Dark Matter and Dark Energy

Honors University Physics II Project

Kristin Kovach

Lab Section: L1

Dark Matter and Dark Energy

Dark matter and dark energy are mysterious forms of matter and energy that constitute approximately 24% and 72% of the universe, respectively (Moffat 123). Although they compose such a large portion of the universe, relatively little is known about them. In fact, both dark matter and dark energy are only known to exist because of their effects rather than direct observation. Dark matter was first theorized in the 1930s as a result of its gravitational effects on the movement of galaxies, (Tyson and Goldsmith 65). Around the same time, Albert Einstein and Edwin Hubble first touched upon the idea of dark energy as they observed that the universe was expanding due to an unknown cosmological property (Tyson and Goldsmith 81). Following the revolution of the quantum theory, the theorizing of these two cosmological entities once again rattled the fundamental ideas of the physical universe.

Dark Matter

Dark matter first revealed itself in the 1933 as Fritz Zwicky studied the motion of the galaxies in the Coma cluster. He was studying the velocity of the galaxies as they moved within the cluster and found that the galaxies were moving much faster than he originally thought. At the speeds that they were moving, these galaxies should not have been able to stay within the cluster due to the lack of visible mass in the cluster. According to Newtonian physics, these galaxies would have reached their “escape velocities” and not have been able to stay in orbit in the cluster. However, the galaxies do stay in the cluster, meaning that this cluster much be much heavier than the visible mass indicates (Moffat 70-71). From this observation, Zwicky coined the term “dark matter” to describe the invisible matter that seemed to make the Coma cluster heavy (Ferris 124).

At this point, partially due to Zwicky's radical and often wrong ideas, new ideas involving dark matter took a rest until the 1970s when Jeremiah Ostriker and James Peebles studied spiral galaxies. They found that spiral galaxies would be unstable if the central part of the galaxy, called the disk, held most of the mass of the galaxy. In fact, the galaxy would not even have maintained a perfectly spiraled shape; it would have formed bars rather than maintain the spiraled arms and have lost some of its stars and other contents. This question of the mass of outer planets of a galaxy brought the question of dark matter to a researcher named Vera Rubin (Ferris 126). Rubin studied the speeds of spiral galaxies and in doing so, stumbled upon dark matter within galaxies, not only in clusters. As Rubin and her colleagues began studying the velocities of spiral galaxies, they expected to find a Newtonian trend. That is, they expected that the center part of a spiral galaxy, the part that is most bright and thus would presumably contain the most mass, would act as a sun would in a solar system. The rest of the galaxy would revolve around this center disk and decreasing velocities as the stars and planets grow farther away from the central disk of the galaxy. However, the researchers found that the contents of the "arms" of a spiral galaxy moved at speeds equal to and sometimes partially greater than the contents near the center (Bartusiak 211-12). To resolve this quandary, Rubin and other researchers theorized that there must be "dark halos" of matter surrounding spiral galaxies, keeping the spiraled arms in shape and the contents of the galaxy in the orbit of the galaxy (Bartusiak 213). In Figure 1, the Milky Way, a spiral bar galaxy, is shown with its dark matter halo which isthe shape of a flattened beach ball.

