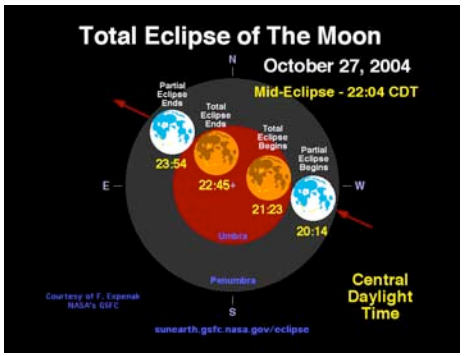
Announcements

- Homework due today.
  - Put your homework in the box NOW.
  - Please STAPLE them if you have not done yet.
- Quiz#3 on Tuesday (Oct 5)
  - Announcement at the end of this lecture.
- If you could not pick up your quiz last time…
  - Please pick it up after this lecture. Sorry for confusion.

Some Good News…

- Quiz#4 on Oct 28 has been canceled.
- Instead of studying for quiz, let's watch the total lunar eclipse!!
  - **Oct 27:8pm to 12am.**



http://sunearth.gsfc.nasa.gov/eclipse/LEmono/TLE2004Oct28/image/TLE2004Oct-CDT.GIF

Lecture 10
The Sun

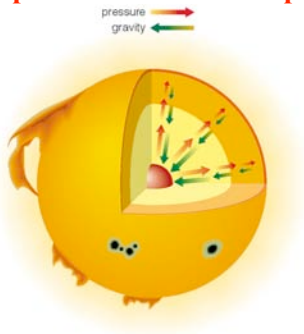
Reading: Chapter 15

How does the Sun shine?
The Sun's Energy Source

- It was actually quite hard to explain why the Sun can shine.
- The first scientific theories involved chemical reactions or gravitational collapse.
  - *mid-1800s:* chemical burning (like the burning of coal) ruled out…it can not account for the Sun's luminosity. Too weak!
  - *late-1800s:* conversion of gravitational potential energy into heat as the Sun contracts would only keep the Sun shining for 25 million years.
    - geologists already knew that the Earth was older than that!!
- Development of nuclear physics led to the correct answer. ***VIVA! QUANTUM MECHANICS!!***
  - **the Sun generates energy via nuclear *fusion* reactions**
  - Hydrogen is converted into Helium in the Sun's core
  - the mass lost in this conversion is transformed into energy
    - the amount of energy is given by Einstein's equation: $E = mc^2$
  - given the Sun's mass (which is huge!), this will provide enough energy for the Sun to shine for 10 billion years. We've got some 5billion more years!

Striking a Balance: Collapse vs Pressure

- The Sun began as a cloud of gas undergoing gravitational collapse.
  - the same heating process, once proposed to power the Sun, did cause the core of the Sun to get hot & dense enough to start nuclear fusion reactions
  - But, this is not the whole story --- this is just the beginning!!
- Once begun, **the fusion reactions generated energy which provided an outward pressure.**



- This pressure perfectly balances the inward force of gravity.
  - deep inside the Sun, the pressure is strongest where gravity is strongest
  - near the surface, the pressure is weakest where gravity is weakest
- This balance is called **gravitational equilibrium**.
  - it causes the Sun's size to remain stable

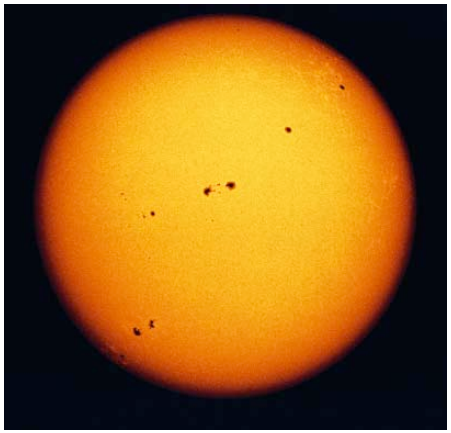
Basic Properties of the Sun

Distance: 1.48×10^8 km
= 1 A.U.

