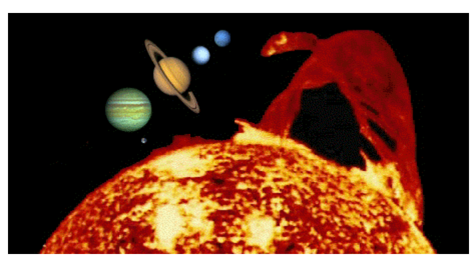
Stars

- Huge spheres of gas floating in space
  - Composed primarily of H, He.
- Produce their own energy.
- Our Galaxy: 10^{11} (100 billion) stars.
- The Sun: a typical star
  - Stars range from ~ 0.1 to ~ 20 $M_{\odot}$

    $M_{\odot}$ = solar mass
  - Individual stars evolve as they age… sun is in middle of its ~ 10^{10} year lifespan.

The size of the Sun



- Diameter: 1.4×10^6 km
  - 109 x Earth
- Mass: 2×10^{33} g
  - 333,000 x Earth
- Distance from Earth
  - 93 million miles
  - 1.5×10^8 km
  - 8 light minutes
- Luminosity (amount of energy emitted per unit time): 4×10^{26} watts
  - 10^{15} times average power consumption of US.

The Composition of the Sun

- From spectroscopy of outer layers

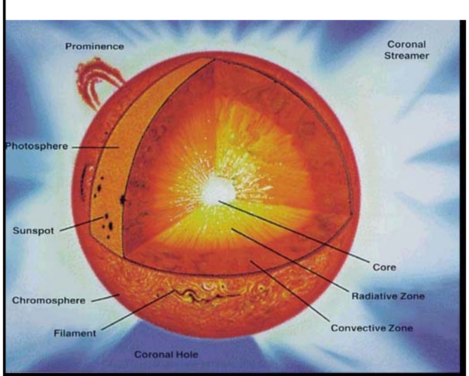
The Abundance of Elements in the Sun

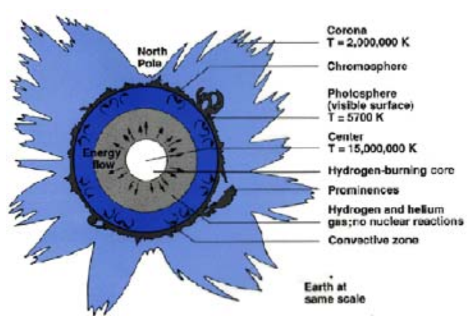
Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.8
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

[Table 14.2]

The Interior of the Sun

- (almost) no observations of interior
- Interior structure deduced from observing the outside
  - Luminosity
  - Mass

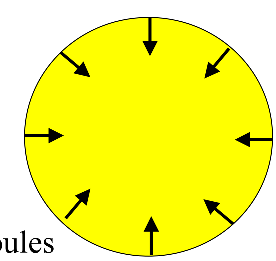




What Powers the Sun?

- Need to provide
  - $4\text{x}10^{26}$ watts
  - $< 2\text{x}10^{33}$ grams (mass of Sun)
  - $>$ 4.5 billion years (age of Earth)
- Duracell batteries?
- A single D-cell:
  - 0.5 watts/battery ==> $8\text{x}10^{26}$ batteries required. 😐
  - 139g/battery ==> 10^{29} batteries total
    - room for 20,000 times more batteries in reserve. ☺
  - *but…* each battery lasts only 43 hours
    - 43 hrs x 20,000 = 98 years. ☹

Gravitational contraction?



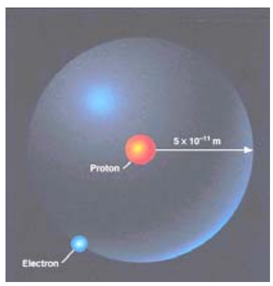
- Converts gravitational potential energy into kinetic energy
- Kinetic energy in a gas = heat
- Collisions between atoms convert heat to light
- To provide $4\text{x}10^{26}$ watts
  - sun must contract by 40 meters per year
  - 40m x 2000 years of observations: *undetectable!*
- But total available gravitational energy = 10^{42} Joules
  - 1 watt = 1 Joule/second
  - 10^{42} J / $4\text{x}10^{26}$ J/s = $2.5\text{x}10^{15}$ seconds = 79 million years.
- 800,000 x better than Duracell batteries ☺
- *But not good enough* (we need > 4.5 billion years). ☹

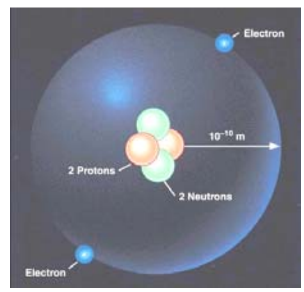
What Powers the Sun?

