Astronomy 210

Solar Observing starts on Monday

HW 8 due on Friday.

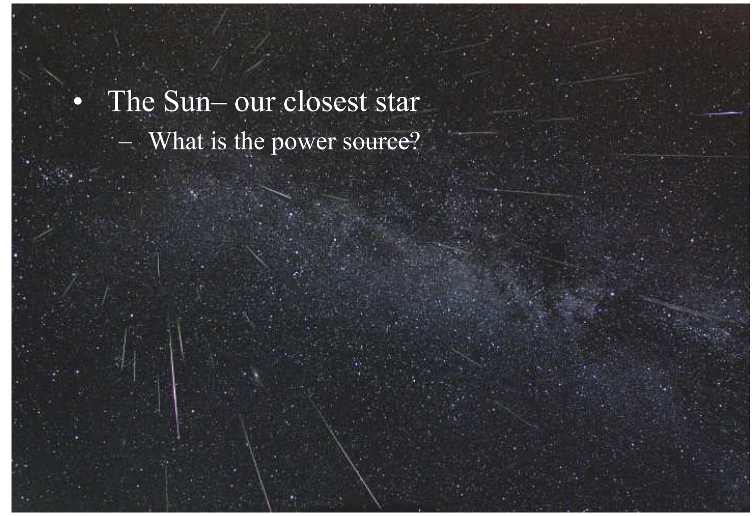
This Class (Lecture 28):

The Sun: Stability and Energy

Next Class:

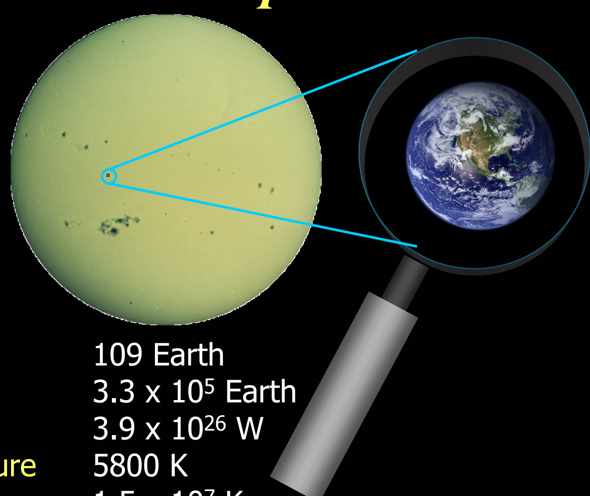
Solar Neutrinos

Outline



- The Sun– our closest star
  - What is the power source?

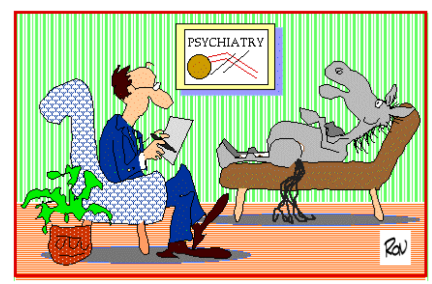
Earth-Sun Comparison



Visual radius	109 Earth
Mass	3.3×10^5 Earth
Luminosity	3.9×10^{26} W
Surface temperature	5800 K
Central temperature	1.5×10^7 K
Rotation period	25 days

Question of Stability

- The Sun's size is constant.
- No weatherman says it will be especially hot tomorrow as the Sun's size will be increasing.
- Not expanding or collapsing. The Sun is stable! Why?
- Not trivial, could have gone the other way
- Think: Sun is made of gas, yet not like cloud, for example, which is made of gas but size, shape changes all of the time
- Not a coincidence: really good reason



"I just don't feel stable."

http://www.londonstimes.us/toons/index_medical.html

They Keep Pulling me in!

- Image a parcel of gas in the Sun. What happens to it?
- How many forces are acting on it?
  - Zero? One? More?

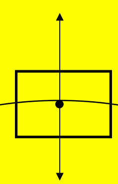
They Keep Pulling me in!

- Hot gas pressure is pressing against gravity in equilibrium!
- This is called hydrostatic equilibrium!

They Keep Pulling me in!

