.) follows the solar cycle.

The black-and-white patterns show the surface magnetic field variation through one sunspot cycle (11 years).
The solar dynamo is responsible for the 11-year solar cycle (also called the 22-year solar cycle, the sunspot cycle, magnetic cycle).

Two important points:

- The sunspot cycle itself varies
- All of the types of energy input to Earth exhibit greater fluctuations on shorter timescales (flares, CMEs)
The Solar Cycle

After 11 years, North/South order of leading/trailing sun spots is reversed

=> Total solar cycle = 22 years
Solar Cycle---Sunspot Numbers and the Butterfly Diagram

Solar Cycle
The number of sunspots on the surface of the Sun follows a 11-year cycle.

Butterfly diagram
Sunspots appear at higher latitude at the beginning of the solar cycle, and migrate toward the equator as the cycle evolves. So, when we plot the latitude of the sunspots as a function of time, the patterns looks like a series of butterfly… therefore it is referred to as the butterfly diagram’
Classical Signature of Solar Cycle

DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

Average daily sunspot area (% of visible hemisphere)

SUNSPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)

http://science.msf.nasagov/ssl/pad/solar/images/bfly.gif

NASA/NSSTC/HATHAWAY 2005/10
Properties of Solar Cycle

- Equatorward migration of sunspot-belt
- Poleward drift of large-scale radial fields, from follower spots
- Polar field reversal at sunspot maximum

Courtesy: D.H. Hathaway
Since the magnetic field of the Sun reverse its orientation every 11 years, the solar cycle is really a 22-year magnetic cycle.

How does the Sun change its magnetic field orientation every 22 years?
The Sun does not rotate like a solid body. It rotates every 25 days (1/462 nHz) at the equator and takes progressively longer to rotate one revolution at higher latitudes, up to 35 days (1/330 nHz) at the poles. differential rotation.
Helioseismic determinations of the internal rotation rate show that the latitudinal differential rotation seen at the surface extends through the convection zone. Layers of strong radial shear are found near the surface and at the base of the convection zone (the tachocline).
Internal Meridional Flow

Helioseismic determinations of the internal meridional flow show that the poleward flow seen at the surface extends into the convection zone. An equatorward return flow must exist at the base of the convection zone but has not yet been observed.
Giant Cells are the largest cells with diameters of ~ 200,000 km and lifetimes of ~ weeks. They produce the Sun’s differential rotation and meridional flow. They have been modeled by numerical simulations but are NOT well observed.

Meisch et al. (2000)
The Sun’s Magnetic Dynamo

The sun rotates faster at the equator than near the poles.

This differential rotation might be responsible for magnetic activity of the sun.
(i) Generation of toroidal (azimuthal) field by shearing a pre-existing poloidal field (component in meridional plane) by differential rotation (Ω-effect)
Large-scale Dynamo Processes

(ii) Re-generation of poloidal field by lifting and twisting a toroidal flux tube by helical turbulence (α-effect)
Large-scale Dynamo Processes

(iii) Flux transport by meridional circulation
Schematic summary of predictive flux-transport dynamo model

Shearing of poloidal fields by differential rotation to produce new toroidal fields, followed by eruption of sunspots.

Because, leading sunspots are slightly equatorward of their following ones, there is more cancellation of leading-polarity flux than following-polarity flux by diffusion across the equator.

This leaves a surplus of following-polarity flux in each hemisphere, north and south. Over the course of the cycle, in each hemisphere meridional flow sweeps the remnant flux toward the pole and builds up a polar cup of predominantly following-polarity flux (Moore 1990).
The Sun’s Magnetic Cycle

After 11 years, the magnetic field pattern becomes so complex that the field structure is re-arranged.

→ New magnetic field structure is similar to the original one, but reversed!

→ New 11-year cycle starts with reversed magnetic-field orientation
Wolf number:

- Wolf number, $W$, depends on the number of sunspots by the formula: $W = 10g + p$
  ($g$ - number of sunspot groups, $p$ - number of all sunspots)
- From XIX century Wolf number is a measure of solar activity
- Observations should be systematic and the results should be sent to astronomical organizations
Wolf number:

- $g = 3$
- $p = 11$
- "w" = 41

If a single sunspot were here, one should count it as a group, too.