- Need to provide
  - 4×10^{26} watts
  - $< 2\times10^{33}$ grams (mass of Sun)
  - $>$ 4.5 billion years (age of Earth)
- How about H bombs?
  - $4 \times {}^{1}H \rightarrow {}^{4}He$ + neutrinos + energy

Hydrogen: ^{1}H Helium: ^{4}He

4 x





Special Relativity ➔ $E = mc^2$

- **The Principal of Relativity.** The laws of physics are the same in all inertial reference frames.
- **The constancy of the speed of light.** Light travels through a vacuum at a speed *c* which is independent of the light source.

➔ distance, time, velocity add up in funny ways

60 mph → 100 mph →

Classical: **$v' = (v-u)$**

Special relativity: **$v' = (v-u)/(1-uv/c^2)$**

➔ Total energy of a particle moving at constant velocity v:

Classical: $E = 1/2\, mv^2$

Special relativity: $E = mc^2/\sqrt{1-v^2/c^2} \sim \underbrace{1/2\, mv^2}_{\text{Kinetic energy}} + mc^2$

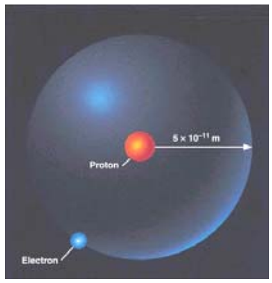
"Rest Energy" is there even when v = 0

How about H bombs?

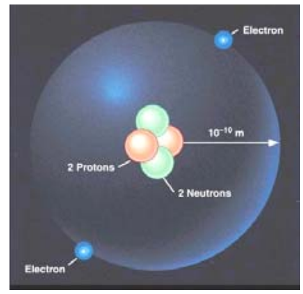
- $4 \times {}^{1}H \rightarrow {}^{4}He$ + neutrinos + energy

Hydrogen: ^{1}H

4 x



Helium: ^{4}He



- Atomic structure
  - Proton: + charge, 1.67265×10^{-27} kg
  - Neutron: 0 charge, 1.67495×10^{-27} kg
  - Electron: - charge, 9.11×10^{-31} kg
  - Neutrino: 0 charge, 0(?) mass

[Table 15.1]

Mass to Energy

$4 \times {}^{1}H \rightarrow {}^{4}He$ + neutrinos + energy

- $E = mc^2$ is one way to describe how much energy is released.

$$\frac{\text{Mass of } 4 \times {}^{1}H}{\text{Mass of } {}^{4}He} = \frac{4 \times (1.67353 \times 10^{-27}\ \text{kg})}{6.64648 \times 10^{-27}\ \text{kg}} = \frac{6.69414 \times 10^{-27}\ \text{kg}}{6.64648 \times 10^{-27}\ \text{kg}} = 1.007$$

- The neutrinos have negligible mass
- ...so 0.007 x mass of H is converted to energy.

- $0.007 \times \underbrace{2 \times 10^{30}\ \text{kg}}_{\text{Mass of Sun}} \times \underbrace{(3 \times 10^{8}\ \text{m/s})^2}_{c^2} = 10^{45}$ Joules (total available energy)

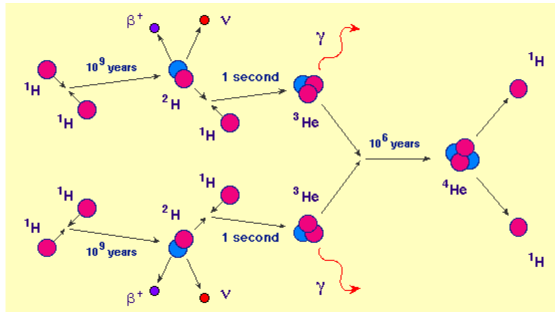
- (Available energy) / (Luminosity) = 10^{45} J / 4×10^{26} W = 3×10^{18} s

  = 10^{11} years

Actual number ~ 10^{10} yrs because Sun will evolve after central 10% of its mass is consumed, and then will die.

The proton-proton fusion reaction

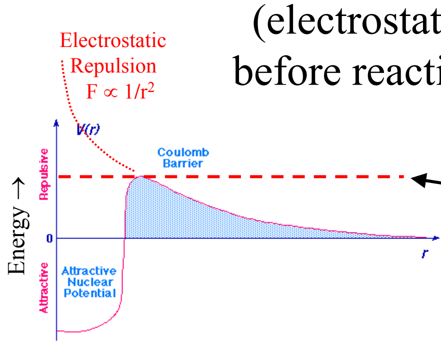
See [Figs 15.4,15.5]



- Starts with energetic collisions between pairs of protons.
- Intermediate products are deuterium (^{2}H) and ^{3}He.
- End result:

$$4\ {}^1\text{H} \rightarrow {}^4\text{He} + \text{neutrinos} + \text{energy}$$

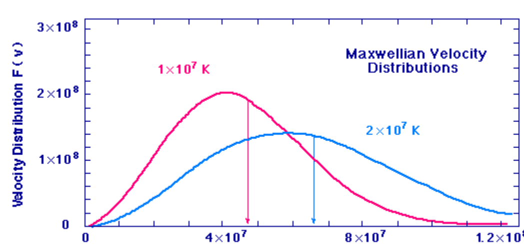
But must get past "coulomb barrier" (electrostatic repulsion) before reaction can occur.



