Demonstrations: none
Text: Mod. Phys. 10.A, 10.B, 10.C
Problems: 1, 2, 3 from Ch. 10

What's Important:
•density-dependence of Hubble parameter
•helium production in the early universe

Universal helium abundance

In the last two lectures we talked about two characteristics of the Universe:
i) expansion according to Hubble's Law
ii) 2.7 °K microwave radiation background.

There is another characteristic as well, which is the chemical composition of the Universe as a whole:

Sun	78% H, 22% He
massive young stars	72% H, 28% He
ionized interstellar gas [emitting]	71% H, 29% He
dilute interstellar gas [absorbing]	74% H, 26% He

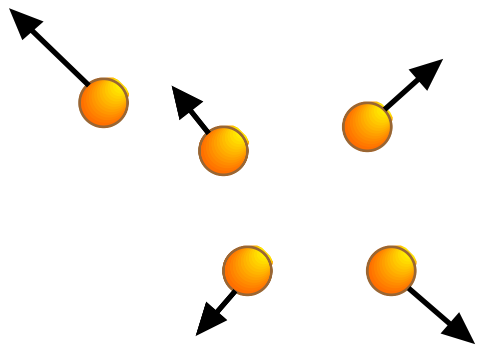
If we take into account the fact that helium has been produced in stars since the Big Bang, we find an average abundance of 75% H, 25% He.

Note: the chemical composition of the Earth is very different from that of the Universe as a whole: Earth's surface: Si, O, Al
Earth's interior: Mg, Fe, Ni...

The Expanding Universe

From Hubble's Law, we conclude that the Universe was once very dense [not "small"]. We predict that the age of the Universe is 7-14 x 10^9 years, which is largely (but not entirely) consistent with experimental data on the ages of meteorites, distant objects, etc.

As the Universe expands, its density decreases. To find how the mass density varies as a function of time, we solve the Newtonian problem of particles expanding against their mutual gravitational attraction.



We expect to find that the rate of expansion slows down as the objects move away from each other, and their gravitational attraction is weaker:

Large velocities at small time:

Small velocities at large time:

For any system acting under gravity, we can solve Newton's equations to obtain velocities and distances as a function of time, thus determining **H** as a function of time or density. If system asymptotically "stops" at infinite separation or infinite time, one finds the Hubble parameter is given by

$$\mathbf{H} = \left(\frac{8\pi \mathbf{G} \rho}{3} \right)^{1/2}$$

Note that **H** $\rightarrow$ 0 as $\rho \rightarrow 0$, as expected. In fact, the observed value of **H** today is within a factor of 3 of that predicted by this expression, using ρ as determined from visible matter. For a universe composed of photons, $\rho = \mathbf{U}_\gamma / \mathbf{c}^2$.

What about the temperature of the Universe? We know today that the Universe is filled with microwave radiation at a temperature of 2.7 °K. If the universe were more dense at early times than it is today, then the energy density $\mathbf{U}_\gamma$ had to be higher at early times as well. If $\mathbf{U}_\gamma$ increases, so does **T**: the Universe must have been hotter at early times than it is today.