Mass: 1.99×10^{30} kg
(300,000 times Earth's mass)

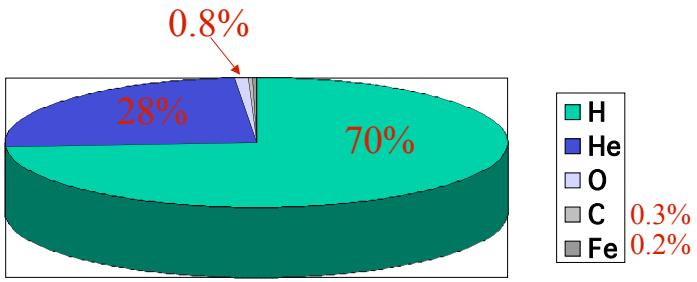
Radius: 6.96×10^5 km
(109 times Earth's radius)

Density: 1.41 g/cm^3



Luminosity: 3.8×10^{26} watts

Composition of the Sun



How the hell do we know it?

Composition of the Sun

We know this by identifying the **absorption lines** in the Sun's spectrum.

These lines are formed in the photosphere.

Layers of the Sun

Temperature Depth

- Core
  - 15 million K 0.25 $R_\odot$
- Radiation Zone
  - > 2 million K 0.70 $R_\odot$
- Convection Zone
  - < 2 million K 0.85 $R_\odot$
- Photosphere
  - 5,800 K 400 km thick
- Chromosphere
  - 10,000– 50,000 K 2,500 km thick
- Corona
  - 2 million K 600,000 km thick
- Solar Wind
  - > million K beyond the orbit of Pluto

Layers of the Sun

- Core
  - 15 million K
- Radiation Zone
  - > 2 million K
- Convection Zone
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  - 5,800 K
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- Solar Wind
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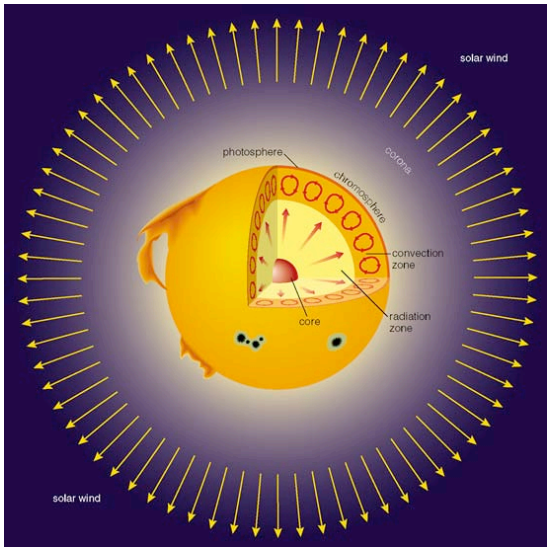
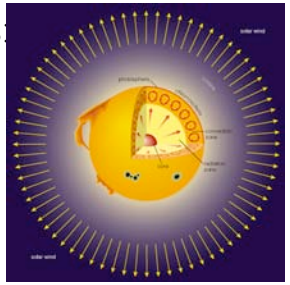


Core

- T = 1.5 x 10^7 K; depth = 0 – 0.25 R
  - This is where the Sun's energy is generated.

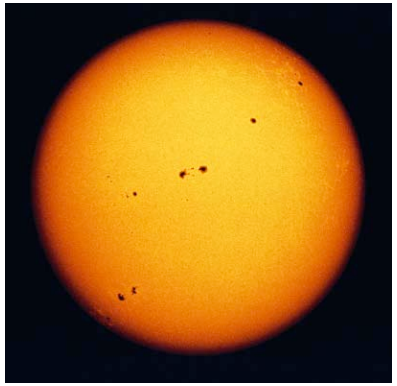
Interior Zones

- T < 8 x 10^6 K; depth = 0.25 – 0.86 R
  - Energy is transported through the interior.
- The interior is divided into 2 zones:
  - Radiation Zone
  - Convection Zone
- Boundary between them is at:
  - T = 2 x 10^6 K; depth = 0.70 R



Photosphere

- T = 5,800 K; depth = 400 km
- This is the yellow "surface" that we see.



Chromosphere

- T = 1 – 5 x 10^4 K; depth = 2,500 km
- A thin layer above the photosphere where most of the Sun's UV light is emitted.

