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TIME ENOUGH FOR EVOLUTION

Homework #1 on WeBWorK - due Monday at 7pm

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Measurements of the time available for life in the Universe to evolve

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

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How much time for life?

An explanation for the origin of life has to be consistent with how much time life had to become the way it looks now.

Until about a century ago, estimating the age of the Universe lay in the domain of religion or philosophy

- "Calculating" from the Bible, Bishop Ussher got the night before 23 October 4004 BC for the Creation
- In the Rig Veda, the universe is cyclically created and destroyed every 4.32 billion years ("one day of Brahma"). It was never explained why the number is 4.32 billion.
- When Albert Einstein began to work on cosmology, he approached the question of time philosophically at first. Without experimental support, he initially assumed that the Universe has no beginning or end: that is, to be infinitely old.

But now we can accurately **measure** the age of the Universe and its contents in several different ways.

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Age of the Universe from expansion

The Universe began in an explosion that we can still see today: the **Big Bang**. The explosion set the Universe's contents into expansion, which is currently described by **Hubble's Law**: $v = H_0 d$

where v and d are the relative speed and distance of two galaxies, and $H_0 = 22.5 \text{ km/s/Mly}$. (Find out more in AST 102.)

• Trace the paths back. How long ago do the galaxies' diverging paths intersect?



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Age of the Universe from expansion

Suppose that the Universe has always expanded at a constant speed – at the rate we measure today. Then, if the Big Bang happened when t = 0, two bits of matter in the explosion which we now see as galaxies spread apart according to

$$d = vt$$

$$t = \frac{d}{v} = \frac{d}{H_0 d} = \frac{1}{H_0} = \frac{1}{22.9 \text{ km s}^{-1} \text{Mly}^{-1}}$$

$$= \frac{1}{22.9 \text{ km s}^{-1} \text{Mly}^{-1}} \left(\frac{\text{km}}{10^5 \text{ cm}}\right) \left(\frac{9.46 \times 10^{23} \text{ cm}}{\text{Mly}}\right)$$

$$= 4.13 \times 10^{17} \text{ s} = 1.31 \times 10^{10} \text{ yr}$$

So it has been roughly 13.1 billion years since the Big Bang.

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Age of the Universe from expansion

2.00 Precise measurements for very 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 more accurate Universal age: $t = 1.40 \times 10^{10}$ years Measurements by Riess et al. (2007) × 0.0<u>0</u>⊮1 ____15 -10Ò 5 10 15 -5 Time from present [Gyr]

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Age of the Milky Way Galaxy

Neither the Universe nor our Milky Way Galaxy can be younger than their oldest contents.

Among the stars near enough to measure their luminosities and temperatures accurately are many white dwarfs.

- White dwarfs are very simple objects: the remains of dead stars, they have a mass similar to stars but size similar to Earth-like planets; they act much like giant molecules.
- They are hot when first formed: upwards of $T = 10^8$ K. (Normal stars are several thousand K.)
- The rate at which they cool can be calculated very precisely and simply, since they are opaque at essentially all wavelengths of light and remain the same size forever.
- White dwarf temperatures can be measured from their colors. (Only the hottest ones are white; most are red.)
- Since many white dwarfs are nearby, their distances can be measured. Combined with their apparent brightness, accurate luminosity measurements can be made.

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Age of the Milky Way

These observations show a spread of luminosity and temperature that agrees very nicely with the expected cooling rate, except that there are not 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 4×10^9 years, so in all, the Milky Way is probably about **13.5**×10⁹ yrs old. (Younger than the Universe, so no inconsistencies...)



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Age of the Solar System

Known from radioisotope dating of rocks, which tells us accurately how long it has been since a rock was last melted.

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

- Igneous rocks
 - Examples: basalt, granite, anorthosite, and the small grains within meteorites





Ordinary – chondrite meteorite (<u>J.M.</u> <u>Derochette</u>)

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Granite (geology.com)



Basalt (geology.com)

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 elements with high (> 1000 K) melting points.



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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.

Example: 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 (⁸⁵Rb or ⁸⁷Rb) nor the four of Sr (⁸⁴Sr, ⁸⁶Sr, ⁸⁷Sr, ⁸⁸Sr).



