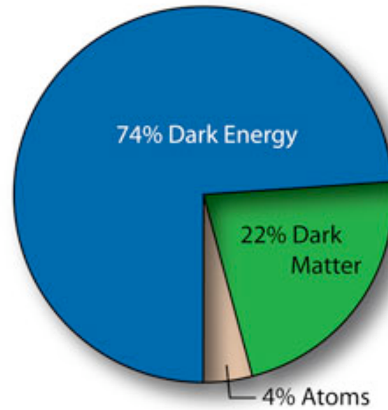
Section 40 – Matter, Dark Matter, and Dark Energy

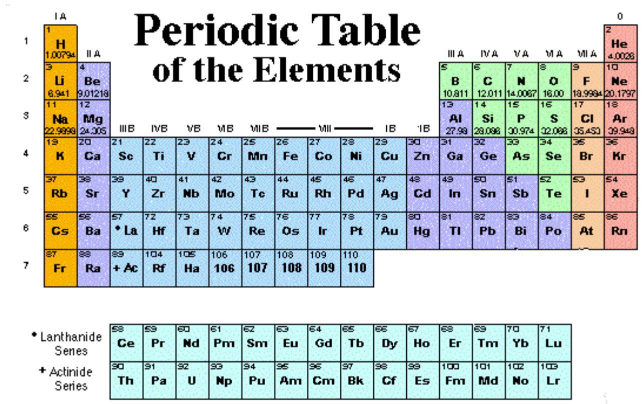
What is the universe made out of and how do the parts interact? We've learned that objects do what they do because of forces, energy, linear and angular momentum. We haven't spent much time on what the universe is made of. The answer turns out to be matter, dark matter, and dark energy in the proportions shown at the right. As we look at these things, it won't take long for us to reach the end of our knowledge. There is much more for humans to understand about matter, dark matter, and dark energy. Such is the never-ending nature of the scientific endeavor.



Section Outline

1. Matter
2. Dark Matter
3. Dark Energy

1. Matter



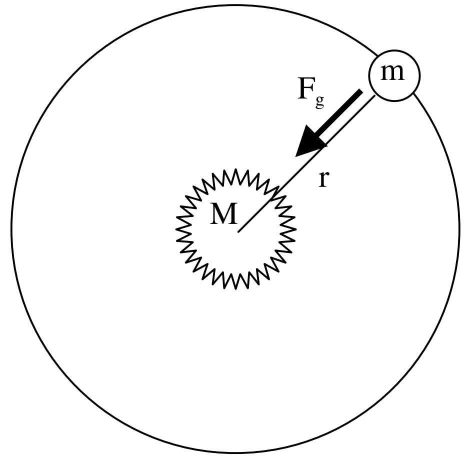
Matter refers to atoms and their internal composition. The fact that the periodic table is not just a list, but has a structure hints at the fact that atoms are composed of smaller parts. Another way to come to understand that atoms have parts is that they have a measurable size, about 10^{-10}m. Any object that has size, must have parts for it is the extent of the parts that determines the size. Think about the desk at which you study. Its size is determined by the extent of the hydrocarbon molecules that make up the wood. The size of the molecules is determined by the size of the atoms that compose it. The size of an atom is determined by the range of motion of its electrons. The size of a nucleus is established by the range of motion of its neutrons and protons. Objects that have size have parts.

That leaves us with the electron, the proton, and the neutron. Both the proton and the neutron have been measured to be about 10^{-15}m in size. Thus, they have smaller parts. These parts are called quarks. All measurements to date indicate electrons have no size. That is, they are infinitely small. This is also true of the quarks as far as we know.

Since thinking about what it might mean to have mass and no size can be rather mindboggling, let's stop this discussion of ordinary matter at this point.

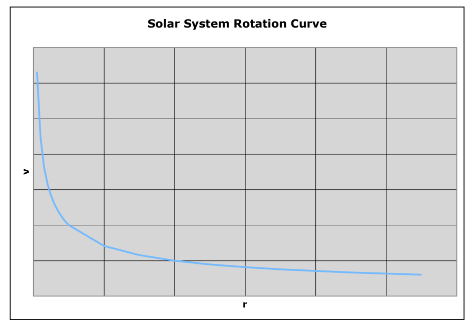
2. Dark Matter

Gravity can tell us a lot about what the universe is made of. We have seen that gravity is exerted by and gravity exerts forces on matter in a distinct way predicted by Newton's Law of Gravitation. Specifically, let's predict the velocity of planets as a function of their distance from the sun. Using the sketch at the right,



