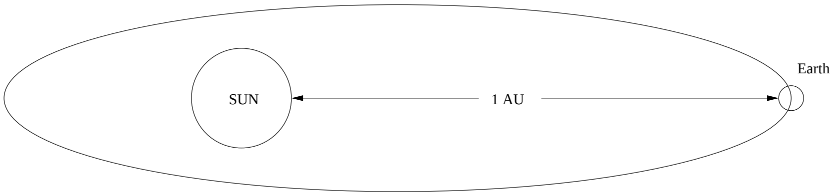
A Brief Survey of Cosmology

What does the universe look like at large distance scales?
What is the history of the universe?
What is its probable future?

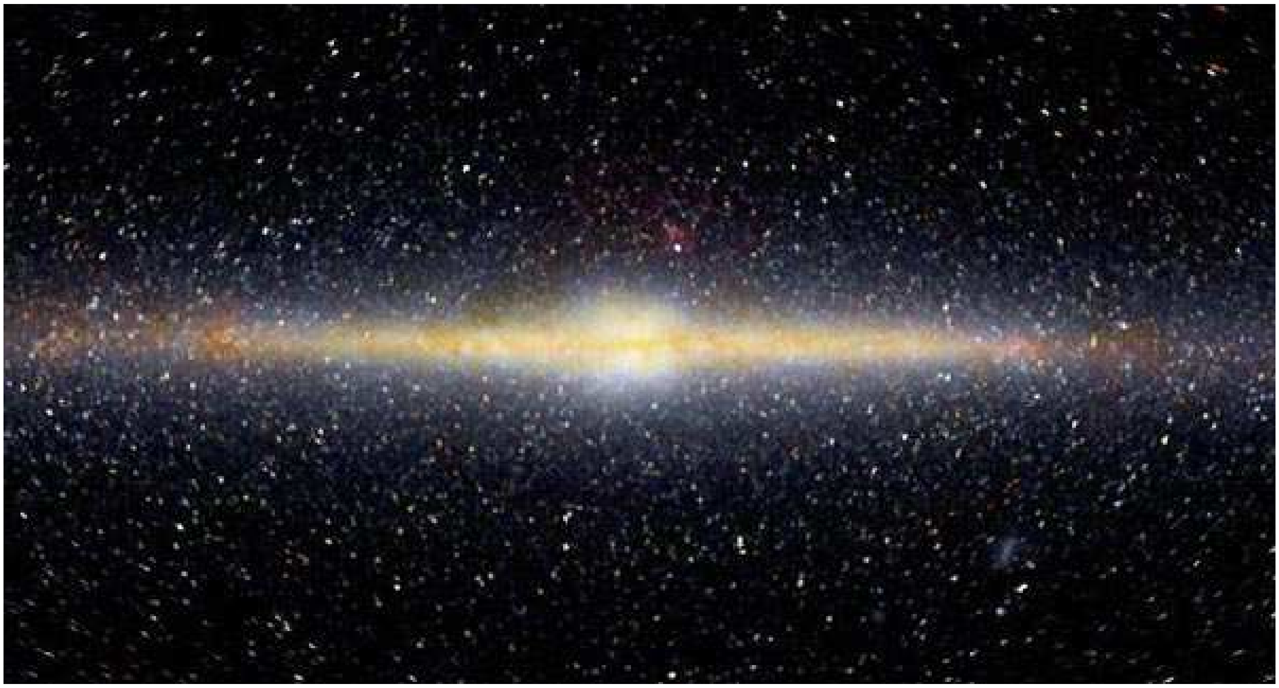
The first thing to notice is that there is lots of structure. Locally, we have the sun and planets. The earth is on average $1.5 \times 10^{11}\ m$ (=1 AU) apart from the sun:



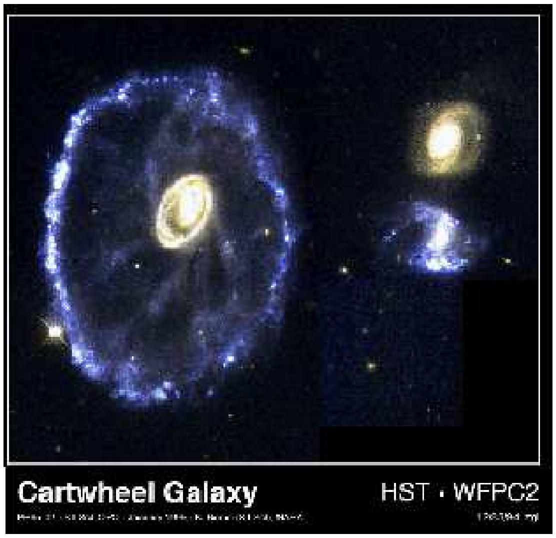
$R_{sun} = 6.96 \times 10^8\ m$ $\qquad$ $R_{earth} = 6.37 \times 10^6\ m$

$M_{sun} = 1.99 \times 10^{30}\ kg$ $\qquad$ $M_{earth} = 5.98 \times 10^{24}\ kg$