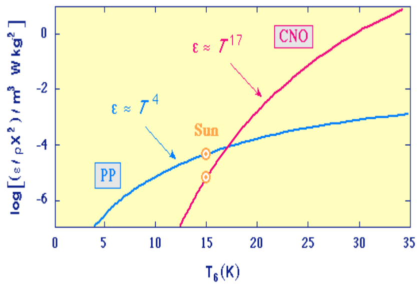
Need at least this much energy to be able to get close enough for strong nuclear force to grab hold.

Energy comes from kinetic energy = 1/2 mv^2 of colliding protons.

High temperature = large kinetic energy.



Alternate mechansim - the Carbon-Nitrogen-Oxygen (CNO) cycle



CNO cycle:

$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$

$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$

$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$

$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$

$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$

$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$

γ = gamma ray (light)

ν = neutrino

- Uses carbon (^{12}C) as a catalyst.
- So only works if C (or N or O) already present in star.
- Net result: $4\ {}^{1}H \rightarrow {}^{4}He$ + neutrinos + energy

Computing the structure of the sun

See [15.3]

- For every point in the Sun, we want to compute
  - temperature
  - pressure
  - density
  - composition
  - energy generation
  - energy transport mechanism
- We can write 4 equations expressing the following ideas:
  - The Sun is a gas.
  - The sun is neither contracting nor expanding.
  - The sun is neither heating up nor cooling down.
  - Specify method of energy transfer.

- The Sun is a gas:

pressure $\propto$ density x temperature

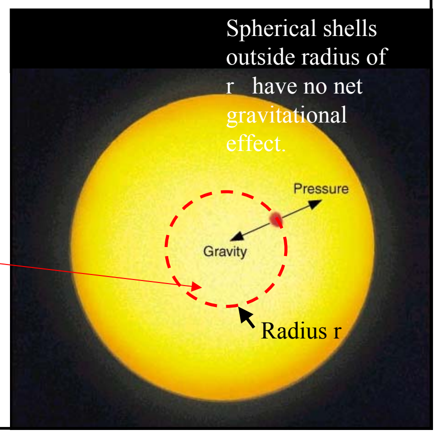
$$P \propto \rho \times T$$

- The sun is neither contracting nor expanding:
  - Pressure support from below = gravitational attraction towards center

$$dP/dr = -GM_r \rho / r^2$$

M_r = mass interior to r

Mass interior to r has same gravitational attraction as if it were all exactly at the center.



[Fig 15.7]

- The sun is neither heating up nor cooling down
  - Equation saying that at each point in the star:

Energy losses = energy generation

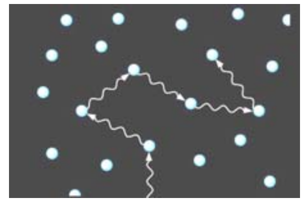
$$dL_r/dr = 4\pi r^2 \rho \varepsilon$$

- ε = energy generation
  - complicated, but known, function of density, temperature and composition.
- Energy generation changes composition

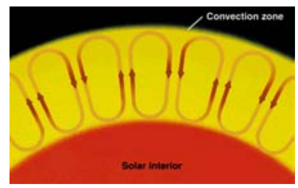
$$4\ {}^1H \rightarrow {}^4He + \text{neutrinos} + \text{energy}$$

• Energy transfer

- Possibilities are:
  - Radiation
    - photons (light) travel a short distance.
      - absorbed by atoms.
      - re-emitted.
      - random walk.
  - Convection
    - hot bubbles rise.
    - cooler bubbles fall.
    - occurs when pressure changes very little with temperature.
  - Conduction
    - Not important in Sun

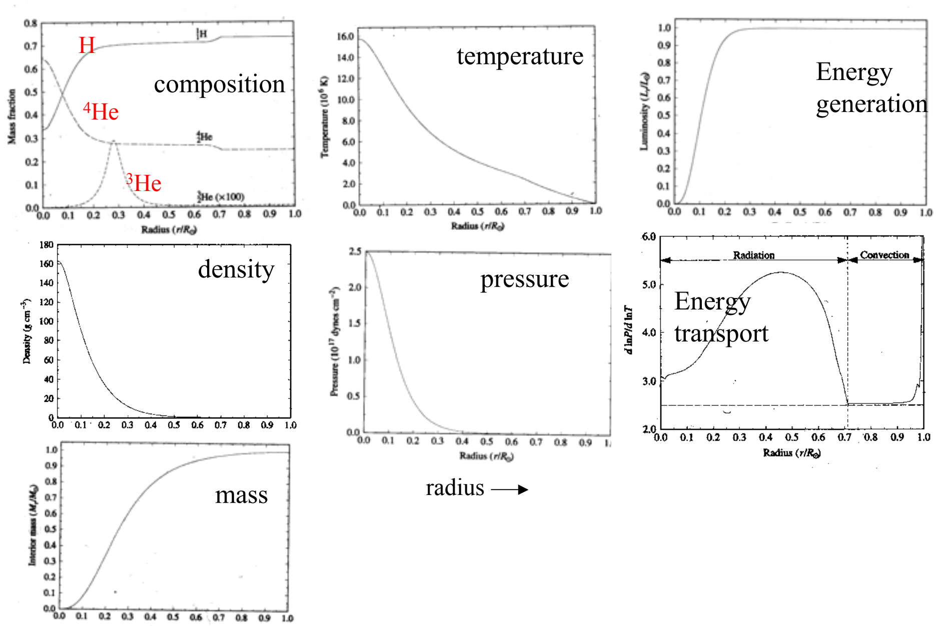


[Fig 15.9]