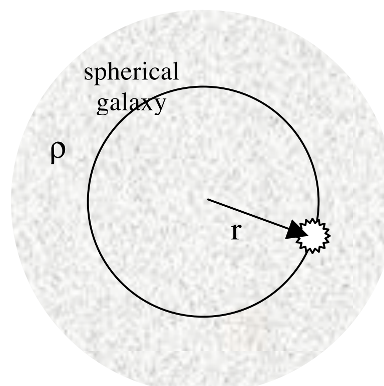
$$\Sigma\vec{F} = m\vec{a} \Rightarrow F_g = ma \Rightarrow G\tfrac{Mm}{r^2} = m\tfrac{v^2}{r} \Rightarrow v = \sqrt{\tfrac{GM}{r}}\,.$$

The graph of speed versus radius is called the rotation curve. It falls off as $r^{-0.5}$ so planets further away move more slowly in their orbits. It is shown at the right. This curve precisely agrees with the speed of planets in our solar system.



Now, let's think about stars orbiting a galaxy and, just to get started, let assume the galaxy is a spherical ball of stars as shown at the right. If we want to find the rotation curve for a star, we need to think about what mass to use for M. It turns out that the mass we need is only the mass of the stars inside the orbit of the star at which we are looking. If the galaxy has an average density of stars given by ρ, then the mass of all the stars inside an orbit of radius r can be found by multiplying the density by the volume,

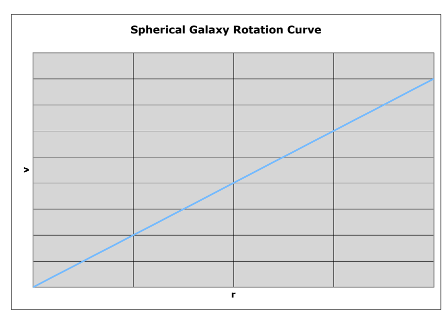
$$M = \rho(\tfrac{4}{3}\pi r^3)\,.$$



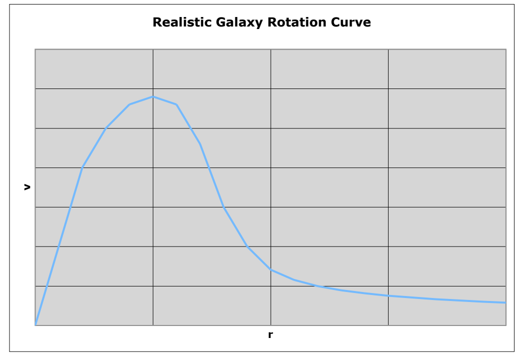
Using the expression above for the velocity as a function of the radius,

$$v = \sqrt{\frac{GM}{r}} = \sqrt{\frac{G\rho\frac{4}{3}\pi r^3}{r}} = \sqrt{\frac{4G\rho\pi r^2}{3}} \Rightarrow v = r\sqrt{\frac{4G\rho\pi}{3}}\,.$$

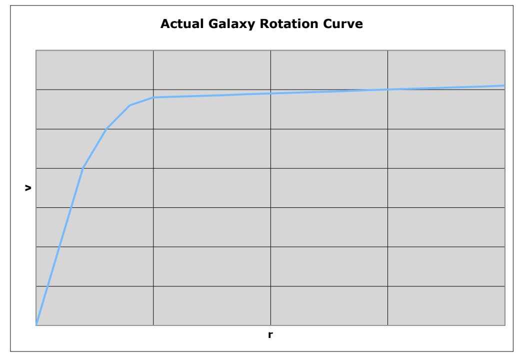
The rotation curve should be linear with stars further from the center moving faster than closer stars. The rotation curve for a spherical galaxy is shown at the right.



Galaxies aren't spherical balls of stars. They look more like a ball near the center and a thin disk near the edge as shown in this picture from the Hubble Space Telescope.



