Today in Astronomy 106: time enough for evolution

Measurements of the time available for life in the Universe to emerge:

- The age of the Universe
- The age of the Milky Way Galaxy
- The age of the Solar system
- The age of the Earth's surface

The northern Hubble Ultra Deep Field (STScI/ NASA)

Take a Guess

How old is the universe?

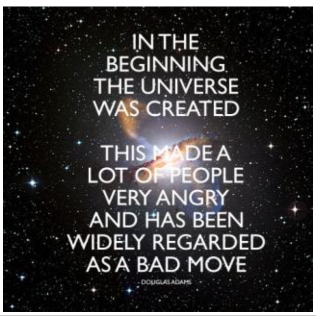
A. 4,600 years old

B. 13.7 billion years old

C. 4.6 billion years old

D. 13,700 years old

E. Really old.



Age of the Universe from expansion

The Universe began in an explosion we can still see today, which we call the Big Bang. This set the Universe's contents into expansion, which currently is described by Hubble's Law, $V = H_0 D$ ($H_0 = 20\ \mathrm{km\ sec^{-1}\ Mly^{-1}}$).

- But if the Universe has always **expanded at constant speed**, and if the Big Bang happened when $t = 0$, then the expansion to D took a time given by $D = Vt$, or

$$t = \frac{1}{H_0} = \frac{1}{20\ \mathrm{km\ sec^{-1}\ Mly^{-1}}}$$

$$= \frac{1}{20\ \mathrm{km\ sec^{-1}\ Mly^{-1}}}\left(\frac{\mathrm{km}}{10^5\ \mathrm{cm}}\right)\left(\frac{9.46\times10^{23}\ \mathrm{cm}}{\mathrm{Mly}}\right)$$

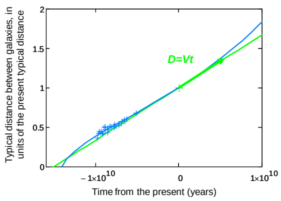
$$= 4.73\times10^{17}\ \mathrm{sec} = 1.5\times10^{10}\ \mathrm{years.}$$

(c) University of Rochester

Age of the Universe from expansion (continued)

Precise measurements for more distant galaxies indicate that the expansion decelerated at first – consistent with the mutual gravitation of the known contents of the Universe – and may be accelerating now.

- ❑ Accounting for these other effects we get a slightly different age: ***t* = 1.37×10[10] years.**



\+ Measurements by Riess et al. (2007)

When Universal expansion was discovered, astronomers weren't as good at measuring distances as they are now, and the first value reported for the Hubble constant was

$$H_0 = 140 \text{ km sec}^{-1} \text{ Mly}^{-1}.$$

What would the age of the Universe be, if this were true?

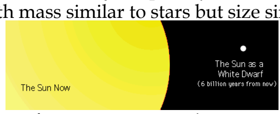
A. 1920 billion years B. 95.9 billion years
C. 1.96 billion years D. 0.01 billion years

Age of the Milky Way Galaxy

The Milky Way cannot be younger than its oldest contents.

Some the oldest stars in the Milky Way are **white dwarfs**.

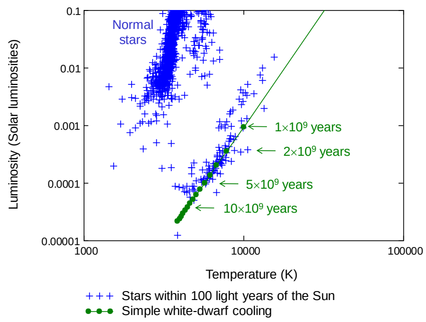
- ❑ White dwarfs are very simple objects: the remains of dead stars, with mass similar to stars but size similar to Earth.



G.H. Rieke

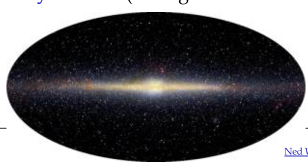
- ❑ White-dwarf temperatures can be measured from their colors. (Only the hottest ones are white.)
- ❑ Since there are many white dwarfs nearby, their distances can be measured, and combined with their apparent brightness to yield accurate luminosity measurements.

Age of the Milky Way Galaxy (continued)



Age of the Milky Way Galaxy (continued)

- These observations show a spread of luminosity and temperature that agrees very nicely with the expected cooling rate, **except** that there aren't any luminosities and temperatures that correspond to ages greater than 9.5×10^9 years. **The Galaxy is thus at least this old**.
- The shortest-lived stars that give rise to white dwarfs live about 2×10^9 years, so in all the Milky Way is probably about **12×10^9 years old**. (Younger than the Universe!)



