

# The Vital Statistics of the Sun

Astro 342 Fall 2006: The Sun page 1

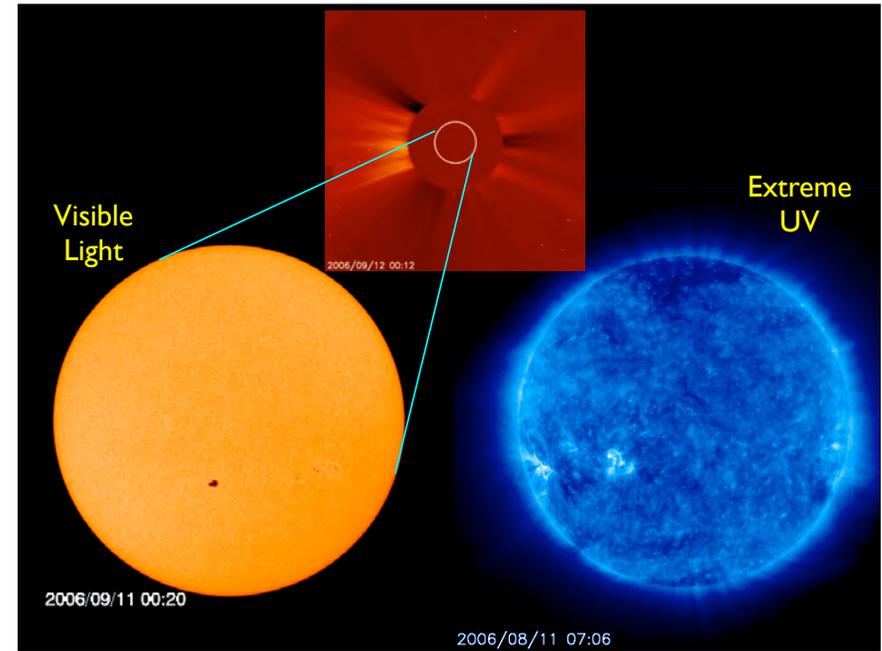
**Distance:**  $1.5 \times 10^8$  km      Kepler's 3rd law  
**Mass:**  $2 \times 10^{30}$  kg      Kepler's 3rd law  
**Radius:**  $7 \times 10^5$  km      angular size & distance  
**Luminosity:**  $4 \times 10^{26}$  W      solar constant & distance  
**Temperature:** 5800K (10,000° F)      Thermal Balance  
**Composition:** spectroscopy

		by mass
<b>Hydrogen</b>	<b>73.4%</b>	
<b>Helium</b>	<b>21.8%</b>	“ “
Oxygen	0.8%	“ “
Carbon	0.4%	“ “
everything else	<b>0.6%</b>	“ “

i.e. Silver ~ 0.00000066% (still, that's  $5 \times 10^{20}$  tons of silver in the Sun!)

1868: Lockyer & Jansen find spectral lines in Sun never seen on Earth  
 → Helium proposed as a new element

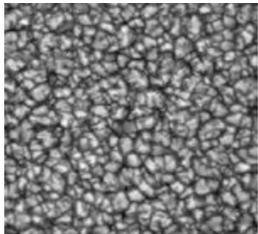
1891: Helium finally discovered on Earth



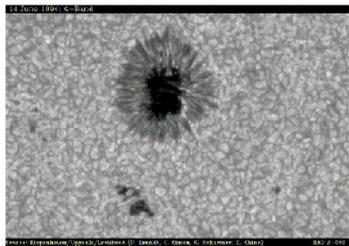
## The 'surface' of the Sun:

