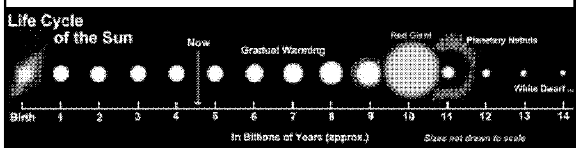
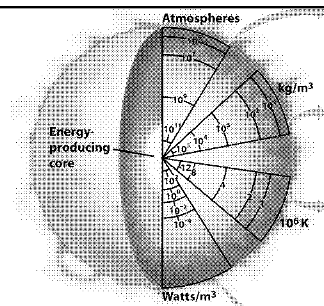
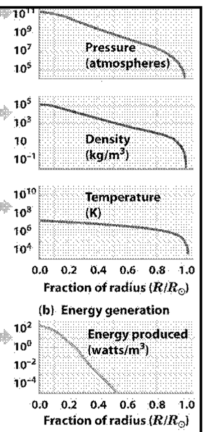
# Stars as Nuclear Reactors




## Monday, November 9

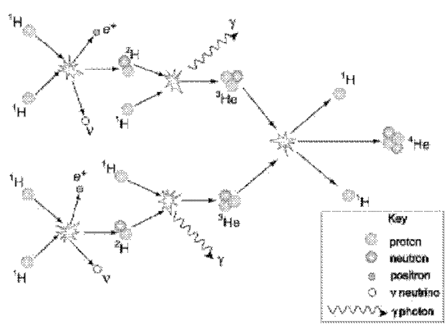
No class on **Wednesday**;
Problem Set 5 due on **Friday**.




**Nuclear fusion occurs in the hot, dense central regions of stars.**

Fusion in the Sun: start with 4 protons, end with 1 helium nucleus.



mass of 1 proton = $1.67262 \times 10^{-27}$ kilograms

mass of 4 protons = $4 \times (1.67262 \times 10^{-27}$ kg)
= $6.69048 \times 10^{-27}$ kg

mass of 1 helium nucleus = $6.64466 \times 10^{-27}$ kg

mass loss =
$6.69048 \times 10^{-27}$ kg – $6.64466 \times 10^{-27}$ kg
= **$0.0458 \times 10^{-27}$ kg**

Where is the lost mass?
It's been converted to **energy**.

$$E = m c^2$$

$m = 0.0458 \times 10^{-27}$ kg

$E = m c^2$
$E = (0.0458 \times 10^{-27} \text{ kg}) \times (3 \times 10^8 \text{ m/sec})^2$
$E = 4.12 \times 10^{-12} \text{ kg m}^2/\text{sec}^2$
$= 4.12 \times 10^{-12}$ **joules**

Energy released
per kilogram of hydrogen =

**energy released when 4 protons fuse**

$$\frac{4.12\times10^{-12}\text{ joules}}{6.6904\times10^{-27}\text{ kg}} = 6.2\times10^{14}\text{ joules/kg}$$

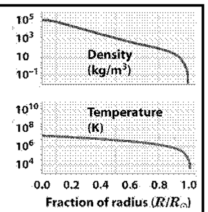
**mass of 4 protons**

620 **trillion** joules of energy released by fusing one kilogram of hydrogen!

(Recall: burning the same amount of hydrogen releases just 140 million joules.)

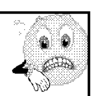
620 trillion joules: energy needed to drive 300 million km (assuming 40 mpg).

Only the central 10% of the Sun is hot & dense enough for fusion to occur.



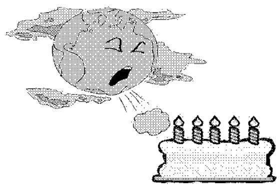

That central core started with enough hydrogen to keep the Sun shining for **10 billion years**.

Should we be worried?
Is the Sun nearly out of hydrogen?



Don’t panic. The Sun’s only halfway through its “life expectancy”.

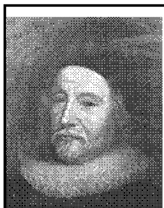
How do we **know** the Sun's age
(that is, the time since it started fusion)?



Hint: Stars form at the same time as
their entourage of planets.
The Sun and the Earth are the same age.

Before the 18th century,
**biblical chronology** was the accepted
method of finding the Solar System's age.

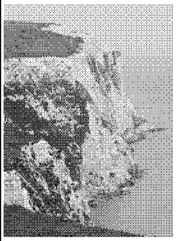
St. Augustine: Earth created 5500 BC
J. Kepler: Earth created 3993 BC
Isaac Newton: Earth created 3998 BC



Ultimate precision:
in the 17th century, Archbishop
James Ussher wrote:

"The beginning of time…fell on the
beginning of the night which preceded the
23rd day of October, in the year 4004 BC."

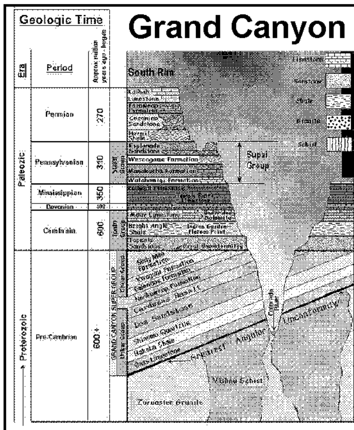
18th century: Geologists realized that the Earth is much more than 6000 years old.



The White Cliffs of Dover: a layer of tiny shells, 100 meters thick.

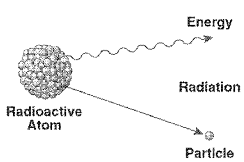
A huge number & variety of fossils on Earth (> 99.9% of all species are extinct).