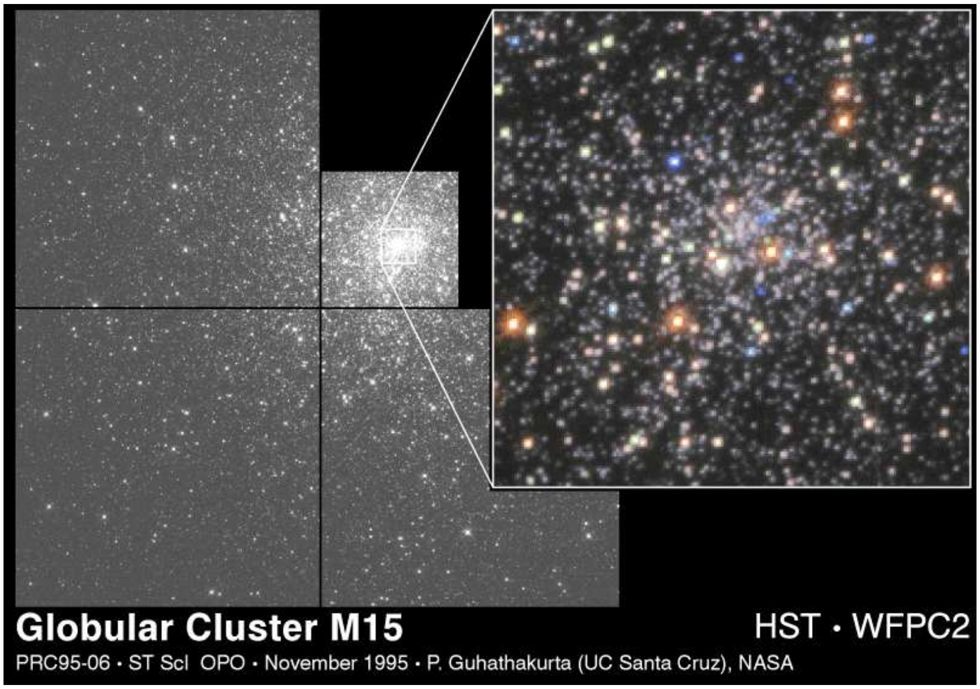
The sun is part of the Milky Way Galaxy containing about 10^{11} stars in a spiral pancake. The sun is located about $2.5 \times 10^{20}\ m$ (or 2/3) from the center of the galaxy. This is an actual view of the Milky Way Galaxy as seen by the Hubble telescope.



Galaxies come in various sizes and shapes and tend to be found in clusters. Here are two examples, one of a spiral and one of a cartwheel galaxy.



The clusters themselves are concentrated in superclusters.



Hubble (and others) discovered that galaxies are moving away from us with a speed that is proportional to their distance from us, with

$$v = H\ R,$$

where H is the Hubble parameter, and $1/H \propto$ age of universe (13.7 ± 0.2 billion years or $13.7 \times \pi \times 10^7\mathrm{s} = 4.3 \times 10^{17}$ and $H = 71$ km/s/Mpc). Remember that velocities were determined by measuring Doppler shifts of atomic spectral lines. This leads to an inescapable conclusion:

<u>The Universe is Expanding.</u>

Playing the "movie" of the universe back leads to the idea of the <u>Big Bang</u>.

Matter (and radiation) becomes ever more localized and energetic as $t \to 0$. The energy of particles can be characterized by a temperature:

$E \approx \frac{3}{2}\, kT$,

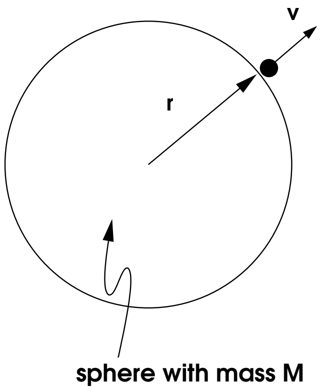
(for monoatomic gas $E_{\text{kin}} = \frac{3}{2}\, kT$, and for an ideal gas $E_{\text{pot}} = 0$, leading to $E = E_{\text{kin}} + E_{\text{pot}} = \frac{3}{2}\, kT$)

where k is the Boltzmann constant, with $k = 8.62 \times 10^{-5} eV/K$. When $E > Mc^2$, particles of mass M can be created. The Particle Physics described earlier in the semester dominated the universe during the first 1000 seconds of its existence.

A remnant of this early universe (discovered in 1964-65) is a faint glow of photon radiation left over from a time about 14 Billion years ago when the universe was "red-hot". This cosmic background radiation is everywhere (about 400 photons/cm^3) and has a temperature of 2.7 K ($\sim 300,000$ years after the Big Bang).

The expansion of the universe has "stretched" the wavelength of the "red-hot" photons by a factor of about 1000, cooling the temperature from about 3000 K to the present 2.7 K. (At $T \approx 3000\ K$, electrons and protons combined to form hydrogen, neutral matter that does not disturb the primordial photons.)