Astro 342 Fall 2006: The Sun page 3

### the Photosphere

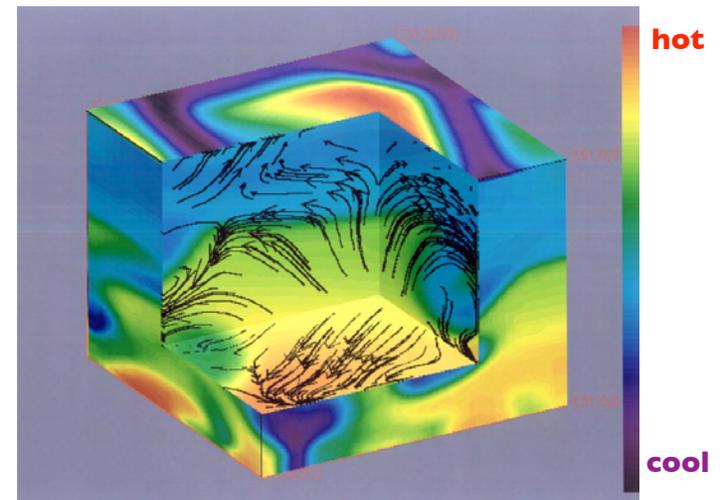


- T ~ 5800K
- Granulation
  - cells of rising gases (~1000 km across)
  - give mottled appearance to photosphere
- Sunspots
  - relatively cooler than photosphere (T ~ 4500K)
  - site of strong magnetic fields



## Granules as 'convection cells'

Astro 342 Fall 2006: The Sun page 4

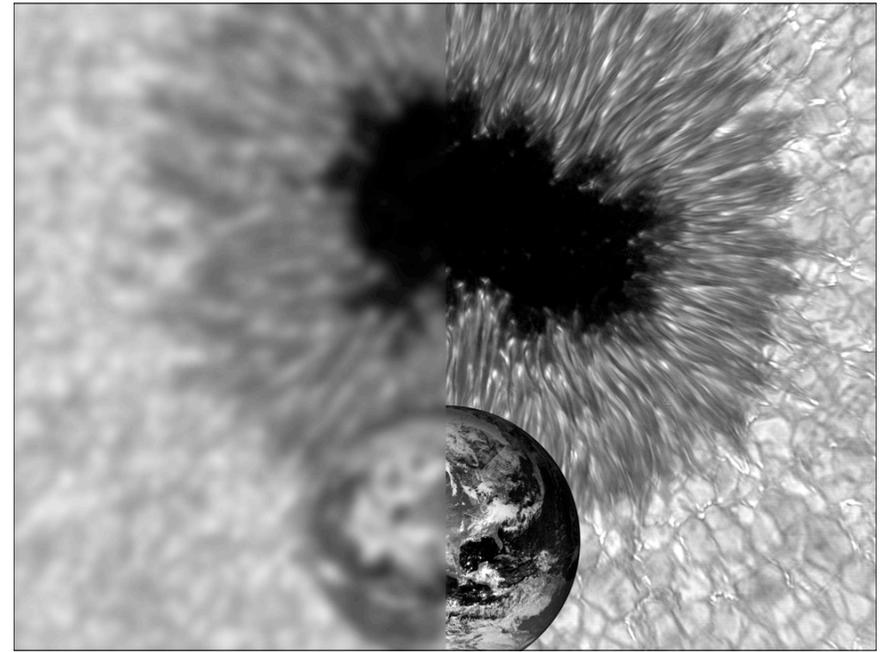
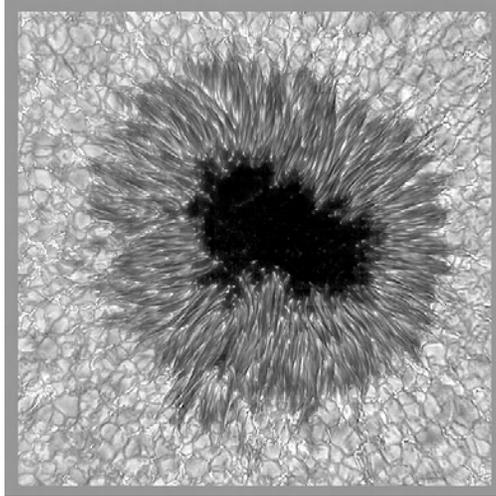


simulation by Stein & Nordlund (1998)

## an ultrasharp view

Astro 342 Fall 2006: The Sun page 5

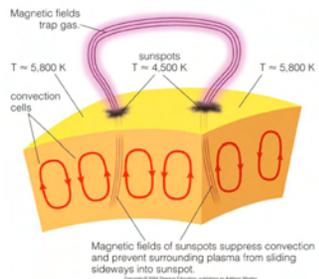
- from the National Solar Observatory
- sharpness achieved via Adaptive Imaging (AO)