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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

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

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

As one half-life elapses, the number of radioactive nuclei drops by a factor of 2.

n and n_0 can be number of nuclei, or number per gram of sample, or number times any constant.

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After 12 half-lives have passed, what fraction of a sample of radioactive atoms remains undecayed?

Question!

- A. 1/12
- B. 1/256
- C. 1/1024
- D. 1/4096
- E. None of the above

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Radioactive trace elements in minerals

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

 87 Rb $\rightarrow ^{87}$ Sr + $e^- + v_e$ + energy

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

Terminology: the radioactive species (like 87 Rb) is called the **radionuclide**, and the species produced in the decay (like 87 Sr) is called the **daughter**.

And species which are neither radionuclides or daughters – that is, are not involved in a radioactive decay chain – can be used as a **reference**. ⁸⁶Sr often plays this role for Rb and Sr.

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Using radionuclides to determine how long ago an igneous rock was last melted

There are many radioisotopes, with half-lives 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 "simply" by taking rocks apart into the minerals of which they are made, and in turn taking the minerals apart into atoms, and counting the number for each **element** and **isotope** in a **mass spectrometer**.

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



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Aging with radionuclides

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

$$N = \frac{n(\text{radionuclide})}{n(\text{reference})} \qquad D = \frac{n(\text{daughter})}{n(\text{reference})}$$
$$N = N_0 \times (\frac{1}{2})^{t/t_{1/2}}$$

and, still,

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Evolution of isochron diagram Simulation by Jon Fleming

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A simple case: two minerals

A little bit of algebra is useful at this point. You will not have to do any algebra on the problem sets or exams, but in the interest of offering a simple proof of an important formula, I will risk showing you some here. If you prefer a faith-based approach, you may doze off 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 , respectively, at that instant.

• Different minerals will have different values of N_0 , but all will have the same value of D_0 . At later times, each mineral will obey

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

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Two minerals example

We live at time t and can measure N and D. Suppose the rock contains two minerals, A and B. Then the measurements for these minerals will be related by

$$D_A = D_0 + N_A (2^{t/t_{1/2}} - 1)$$
 $D_B = D_0 + N_B (2^{t/t_{1/2}} - 1)$

We do not know t or D_0 , but we know that it is the same D_0 for both minerals. This is two equations with two unknowns. We are mostly interested in t, the time since the rock froze. Find it by subtracting the two equations (eliminating D_0) and solving for t.

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

You need to know how to use this formula.

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Two minerals example

The half-life of 87 Rb is measured in the lab to be $t_{1/2} = 4.99 \times 10^{10}$ years

Example: Samples of two 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:

Mineral	⁸⁷ Rb/ ⁸⁶ Sr (N)	⁸⁷ Sr/ ⁸⁶ Sr (D)				
Plagioclase (B)	0.0755	0.7037				
Pyroxene (A)	0.3280	0.7133				

How old is the rock?

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Two minerals example



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What do we get when we make these measurements on rocks?

The oldest rocks turn out to be meteorites. All meteorites are **nearly the same age**.

The very oldest are the "CAI" parts of certain primitive meteorites called **carbonaceous** chondrites: these all solidified precisely $4.5677 \pm 0.0009 \times 10^9$ years ago.

Nearly all meteorites come to us from the asteroid belt or the comets, so they are members of the Solar System. Thus, the Solar System has to be at least 4.5677×10^9 years old.

There are good reasons to think that small bodies were all molten when the Solar System formed, so this is essentially the same as the Solar System's age.

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Age of the Solar System



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Ages of the surfaces of Earth and Moon

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.

Igneous rocks in Earth's crust show ages all the way from very recent to about 3.8×10^9 years; none are older.

• ...though some minerals are older. Some small zircons, found embedded in younger rock, are as old as the meteorites. Zircon has a particularly high melting point.

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.

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Age of the surfaces of Earth and Moon



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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 13.5 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.

These time spans are **much** longer than the age the world was thought to have in Darwin's time. This has expanded dramatically the scope of the slow processes of **evolution**.

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