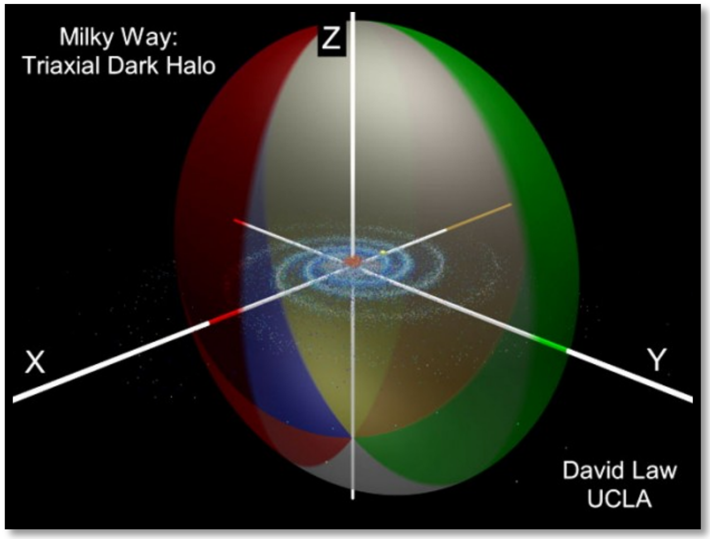

Figure 1. Spiral Galaxy with Beach-Ball Shaped Halo (Law)

Another measure of this extra mass resulted from a study of the Milky Way galaxy. From studies of the light that the Milky Way emits, this galaxy should contain the weight of 100 billion suns. To measure the actual weight, scientists can measure the velocity at which the Milky Way moves gravitationally toward another mass, the Andromeda galaxy. From this test, the Milky Way galaxy should weigh ten times greater than 100 billion suns (Bartusiak 212).

From all of these gravitational observations, scientists know what dark matter does, but have little understanding of what it actually is or of what it consists. Dark matter shares only the properties of gravity with normal matter. It does not react with light nor does it have any other properties of normal matter, and it cannot be detected in any other way than gravitationally. Dark matter tends to exist in the same places that regular matter does. Usually dark matter is found near galaxies and clusters, while there is very little dark matter found in empty space (Tyson and Goldsmith 70). It has been determined that that dark matter only has effects on galactic systems, while there is no effect on such interactions as the earth and the moon (Tyson and Goldsmith 71). Essentially, all that physicists have discovered about dark matter is that it does not interact with strong nuclear force (so it does not make nuclei), weak nuclear force, or electromagnetic force (so it "doesn't make molecules, or absorb or emit or reflect or scatter light") (Tyson and Goldsmith 76).

As dark matter grew to be a more popular theory, the importance of dark matter to the universe grew more apparent. Had dark matter not existed, it is unlikely that the universe would look like it does. Had dark matter simply been normal matter, then the amount of hydrogen fusion in the early universe would have been far greater than what it actually was. While keeping the hydrogen fusion rate correct, the non-reacting dark matter also helped to pull the universe into shape it is with its gravity (Tyson and Goldsmith 72-73). Another way that dark matter can help to understand the creation of the universe is through understanding the difference between hot and cold dark matter. Hot and cold refers to how fast or slow the particles composing the dark matter are moving. Hot, fast moving particles would mean that galaxies were formed first in the universe. Cold, slow moving particles would mean that larger structures were formed before galaxies. Currently, physicists believe that this universe is made of both hot and cold dark matter (Levine). Dark matter is also integral to the future of the universe. The more massive the universe is—meaning the more dark matter—the more likely that it will eventually collapse upon itself; while the lighter, the more likely that the universe will always expand (Levine).

While dark matter cannot be directly viewed in the galaxy, its gravitational effects can be seen with advanced telescopes. Using Hubble telescope, the bending of light due to gravitational effects can be seen. By observing this phenomenon, a 3D map of dark matter was created using the data (see Figure 2).