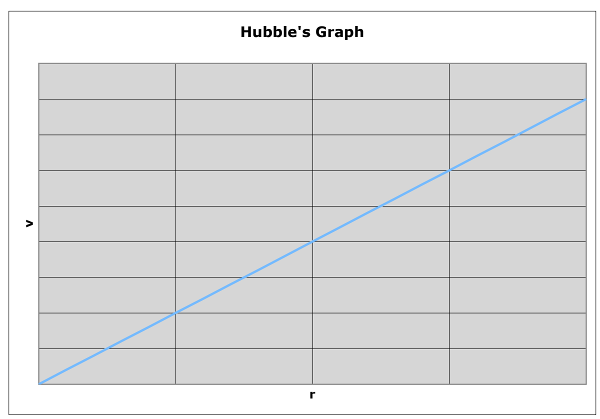
To get an idea of the rotation curve for a real galaxy we would expect the rotation curve to start off from the center as if the galaxy was a spherical ball of stars. As we get further and further out, the galaxy begins to be more like a disk, in other words, more like our solar system. The rotation curve at the right for a realistic galaxy grows linearly near the center and drops of like one over root r at large distances as shown at the right.



At the right is an actual rotation curve for a typical galaxy. You can see that there is a problem. The orbital speed of the outer stars doesn't drop off. In fact, they stay nearly constant. Our theory is clearly wrong! There are many possible reasons. For example, the Law of Universal Gravitation could be incorrect at these large distances. That possibility is not very appealing because it works so well for our solar system, our planet, as well as for other planets.

Another possibility is that there is more matter in a galaxy than we can see. This is the scenario most scientists suspect is correct. We are very sure of the amount of normal matter (neutrons, protons, and electrons) in our galaxy. So this scenario points toward a new type of matter that we cannot see. It has been given the name "dark matter." Evidence is building for the existence of dark matter. You can read about it on-line. It is exciting, even comforting in some ways, that we have recently learned of a whole new type of matter in our universe. Most scientists would hate to believe that they really know everything about the universe. They are in science for the surprises!

<u>3. Dark Energy</u>



Edwin Hubble (1889-1953) was the first scientist to produce solid evidence that the universe is expanding. He did this by measuring the speeds of distant galaxies to produce the v vs. r graph for the universe. Unlike stars in a galaxy, which orbit around the galactic center, galaxies are all moving away from each other. Hubble's graph of speed versus distance is shown at the right.

The slope of the curve is called the "Hubble Constant." Its value is about 72 kilometers per second per megaparsec, which is not too helpful. Converting,

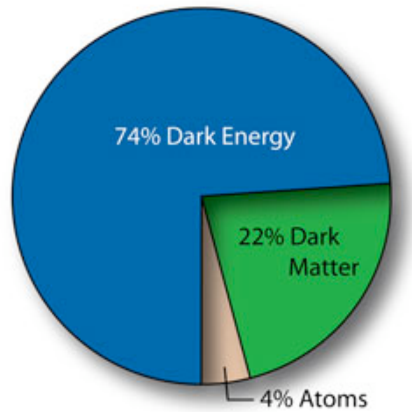
$$H_o = (72\tfrac{km}{s\cdot Mpc})(\tfrac{1Mpc}{3.086\text{x}10^{19}\,km})(\tfrac{3.17x10^7\,s}{year}) = \tfrac{1}{13.5\,Billion Years}.$$

If you can imagine all the matter in the universe beginning in a small space at the Big Bang, then the Hubble Constant can be thought of as the reciprocal of the age of the universe, 13.5 billion years.

This is all consistent with the gravitational attraction associated with the Law of Gravitation. Even though a ball may be traveling upward we know that gravity slows it down as it rises. Eventually it will reverse its motion. The same was thought to be true for the universe as a whole. Even though galaxies are all heading away from each other due to the motion originating in the Big Bang, it was thought that gravity would continually slow the motion of the galaxies. However, in the last few years, scientists have discovered that instead of slowing with time, the galaxies are actually speeding up!

There is very strong evidence from the super nova explosions of stars that show the existence of some new force that actually pushes distant galaxies apart. This force is not given a name, but instead the energy needed to create the force is called "Dark Energy." If you assume that the dark energy is uniformly distributed throughout the universe, there must be about one-billionth of a joule of energy in every cubic meter. This energy is going to be very hard to measure because we can only measure changes in energy. There are many theories as to the origin of the dark energy. As with all science, we'll have to wait for the results of many experiments to learn more.

Our goal was to learn what the universe is made of and how the parts interact. The current best understanding is that the universe is made up of matter, dark matter, and dark energy in the proportions shown at the right.



"We still do not know one thousandth of one percent of what nature has revealed to us."
- *Albert Einstein*

Section Summary

We have discussed some very new physics; the dark matter that explains the rotation curves of stars in galaxies and the dark energy that addresses the fact that galaxies are moving away from each other at ever increasing speeds. Scientists are looking to solve these riddles, but the answers they get will likely just lead to even more interesting riddles. Such is the nature of our universe.