Ned Wright

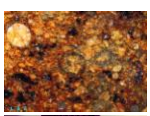
Age of the Solar system

Known from **radioisotope dating of rocks**, which tells us accurately how long it has been since a rock last melted. **A longer story**…

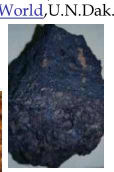
Suppose you start with molten rock, cool and solidify it. What do you get?

- Igneous rocks. Examples: basalt, granite, anorthosite, meteorites.

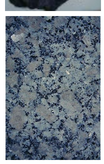
Chondrite meteorite (J.M. Derochette)



Basalt (Volcano World,U.N.Dak.)



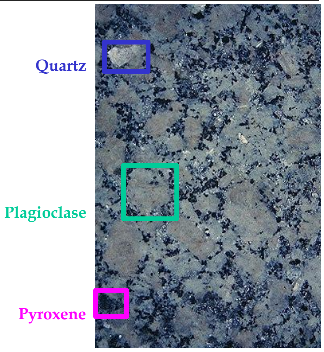
Anorthosite (*Apollo 16*)



Granite (Volcano World,U.N.Dak.)

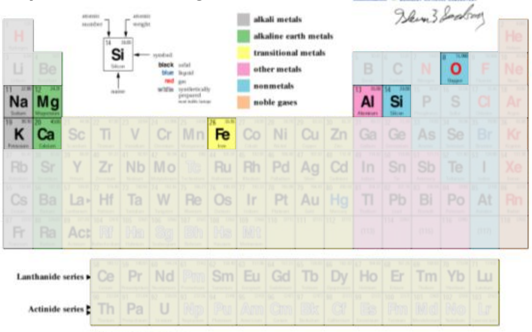
Rocks and minerals

- Rocks are made of minerals. Minerals are crystals with a specific chemical composition. Examples: olivine, pyroxene, plagioclase, quartz.
- Mineral crystals are formed from the dominant, most abundant heavy elements.



Granite (Volcano World, U.N.Dak.)

Major mineral-forming elements



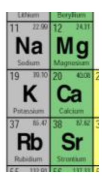
Trace elements (impurities) in minerals

Elements that are *not* very abundant can substitute for abundant ones in the mineral crystals.

- Examples: rubidium (Rb) can replace the more-abundant Na or K in minerals.
  Strontium (Sr) can similarly replace Mg or Ca.

Some minerals have greater capacities than others for replacing normal ingredients with impurities.

- Examples: olivines and pyroxenes can take more Rb per amount of Sr, than plagioclase can.
- At the temperatures that minerals crystallize, different **isotopes** of the elements are chemically identical. So there would be no preference among the two isotopes of Rb (^{85}Rb and ^{87}Rb), nor the four of Sr (^{84}Sr, ^{86}Sr, ^{87}Sr, ^{88}Sr).



(LBNL)

Radioactive trace elements in minerals

Some atomic nuclei, of course, are **radioactive**, and will transmute into other nuclides over time.

If one starts with a bunch of groups of radioactive nuclei, each group having a total of n_0 at $t = 0$, then after a time t the average number remaining in a group is

$$n = n_0 e^{-t \ln 2 / t_{1/2}} = n_0 \times \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} ,$$

where $t_{1/2}$ is the **halflife** for the radionuclide, a quantity that has (usually) been measured accurately in the laboratory.

- As one halflife elapses, the number of radioactive nuclei drops by a factor of two.
- n and n_0 can be number of nuclei, or number per gram of sample, or number times any constant.

Radioactive trace elements in minerals (continued)

- For example: ^{85}Rb is not radioactive, but ^{87}Rb beta-decays into ^{87}Sr:

$$^{87}\text{Rb} \rightarrow {}^{87}\text{Sr} + e^- + \bar{\nu}_e + \text{ energy}$$

$$t_{1/2} = 4.99 \times 10^{10} \text{ years}$$

- Terminology: the radioactive species (like ^{87}Rb) is called the **radionuclide**, and the species produced in the decay (like ^{87}Sr) the **daughter**.
- And species that are neither radionuclides nor daughters – that is, are not involved in a radioactive decay chain – can be used as a **reference**. ^{86}Sr often plays this role for Rb and Sr.

After 12 halflives have passed, what fraction of a sample of radioactive atoms remains, un-decayed?