## Grand Canyon



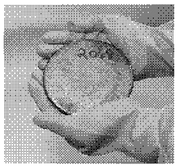

Thick layers of sedimentary rock, deeply eroded canyons.

Best method for finding the age of rocks:
**Radioactive dating**



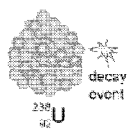

Some atomic nuclei are unstable. They undergo radioactive decay, emitting particles to become a smaller, stable nucleus.

Example of an unstable nucleus:
Uranium-238
(92 protons + 146 neutrons = 238)



Uranium-238 decays to Lead-206
(82 protons + 124 neutrons = 206)

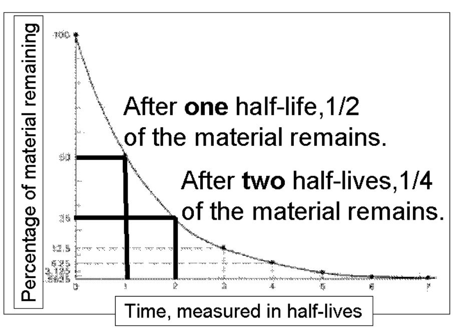
Decay of unstable nuclei
is a **random** process.




You can't say when any particular nucleus is going to decay.

You can only give the **half-life**:
the time it takes **half** the nuclei in a lump of material to decay.

## Decay of radioactive material:



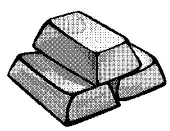
The half-life of uranium-238 is
4.5 billion years.

Start with an ingot of solid uranium-238.

After 4.5 billion years (1 half-life),
½ the uranium will have turned to lead.

After 9 billion years (2 half-lives),
¾ the uranium will have turned to lead.

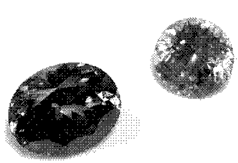
Radioactive dating (in principle):



Someone hands you an ingot of metal.
It is ¼ uranium-238, ¾ lead-204.

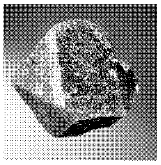
Age of ingot = 2 half-lives =
9 billion years, **IF** it started as
pure uranium-238.

When it comes to radioactive dating,
**zircons** are a geologist's best friend.



Zircon = zirconium
silicate, with various
impurities

Newly formed zircon crystals are
frequently contaminated with uranium,
never with lead.

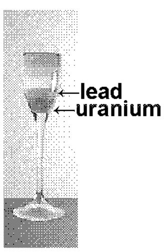


Zircon crystals are hard to destroy, easy to detect.

Grind up a zircon, do a chemical analysis, find the relative amounts of lead-204 and uranium-238.

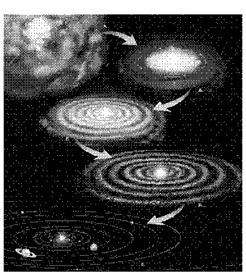
Compute the number of half-lives that have elapsed.

**Caveat:** when zircon melts, very dense uranium sinks to bottom, separating from slightly-less-dense lead.




The age of a rock found by radioactive dating is the time since the rock solidified.

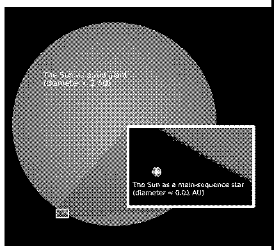
Best estimate of age of the Solar System: Sun, meteorites, planets all formed **4.56 billion years ago**.



(This was more than 9 billion years after the Big Bang.)

What will happen when the Sun runs out of hydrogen in its core?

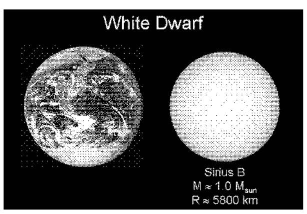
For another billion years, it will be powered by the fusion of helium into carbon.




During this time, it will swell into a **red giant**

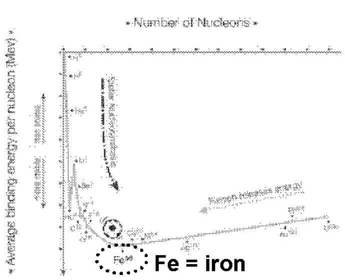
What will happen when the Sun runs out of **helium** in its core?

It blows off its outer layers: its remaining core becomes a dense **white dwarf**.



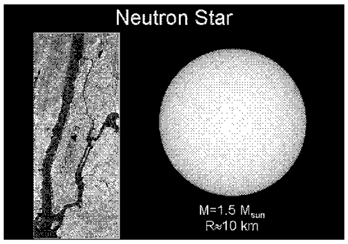

Stars much more massive than the Sun have a more spectacular fate!

Fusion continues as far as **iron**.



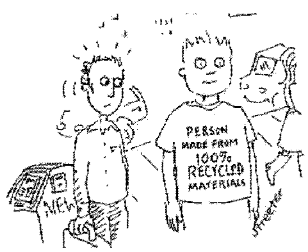

Iron's the end of the line.

Star's iron core collapses to a **very** dense neutron star.




Outer layers are violently ejected in a supernova.

Material ejected in a supernova is rich in carbon, oxygen, and other elements.




You really **are** made of recycled starstuff.

Friday's Lecture:

The Early Universe as a Nuclear Reactor

Reminders:

Have you read chapters 1 – 9 ?
Problem Set 5 is due on Friday the 13th.