- UV image of the Sun
- light emitted from neutral Helium at 20,000 K

courtesy of SOHO/SUMER consortium
SOHO is a project of ESA and NASA

Corona

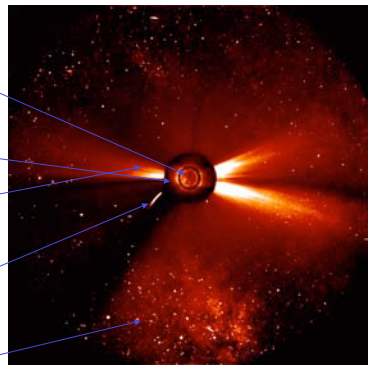
- T = 2 x 10^6 K; depth ≈ 600,000 km
- The hot, ionized gas which surrounds the Sun.
  - it emits mostly X-rays
- It can be seen in visible light during an eclipse.

X-ray image (YOHKOH telescope)

Visible image

Solar Wind

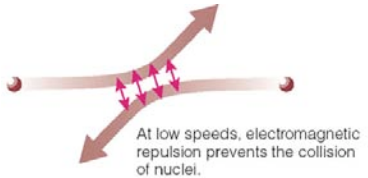
- The stream of electrons, protons, Helium nuclei and other ions which flow out from the Sun.
- It extends out beyond Pluto.

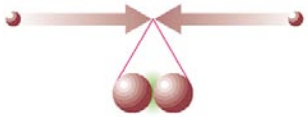


courtesy of SOHO consortium
SOHO is a project of ESA & NASA

Nuclear Fusion in the Sun's core

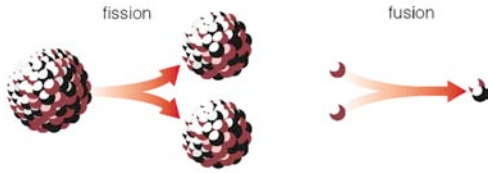
- Nuclear fusion
  - a reaction where heavier nuclei are created by combining (*fusing*) lighter nuclei.
  - all nuclei are positively charged
- Electromagnetic force causes nuclei to repel each other.
  - for fusion to occur, nuclei must be moving fast enough to overcome E-M repulsion
  - this requires high temperatures & pressures
  - Quantum tunneling also helps.
- When nuclei touch, the nuclear force binds them together





What about nuclear *fission* ?

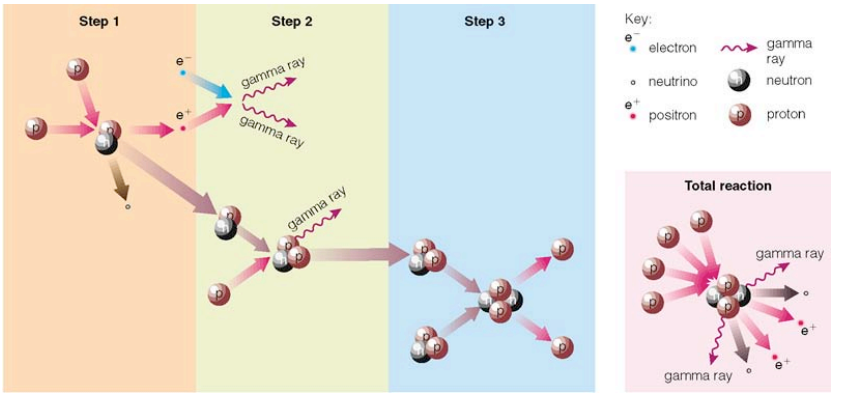
- Nuclear fission
  - a reaction where lighter nuclei are created by splitting heavier nuclei.



Only fission has been achieved by mankind

It is easier to destroy than to create.

Proton-Proton Chain



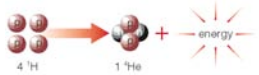
IN: 6 H, (2 e^-)
OUT: He, 2 H, 2 ν_e, 4 γ

Effectively 4 H nuclei are converted into 1 He nucleus and energy is released.

Why does the Sun Shine ?

Nuclear Fusion… Where would the energy come from?

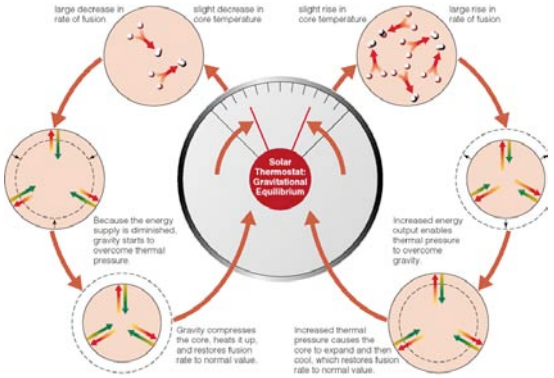
Let's count the mass.