A. 1/12 B. 1/256 C. 1/1024 D. 1/4096
E. None of these.

Mid-lecture Break

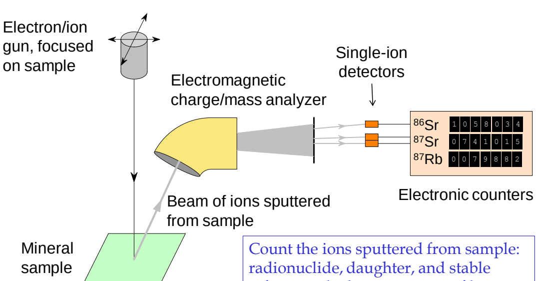
- ❑ Homework problem set #1 will appear on WeBWorK on Wednesday. We'll remind you by email.
- ❑ No recitation today, as there's no homework to discuss yet.

Top: anorthosite boulder, retrieved from the Lunar highlands by the crew of Apollo 16.
Bottom: anorthosite boulder, left behind in the Adirondack highlands, by Ronald Correia.

The use of radionuclides to find out how long ago an igneous rock was last melted

- ❑ There are many radioisotopes, with halflives spread from thousands to many billions of years, all accurately and precisely measured in the laboratory.
- ❑ We can measure the abundances of stable and radioactive isotopes "simply" by taking rocks apart into the minerals of which they are made, and in turn taking the minerals apart into atoms, counting the number for each **element** and **isotope** in a **mass spectrometer.**
- ❑ These days mass spectrometers are often built like scanning **electron microscopes**, so that an experimenter can make images of tiny mineral inclusions in rocks or meteorites, and then **selectively** dissect them and count the numbers of each element and isotope present.

Mass spectrometer analysis of mineral sample



Count the ions sputtered from sample: radionuclide, daughter, and stable reference, the last a measure of how many grams of sample were used.

(c) University of Rochester

The use of radionuclides to find out how long ago an igneous rock was last melted (continued)

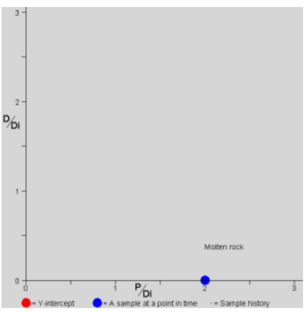
So as time goes on, n(radionuclide) decreases, and n(daughter) increases by the same amount.

- In order to compare results on different minerals and samples, though, we should rather speak of the **concentrations**: the numbers per gram of sample.
- Or, better yet, the ratios of n(radionuclide) or n(daughter) to the number of **reference** nuclei counted, since n(reference) is constant for each mineral: define

$$N = \frac{n(\text{radionuclide})}{n(\text{reference})} \quad , \quad D = \frac{n(\text{daughter})}{n(\text{reference})}$$

and, still, $$N = N_0 \times (1/2)^{t/t_{1/2}}$$

The use of radionuclides to find out how long ago an igneous rock was last melted (continued)



Simulation by [Jon Fleming.]

A simple case: two minerals

A little bit of algebra is useful at this point. You won't have to do any algebra on homework or exams, but in the interest of offering a simple proof of an important formula I'll show you some here. If you prefer a faith-based approach you may doze until the final result.

Suppose a rock solidifies at t = 0. A mineral in this rock has radionuclide and daughter number ratios N_0 and D_0 at that instant.

- Different minerals will have different values of N_0, but all will have the same value of D_0.
- We live at time t, and can measure N and D.

At later times, each mineral will obey

$$D = D_0 + (N_0 - N) = D_0 + N\left(2^{t/t_{1/2}} - 1\right) \quad .$$

A simple case: two minerals (continued)

Suppose the rock contains two minerals, A and B. Then the measurements for these minerals will be related by

$$D_A = D_0 + N_A\left(2^{t/t_{1/2}} - 1\right) \quad , \quad D_B = D_0 + N_B\left(2^{t/t_{1/2}} - 1\right) \quad .$$

We don't know t or D_0, but we know it's the **same** D_0 for both minerals. This is two equations in two unknowns. We're mostly interested in t, the time since the rock froze. Find it by subtracting the equations (eliminating D_0) and solving for t:

$$\boxed{t = \frac{t_{1/2}}{\ln 2}\ln\left(\frac{D_A - D_B}{N_A - N_B} + 1\right) \quad .}$$

You need to know how to use this formula.