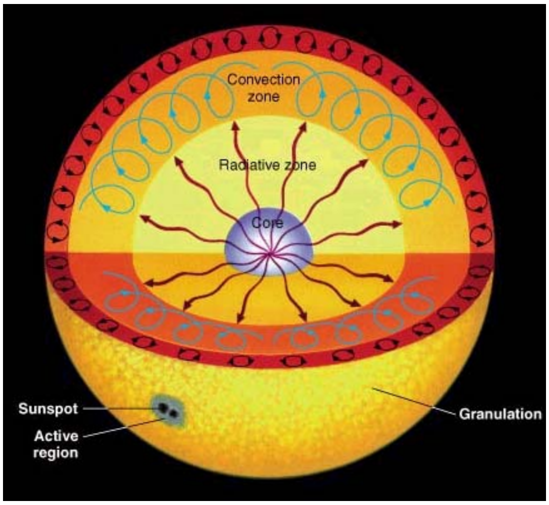


[Fig 15.8]

The Resulting Model of the Sun



The solar interior



[Fig 15.11]

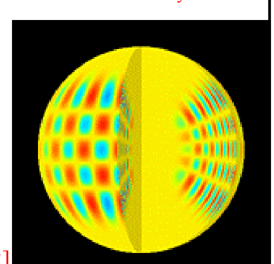
Central Conditions

- Temperature: 1.6×10^{7} K
- Pressure: 2.5×10^{11} atm
- Density: 162 g/cm^3
- % H (by mass): 0.336
- % He: 0.643

Solar oscillations

- 2D mapping of velocity of gas on Sun's surface
  - Seismic wave patterns.
    - Caused by sudden collapses of large volumes of gas on surface.
  - Wave pattern shows interior structure
    - similar to analysis of Earth's, Moon's interior structures.
- Results
  - Convection zone down to 30% of Sun's radius.
  - Differential rotation throughout convection zone.
  - Helium abundance same as at surface, except in energy generation zone.

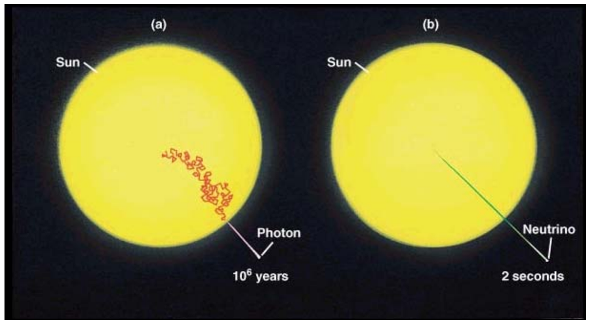
GONG network continuously maps Sun's surface velocity field.



[Fig 15.12]

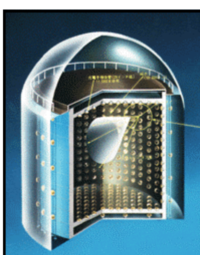
The solar neutrino problem

$4\,{}^{1}H \rightarrow {}^{4}He$ + neutrinos + energy



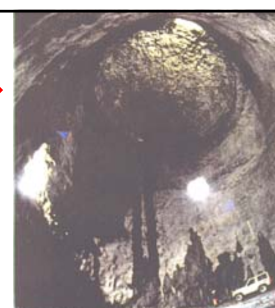
[Fig 15.10]

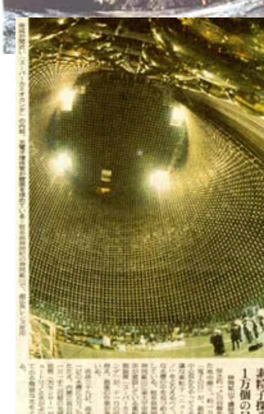
- Observed luminosity of sun ➔ number of neutrinos produced.
- Neutrinos very hard to measure.
  - Only interact through weak nuclear force.
- Initial measurements show only 1/3 expected rate of neutrinos.



Super Kamiokande Neutrino Detector (Japan)

DECEASED



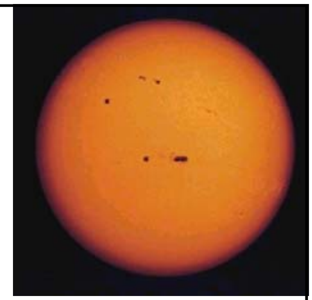


- Large chamber deep underground.
  - Filled with pure water.
  - Neutrinos interact (weakly) with water.
  - 13,000 photocells on walls detect resulting Cherenkov radiation.
- Found *neutrino oscillations*
  - Three types of neutrinos known.
  - Neutrinos change back and forth between types while in transit.
  - Previous experiments only sensitive to one type.

