Chapter 16: The Sun

- **Bulk Properties of the Sun**
  - Mass, Radius, Luminosity, etc.

- **Overall Solar Structure**

- **Solar Atmosphere**
  - Composition, Chromosphere, Transition Zone and Corona

- **Solar Magnetism**
  - Sunspots, Prominences and Mass ejections

- **Solar Core**
  - Particles and Interactions, Fusion: the p-p chain

- **Solar Neutrinos**

- **Summary**
The energy emitted by our sun in **one second** would satisfy the energy needs of humanity for **one million years**!
In equilibrium, inward gravitational force must be balanced by outward pressure.

- Nuclear fusion in the core maintains a high temperature and outward pressure
- The weight (gravitational pull) of the matter contains the matter and prevents the sun from simply exploding.
Hydrostatic Equilibrium

- If the core cools, the pressure decreases and the sun contracts.
- The contraction increases the pressure in the core and speeds up the nuclear reactions, which causes the outward pressure to increase.
- The sun then expands again and the cycle repeats itself! The equilibrium is stable.

This causes the sun to oscillate radially, a sort of “breathing”.
The Solar Interior

• Assuming Hydrostatic Equilibrium, we are able to theoretically model the sun in terms of the variation of density and pressure across its interior.

• The models then make predictions about the sun’s properties (like the radius, luminosity, spectrum, etc.)

• The models are not perfect and are constantly tested against experiments.

• With more data, the models are tweaked and our understanding improves.

• This is the scientific method, which will be applied to all of Astronomy in what follows.
By listening carefully to the timbre of the sound from a musical instrument, we can tell quite accurately what instrument we’re listening to.

The timbre of an instrument is produced by “overtones” or resonances, which depend very strongly on the shape and composition of the instrument!
• Turns out the sun has resonances as well!
• Apart from the breathing oscillation, the sun will “ring” (like a bell!) in a variety of different tones.
• By studying these resonances as the sun oscillates we can tell a lot about the interior structure of the sun.
Helioseismology

- **Helioseismology** is the study of solar surface patterns.
- These patterns are observed using **Doppler shifts** of the sun’s spectral lines as the sun oscillates.
- The process is similar to the way in which geologists study the structure of the earth by studying the waves in the earth’s crust produced by earthquakes.
Helioseismology

- The relative strengths of the different resonances tell us a lot about the internal structure of the sun.
- They tell us how temperature and density vary from the surface all the way into the center of the sun.
• Remember that the speed of a mechanical wave can be recovered from its wavelength and frequency.
• Remember also that the wave speed is related to the density, pressure and temperature of the material through which it travels.
• Thus, the waves allow us to probe the density of the sun across its interior because they can travel deep inside it.
The **Global Oscillation Network Group** (GONG) observes the surface of the sun continuously and has been doing so since roughly 2001 with six coordinated observatories all over the world.
• Interior structure of the Sun
  – Outer layers are not to scale.
  – The core is where nuclear fusion takes place.
Solar Interior

- Solar density and temperature, according to the standard solar model:
  - **Average Density**: 1400 kg/m³
  - **Core**: \( T = 15 \text{ million K} \)
    - Density = 110 X Average
  - **Radiation Zone**:
    - \( T = \text{few million K} \)
    - Density = 50 X Average
  - **Convection Zone**:
    - \( T \) drops to 5780 K
    - Density drops to approx. zero
Whatever energy is produced in the core of the sun must be transported from the core to its surface and expelled from into space. The sun uses two mechanisms to expel this energy:

- Radiation
- Convection

The region in which energy is transported by radiation is called the RADIATION ZONE.

The region in which energy is transported by convection is called the CONVECTION ZONE.
Solar Interior

- Energy transport:
  - The radiation zone is *relatively* transparent; the cooler convection zone is opaque.
• **Core**: Energy is produced in the core by nuclear fusion, primarily involving the “proton-proton” chain.

• **Radiation Zone**: X-ray photons produced by the nuclear fusion random walk through the dense proton plasma in the radiation zone. The time it takes for a photon to cross this zone is about 2 thousand years. As the photons move outward they lose energy and cool. Nuclei begin to recapture electrons to form atoms.

• **Convection Zone**: By the outer edge of the radiation zone, matter is cool enough to reform atoms, in particular ionized Hydrogen, which is opaque to photons; the photons from the core get captured by the atoms. In the convection zone, energy is transported by convection.