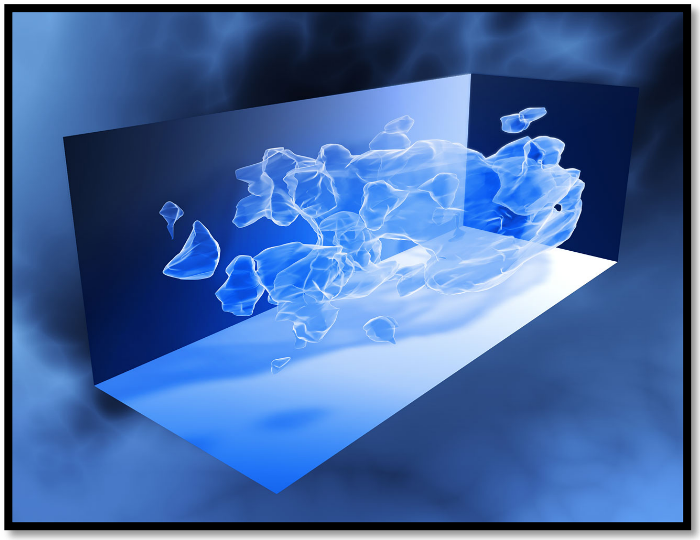

Figure 2. 3-D Map of Dark Matter (NASA/ESA and R. Massey)

From the left to the right of the image shows from closer to earth to farther away. Thus, the farther left is the more recent and the farther right is the past (NASA/ESA and R. Massey).

Some, although few, physicists believe that dark matter does not exist, and that Newtonian equations simply need to be modified to account for the strange gravitational phenomena observed in galactic clusters and galaxies. These physicists believe that there is not some unknown kind of matter, but rather that humans have an incomplete grasp upon the concept of gravity. This movement resulted in a theory known as Modified Newtonian Dynamics (MOND). However, in complicated systems, this theory fell apart and grew less popular (Tyson and Goldsmith 71-72).

Theories regarding the composition of dark matter suggest that dark matter might be composed of particles called Massive Compact Halo Objects (MACHOs), particles called Weakly Interacting Massive Particles (WIMPs), neutrinos, or neutralinos. MACHOs are halos of "baryonic objects" surrounding galaxies. Baryonic objects are simply are protons and neutrons, normal matter. The MACHOs that make up dark matter would simply be matter that is dark. If dark matter were made of MACHOs, they would most likely make up a small portion of the dark matter because too many observations of dark matter are inexplicable by normal matter, especially in larger systems (Ferris 133-134). Some MACHOs may have been found to exist in our universe, such as brown dwarfs and some planets. WIMPs are particles that only respond to weak nuclear force and gravity, meaning that they do not respond to strong nuclear force or electromagnetic force. They would also be extremely massive particles, around 100-1000 times the mass of a proton. If WIMPs turn out to exist, they would most likely make up most of what we call dark matter. In the 1930s, Wolfgang Pauli first suggested neutrinos as he studied radioactive beta decay. An attractive factor to the neutrino theory involves the fact that scientists know neutrinos exist and that they exist in a ratio of one billion for every proton and electron. Thus, if neutrinos have mass, they could account for the massiveness of dark matter. However, currently, it is unknown whether neutrinos even have mass. A neutrino might also be a type of WIMP (Levine). Neutralinos are possibly another type of WIMP. According to particle physics supersymmetry theories, a neutralino would be a neutrino's symmetric partner with opposite quantum properties. Scientists are hoping to find the neutralino with the Large Hadron Collider at CERN (Moffat 76). These particles are just some of the particles that physicists theorize may comprise dark matter. There are many possibilities that have the potential to be discovered through super-colliders, if dark matter exists at all.

Dark Energy

When Einstein was contemplating his theory of general relativity, he realized that space might not be static, but rather be expanding. Since he did not like this idea, he created the idea of a "cosmological constant" which described the amount of energy per cubic centimeter in the universe (Tyson and Goldsmith 80). As long as this value was constant, the universe was not expanding. However, a decade later, Edwin Hubble discovered that the universe was indeed expanding. As a result, Einstein's theories of cosmological constant and energy were put to rest until the late 1990s. At this point in time, scientists declared that there actually was a cosmological constant. From the research done involving the cosmological constant and expansion of the universe, the universe was found to not be curved like many thought, but rather flat. A scientist named Alan Guth explained that the universe initially went through rapid expansion after the big bang, with flat space expanding faster than the speed of light, and then slowing (Tyson and Goldsmith 81 and 84). The discovery of the entity that is dark energy resulted from the study of supernova explosions. No matter where they are, white dwarf supernovas explode with the same intensity. Thus, scientists can figure out how far away the supernovas occur based on the intensity of the explosion. While studying these supernovas, these scientists were also using the Doppler effect, which shows entities in space receding from earth in different colors based upon their different speeds, to create a better "Hubble diagram" (Tyson and Goldsmith 89).