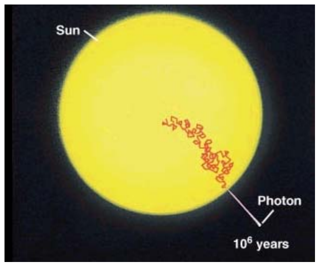
The Surface of the Sun

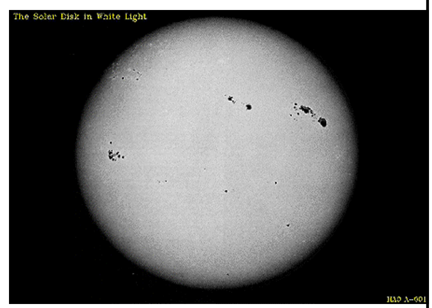
- Most stars are so far away that no surface detail can be resolved
  - Sun is *only* example where we can make a detailed study
  - Surfaces of other stars presumably similar.

Photosphere



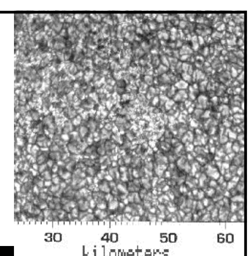
- Deepest layer from which light directly escapes into space.



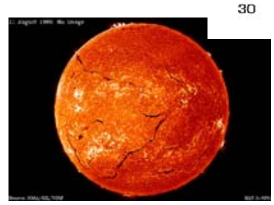


- Low density and pressure (10^{-4}, 0.1 x Earth's surface values)
- But *hot* (5800° K)

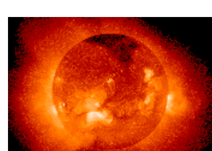
- Granules (in photosphere)
  - Tops of convection currents.

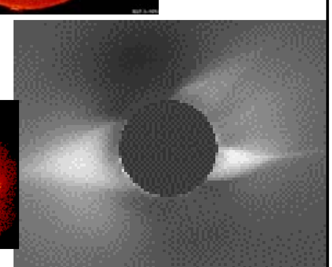


- Chromosphere
  - Transparent gas layer, reaches 2000-3000 km above photosphere.
  - T ~5,000-10,000° K
  - Photosphere = point we can no longer see through chromosphere.



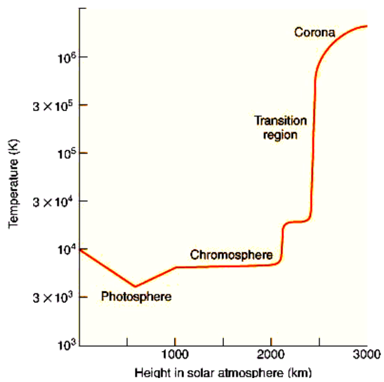
- Corona
  - T > 1,000,000° K
  - Very low density: 10^{-10} bar.
  - Heated by magnetic energy.
  - Several x diameter of photosphere.

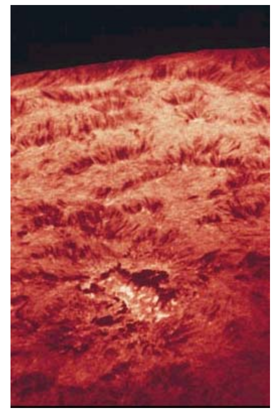




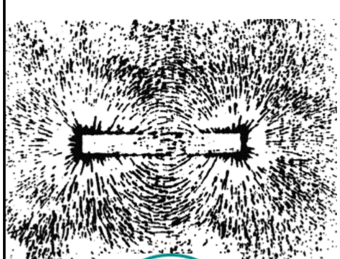
Transition region

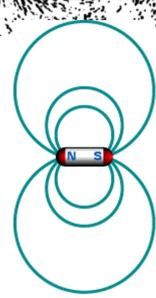
- Interface between Chromosphere & Corona
- Spicules
  - Small jets of cooler Chromospheric gas squirting up into Corona
  - Come and go on 10 minute timescale