• **Photosphere**: By the end of the convection zone, the density is too low to produce convection. Light emitted by the top layer of atoms in the convection zone flies through unimpeded.
Solar Interior

- We can actually see the effects of the circular motion of matter in the convection zone:
- The visible top layer of the convection zone is **granulated**, with areas of upwelling material (bright) surrounded by areas of sinking material (dark).
Absorption Spectra

- Spectral analysis can tell us what elements are present, but only in the chromosphere and photosphere.
The cooler **chromosphere** is above the photosphere and is characterized by its ultra-low density (about $10^4$ km thick).

The density of the chromosphere is $10^{-4}$ that of the photosphere.

It is difficult to see directly, as the photosphere is too bright, unless the Moon covers the photosphere and not the chromosphere during an eclipse.
Chromosphere

- It appears faintly reddish. This is characteristic of Hydrogen ($\text{H}\alpha$).
- On the right is a picture of the sun through a telescope with a $\text{H}\alpha$ filter.
Chromosphere

- A **spicule** is a dynamic jet of plasma about 500 km in diameter in the chromosphere of the sun.
- Small solar storms in the chromosphere emit **spicules**.
- Spicules move upwards at about 20 m/s and last only a few minutes.
The Solar **Corona** can be seen during an eclipse if both the photosphere and the chromosphere are blocked.

It extends out to roughly 7 times the radius of the sun, or about 5 million km.
The Corona is much hotter than the layers below it. It must have a heat source, probably the magnetic field of the sun and electromagnetic interactions.
The sun’s magnetic field is produced by the rotating plasma. This is called the **dynamo model**. This is thought to be the source of the magnetic fields of the planets and other stars as well. One prediction of this theory is that the magnetic field should rise, decay and reverse itself, rising again and decaying but in the opposite direction. This is called **dipole reversal**.
The Solar Magnetic field

- The sun’s magnetic field is very complicated because magnetic fields are produced by moving charges and the motion of the plasma is extremely complex (apart from an overall rotation).
Sunspots

- Magnetism blocks the convective flow in certain regions, preventing those regions from releasing energy from the interior of the sun into space.
- This makes these regions slightly cooler than the rest of the surface.

Sunspots appear dark because they are slightly cooler than the surrounding gas.
**Sunspots** appear dark because they are slightly cooler than their surroundings.
Sunspots

- Sunspots take shape when intense magnetic fields from the interior of the sun pierce the surface, changing the direction of the flow of charged particles.
- The magnetic fields are strong enough to stop the convective motion of the material from parts of the convection zone!
Sunspots

- Sunspots come and go, typically in a few days.
- Sunspots are linked by pairs of magnetic field lines.
Sunspots

- Sunspots come with a polarity.
- Astronomers label “S” the point at which the magnetic field emerges from the interior and “N” the point at which it reenters the interior.
- They almost always come in pairs having opposite polarities.
Solar Magnetism

- We had seen that the Sun rotates differentially.
- The rotation of the Sun drags magnetic field lines around with it, causing kinks.
The Solar Cycle

- The Sun has an 11-year sunspot cycle, during which sunspot numbers rise, fall, and then rise again.
The Solar cycle

- **Recall** that the dynamo model predicts that the solar magnetic field will flip-flop, so that the North and South poles switch places.
- Thus, what appears to be an 11 year cycle in sunspot activity is actually a 22 year cycle, with the Northern and Southern hemispheres switching every 11 years.
The Solar Cycle

- Every so often, however, there is a prolonged drop in the sunspot activity.
- This occurred between 1645-1715 and is referred to as the Maunder minimum.
Questions

- Why is the sun stable? Why does it not implode/explode?
- What are the main regions of the sun?
- What is helioseismology? How does it tell us about the interior?
- What is **Luminosity**? How is it measured?
- How do we know the temperature of the sun’s surface?
- How does energy produced in the **core** get out of the sun?
- What is the origin of solar magnetism?
- What causes sunspots?
Prominences

- Areas around sunspots are active; large eruptions may occur in the photosphere.
- Solar prominence is a large sheet of ejected gas.
Prominences

• Fueled by magnetic fields and instabilities found near sunspots, the matter loops along the field lines because it is guided by the magnetic field lines on the surface of the sun.