- Hydrostatic equilibrium! Sort of like Lect 20.

$$\frac{dP}{dr} = -g\rho = G\frac{M(r)\rho(r)}{r^2}$$



$F_{pressure} = F_{gravity}$

Mass inside radius r.

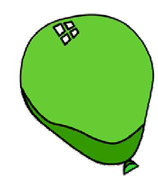
This is why the atmosphere doesn't pool at your feet but different temperatures.

Pressure

- What is pressure?
  - Pressure $= \frac{Force}{Area}$

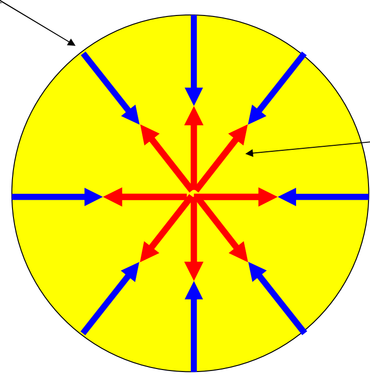
Pressure of Earth's atmosphere is 14.7 pounds per square inch

- Explain blowing up a balloon?



- http://www.phy.ntnu.edu.tw/java/idealGas/idealGas.html

The Battle between Gravity and Pressure



Hydrostatic equilibrium

The Sun's Energy Output

3.85×10^{26} Watts, but how much is that?

A 100W light bulb…

…the Sun could supply 4×10^{24} light bulbs!

U.S. electricity production in 2000: 3.8 trillion kWh…

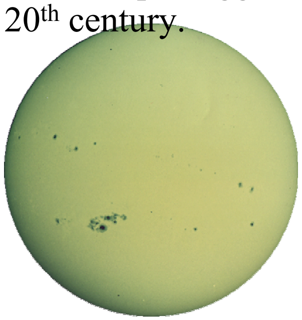
… Sun = 3×10^{7} times this *every second*

World's nuclear weapons: 3×10^{4} megatons…

… Sun = 4 million times this *every second*

So, What Powers the Sun?

- Sun shines by its own power.
- But what is the power source?
- What keeps the Sun hot? It doesn't cool like a hot coffee cup. Biggest mystery in Astronomy until 20th century.



How to Test?

- Process must be able to power Sun for a long time! At least 4.5 Byrs.
- Think of more familiar light source: flashlight. Battery is energy source. If kept on at same brightness, then light stays on for fixed amount of time: energy conservation!
- So, the power output = rate of energy emission.
- This is better know as...?
  - **Solar Luminosity = 3.8×10^{33} erg/s**
- Recall: power $L = dE/dt$
- So, if lose energy at constant rate, then $E = L\tau$ and τ = lifetime of Sun
- Now we need to try different power sources

Gravity!

- Seems like a good idea. Remember Jupiter.
- First from Kelvin-Helmholtz in 19th century.
- A contracting Sun releases gravitational PE
- For a uniform sphere, the gravitational PE can be calculated as

$$PE = -\tfrac{3}{5} G \frac{M_\odot^2}{R_\odot} = 2 \times 10^{48}\, erg$$

Gravity!

- Energy contraction = - PE
- If gravitational energy fuels the Sun, then it would last for

$$\tau = \frac{E_{contraction}}{L} = 5 \times 10^{14}\ \text{sec} = 17\ \text{million years!}$$

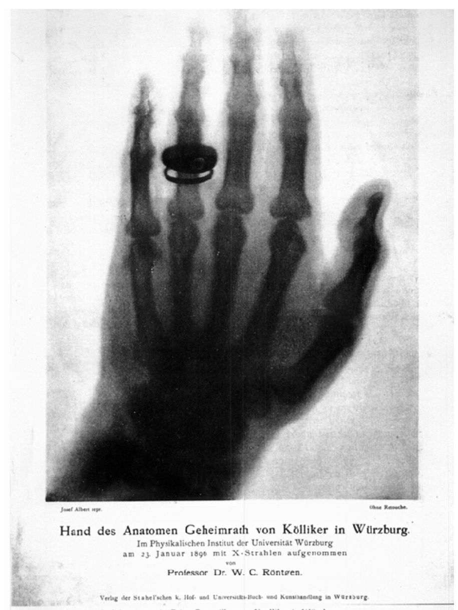
- Not good enough!