- We had 4 protons.
- 4 protons fused to form 1 Helium.
- Actually, 1 Helium is slightly LIGHTER than the total mass of 4 protons. (by 0.7%)
- Where did the mass go?
- Energy!

$$E = mc^2$$

The Solar Thermostat: The Sun is an ideal, stable energy factory!



- The rate of fusion reactions depends on temperature.
  - the higher the T, the faster the rate, the more energy is produced
- This fact, coupled with gravitational equilibrium, acts as a mechanism which **regulates** the Sun's energy output.
  - its energy output (luminosity) remains stable

The Solar Luminosity Changes over Time

- The Sun's luminosity is stable over the short-term.
- However, as more Hydrogen fuses into Helium:
  - four H nuclei convert into one He nucleus
  - the number of particles in Sun's core *decreases* with time
  - the Sun's core will contract, causing it to heat up
  - the fusion rate will increase to balance higher gravity
  - a new *equilibrium* is reached for stability at a higher energy output
  - the Sun's luminosity increases with time over the long-term
- Models indicate the Sun's luminosity has increased 30% since it formed 4.6 billion years ago.
  - it has gone from 2.9 x 10^{26} watts to today's 3.8 x 10^{26} watts

Wait a minute, man.

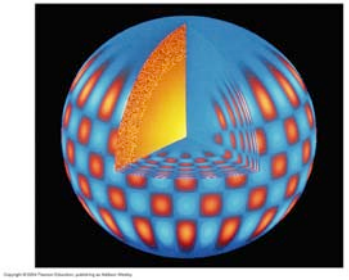
How the hell do you know about all this?

Did you go there?

Did you actually go inside the Sun?

"Observing" the Solar Interior

- The Sun's interior is opaque…
  - we can not see directly into it with light
- We can construct mathematical computer models of it.
  - the models are a grid of temperature, pressure, & density vs. depth
  - these values are calculated using known laws of physics
  - they are tested against the Sun's observable quantities
- We can directly measure sound waves moving through the interior
  - we observe "**sunquakes**" in the photosphere by using **Doppler shifts**
  - motion of sound waves can be checked against interior conditions predicted by models
- There is another way to see directly into the core…**neutrinos**!

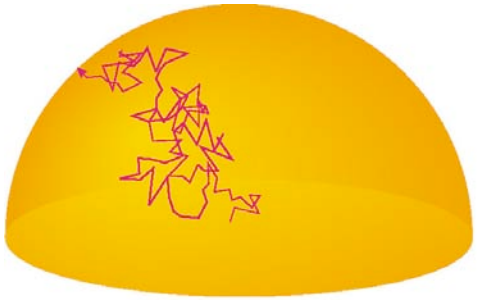


The Neutrino Problem

- Neutrinos come to us directly from the core of the Sun, a product of the proton-proton chain.
- They interact only very weakly, so we don't feel them at all → detection is not easy. It's hard to stop them.
- But we have detected them anyway, proving that the theory of nuclear fusion reactions is correct!
- But we only detect about 30% - 50% of the neutrinos which are predicted by theoretic models.
  - either our understanding of nuclear fusion reactions or **our understanding of neutrinos is wrong**!
  - The solar neutrino revolutionized our understanding of neutrinos. Nobel Prize in Physics 2002.

Core to Surface: Methods of Energy Transport

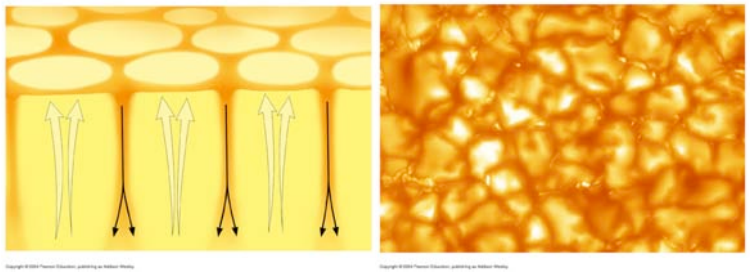
- Radiation Zone
  - energy travels as photons of light, which continually collide with particles
  - always changing direction (*random walk*), photons can change wavelengths
  - this is called **radiative diffusion**



- This is a slow process!
- It takes about 1 million years for energy to travel from the core to the surface.
- So, even if the Sun runs out of hydrogen today, it will keep shining for 1 million years.