A simple case: two minerals (continued)

The halflife of $^{87}\mathrm{Rb}$ is

$$t_{1/2} = 4.99 \times 10^{10} \text{ years.}$$

Samples of two different minerals from the same igneous rock from northern Ontario are analyzed in a mass spectrometer, with these results for the number ratios N and D:

Sample	$^{87}\mathrm{Rb}/^{86}\mathrm{Sr}$	$^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$
1	0.0755	0.7037
2	0.3280	0.7133

How old is the rock?

A simple case: two minerals (continued)

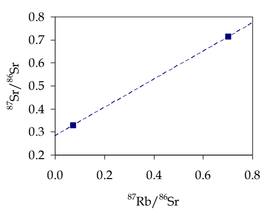
Solution:

$$t = \frac{t_{1/2}}{\ln 2}\ln\left(\frac{D_A - D_B}{N_A - N_B} + 1\right)$$

$$= \frac{4.99 \times 10^{10}\text{ year}}{0.693}$$

$$\times \ln\left(\frac{0.7133 - 0.7037}{0.328 - 0.0755} + 1\right)$$

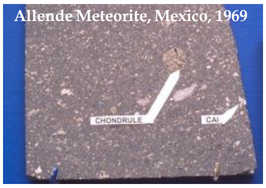
$$\boxed{= 2.7 \times 10^9 \text{ yr.}}$$



The y intercept gives the value of D that the rock had at the time it froze: $D_0 = n(^{87}\mathrm{Sr})/n(^{86}\mathrm{Sr}) = 0.2817$.

Age of the Solar system (continued)

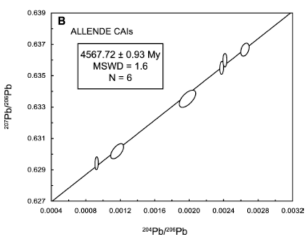
- The oldest rocks in the Solar system turn out to be meteorites. All meteorites are **nearly the same age**.
- The very oldest are the "CAI" parts of primitive meteorites called **carbonaceous chondrites:** these all solidified precisely $4.5677 \pm 0.0009 \times 10^9$ years ago.



University of Arizona/Joe Orman

- Nearly all meteorites come to us asteroids or comets, so they are members of the Solar system. Thus the Solar system has to be at least **4.5677×10^9 years old**.

Age of the Solar system (continued)



Age of the Allende (1969) meteorite, derived from U-Pb radioisotope dating (Connelly et al. 2008). U-Pb is the isotope system currently favored for use on the oldest meteorites, as Rb-Sr is for the oldest terrestrial and lunar rocks.

Maybe this is unfair to all who haven't taken AST 102: If the rest of the Universe were the same age as the Solar system, what would the Hubble constant be?
Could they all have been "created" at once?

A. 60 km sec^{-1} Mly^{-1} B. 180 km sec^{-1} Mly^{-1}
C. 4567.7 km sec^{-1} Mly^{-1} D. None of these.

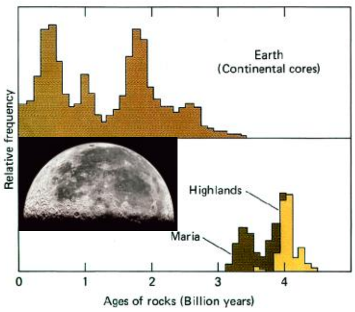
(c) University of Rochester

Age of the surfaces of Earth and Moon

Closer to home,

- The radioisotope ages of lavas are comfortingly close to the real ages of recent (e.g. Mauna Loa) and historically-attested (e.g. Vesuvius, Etna) eruptions.
- Dating of igneous rocks in Earth's crust shows the oldest rocks are about 3.8×10^9 years; none are older.
  - …though some minerals are older. Small zircons, found embedded in younger rock, are as old as the meteorites.
- Moon rocks, on the other hand, are all older than 3.2×10^9 years, and range up to nearly the age of the meteorites.

Results for Earth and Moon



- The lunar highlands (light parts) are clearly older than the maria (dark parts), as the cratering record also shows.
- So the Moon started solidifying about a billion years before the Earth did.

Figure from Jay Frogel.

Age summary

So we have these experimental facts:

- The Universe is 13.7 billion years old, give or take about 0.1 billion.
- The Milky Way Galaxy is about 12 billion years old; certainly it cannot be younger than the oldest white dwarfs it contains, which are 10 billion years old.
- The Solar system – Sun, planets, asteroids, etc. – is 4.5677 billion years old, give or take about a million years.
- The Earth's surface solidified about 3.8 billion years ago.

All of these timespans are **much** longer than the world was thought to be in Darwin's time. This has expanded dramatically the scope of the slow processes of **evolution**.