The Sun

- The Sun is a “typical” star that generates energy from fusion of hydrogen into helium.
- Stars are gaseous bodies that support their weight by internal pressure.
The Sun: Basic Properties

- Radius $6.96 \times 10^5$ km = $1 \, R_\odot$
- Luminosity $L_\odot = 3.9 \times 10^{26}$ watts (joules/sec)
- Effective temperature is blackbody temperature that gives luminosity for measured radius: $\sigma T_{\text{eff}}^4 = L_\odot / 4\pi R_\odot^2$
- $T_{\text{eff}} = 5800$ K
Observable Layers of the Sun

• Photosphere
  – where almost all the visible light arises. Think of the photosphere as where the optical depth of the atmosphere equals unity.

• Chromosphere
• Corona

Difficult to observe
Astronomy 291

North Pole

Corona
T = 2,000,000 K

Chromosphere

Photosphere
(visible surface)
T = 5700 K

Center
T = 15,000,000 K

Hydrogen-burning core

Prominences

Hydrogen and helium gas; no nuclear reactions

Convective zone

Earth at same scale
Elemental Abundances

Elemental abundances are typical for cosmic sources, but very different from Earth. By mass:

- 73.4% Hydrogen
- 25.0% Helium
- 1.6% everything else ("metals")
Relative Abundance of Elements

Note that each vertical bar represents a factor of 100 (number of protons)
Solar Interior

• The interior of the Sun is hot and highly ionized
  – a plasma of free electrons and nuclei
• The Sun becomes increasingly neutral with increasing altitude in the photosphere.
• Depth to which we can see depends on “opacity”.
Opacity

• In the photosphere, the principal source of opacity is the H\textsuperscript{−} ion.
Opacity

- The extra electrons needed for H⁻ are from easily ionized heavier elements.
- H⁻ forms under conditions of high density and moderate temperature.
- H⁻ can be photodissociated by photons with $\lambda < 22000\text{Å}$ (2.2 μm; $E = 0.75$ eV).
- The H⁻ layer is opaque to UV/visible/near IR light.
Opacity

- In the photosphere, the particle density decreases with height.
- Density eventually drops to the point where formation of $\text{H}^-$ is too slow to balance the rate at which it is destroyed.
Opacity

- We see to different depths into the photosphere depending on where in the disk we look.
  - Depth determined by how much H\(^{-}\) is along our line of sight.

\[
\tau = \int_{0}^{D} n(r) \sigma dx(r)
\]
Limb Darkening

Top of photosphere
\( T = 4400 \text{ K} \)

To Earth

Bottom of photosphere
\( T = 8000 \text{ K} \)

At the center of the disk, we can see to a depth of about 400 km (0.0006 \( R_\odot \)).

Near the limb of the Sun, the 400 km line of sight does not penetrate to deep layers.
Limb Darkening

• The edge, or limb, of the Sun looks darker because we can see only the upper, cooler levels.
Limb Darkening

- Average temperature at center of disk is thus about 6100 K.
- Averaged over the whole Sun the typical photospheric temperature we observe is about $T = 5700$ K.
Photosphere

- The photosphere is broken up into granules.
- Granules are convective cells, whose motions are primarily vertical.
Convection

- Convection means mass motions of rising hot gas, followed by descent after cooling.
  - Typical size of granules: 1000 km
  - Typical lifetime: 8 minutes
Limit of the Photosphere

• At top of photosphere, density decreases and particle collision become rarer.
  – Formation of $\text{H}^-$ is rarer, can’t keep up with rate of destruction
  – Opacity decreases
  – Since collision rate drops, cooling rate (via collisions) drops, and $T$ increases.
  – This defines the transition from the photosphere to the chromosphere.
Chromosphere

• $T$ increases through the chromosphere
  – $T_{\text{bottom}} (h = 0 \text{ km}) \approx 4400 \text{ K}$
  – $T_{\text{top}} (h = 2000 \text{ km}) \approx 9000 \text{ K}$

• Balmer absorption lines arise primarily in this layer.
  – Density still reasonably high, temperature approaching $10^4 \text{ K}$.
Chromosphere

• The chromosphere is a thin emission-line region seen above the limb of the Sun during a total solar eclipse.
  – Height: 2000 - 3000 km
Chromosphere

• The chromosphere is hotter than the photosphere.
  – heating by acoustic waves deposits mechanical (kinetic) energy into the chromosphere.
Chromosphere

• Structure:
  – bright areas: **plages**
    • Plages are regions where the magnetic field is breaking through the photosphere.
  – dark areas: **filaments**
    • Filaments made of are cool gas that has been lifted up above the photosphere.
Spicules

- Spicules are upward moving (10 km s\(^{-1}\)) gas.
- They are due to charged particles following magnetic field lines.
Corona

- The temperature increases dramatically through the solar corona.
  - The density is low, so there are not enough collisions to cool the gas.
  - Primary source of opacity is free electrons.
Corona

- Temperature is about $2,000,000 \text{ K} = 2 \times 10^6 \text{ K}$, and increases outwards.
- Brightness about $10^6$ times fainter than photosphere (comparable to full Moon).
Particle Speeds in the Corona