Methods of Energy Transport

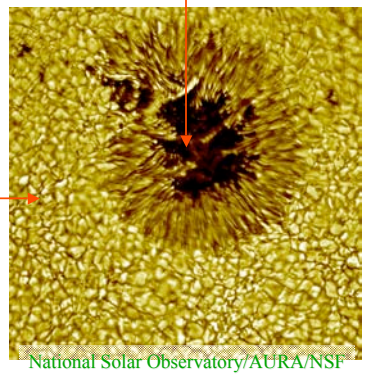
- Convection zone
  - photons arriving at bottom of convection zone are absorbed instead of scattered by matter
  - the bottom of the zone is heated … hot gas rises to the top
  - cooler gas sinks to the bottom…just like when you boil a pot of water!
  - energy is brought to the surface via bulk motions of matter (**convection**)



Photospheric Features

Sunspots: dark spots on the surface where the temperature is cooler.

Granulation: the tops of convection cells seen "bubbling" on the Solar surface



National Solar Observatory/AURA/NSF

Sunspots

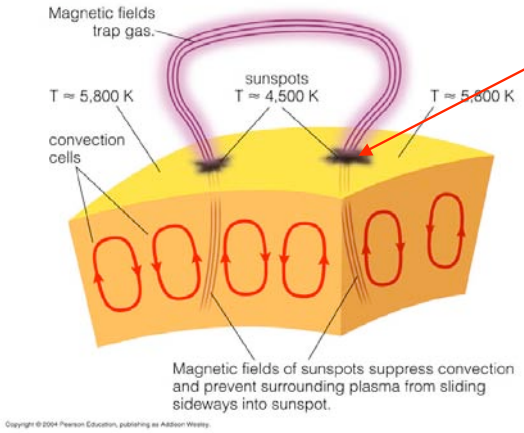
courtesy of SOHO/MDI consortium
SOHO is a project of ESA and NASA

Movie. Click to play.

Sunspots occur in pairs; the pairs cluster into groups; and they rotate with the Sun

Sunspots come and go over an 11-year cycle.

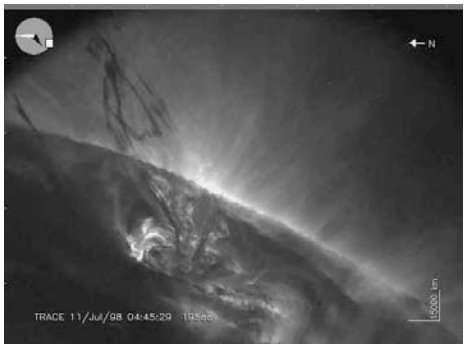
What causes a sunspot?



magnetic field slows down convection;
Less heat is transported to surface;
so that part of photosphere is cooler

Coronal Features

Prominences – gas trapped in the magnetic fields is heated and elevated through the chromosphere to the corona

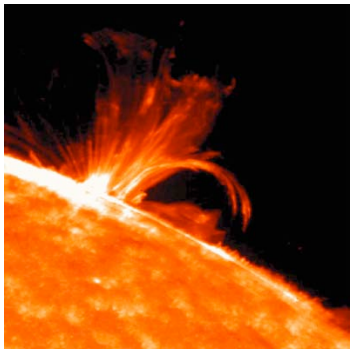


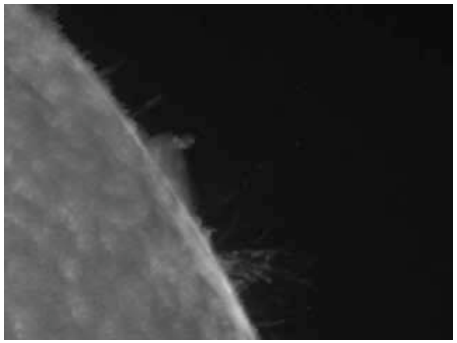
X-ray images from NASA's TRACE mission.

Movie. Click to launch.

Coronal Features

Flares – when a magnetic loop breaks, it releases matter and energy into space



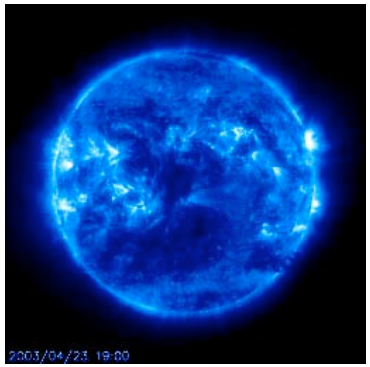


Movie. Click to play.

