The Sun

- $R_{\text{sun}} = 6.96 \times 10^5$ km
- $M_{\text{sun}} = 1.99 \times 10^{30}$ kg
- $L_{\text{sun}} = 3.86 \times 10^{26}$ W
- $\langle \rho \rangle \sim 1410$ kg/m$^3$ $\rightarrow$ H and He
Solar Structure

- Photons diffuse outwards through radiative zone until they reach convective zone. Transport in convective zone is via “boiling motions” of the gas. Visible surface of the sun is the photosphere.
Solar Atmosphere

• Base is the photosphere (with sunspots)
• Next layer is the chromosphere (with spicules and prominences)
• Next layer is corona (tenuous) with solar wind
The Photosphere

• This is the “surface” of the sun.
• Note: we cannot peer further into the sun because the gas becomes opaque to visible light.
• Features:
  – **Granules**: bright irregular formations surrounded by dark lanes
    • These are the top layer of the convective zone; hot masses of gas rise (appear as granules) and dissipate energy in the photosphere. Cooler gases sink back down.
    • Why? $PV = nkT \Rightarrow$ as $T$ increases, $P$ increases, which pushes gas upwards (“buoyancy”).
Solar Granules

Granules are about 1000 km across.

Schematic of the convection zone.
The Photosphere continued

• Features continued
  – **Limb darkening**: brightness decreases radially from center
  • Optical depth effect.

Since $F = \sigma T^4$, $F$ is strongly dependent on $T$!
The Interior

Most of the solar interior will be covered next semester. For now, important detail is **helioseismology**.

**Solar oscillations** with periods between 5 minutes and 2h 40 min.

**GONG** (Global Oscillations Network Group)
- 6 stations around earth to monitor solar oscillations
- studies of the harmonics tell us about the interior structure.
- 5 min oscillations are “sound” waves (pressure waves) from the interior trapped within acoustic cavities.
  → analysis of surface patterns allows us to probe interior, just like S and P waves help determine Earth’s interior.

**SOHO** (Solar and Heliospheric Observatory)
- located at the L1 Lagrange point;
- studies solar wind, internal vibrations, corona, & magnetic field.
Results…

- Sun’s rotation speed varies with depth.
- Surface layers have “zonal flow” with alternating layers of higher than average and lower than average rotation rates.
The Solar Spectrum
Spectral Lines

• Fraunhofer designated the strongest lines, starting from the red, with capital letters.
  – A & B are telluric features
  – D is the sodium doublet: Na I
  – G-band is the blend of several metal lines
  – H & K are Calcium

Note: these strong lines all come from the same region as the continuum.

Weaker lines originate lower in the photosphere than the strong lines. The shape of the spectral line tells us about the depth of formation.

Based on line strengths, the sun is composed of:
  71% H; 27% He; 2% other stuff
The Chromosphere

• You can only see the chromosphere when the photospheric light is blocked.

• Emission lines $\rightarrow$ high temperatures
  – Helium (Helios) was found in chromospheric spectra before it was found on Earth.
  – Hydrogen Balmer lines $\rightarrow$ absorption when viewed against photosphere; emission when viewed past solar limb.
  – Photographs in H\(\alpha\) show filaments, plages, and spicules.

  – Spicules are jets of hot gas connecting the chromosphere to the corona. They are NOT distributed uniformly and are associated with magnetic fields and with supergranules.
Hα image

Filaments

Plages
The Corona

Two parts: K corona (near sun)
F corona (out to a few solar radii)

\[ T \sim 1 - 2 \times 10^6 \, \text{K} \]

During solar maxima, corona is bright and uniform.
During solar minima, corona is oblate, with more at the equator than at poles.

Emission lines at high T:

The two strongest are Fe XIV (530.3 nm)
Fe X (637.4 nm)

Both are forbidden lines, and therefore took awhile to recognize.
Coronal Loops

X-ray images show that the coronal gas has an irregular distribution.

→ Ionized gas flows along magnetic field lines.

Note: coronal gas does not follow the differential rotation of the photosphere.
→ Bottoms of magnetic loops are anchored below the photosphere.
Solar Wind

- High coronal temperatures “blow” the corona away from the sun → solar wind
- Solar activity changes the magnetic field structure; occasionally, this results in “bursts” or solar wind → solar flares.
- Flares have clouds of high energy protons which can have disastrous effects on unshielded electronic equipment (and humans!) in space.
Solar Activity

- **Sunspots** – dark splotches on the photosphere
  - The darkest region is the *umbra*; surrounded by the lighter *penumbra* with radial, filamentary structure.
  - Most important characteristic: magnetic field
    - B field inhibits the convective transport of energy
      → sunspot is cooler than surrounding photosphere.
    - Every sunspot has magnetic polarity
      - Sunspots come in pairs

Diagram:
- N
- S

Rotation:
- Following
- Preceding
Sunspots

(a) Umbra

(b) Penumbra
Magnetogram

Optical image

Magnetogram: blue = north; yellow = south polarity
Solar Cycle

- Sunspot counts go from minima to maxima in 11 years.
- From one 11 year cycle to next, the sense of polarity of “preceding” and “following” spots reverse.
- Therefore, **full** cycle takes 22 years
- Note: sunspots tend to be at high latitude at start of cycle and near the equator near maximum.
Solar Rotation

- Can use sunspots to determine rotation period of sun.
- Rotation is differential:
  - Solar equator: 25 days
  - High latitude: 27 days at 40°
    30 days at 70°
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Lots still to learn about our nearest star....

• What causes solar flares?
• What causes sunspot cycle?