• How fast are protons moving in the corona?

\[
V_{\text{rms}} = \left( \frac{3kT}{m} \right)^{1/2} \\
= \left( \frac{3 \times 1.38 \times 10^{-23} \times 10^6}{1.67 \times 10^{-27}} \right)^{1/2} \left( \frac{T}{10^6} \right)^{1/2} \times 10^{-3} \left( \frac{\text{km}}{\text{m}} \right) \\
= 160 \left( \frac{T}{10^6} \right)^{1/2} \text{ km s}^{-1}
\]
Particle Speeds in the Corona

• Compare this to escape velocity in the corona.

\[
V_{\text{esc}} = \left( \frac{2GM}{r} \right)^{1/2}
\]

\[
= \left( \frac{2 \times 6.67 \times 10^{-11} \times 2 \times 10^{30}}{6.96 \times 10^{8} (r/R_{\text{Sun}})} \right)^{1/2} \times \left( \frac{10^{-3} \text{km}}{\text{m}} \right)
\]

\[
= \frac{620}{(r/R_{\text{Sun}})^{1/2}} \text{ km s}^{-1}
\]
Solar Wind

• At 4 $R_{\odot}$, a significant fraction of coronal particles are moving faster than escape speed.
• The corona thus “boils off” the Sun.
• This outward stream of particles is called the “Solar Wind,” which we will return to shortly.
Solar Activity

- Many observable properties vary with the Sun’s variable magnetic field.
- Most obvious activity associated with magnetic fields is *sunspots*.

Sun’s Magnetic Field
Solar Cycle

Sunspot numbers

Chromospheric activity

Shape of corona
Sunspots

- Discovered by Galileo
- Show that the Sun is *not solid*
  - Rotates differentially; equator rotates about 30% faster than the poles.
- Individual spots last a few hours to a few months
Sunspots

- Photospheric Temperatures:
  - Mean photosphere (at center of disk): 6100 K
  - Typical sunspot temperature: 4300 K
Sunspots

- Large magnetic fields are associated with Sunspots.
- This is seen in the spectra of lines that are sensitive to “Zeeman splitting.”
  - Some energy levels in atoms are actually “degenerate” (i.e., multiple levels at the same energy).
  - These are separated in the presence of a magnetic field.
Zeeman Splitting

Absorption spectrum

No magnetic field

Splitting proportional to magnetic field strength

Strong magnetic field:
Zeeman Splitting

Spectrograph slit

Spectrum
Sunspots

• Distribution of sunspots varies on an 11-year cycle.
  – Number of spots varies from cycle to cycle.
Solar Cycle

- Sunspots may disappear for extended periods (e.g., “Maunder Minimum”, from 1645–1715).
Sunspots

- Location (solar latitude) of spots varies on an 11-year cycle. A plot of latitude vs. time produces a “butterfly diagram.”
**Solar Cycle**

- Sunspots tend to occur in pairs
  - pairs have opposite magnetic polarity
  - northern hemisphere and southern hemisphere spots have reversed polarity.
  - polarity pattern complete reverses every 11 years.

The true solar magnetic cycle is thus 22 years long.
Origin of Filaments and Prominences

- Convection produces kinks in magnetic field.
- Kinked magnetic field can erupt through photosphere $\Rightarrow$ sunspots
Hot gas unable to rise here because of magnetic field.

Magnetic field loops out of Sun

Photosphere

Sunspot (cool surface)

Hot surface

Hot gas

Hot rising gas

Magnetic field inside Sun
Origin of Filaments and Prominences

- Ionized gas stuck between merging spots forms prominence.

A solar prominence

Sunspot pair
Origin of Filaments and Prominences

- *Prominences* consist of relatively cool gas seen in *emission* above limb of Sun.
- These can be seen in *absorption* against hotter photosphere as *filaments.*
Origin of Filaments and Prominences

Solar prominence

Filaments and prominences are physically the same thing.
A Large Arch Prominence

- Prominences can be very large energetic events.
- Vertical speeds can reach 1300 km s$^{-1}$. 
Chromospheric Eruptions

- Large-scale chromospheric eruptions can lead to mass-loss events called solar flares.
Solar Flares

- Get bright in a matter of minutes
- Typically last 5 - 10 minutes, but can last for several hours
- Seen initially as a brightening of a plage area
- Temperatures can reach $10^7$ °K
Coronal Mass Ejection
Coronal Mass Ejection

• This sequence shows several things:
  – two Sun-grazing comets
  – a prominence
  – a coronal mass ejection
Solar Flares

- Flares released energetic particles that interact with particles trapped in the Earth’s magnetic field
Solar Flares

• The interaction between high-energy solar particles and the Earth’s upper atmosphere produce aurorae (Northern Lights) and can disrupt communications
The Sun’s Angular Momentum

- Whereas the Sun contains 99.9% of the mass of the Solar System, Jupiter has most of the angular momentum.
- Young solar-type stars rotate much more rapidly than the Sun.
- These imply that the Sun has lost much of its angular momentum.
- Mechanism: carried away by solar wind.