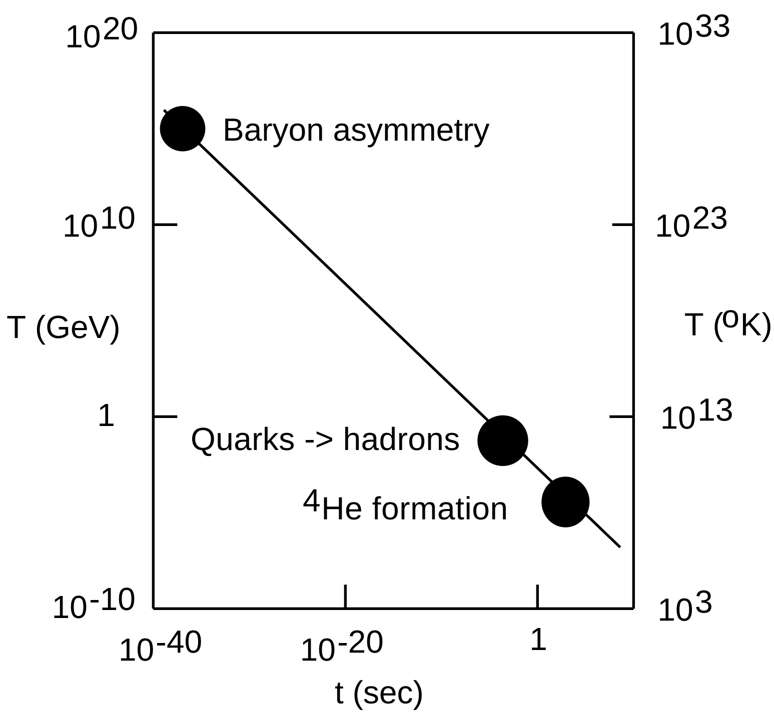
We put these observations together to form the Big Bang model, which can be tested against experimental observation:

Model: once the Universe was very hot and dense: before 10^{-6} s, **T** is > 10^{13} °K and no atoms or nuclei are bound.
Predict: **H** as a function of time (confirmed)
Predict: chemical composition of light elements (confirmed)

Scenario for the early universe

The expression for **H** can be used to obtain a temperature-time history of the early universe. The procedure is:
(i) select a temperature **T**
(ii) determine U_γ at that **T**
(iii) determine ρ corresponding to U_γ
(iv) use ρ to obtain **H**
(v) use **H** to obtain time **t** (via **t** ~ 1/**H**)

Putting in the correct prefactors in (iii) and (v), the temperature-time history of the early universe looks like:



Let's describe what's going on at some important epochs in the early Universe:

Earliest times: universe more dense than a nucleus, behaving like a hot gas of quarks, gluons, photons and leptons.

T = 10^{11} °K, time = 0.01 sec.

1. k_B**T** = 8.6 MeV, which means that all particles have so much energy that they break apart any nuclei which try to form.
2. Protons and neutrons interconvert freely by collisions with high energy electrons.

T = 10^{10} °K, time = 1 sec.

1. k_B**T** = 0.86 MeV, still no nuclei
2. Protons and neutrons fixed in number, neutrons start to decay.

T = 10^{9} °K, time = 200 sec.

1. k_B**T** = 0.086 MeV; nuclei can form, but no atoms
2. Any free neutrons around are scooped up to form ^{2}H, which then reacts to form ^{4}He. Very few nuclei heavier than ^{4}He are formed, because no stable A = 5 nuclei exist. material in planets must have a source other than the early universe.
3. Predict: Universe is 24% by weight helium.

T = 3000°K, time = 700,000 years

1. k_B**T** = 0.26 eV, cool enough so that atoms can form.

T = 2.7 °K, time = 10 billion years

1. k_B**T** = 2.3 x 10^{-4} eV, today.

Where do the elements in the Earth come from? Obviously not the H and He of the Big Bang. For most of a star's life, H is converted to He through a reactions involving the addition of nucleons to nuclei one-by-one. But when a star is very hot, helium can fuse with other nuclei to form a series of elements, each a multiple of ^{4}He:

^{8}Be (unstable) $\rightarrow$ ^{12}C $\rightarrow$ ^{16}O $\rightarrow$ ^{20}Ne $\rightarrow$ ^{24}Mg $\rightarrow$ ^{28}Si

This process can produce nuclei as heavy as ^{56}Fe, the most deeply bound nucleus. Thus, the iron and magnesium silicates that make up the Earth were produced in a first generation star, which then exploded, spewing its contents into the Milky Way.

But that's not the end of the story, because the Earth contains heavy elements such as uranium and thorium, that are produced in explosive events from a star already containing iron. Thus, the solar system is likely a third generation system, the atoms making up our bodies having been synthesized in two previous stars.