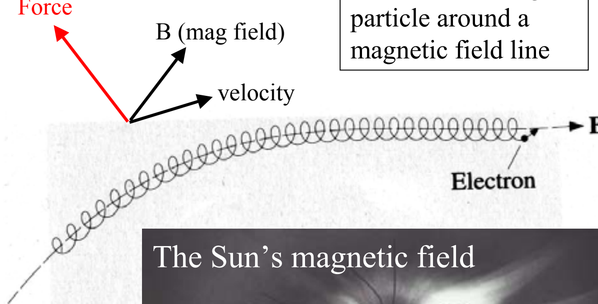


Magnetic Field Lines

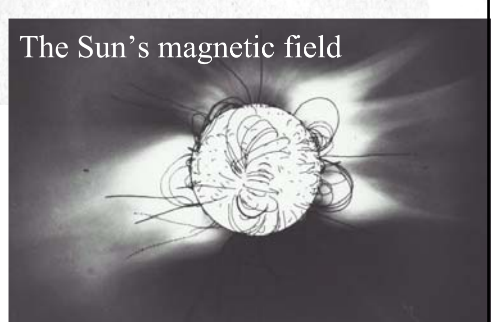




Magnetic field lines of force



Motion of a charged particle around a magnetic field line

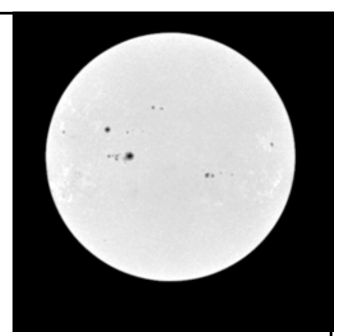


The Solar Wind

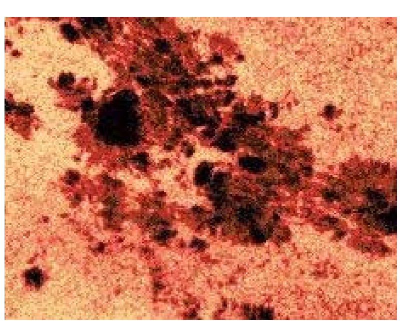
- Hot gas boils off surface of sun
  - *Ionized*: collisions knock electrons off atoms.
  - Magnetic field controls movements of charged particles.
- Solar wind escapes through holes in magnetic fields
- Escape velocity $v_{\mathbf{escape}} = \sqrt{2GM/R} =$ 600 km/s
  - Only ~ 50 x higher than from Earth's surface
  - But corona has T > 10^6 degrees
  - Very highest energy atoms have escape velocity
- Solar wind flows outward at 400 km/s (900,000 mph).
  - Charged particles then interact with
    - Earth's atmosphere (auroras)
    - Comet tails

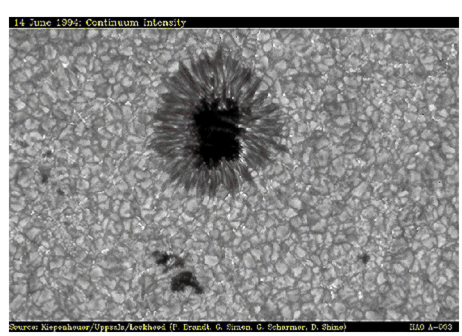
But it actually involves a very complicated interaction with the Sun's magnetic field.

Sunspots

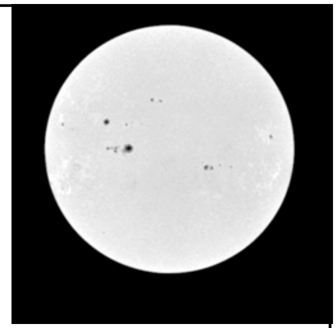


- Cooler areas
  - as much as 1500º less than photosphere.
- This makes them look darker.
  - But they actually are still very bright.
    - Glowing at 4300º K instead of 5800º

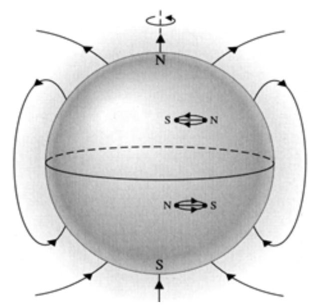




Sunspots

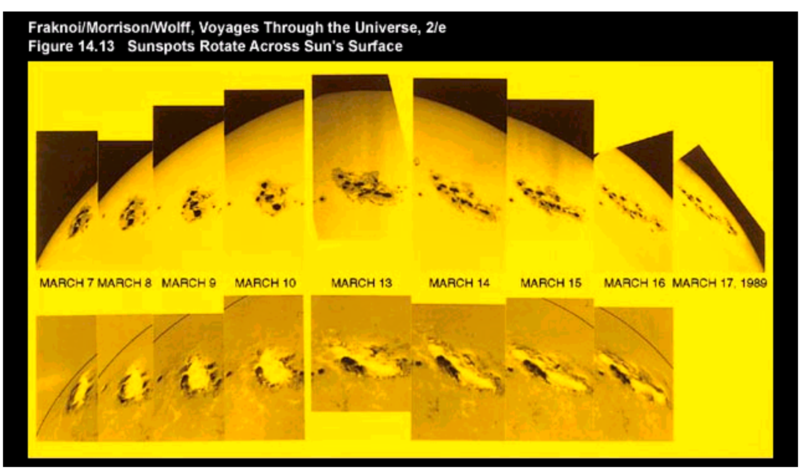


- occur where magnetic field lines leave, re-enter photosphere.
  - Spots come in pairs.
    - leading = 1 magnetic polarity
    - trailing = opposite polarity
  - polarity reveres between N, S hemispheres.