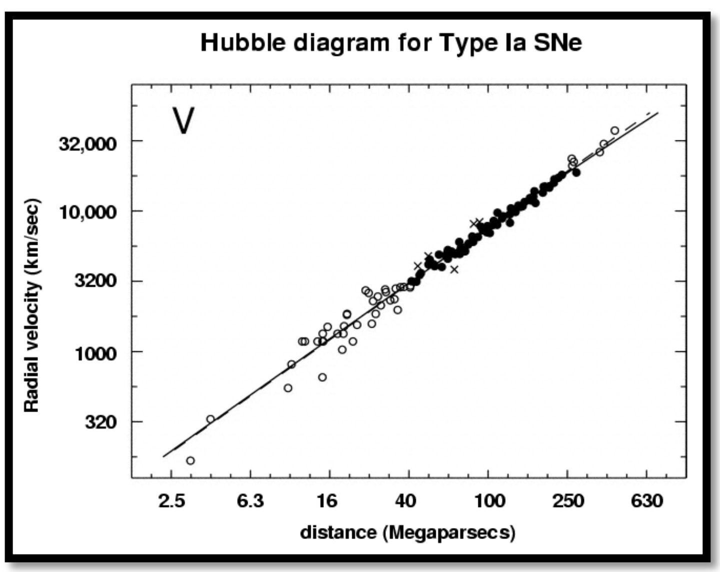

Figure 3. Example of Hubble diagram (Richmond)

All of the basic behavior of space can be described through the equation $v = H_0 \times d$, where v is the velocity of the object moving away from earth, d is the distance from earth, and H_0 is the Hubble constant. Points upon the Hubble diagram could be plotted from the observation of supernovas. It was from this Hubble diagram and supernova observations that scientists found evidence for the existence of dark matter (Tyson and Goldsmith 90). Some of the most distant supernovas were observed to be slightly farther away than they should have been. This means that they were moving faster than expected, meaning that something was making the universe expand faster than it should have been. This accelerating expansion of the universe is accredited to dark energy.

This idea of dark energy being the driving force of expansion is the same idea as Einstein's cosmological constant. Dark energy's effects upon the universe can be thought of as a "repulsive, antigravity force" which essentially pushes the universe into expanding (Moffat 122). Dark energy is equally distributed throughout the universe. If dark matter were not equally distributed, then when the universe was being formed, galaxies would not have been formed at all. This uniform distribution of dark energy is what differentiates dark energy from dark matter since energy and matter are essentially equal ($E=mc^2$) (Moffat 121). Since dark energy has always been of uniform density, this means that at some point, right after the big bang before matter began to dispurse, dark matter was denser than dark energy. When dark matter was denser than dark energy, the expansion of the universe would have been decelerating since a greater density of dark matter would constrain the expansion of the universe. As the universe continued to expand, dark matter spread out and grew less dense until eventually dark energy was more dense and the universe began to expand at an accelerating rate (Moffat 122).

Figure 4. The Expansion of the Universe ("Hubble")

Some scientists describe the nature of dark energy as being vacuum energy. While a vacuum is, by definition, nothing, according to particle physics, a vacuum is actually composed of matter and antimatter constantly being created and annihilating one another. The amount of energy resulting from this balance of creation and annihilation is a constant minimum value for energy of the vacuum. This energy of a vacuum has been proven by an experiment involving two metal plates within a vacuum. The creation of matter and antimatter between the plates causes an attractive electric field between the plates. This effect is called the Casimir effect. The vacuum energy that this creates is simply dark energy on a subatomic level. On a much larger level, the universe would also have a constant vacuum energy (Alexander 61-62). This energy of a vacuum has unique properties of having a positive density with negative pressure, thus working against gravity causing expansion (Moffat 209).