## The Chromosphere

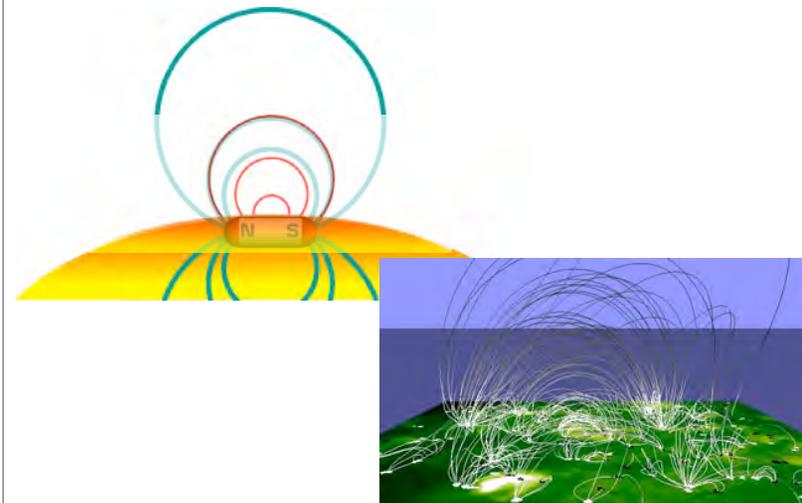
Astro 342 Fall 2006: The Sun page 7

- cooler (and hotter) layer above photosphere
- dominated by light of hydrogen emission
- **Prominences**
  - material suspended above photosphere
- **Flares**
  - giant eruptions



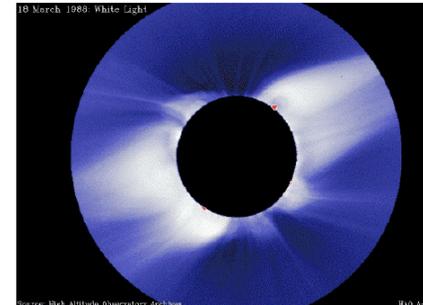
## Magnetic fields on the Sun

Astro 342 Fall 2006: The Sun page 8

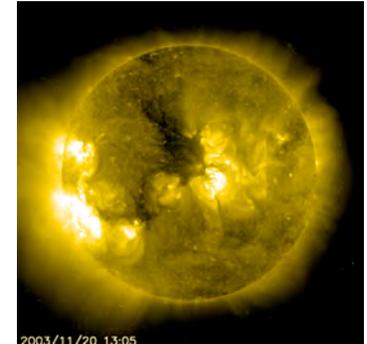


# The Solar Corona

- rarefied outer solar atmosphere
  - visible during eclipses or from space
- strange emission lines
  - identified as highly ionized heavy elements
  - $T \sim 2,000,000K$



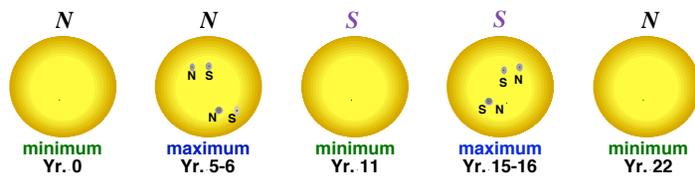
Optical image (eclipse)



Extreme UV (space)

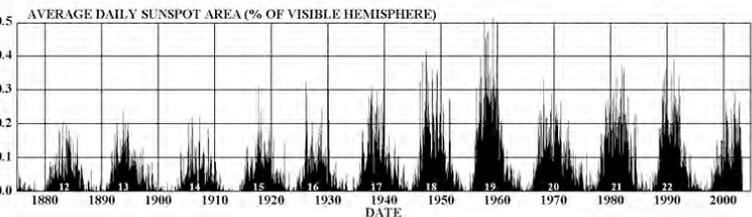
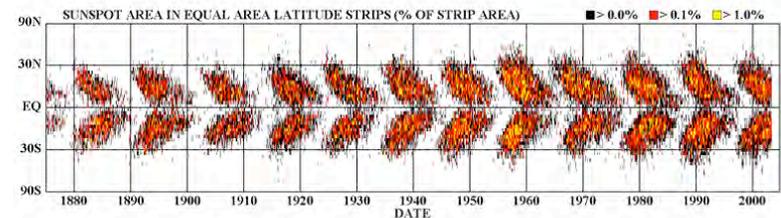
# The Solar Cycle