Chemical

- If the Sun was made from TNT, something that burns very well, then it would last for

$$\tau = \frac{E_{burning}}{L} = 20{,}000\ \text{years!}$$

- Not good enough!
- To last for 4.5 BYrs, we need a lot of energy!



Radiograph of the hand of the anatomist Privy Councillor von Koelliker in Würzburg, taken by W. C. Röntgen in Würzburg on January 23, 1896

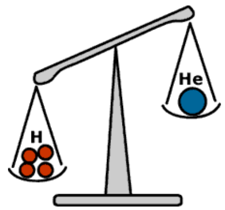
Eyes began to turn to the nuclear processes of the Atoms

Why does fusion release energy?

Fusion: $4\,p \rightarrow {}^4\mathrm{He} \quad (2\,p, 2\,n)$

Fact: **4m(*p*) > m(^{4}He)** !

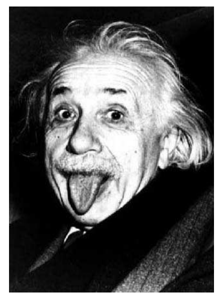
<u>mass of whole < mass of parts</u>!



Einstein says ***E = mc²***:

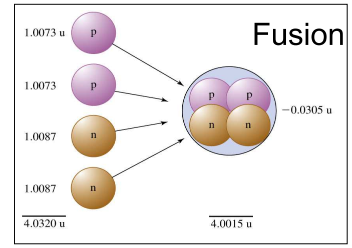
- Mass is a form of energy!
- Each ^{4}He liberates energy:

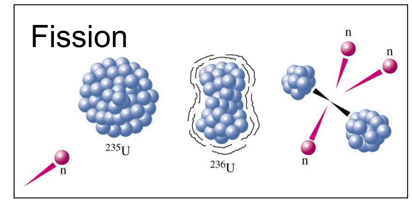
$$E_{\rm fusion} = m_{\rm lost}c^2 = 4m(p)c^2 - m(^4\mathrm{He})c^2 > 0!$$



Fusion vs. Fission

- Light nuclei: fusion
  - Happens in the Sun
  - H-Bomb
- Heavy nuclei: fission
  - Used in power plants
  - A-Bomb



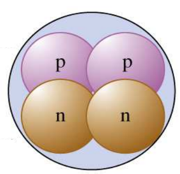


The Nucleus

- Okay, so we know that the nucleus can have numerous protons (+'s) very close.

Helium

- **Something is odd here!**
- **What is it?**

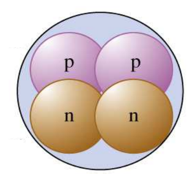


The Nucleus

- **Why doesn't the nucleus of the atom fly apart?**

Helium

- **Something is odd here!**
- **What is it?**

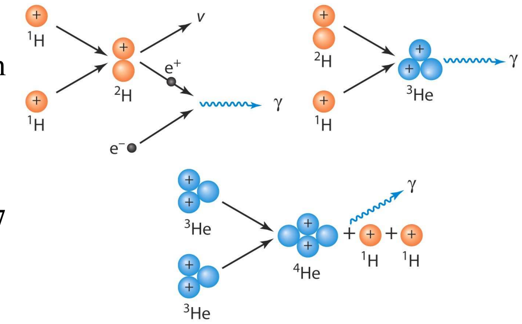


4 Fundamental Forces

- Gravity
- Electromagnetic
- Strong Nuclear
  - The strongest of the 4 forces
  - The force which holds an atom's nucleus together, in spite of the repulsion between the protons.
  - Does not depend on charge
  - Not an inverse square law– very short range.
- Weak Nuclear

Nuclear Fusion in the Sun's Interior

- Proton-Proton Chain
  - 4 Hydrogen atoms fuse to make 1 helium atom
  - Requires very high density and temperature (at least 7 million K)



The Proton-Proton (p-p) Chain

Nuclear Reactions in the Sun

- Chain: 4 protons ⇒ helium
- First step in chain (2 protons combine):

$$p + p \rightarrow [np] + e^{+} + \nu$$

- Start with 2 particles (protons)
- End up with 4 particles (two of which are glued together)
- each of products is very interesting in its own right....

