The Sun: Structure and Activity

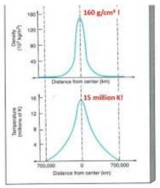
We have one more object in the Solar System to talk about, and since the next part of the course deals with **stars and stellar astronomy**, we should start with what we know about the nearest star to us: **The Sun**.

Properties of the Sun:

- **Radius** = 700,000 km (a little less than twice the distance from the Earth to the Moon)
- **Mass** = 2 X 10^{30} kg (~99.9% of the mass of the entire solar system)
- So, **Average Density** = 1.4 g/cm^3
- **Composition:** 70% Hydrogen, 28% Helium, 2% everything else
- Surface Temperature: 5800 K; increasing to 15 X 10^6 K at the center
- At these high temperatures, **atoms are partially or fully ionized** (one or more electrons removed from the atoms). So the Sun is a **plasma**, i.e. positive ions and free negative electrons, a charged gas.

Unlike a planet, **a star like the Sun is rather simple**. To a large extent, the Sun's internal structure can be characterized by two properties: **the temperature and the density.**

The Temperature and Density in the Interior of the Sun



Solar Structure

Hydrostatic Equilibrium:

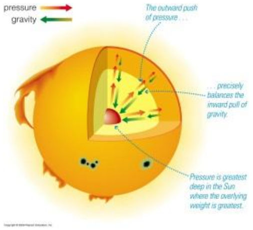
If the Sun is so hot, and hot gases tend to expand, you might ask:
What keeps the Sun from flying apart? (LC)

Its own Gravity pulls the other way, and holds it together.

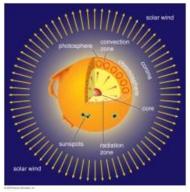
Or, take the reverse of this question: If the Sun is so massive:
What holds it up and keeps it from collapsing in on itself? (LC)

The high gas pressure provided by the high temperature.

This balance is called Hydrostatic Equilibrium.
At every point inside the Sun, the inward force of gravity balances the outward force of pressure.
It's very much like a balloon; but for a balloon, it's the elastic stress produced by the material that pulls in, not gravity.



Solar Structure



The interior and exterior of the Sun are characterized by several layers:

- **Core:** central region where the temperature and density are high enough for hydrogen to fuse into helium. **This is the only region of the sun where energy is produced.** (*we'll cover the details at great length in our next class.*)

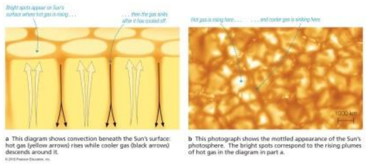
- **Radiation Zone:** the energy produced in the core is transported as radiation, i.e. high energy photons. **How long does it take for the energy to be transported through the radiation zone? (LC)**

  Several thousand years! Why?

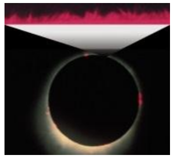
  The photons can travel only a very short distance before being scattered by free electrons; thus they follow a random walk path and slowly drift to to the top of the radiation zone which takes several thousand years.

Solar Structure

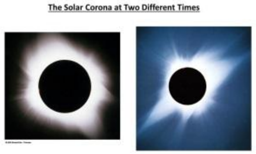
- **Convection Zone:** as the temperature and density falls above the radiative zone, photons can be absorbed instead of scattered. This heats the plasma and convection currents carry the energy to the surface. We can see the tops of the Convection Cells at the bottom of the photosphere (granulation).



- **Photosphere:** the point at which the material above is transparent and opaque below. So the light that we get from the Sun comes from the photosphere. The temperature of the photosphere is 5800 K.



- **Chromosphere:** low density gas at ~10,000 K; emits most of the ultraviolet that we get from the Sun.



- **Corona:** highly variable, low density, high temperature gas (~1 million K), emits most of Sun's continuous X-rays.

- **Solar Wind:** variable stream of high energy particles (protons and electrons); extends into interplanetary space

Solar Structure

Some important points about solar structure:

- We can only see as deep as the photosphere. The visible light that we get from the Sun comes from this depth.