Assuming the Universe is made of matter only: Will the universe expand forever? Or will it re-collapse into another intense fire ball? The answer depends on the density of the universe. To see this, imagine a test particle with mass m at a distance r from us. (We can ignore mass outside of r.)



$$\underbrace{\frac{1}{2}mv^2}_{\text{kinetic energy}} - \underbrace{\frac{GMm}{r}}_{\text{potential energy}} = \underbrace{E}_{\text{total mechanical energy}}$$

If $E > 0$ will expand forever

If $E < 0$ will collapse

The case $E = 0$ is called "critical".

$M = \frac{4}{3}\pi r^3 \rho$.

Substituting the Hubble relation $V = H\ r$ and $M = \frac{4}{3}\pi r^3 \rho_c$, with ρ_c being the critical density, then for $E = 0$ we obtain

$$\frac{1}{2}m\,(H\ r)^2 - \frac{G\,\frac{4}{3}\pi r^3 \rho_c\, m}{r} = 0.$$

or

$$\boxed{\rho_c = \frac{3H^2}{8\pi G},}$$

with $G = 6.67 \times 10^{-11}$ m/(kg s^2) is Newton's constant.

The Hubble parameter is measured to be about $H = 71$ km/s/Mpc, giving $\rho_c \approx 10^{-29}$ g/cm^3. (This is roughly equivalent to 7 H atoms/cm^3.)

There are strong theoretical reasons to believe that

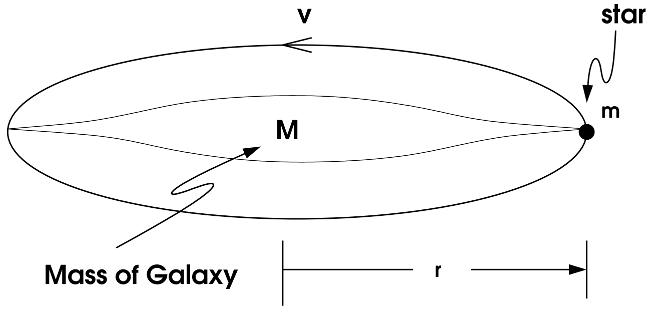
$$\Omega = \frac{\rho_{\text{of actual universe}}}{\rho_c} = 1,$$

or $\rho = \rho_c$. There is now also experimental evidence that $\Omega_{\text{tot}} = 1.02 \pm 0.2$. However, when we start counting up all the stars and galaxies we observe that the density of luminous matter averaged over the universe is only about

$$\rho_{\text{luminous}} \approx 0.005\ \rho_c.$$

Is that all there is? or is $> 99\%$ of matter in the universe invisible?

We have strong evidence for "dark matter". For example, when we measure the rotational speed of spiral galaxies using the Doppler effect, we find that the speeds are much higher than we expected from the visible (luminous) mass of the galaxy. For stars at their outer radius of a galaxy, we expect



$$ma = \tfrac{mv^2}{r} = \underbrace{\frac{GMm}{r^2}}_{\text{Force of gravity}}$$

$$\text{or } M = \tfrac{v^2\, r}{G}$$

Plugging in a (typical) observed rotational speed $v \approx 2 \times 10^5\ m/s$ gives $M \approx 5\ M_{\text{luminous}}$. So even in our galaxy, 80% of matter is invisible.

We don't know what constitutes the bulk of the dark matter, but the most likely possibilities are new (super-symmetric) particles.

We have strong evidence for "dark energy" as well. For example, Hubble discovered in 1929 that all galaxies are moving away from our galaxy with velocities that are proportional to their distance from our galaxy, with

$$v = H\ R.$$

In 1998, observations of distant supernovae indicated that this expansion of the universe is not coming to a halt but instead is accelerating. Further evidence shows that we seem to live in a flat ($E = 0$) universe, i.e.

$$\frac{1}{2}mv^2 - \frac{GMm}{r} = E = 0.$$

How are these observations related to dark energy? Imagine that the M in the above equation results from some mysterious constant energy density filling all of space,

$$M = \rho \left(\frac{4}{3} \pi r^3 \right),$$

with ρ = constant = dark energy or vacuum energy. Then:

$$\frac{1}{2} m v^2 - \frac{G\rho \left(\frac{4}{3} \pi r^3 \right) m}{r} = 0,$$

or

$$v = \frac{dr}{dt} = \sqrt{\frac{8\pi}{3} G\rho}\, r = \frac{1}{\tau}\, r,$$

where

$$\tau = \frac{1}{\sqrt{\frac{8\pi}{3} G\rho}\, r} = \text{constant with dimension of time.}$$

Rearranging, $\frac{dr}{r} = \frac{dt}{\tau}$ and integrating gives:

$$\int_{r_0}^{r} \frac{dr}{r} = \int_{0}^{t} \frac{dt}{\tau} = \ln \frac{r}{r_0} = \frac{t}{\tau},$$

or

$$r = r_0 \exp^{t/\tau} = \text{exponential expansion of the universe.}$$

Today, approximately 70% of ρ_c appears to be "dark energy". In fact, the latest data from WMAP establish the following parameters for our universe:

$73 \pm 4\%$ Dark Energy
$27 \pm 4\%$ Dark Matter
0.5% Bright Stars

Matter is made of
- 22% Cold Dark Matter
- 4.4% Baryons
- 0.3% ν's