Nuclear Reactions in the Sun

$$p + p \rightarrow [np] + e^{+} + \nu$$

$[np]$ = **deuterium**

- 1 proton + 1 neutron bound together into nucleus of element…
- Hydrogen, but has neutron, so 2 times mass of normal H
  - "Heavy Hydrogen"
- Simplest composite nucleus

Discovery of D in lab: *Nobel Prize*
about 0.01% of all H on earth is D
✓ including in your body:
you contain about 10 kilos (20 lbs) of H, and about 2 grams of D
✓ Water (normally H_2O) with D is D_2O : "heavy water"

Nuclear Reactions in the Sun

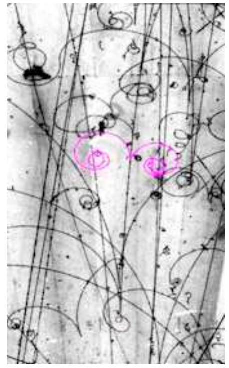
$$p + p \rightarrow [np] + e^{+} + \nu$$

e^{+} = **positron**

- Exactly the same as electron but charge **+1**
- **Antimatter**
- Combines with normal e^{-}
  - Both are gone, release of energy
  - ***Annihilation***

Discovery of positron in lab: *Nobel Prize*
Because of this reaction

➢ The Sun contains a small amount of antimatter!



Nuclear Reactions in the Sun

$$p + p \rightarrow [np] + e^{+} + \nu$$

ν (Greek letter "nu") = **neutrino**

- Particle produced in nuclear reactions ***only***
- Tiny mass: $m(\nu) < 10^{-6} m(e)$!
- Moves at nearly the speed of light
- ***Very*** weakly interacting

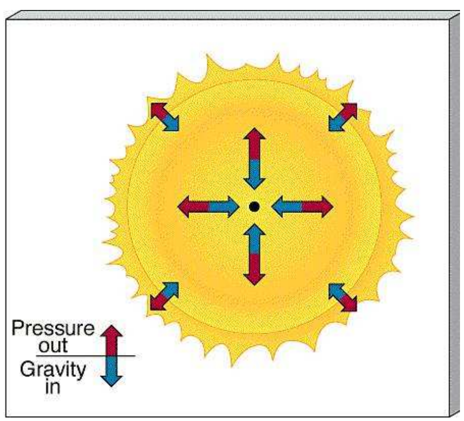
Discovery of neutrino in lab: *Nobel Prize*

10 billion from Sun go through hand every sec

➢ Reach out!
➢ Go through your body, Earth, but almost never interact

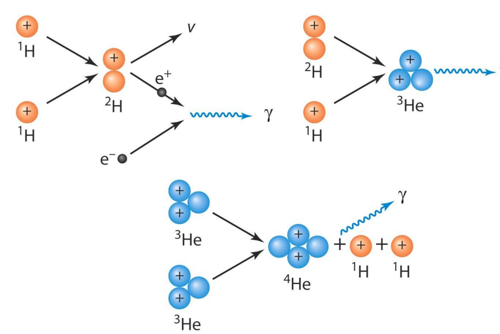
Why Doesn't The Sun Shrink?

- Sun is currently stable
- Pressure from the radiation created by fusion balances the force of gravity.
- There has to be some pressure. The pressure is from fusion!



Nuclear Fusion in the Sun's Interior

- Proton-proton in stars like the Sun
  - Hydrogen fused to make helium
  - 0.7% of mass converted to energy



The Proton-Proton Cycle

They Might Be Giants
Why Does The Sun Shine

Why Does the Sun Shine?

The Sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

The Sun is hot, the sun is not
A place where we could live
But here on Earth there'd be no life
Without the light it gives

We need its light
We need its heat
The Sun light that we seek
The Sun light comes from our own sun's atomic energy

The Sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

The Sun is hot

The Sun is so hot that everything on it is a gas: Aluminum, Copper, Iron, and many others

The Sun is large... If the sun were hollow, a million Earth's would fit inside
And yet, it is only a middle-sized star

The Sun is far away... About 93,000,000 miles away
And that's why it looks so small

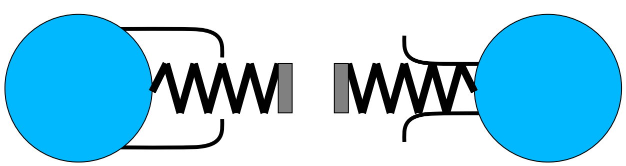
But even when it's out of sight
The Sun shines night and day
We need its heat, we need its light
The Sun light that we seek
The Sun light comes from our own sun's atomic energy

Scientists have found that the Sun is a huge atom smashing machine
The heat and light of the sun are caused by nuclear reactions between Hydrogen, Nitrogen, Carbon, and Helium

The Sun is a mass of incandescent gas
A gigantic nuclear furnace
Where Hydrogen is built into Helium
At a temperature of millions of degrees

Why Nuclear Fusion Doesn't Occur in Your Coffee

- Fusion requires:
  - High enough temperature (> 5 million K)
  - High enough density
  - Enough time



How much Gas do we have left?

- Total energy available is

$$E_{fuse} = \frac{\#\text{ nuclei in Sun}}{4\text{ nuclei/fusion}} \times \Delta mc^2 \approx 1.3 \times 10^{52}\text{ erg}$$

- Or about

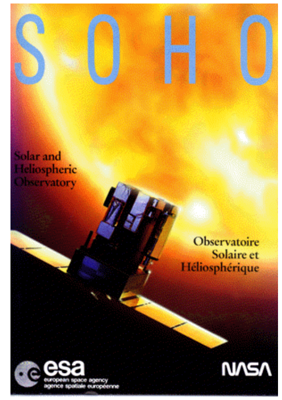
$$\tau = \frac{E_{fuse}}{L} = 100\text{ billion years!}$$

- This is an overestimate, only fuse in core where sufficient temp and pressure. Remember have to get p+p very close. So real number is more like 10 billion years! **We only have 5 billion years left!**

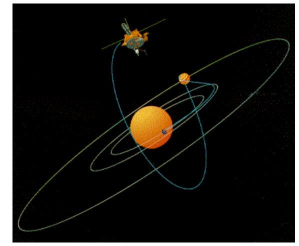
Think-Pair-Share

If we could sustain fusion in the lab we could meet humankind's energy needs forever! Why is it so difficult to achieve this, when stars do it every day?