- **How then do we know anything about the internal structure?**
  - **Stars are quite simple and can be modelled mathematically:**

$$\frac{dP}{dr} = -G\frac{M_r \rho}{r^2}$$

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

$$\frac{dL_r}{dr} = 4\pi r^2 \rho \epsilon$$

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\overline{\kappa}\rho}{T^3}\frac{L_r}{4\pi r^2} \quad \text{(radiation)}$$

$$= -\left(1 - \frac{1}{\gamma}\right)\frac{\mu m_H}{k}\frac{GM_r}{r^2} \quad \text{(adiabatic convection)}$$

The basic equations of stellar structure can be solved.
(no, you don't have to know these!)

  - **Helioseismology:** vibrations in the Sun can be observed and the character of these vibrations gives the properties of the interior.
  - **Solar Neutrinos:** produced in the core – more about these next class.

The Active Sun

What's going on on the surface of the Sun today?

These images are from the SOHO spacecraft which, along with the TRACE spacecraft, have revealed a lot about the Sun's activity in the last 20 years.

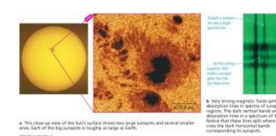
Have you heard of the Parker Solar Probe?

Sunspots:

Galileo was the first person to observe *"blemishes"* on the surface of the Sun that we now call sunspots – it shook the idea that the Sun had to be perfect. *In the right conditions, you can see a large sunspot with the naked eye!*

What are Sunspots?

Regions of high magnetic field activity – remember the Sun is a plasma, so the moving material is an electrical current that can create and be affected by magnetic fields.



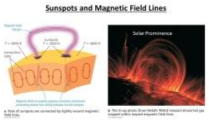
Why are Sunspots Dark?

Sunspots are cooler than the surrounding plasma, T_{ss} ~ 4000 K where $T_{photosphere}$ = 5800 K, so they appear dark against the much brighter background of higher temperature photosphere.

The Active Sun

Why are Sunspots cooler than the surrounding plasma?

Inside the Sun, magnetic field lines can become twisted and loops can poke through the surface. The plasma can't move perpendicular to the field lines, so the regions where the field goes through the surface can't be replenished with warmer plasma from below, so it cools.



What is a Solar Flare and a Coronal Mass Ejection (CME)?

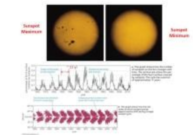
If the magnetic field suddenly breaks or changes near a sunspot group, huge amounts of energy can be released.

- If the energy is in radiation (light), it is a **flare**. This light reaches the Earth in about 8 minutes.
- If the energy blasts particles into interplanetary space, it is a **coronal mass ejection (CME).** If directed at us**,** the particles reach the Earth in a few days.
- Sometimes (but not always) flares and CME's occur together.

If the CME hits the Earth, the particles can be trapped in the Earth's magnetic field creating aurora or damaging satellite electronics or even ground-based power grids. ***What about unprotected astronauts (LC)?*** *If not in low earth orbit, they could receive a very harmful dose of radiation.*

- **Have you ever heard of the Carrington Event in 1859?**

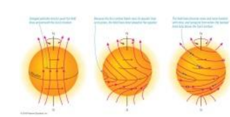
The Active Sun



The Solar Cycle:

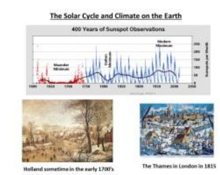
The number of Sunspots on the Sun varies with a fairly regular period of ~11 years between maxima. *(the last minimum was 2019-20; we're nearing a maximum now.)*

Sunspots also reveal that the magnetic field of the Sun reverses polarity (swaps North and South magnetic poles) every 22 years.



What Causes the Solar Cycle?

The Sun is a plasma (charged gas) and it doesn't rotate like a solid planet – the polar regions rotate slower (~30 days) than the equatorial regions (~25 days); called **differential rotation**.
The magnetic field is trapped in the plasma and gets twisted like taffy on a stick, eventually poking through the surface to create sunspots.



Does the Solar Cycle Have an Effect on the Earth's Climate?

Based on events like the Maunder and Dalton minima, some people think there is a connection, but no one has proposed a mechanism for how the connection would work.