• Prominences are extremely wide, i.e., they can extend over hundreds of thousands of kilometers on the sun’s surface. The largest ones only appear when the sunspot activity is at a maximum.

• They can last for days and even weeks.
Solar Flares

- **Solar flare** is a large explosion on the Sun’s surface, emitting an amount of energy similar to a prominence.
Solar Flares

- Flares are also a consequence of magnetic instabilities near sunspots. Matter is ejected upward at very high velocities.
- Flares **do not** loop but rise straight up because the surface magnetic field is not strong enough to bring them back to the surface.
- The central region of a flare is very hot: the temperature can rise to 100 million Kelvin (much hotter than the core!).
- Flares are relatively short lived, lasting for minutes or hours rather than days or weeks.
Coronal Mass Ejections

- A coronal mass ejection emits charged particles that can affect Earth.
Coronal Mass Ejections

• The charged particles are confined in magnetic bubbles that separate from the solar atmosphere and escape the sun entirely, passing through the corona and traveling outward into space. They occur about once per week.

• If a mass ejection comes toward the earth, its magnetic field can reconnect with the earth’s magnetic field and transfer energy into the earth’s magnetosphere. They can lead to a particularly spectacular auroras (Borealis and Australis).

• If a large enough ejection encounters the earth, the disruption can cause damage to communications on the planet.
Corona

- Solar corona appears very different at different times during the solar cycle, reflecting the complex state of the sun's magnetic field.
- Left: Corona at solar min; Right: Corona at solar max.
Corona and Solar Wind

- The corona is very hot, with temperatures of several million degrees K. At this temperature it emits X-rays. Observing these X-rays is a good way to study the solar corona.
- The corona changes in step with the sunspot activity.
- The high energies in the corona are likely fed by the surface activity and multiple magnetic loops that continually sprout up, disconnect and reconnect within it causing heating.
- In addition, more active disturbances on the surface can move through the corona carrying energy.
• **Solar wind** escapes the Sun mostly through coronal holes, which can be seen in X-ray images. The coronal hole is the dark V-shaped region.
The Earth’s magnetic field produces a magnetosphere that deflects and traps particles from the solar wind protecting Earth.
Nuclear fusion requires that like-charged nuclei get close enough to each other to fuse. This can happen only if the protons on the right collide at very high velocities:

\[ v \sim 610 \text{ km/s} \]

Speed in a plasma is related to its temperature. For this, the temperature must be extremely high—over 10 million kelvins.
The process that powers most stars is a three-step fusion process, the proton–proton chain.
Neutrinos

• Each reaction produces only $10^{-12}$ J of energy.

• $10^{38}$ reaction occur per second. This amounts to approximately 570 million tons of H $\rightarrow$ He per second!

• Electron neutrinos are emitted directly from the core of the Sun and escape, interacting with virtually nothing. Being able to observe these electron neutrinos gives us a direct picture of what is happening in the core.

• They are no more likely to interact with Earth-based detectors than they are with the Sun; the only way to spot them is to have a huge detector volume and to be able to observe single interaction events.
Neutrinos

- Neutrino observatories (a) Super K and (b) Sudbury
The Solar Neutrino “Problem”

• **The Solar Neutrino Problem:** The Sun *appears* to produce only about a third of the neutrinos predicted by theory.

• Various proposals have sought to explain this discrepancy. The best (and widely accepted) resolution is that neutrinos possess a small mass that allows them to “oscillate” i.e., *change type*.

• The “missing” neutrinos could be the electron neutrinos (produced in the sun) that changed into other flavors on their way to Earth.

• The other flavors would go undetected in our experiments.
The Sun is held together by its own gravity and powered by nuclear fusion.

Outer layers of the Sun are the photosphere, chromosphere, and corona.

The photosphere is the visible “surface” of the Sun. The corona is very hot.

Mathematical models and helioseismology give us a picture of the interior of the Sun.

Sunspots occur in regions of high magnetic fields; darker spots are cooler.

Nuclear fusion converts hydrogen to helium, releasing energy.
Solar neutrinos come directly from the solar core, although observations have told us more about neutrinos than about the Sun.

The **Solar Neutrino Problem** is that the Sun appears to produce only about a third of the neutrinos predicted by theory.

If neutrinos have a mass, the “missing” neutrinos could be the electron neutrinos (produced in the sun) that changed into other types of neutrinos on their way to Earth.