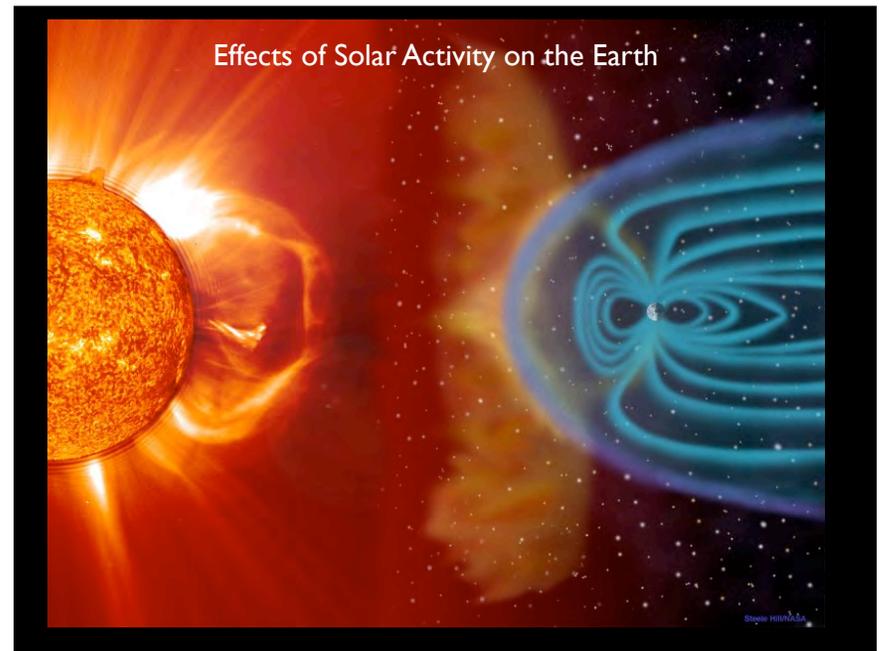
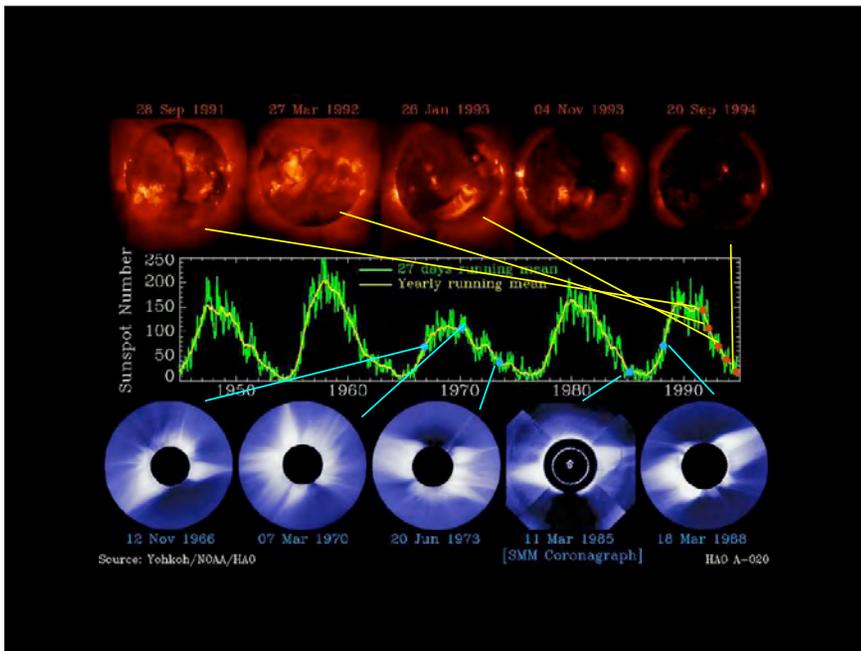
- number of spots changes over 11 year cycle
- magnetic polarity (N/S) of spots flips every 11 years
- —> whole pattern repeats every 22 years (the 'Hale-Nicholson law')