- Magnetic field prevents hotter gas (granules) from entering these regions

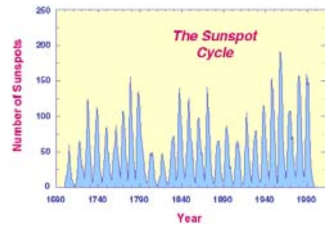
Sunspots rotate with Sun's surface



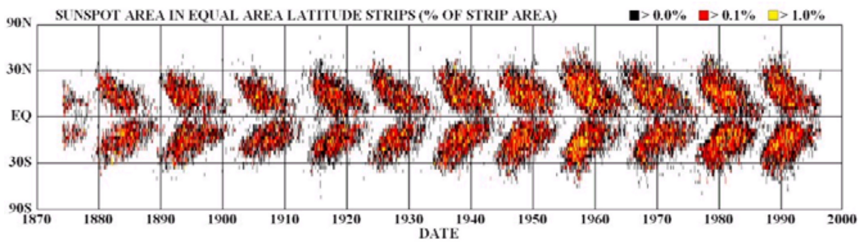
36 days of the magnetic sun movie

The Sunspot Cycle

- 11 years between maxima.
  - we are currently in a maximum.



The Butterfly Diagram: shows change in latitude of sunspots during repeating sunspot cycles.



The Sunspot Cycle

- Caused by cyclical change in Sun's magnetic field.
  - field reverses polarity on 22 year cycle.
  - reverses polarity of leading spots in pairs.
- Sunspots are a detail showing how the Sun's magnetic field is leaking out of the zones just below the Sun's surface.
  - Magnetic field seems to be produced in outer 30% of Sun's radius.

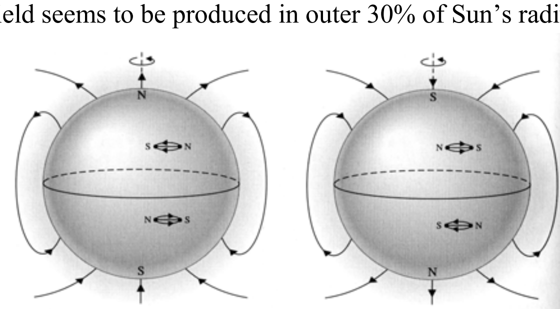
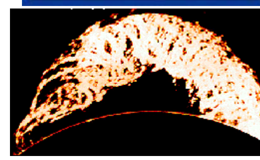


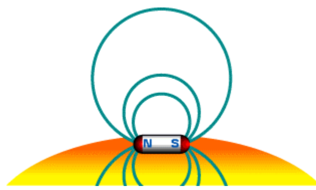
Figure 11.32 The global magnetic field orientation of the Sun, along with the magnetic polarity of sunspots during successive 11-year periods.

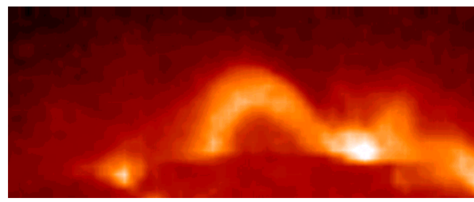
Carroll & Ostlie, *Modern Astrophysics*

Activity in the Chromosphere and Corona



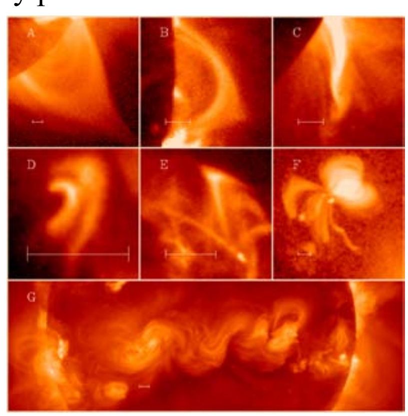
- Plages - hot regions in the chromosphere
- Prominences
  - Flame-like protuberances
  - usually above sunspots
  - follow magnetic field lines ==> loops
  - *eruptive* prominences shoot out material at > 1000 km/s
    - well above 600 km/s escape velocity
    - many times the size of Earth





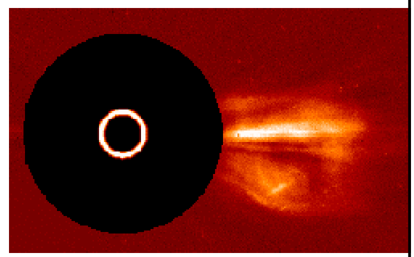
Lots of prominences

X-ray pictures from Yohkoh satellite



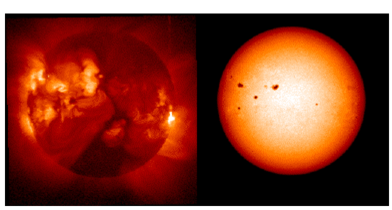
Solar Flares

- Most violent solar activity
- caused by magnetic fields "shorting out"
- can eject large amounts of material from corona
  - can dump huge numbers of fast-moving protons into Earth's atmosphere
  - 1989 power outage in Canada
  - temporarily heated and expanded Earth's atmosphere



Connections between the layers

Movie comparing x-rays to white light.