Spacecraft Observing the Sun



SOHO

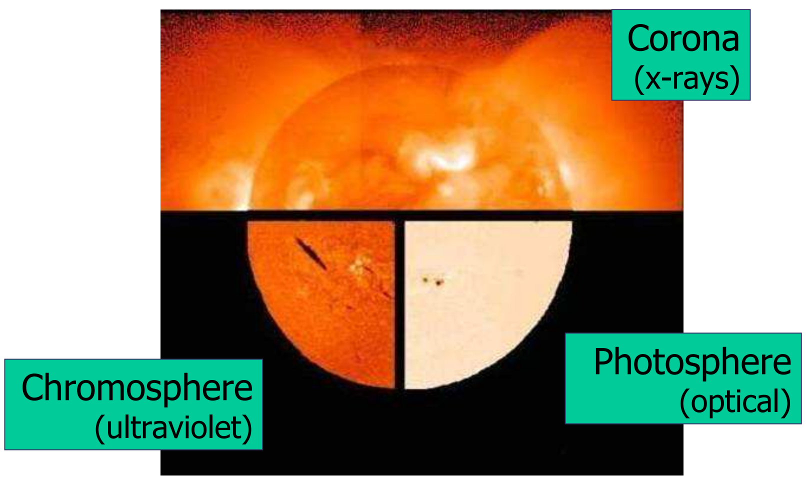


Ulysses

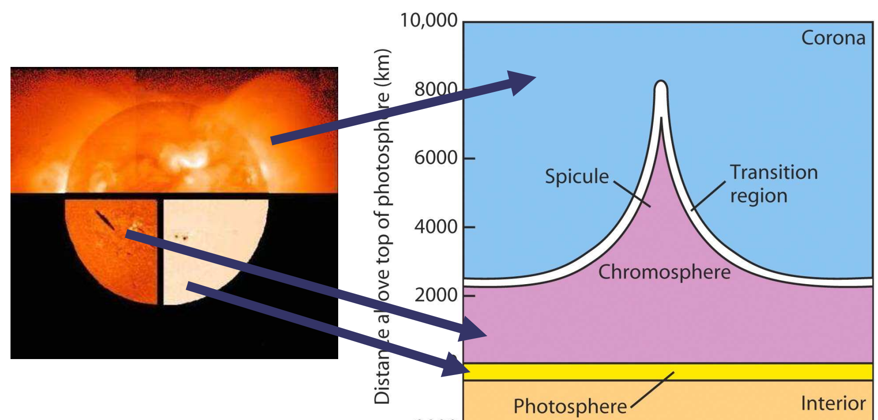
TRACE

RHESSI

The Outer Layers of the Sun

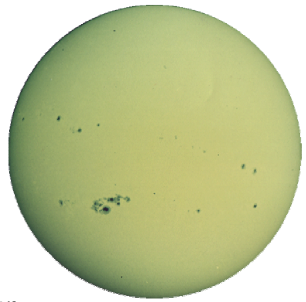


Structure of the Outer Layers



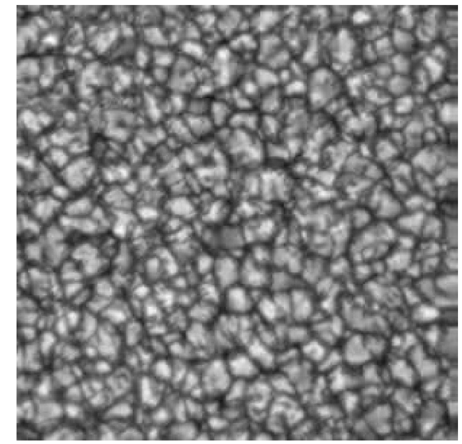
The Photosphere

- Apparent "surface" of the Sun
  - Ionized atoms make the gas highly opaque
- Most of the Sun's light we see comes from the photosphere
- Temperature, about 5800 K
  - Hotter as you go deeper into the Sun



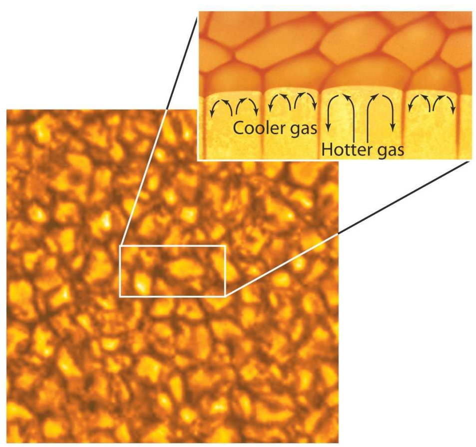
Granules

- The photosphere is not smooth
- Covered in **granules**
  - About 700 km across!
- Like a pot of boiling water



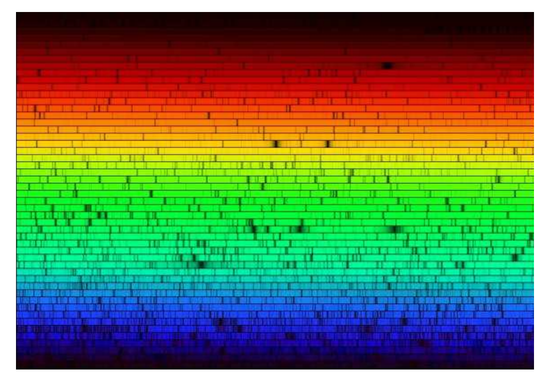
Granules

- Granules are the tops of *convection cells*
- Hot gas from below rises up
- Radiates energy
- Cools and falls back into the photosphere