# The Butterfly Diagram

DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS





## Effects of solar activity on the Earth

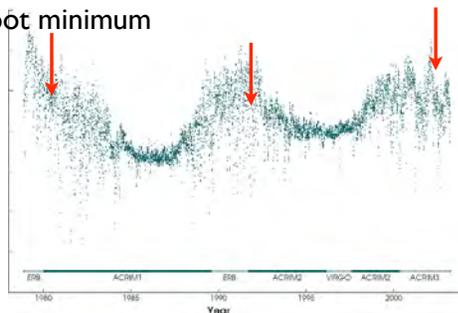
Astro 342 Fall 2006: The Sun page 15

### ● Solar Flares

- X-ray flares produce geomagnetic storms (triggered by particles from the solar wind)
- large flares - power grid overload, communication disruption, X-ray and particle dangers to astronauts and high fliers

### ● Variations of Solar Radiative Output

- low solar output at sunspot minimum
- higher solar output near sunspot **maximum**
- impact on weather / climate ??



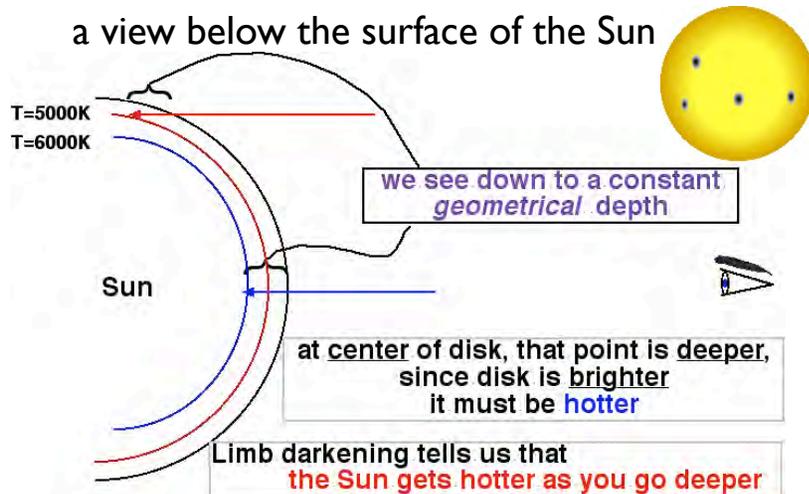
Astro 342 Fall 2006: The Sun page 16



inside the sun

## Limb Darkening:

a view below the surface of the Sun



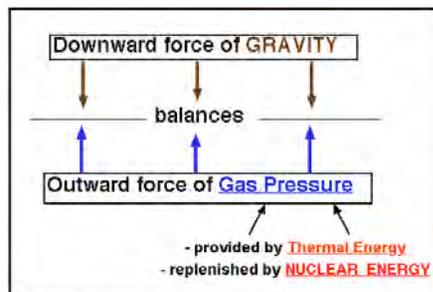
## The Inside of the Sun:

- What keeps the Sun shining?
- What keeps the Sun from collapsing?

- Mechanical Structure
  - balance between gravity and gas pressure
- Thermal Structure
  - production, flow, and escape of radiant energy
- Energy Source

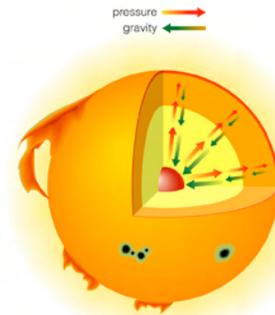
## Mechanical Structure

- Gravity versus Pressure



HYDROSTATIC EQUILIBRIUM

Source: Education, publishing on Addison Wesley



- Pressure increases with depth

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

$$t_{\text{dyn}} \approx \sqrt{\frac{R^3}{GM}} \approx \sqrt{\frac{4\pi}{3G\rho}}$$

$$\approx 7 \times 10^3 \text{ sec} \left( \frac{M}{M_{\odot}} \right)^{-1/2} \left( \frac{R}{R_{\odot}} \right)^{3/2}$$

## Thermal Equilibrium

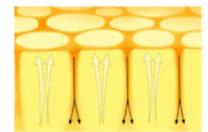
- Energy in = energy out
  - globally: energy produced = energy lost
  - locally: flow in bottom = flow out top

