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)
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.
  - Bishop Ussher, “calculating” from the Bible, 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”). Why it’s 4.32 billion, was not explained.
  - When Albert Einstein began to work on cosmology, he approached the question of Time philosophically at first. He initially assumed, without experimental support, for the Universe to have 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.
The Universe began in an explosion we can still see today: the **Big Bang**. The explosion set the Universe’s contents into expansion, which currently is described by **Hubble’s Law**,

\[ V = H_0 D, \]

where \( D \) and \( V \) are the distance and relative speed of two galaxies, and \( H_0 = 22.9 \text{ km sec}^{-1} \text{ Mly}^{-1} \).

(Find out more in **AST 102**.)

- Trace the paths back. How long ago do the galaxies’ diverging paths intersect?
Suppose the Universe has always expanded at 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

\[
D = Vt, \text{ or } \quad t = \frac{D}{V} = \frac{D}{H_0D} = \frac{1}{H_0} = \frac{1}{22.9 \text{ km sec}^{-1} \text{ Mly}^{-1}}
\]

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

\[
= 4.13 \times 10^{17} \text{ sec} = 1.31 \times 10^{10} \text{ years.}
\]

So it’s been roughly 13.1 billion years since the Big Bang.
Age of the Universe from expansion (continued)

- 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:

\[ t = 1.37 \times 10^{10} \text{ years}. \]

+ Measurements by Riess *et al.* (2007)
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 mass similar to stars but size similar to Earthlike planets; they act much like gigantic molecules.

- They are hot when first formed: upwards of $T = 10^8$ K. (Normal stars are merely several thousand K.)

- The rate at which they cool can be calculated very precisely and simply, as they are opaque at essentially all wavelengths of light, and remain the same size forever.
Age of the Milky Way Galaxy (continued)

- 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, and combined with their apparent brightness to yield accurate luminosity measurements.

- 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 $9.5 \times 10^9$ years. The Galaxy is thus at least this old.

- The shortest-lived stars that give rise to white dwarfs live about $4 \times 10^9$ years, so in all the Milky Way is probably about $13.5 \times 10^9$ years old. (Younger than the Universe, so no inconsistencies...)
Age of the Milky Way Galaxy (continued)

- Normal stars
- Stars within 100 light years of the Sun
- Simple white-dwarf cooling

Luminosity (Solar luminosities)

Temperature (K)

- $1 \times 10^9$ years
- $2 \times 10^9$ years
- $5 \times 10^9$ years
- $10 \times 10^9$ years
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. A longer story...

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 ([J.M. Derochette](Volcano World,U.N.Dak.))


Anorthosite ([Apollo 16](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 elements with high (> 1000 K) melting points.
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 (\(^{85}\text{Rb}\) and \(^{87}\text{Rb}\)), nor the four of Sr (\(^{84}\text{Sr},^{86}\text{Sr},^{87}\text{Sr},^{88}\text{Sr}\)).
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 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.
After 12 half-lives have passed, what fraction of a sample of radioactive atoms remains, un-decayed?

\[
\frac{n}{n_0} = \left(\frac{1}{2}\right)^{t/t_{1/2}} = \left(\frac{1}{2}\right)^{12} = \frac{1}{4096}.
\]

A. 1/12  B. 1/256  C. 1/1024  D. 1/4096  E. None of these.
Radioactive trace elements in minerals (continued)

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

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

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

- Terminology: the radioactive species (like $^{87}\text{Rb}$) is called the **radionuclide**, and the species produced in the decay (like $^{87}\text{Sr}$) 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**. $^{86}\text{Sr}$ often plays this role for Rb and Sr.
Mid-lecture Break

- Homework problem set #1 is available on WeBWorK. Due Wednesday, 16 September, 7PM.

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 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, 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

Electron/ion gun, focused on sample

Electromagnetic charge/mass analyzer

Single-ion detectors

Beam of ions sputtered from sample

Mineral sample

86Sr
87Sr
87Rb

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

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

and, still,

\[
N = N_0 \times \left(\frac{1}{2}\right)^{t/t_{1/2}}
\]
The use of radionuclides to find out how long ago an igneous rock was last melted (continued)

Minerals after aging by a fixed number of half lives

Measure slope to find age.

Different $N$: minerals have different capacities for Rb and Sr.
Same $D$: daughter and stable ref. are chemically identical.

$D = \frac{n(87\text{Rb})}{n(86\text{Sr})}$, for example

$N = \frac{n(87\text{Sr})}{n(86\text{Sr})}$, for example
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 risk showing 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 $D_0$.

At later times, each mineral will obey

$$D = D_0 + (N_0 - N) = D_0 + N \left( 2^{t/t_{1/2}} - 1 \right).$$
A simple case: two minerals (continued)

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

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

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 $t$:

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

You need to know how to use this formula.
A simple case: two minerals (continued)

The halflife of $^{87}$Rb is measured to be

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

**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 $D$:

<table>
<thead>
<tr>
<th>Mineral</th>
<th>$^{87}$Rb/$^{86}$Sr ($N$)</th>
<th>$^{87}$Sr/$^{86}$Sr ($D$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase ($B$)</td>
<td>0.0755</td>
<td>0.7037</td>
</tr>
<tr>
<td>Pyroxene ($A$)</td>
<td>0.3280</td>
<td>0.7133</td>
</tr>
</tbody>
</table>

How old is the rock?
A simple case: two minerals (continued)

Solution:

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

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

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

\[ = 2.7 \times 10^9 \text{ yr.} \]

The \( y \) intercept gives the value of \( D \) that the rock had at the time it froze:

\[ D_0 = n(^{87}\text{Sr})/n(^{86}\text{Sr}) = 0.2817. \]
Age of the Solar system (continued)

So what do we get when we make these sorts of 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±0.0009×10⁹ 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 4.5677×10⁹ 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.
Age of the oldest bits 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.

(Inset credit: Wikimedia Commons.)
Age of the surfaces of Earth and Moon

Closer to home,

- The radioisotope ages of lavas are comfortably 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 $3.8 \times 10^9$ 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 $3.2 \times 10^9$ years, and range up to nearly the age of the meteorites.
Age of the surfaces of Earth and Moon (continued)

- 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 700 million 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 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 timespans 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.