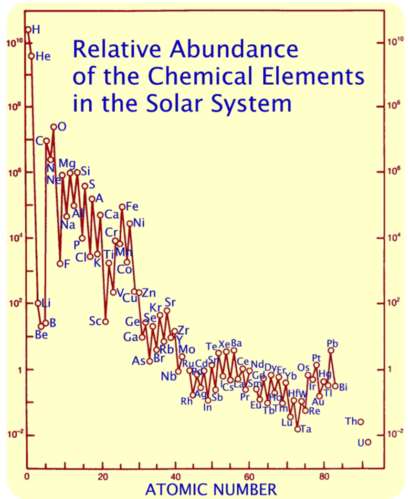
Solar Spectrum Lines

- The Sun shows dark spectrum lines
- Upper part of the photosphere is cooler than the lower part
- Cooler gas around a continuous spectrum source
- Therefore, we get an absorption spectrum!



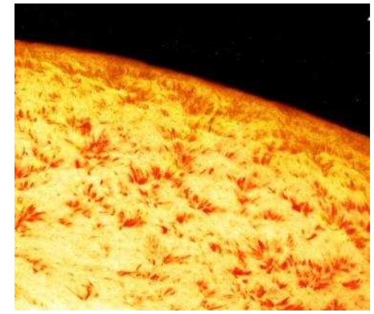
Solar Composition

- From the spectrum lines, we can determine the Sun's composition
  - 92% Hydrogen
  - 8% Helium
  - Less than 0.1% other stuff



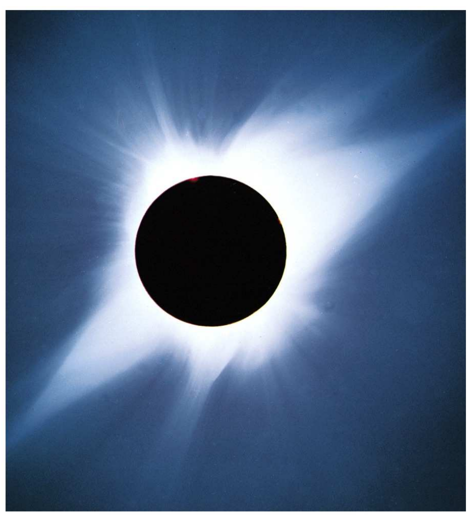
The Chromosphere

- Very sparse layer of gas above the photosphere
- Hot – Over 10,000 K
- Produces very little radiation – too sparse
- Only seen during eclipse or with special instruments
- Helium was first discovered in the chromosphere

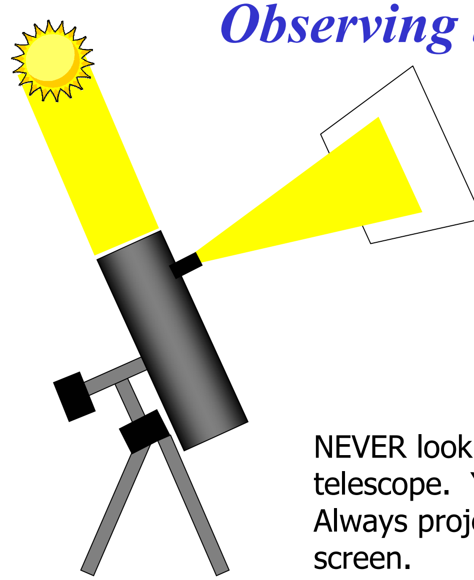


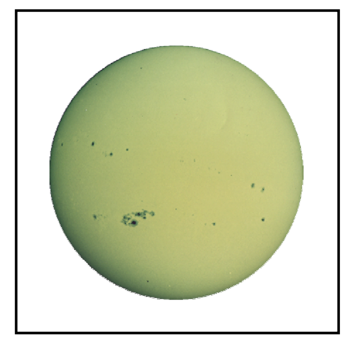
The Corona

- Sun's outer atmosphere
- Visible only by blocking light from photosphere
- Heated by magnetic activity
- Temperatures about 2 million K
- Hot enough to produce X-rays!



Observing the Sun





NEVER look at the Sun through a telescope. You will damage your eyes! Always project the Sun's image onto a screen.

Limb Darkening

- Sun's photosphere is less bright around the edge (limb)
- Top of the photosphere cooler than the base and thus less bright (remember Stefan-Boltzmann law)