- Heat Transport Processes

1. **conduction** - direct contact

2. **convection**

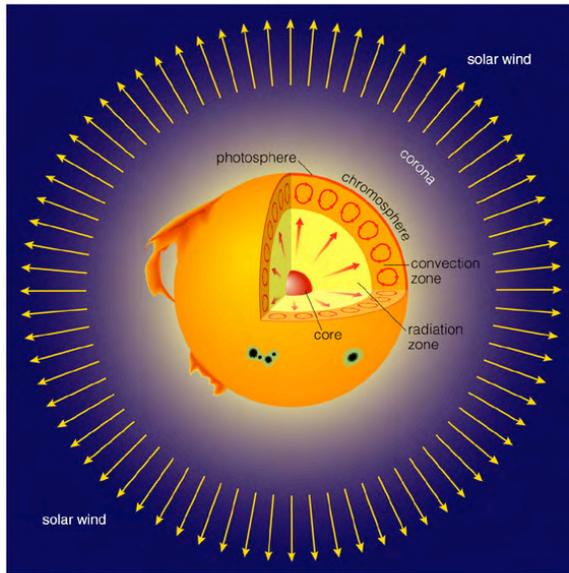
1. bulk motion of matter
2. occurs when temperature changes rapidly with depth



3. **radiation**

- transport by photons
- transparent stuff -- rapid transport
- opaque stuff -- slow transport
- 1 million years for energy to flow out from center!





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## Energy Source for the Sun

- **Combustion?**

- 1 kg of coal per square meter per second!
- whole Sun consumed in **10,000 years!** ... nope

- **Gravitational Contraction?**

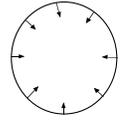
Kelvin and Helmholtz, 1871

- falling objects acquire energy that can be converted to heat

$$E_{grav} \approx \frac{GM^2}{R} \quad L = -\frac{dE}{dt} = \frac{GM^2}{R^2} \frac{dR}{dt}$$

$$\tau = \left[ \frac{1}{R} \frac{dR}{dt} \right]^{-1} = \frac{GM^2}{RL} = 3 \times 10^7 \text{yr} \left( \frac{M}{M_{\odot}} \right)^2 \left( \frac{R}{R_{\odot}} \right)^{-1} \left( \frac{L}{L_{\odot}} \right)^{-1}$$

- contraction by 20 meters each year can keep the Sun shining
- K-H contraction can provide energy for **100 million years!**



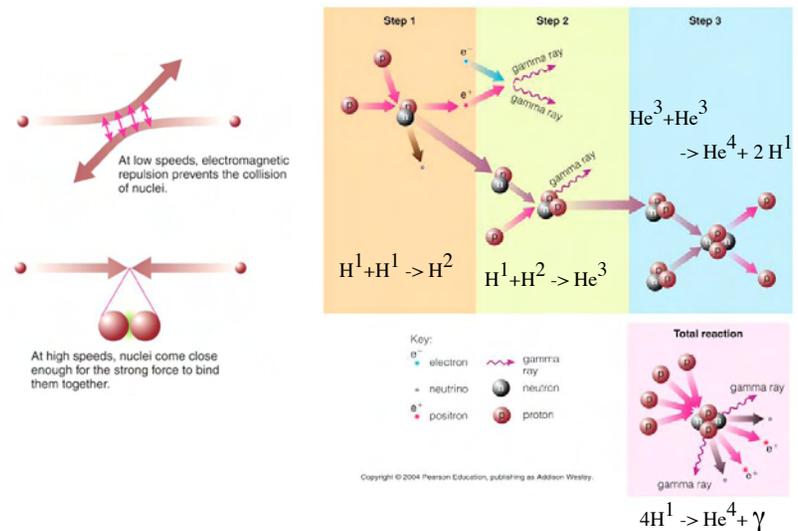
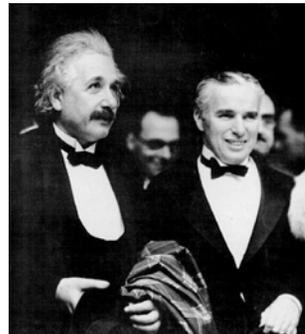
*BUT*