However, the idea of dark energy exists within Quantum Field Theory (QFT). QFT and the idea of gravity do not coexist. To fix this relationship, some people believe that ideas about gravity and general relativity should change. As it is, gravity in the universe should have infinite effects on subatomic levels due to dark energy, while in actuality gravity has almost no effect on subatomic particles. The only way to unite the two theories would be to somehow make gravity ignore the effects of dark energy. However, all of the changes made thus far have not held up in macroscopic calculations. Another way of dealing with the unification of QFT and gravity is string theory, the theory that different kinds of energy are made of strings of different vibrations (Alexander 63-66). While string theory corrects most of the problems of unifying QFT and gravity, it has the unfortunate side effect of having an infinite number of different values for vacuum energy solutions within many universes that come into existence at any given time within a multiverse. Within this multiverse idea, humankind just so happened to exist in the correct universe with the correct balance of dark matter, which many scientists find too improbable to believe (Tyson and Goldsmith 103-104).

Dark matter and dark energy are both unobservable elements of the universe that describe otherwise inexplicable phenomena. Dark matter is a theoretical substance that is only observed through its gravitational effects upon cosmic elements of the universe. Dark matter explains why our universe formed the way it did and describes how the universe will form in the future. Dark matter also is the reason that some stars and galaxies stay within their galaxies and galaxy clusters (Tyson and Goldsmith 65). Dark energy is a constant of the universe that causes the universe to expand at an accelerating rate. It describes the constant volume of energy that is present in the entire universe. Dark energy is a native energy that results from the energy formed within a vacuum due to quantum physics. Quantum physics states that within a vacuum, matter and antimatter are being formed and annihilating one another instantly. This formation and annihilation results in what is called vacuum energy. Dark energy is the vacuum energy of the universe. This positive density and negative pressure as well as the comparably lower amount of dark matter in the universe are what cause the universe to expand at an accelerating rate (Alexander 59-61). Dark matter and dark energy together make up over 90% of the composition of the universe, and yet they are some of the most mysterious topics of particle physicists and astrophysicists today (Moffat 123).

Bibliography

Alexander, Stephon H.S. "Just What is Dark Energy?" What's Next?: Dispatches on the Future of Science. Ed. Max Brockman. New York: Random, 2009. Print.

Bartusiak, Marcia. Through a Universe Darkly. New York: Harper, 1993. Print.

Ferris, Timothy. The Whole Shebang. New York: Simon and Schuster, 1997. Print.

"Hubble Finds Evidence For Dark Energy In The Young Universe." ScienceDailyLLC, 2009. <http://www.sciencedaily.com/releases/2006/11/061116132026.htm>. Web.

Law, David. "Milky Way Has "beach ball" Dark Matter Halo." The International Space Fellowship, 2010. <http://spacefellowship.com/news/art17783/milky-way-has-beach-ball-dark-matter-halo.html>. Web.

Levine, Barry. "Strange Stuff Explained." Stephen Hawking's Universe. Educational Broadcasting Corporation, 1997. <http://www.pbs.org/wnet/hawking/html/ home.html>. Web.

Moffat, John W. Reinventing Gravity. New York: Harper, 2008. Print.

NASA/ESA and R. Massey (California Institute of Technology). Three-dimensional distribution of dark matter in the Universe. Web. <http://www.spacetelescope.org/images/html/ heic0701b.html>. Web.

Richmond, Michael. "The Age of an Expanding Universe." Creative Commons. <http://spiff.rit.edu/classes/phys301/lectures/age/my_hubble_numbers.gif>. Web.

Tyson, Neil deGrasse and Donald Goldsmith. Origins: fourteen billion years of cosmic evolution. New York: W.W. Norton, 2004. Print.