X-ray images from NASA's TRACE mission.

The Corona

- Magnetic loops are shaken at their bases by turbulent motions in the convection zone.
- Kinked, twisted magnetic field loops release energy to heat gas to 2 million K.
- The charged gas (ions) remains stuck to the magnetic loops.
- The corona is not uniform; there are empty patches called **coronal holes**
- Magnetic heating explains why temperatures start to increase above the photosphere.

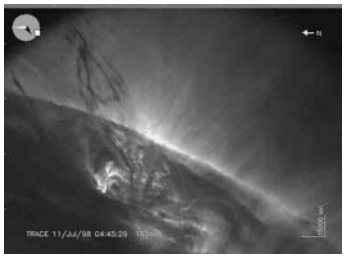


Movie. Click to play.

courtesy of SOHO/EIT consortium
SOHO is a project of ESA and NASA

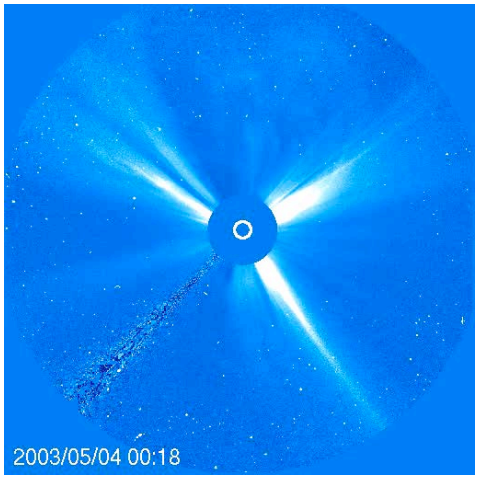
Solar Activity

- The photosphere of the Sun is covered with sunspots.
- Sunspots are not constant; they appear & disappear.
- They do so in a cycle.
- It repeats every 11 yrs.
  - Sun's magnetic field switches polarity every 11 yrs
  - so the entire cycle repeats every 22 yrs



Solar Wind

- When magnetic field lines break, they release the charged particles into space.
- This so-called **solar wind** escapes through the coronal holes.

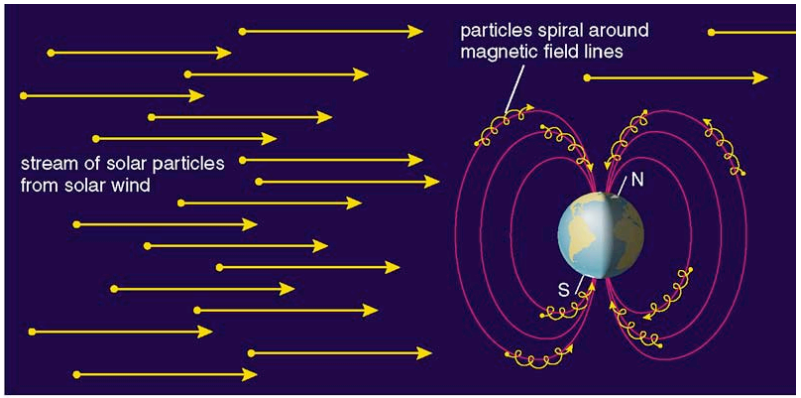


courtesy of SOHO/LASCO consortium
SOHO is a project of ESA and NASA

Movie. Click to play.

Solar Wind

electrons, protons, He nuclei expelled by flares



Interact with Earth's magnetic field to cause…

The Aurorae

the Northern & Southern Lights

- A strong Solar wind can affect human technology by:
  - interfering with communications
  - knocking out power grids
  - damage electronics in space vechicles
- We are not yet sure of the effect which Solar activity has on Earth's climate.

Next: Properties of Stars

- Reading: Chapter 16
- Pick up your quiz if you did not get it last time.
- 20min. Quiz#3 after 60min. lecture.
  - 4 multiple choices from "surprising discoveries?" (Chapter 9)
  - 3 multiple choices from "True or False" (Chapter S4)
  - 4 multiple choices from "Sensible Statements?" (Chapter 15)
  - Short Answer Q's
    - Chapter 9: *Extrasolar Planets* (esp. Doppler and transit methods)
    - Chapter 15: *Solar Activity* (esp. sunspots)