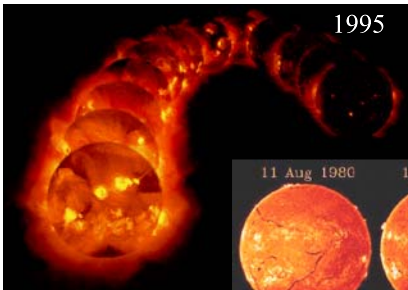


Movie starting with photosphere, then chromosphere, then x-ray view of corona. Note the connections between locations of sunpots in photosphere, and activity further out.

The Corona in X-rays

Movie showing coronal activity seen by Yohkoh satellite, as the Sun rotates (24 day period).

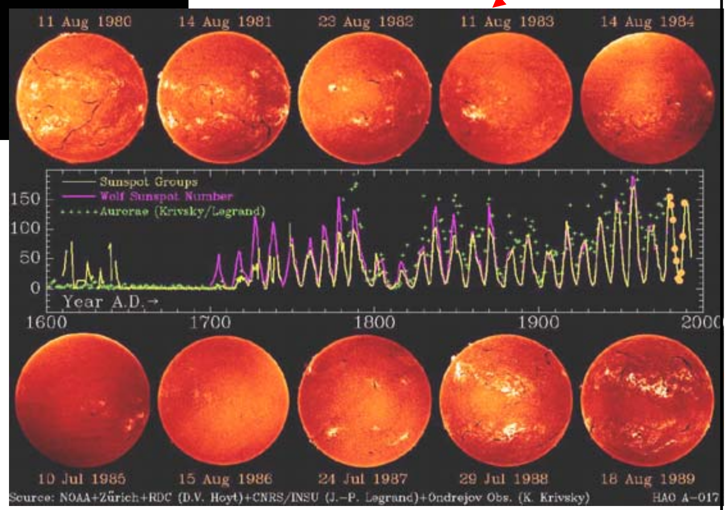
The solar cycle



X-rays

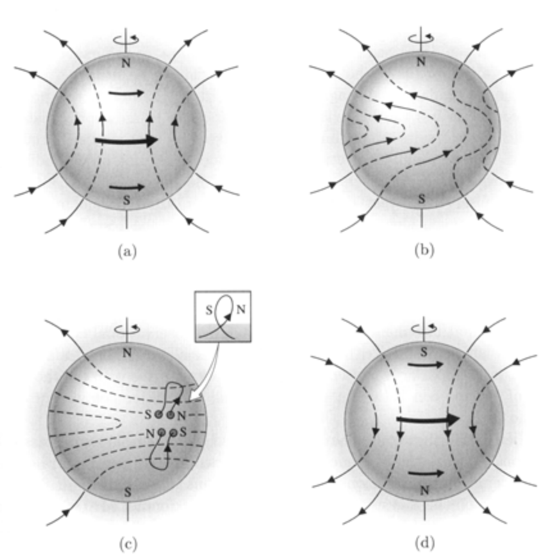
1991
sunspot
maximum

H emission



What causes the solar cycle?

- Differential rotation of Sun's outer layers
  - 24 days at equator.
  - 30 days at pole.
  - reason not understood.
- "Winds up" magnetic field
  - field reverses each 11 yrs, when it gets too wound up.
  - causes 22-year cycle.
  - but why this reversal??? We don't know.

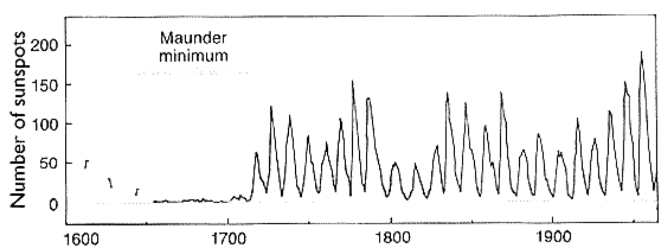


Carroll & Ostlie, *Modern Astrophysics*

Variations in Cosmic Ray Rates

- Cosmic rays: high energy charged particles from outside solar system.
- Produce radioactive ^{14}C which then gets locked up in plant material.
- Higher solar activity = stronger solar magnetic field.
  - this shields Earth from cosmic rays.
- ^{14}C concentrations in tree rings ➔ history of solar activity
  - but smeared out over ~ 10 years it takes ^{14}C to find its way into plants.
  - Goes back 8000 years.

The long-term record on Earth



- Cool periods
  - 1280-1340
  - 1400-1510
  - 1645-1715 (Maunder minimum, “little ice age”)
  - 1800-1830 (Little Maunder minimum)
- Warm period before 1280 coincided with Norse discovery of New World.
- Today, Sun puts out ~ 0.1% more light at sunspot maximum than at sunspot minimum.
  - But 10 x bigger variation needed to explain temperatures during Maunder minimum.