**various evidence shows that the Sun  
has been shining for at least  
4.6 billion years!**

**Where does this energy come from?**

(a hint:  $E = mc^2$ )

**Answer: NUCLEAR FUSION**



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mass of  $\text{H}^1 = 1.0078 \text{ AMU}$   
 so, mass of  $4\text{H}^1 = 4.0312 \text{ AMU}$

**but**

mass of  $\text{He}^4 = 4.0026 \text{ AMU} \dots$

**0.0286 AMU disappears in pp chain!**

...converted into energy via  $E=mc^2$

**0.7% of each gram of H consumed is converted into energy**

$E = 0.007 \times c^2 \text{ ergs per gram of H} \rightarrow \text{He}$

$E = 6 \times 10^{18} \text{ ergs per gram} \quad \text{''} \quad \text{''} \quad \text{''}$

To supply the solar luminosity ( $4 \times 10^{33} \text{ ergs/second}$ )  
 the Sun must consume

**$6.4 \times 10^{14} \text{ grams of hydrogen every second!}$**

How long can this go on?

$M_{\text{sun}} = 2 \times 10^{33} \text{ grams}$

rate of consumption =  $6.4 \times 10^{14} \text{ grams/second}$

lifetime =  $\frac{2 \times 10^{33} \text{ grams}}{6.4 \times 10^{14} \text{ grams/second}} \times 0.1$

=  $3.1 \times 10^{17} \text{ seconds}$

**= 10 billion years!**

...but the “solar neutrino ‘problem’” lurks

• Neutrinos

- massless particles
- travel at the speed of light
- rarely interact with matter
- produced in center of Sun during fusion

• Experiments to detect solar neutrinos

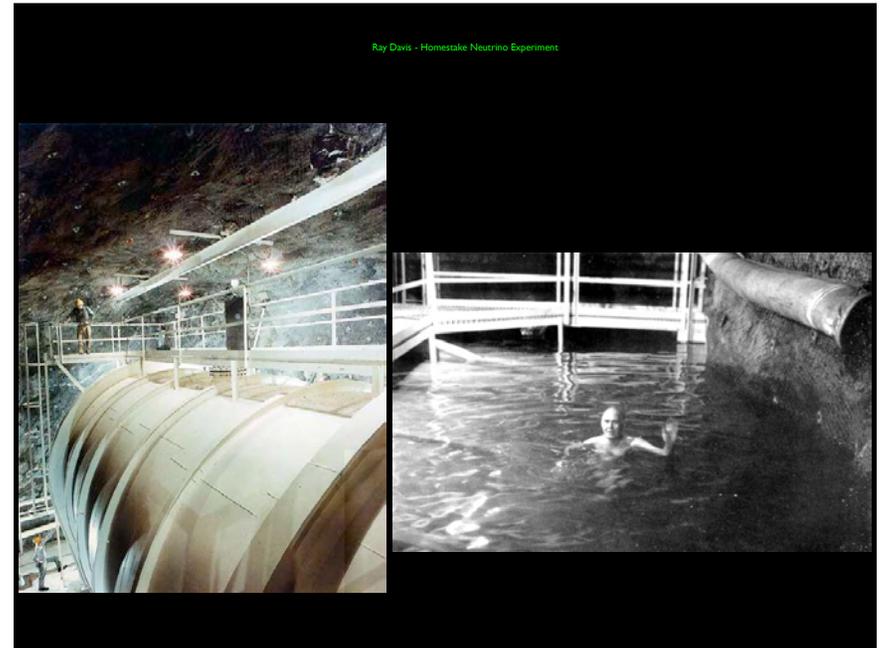
- **Chemical method:** find **rare** changed atom in big sample

**2002 Nobel Prize in Physics** → **Ray Davis** - 100,000 gallons of  $\text{C}_2\text{Cl}_4$  in Homestake Mine

- SAGE/GALLEX - gallium neutrino detector
- **Photodetectors:** detect **rare** recoil of affected particles
- **Kamiokande II** - neutrino flashes in huge water tank
- Sudbury Neutrino Observatory (SNO) - heavy water

• **ALL show ~50% of expected neutrino rate! uh oh ...**

• **Solution: New physics needed - neutrino oscillations**



Ray Davis - Homestake Neutrino Experiment

