A Brief History of Dark Matter Research

Dark Matter is theoretical matter that attempts to explain many recent astronomical observations that defy the known laws of astrophysics. Though there is strong evidence supporting the existence of dark matter, modern science has yet to discover actual proof. The existence of dark matter is inferred only from its effects on regular matter invisible since its lack of electromagnetic radiation makes invisible. Current scientific research estimates that known matter makes up only 15.5 percent of the total matter in the universe, making our current understanding of nature relatively limited [1]. Understanding dark matter would greatly increase our knowledge of the universe and allow us to begin inventing ways to harness its power.

Prior to 1930, most scientists were completely oblivious to the concept of dark matter since they assumed that the universe was expanding at a decreasing rate. This assumption is completely logical because all objects in the universe have always been attracting each other due to gravity, which is the only known force acting on these objects. According to Newton's second law, the net force of gravity causes an acceleration towards the center of the universe for anything with mass, thus slowing the outward expansion of all objects over time. Scientists remained blissfully ignorant to the true behavior of space until the advancement in telescopic technology led to observations that changed our understanding of the universe.
In 1932, Jan Oort became the first scientist to notice a discrepancy between his observations and the laws of physics while observing the orbital velocities of galaxies within clusters [2]. His calculations showed that the orbital velocities of some galaxies were only possible if the mass of the galaxy was greater than the observed mass. Although Oort's own calculations were eventually discarded due to errors, several other scientists also began to observe differences in the theoretical and actual behavior of galaxies. These observations supported the possibility that there could be more mass within galaxies than was visible, but it was equally possible that the data was not reliable due to the difficulty in recording accurate measurements at the time.

Over time, more scientists observed the behavior of galaxies to be different than predicted by the laws of physics. Many of the stars near the centers of galaxies appeared to be moving at almost the same velocity as many of the outermost stars, completely violating the viral theorem. In astrophysics as we understand it, the viral theorem dictates that the total kinetic energy of a system is equal to half the gravitational binding energy of the system. The observations showed the total kinetic energy to be much greater than half of the gravitational binding energy calculated from the visible mass. On average, the calculations based on observation indicated that the mass of the galaxy was around six times that of the visible mass [9].

It is hard to visualize the abnormality of this behavior until it is compared to something we are familiar with such as our solar system. In our solar system, the sun makes up 99% of the mass and is the main gravitational force acting on all of the
planets. The inner planets have a much higher gravitational potential energy than the outer planets because they are closer to the sun, therefore orbiting much more quickly than the outer planets due to the conservation of energy. If a planet were to speed up, its kinetic energy would become greater than its gravitational potential energy and its radial distance from the sun would increase, thus eventually propelling it out of the solar system. This is what we expect to see happen to the outer stars moving at equal velocities as inner stars within galaxies, but instead they remain at a constant orbital radius as seen in the observed line of figure 1.

![Graph](image)

Figure 1: The difference between the observed and predicted orbital velocities as the distance from the center of the galaxy increases.

As telescopic technology advanced, scientists were able to observe the universe in much greater detail, leading to the discovery of another strange phenomenon. Strong gravitational lensing, which is usually caused by super massive objects such as black holes, was observed around a few distant galaxy clusters. Most
objects in space cause weak gravitational lensing, which has very minute effects that can only be detected by thoroughly analyzing the lensing of many others nearby objects. Strong gravitational lensing causes dramatic effects on light such as the formation of multiple images, arcs, and Einstein rings [10]. The distinct effects of strong gravitational lensing in distant galaxies supported the idea of invisible mass.

Figure 2: An illustration of the effects of gravitational lensing

A gravitational lens is formed when light from a very bright source becomes distorted as it is “bent” around an object, such as a cluster of galaxies, which is illustrated in figure 2. [10]. The mass of the object can then be calculated by analyzing the distortion geometry. Since these calculations are based on Newton’s general theory of relativity instead of dynamics, they do not rely on physical observations of the object itself, but rather the gravitational effects of the object. This principle allows us to determine the masses of objects that are impossible to
observe due to the lack of electromagnetic radiation emission. The masses calculated from the general theory of relativity also indicated that the actual mass of these objects was many times greater than observed.

The unexplained behavior that scientists were observing indicated there were one or more factors missing from our astrophysical models of galactic behavior. The idea of “missing” mass within systems began to grow in popularity as advanced technology allowed for easier and more accurate data collection confirming the strange behavior. Though some scientists were highly interested in the idea of invisible matter, many scientists remained skeptical about its existence due to the complete lack of evidence. Invisible matter remained a somewhat insignificant topic in astrophysics until a discovery in 1998 ignited global interest.

In 1998, after an extensive study of a very distant supernova, scientists determined that the universe is expanding more rapidly than it was in the past as shown by the rightmost image in figure 3 [3]. The global scientific community was shocked by this discovery; the findings were impossible according to modern physics thus presenting first piece of evidence proving the existence of unknown forces in the universe. Though dark matter theory had been around since the 1930’s, the proof of unknown forces in space solidified its plausibility. This small shred of proof was enough to create a whole new field of astrophysics research, which continues to grow to this day.
Theoretical physics suggests that dark matter exists all across the universe and is responsible for much of the unexplained galactic behavior observed. There are multiple theories about the specific properties of dark matter, but they are all just different ways of explaining the idea of “invisible” mass. Theories include warm dark matter and hot dark matter, whose are thought to be composed of neutrinos and gravitinos, as well as cold dark matter which has various candidates for its composition. Although many theories about the composition of dark matter have been proposed, there is not sufficient evidence yet to determine which is correct.

The most widely accepted explanation is the idea of cold dark matter, which most believe to be made up of weakly interacting massive particles, or WIMP’s. It is also possible that massively compact halo objects (MACHO) such as black holes and neutron stars or axions may make up the composition of cold dark matter. Cold dark matter is the main focus of study within the scientific community since the results of current research indicates that the existence of WIMP’s is very possible.
WIMPs are particles that interact with the universe through gravity and the weak force but not electromagnetism or strong nuclear force [4]. The lack of electromagnetic interaction with the universe means that WIMPs do not emit any electromagnetic radiation, causing them to be invisible. WIMPs also have no effect on the structure of normal matter since they cannot interact through strong nuclear force, which is responsible for the binding of protons and neutrons within an atomic nucleus. Gravitational attraction and radioactive decay are the only interactions WIMPs share with normal matter.

The proposed characteristics of cold dark matter are very convenient for explaining its effects on the universe but these characteristics also make dark matter particles nearly impossible to detect. Scientists have had to build incredibly complex particle detectors such as cryogenic detectors and noble liquid detectors, which are the two most commonly used today. Since the billions of particles from space that bombard earth every second interfere with these experiments, dark matter detectors are built deep underground in thick steel enclosures to eliminate outside radiation.

Cryogenic detectors consist of a germanium crystal cooled to near absolute zero so the individual germanium atoms contain almost no energy and are completely still. Any germanium atom within the crystal absorbs energy during a particle interaction and begins to vibrate as it enters an excited state. Since the entire crystal is near absolute zero and also completely still, the energized atom distributes some of the energy to surrounding atoms as seen in figure 4, causing them to enter an excited state as well. This collective excited state is called a
phonon and is used to calculate the energy resulting from a particle interaction within the germanium crystal. Some of these excited atoms also experience ionization, ejecting electrons that get recorded by the detector.

The total energy deposited is measured by the ionization and phonons produced by the reaction [5]. The ratio of the ionization signal to phonon signal is different for interactions with atomic electrons, called electron recoils, than for interactions with atomic nuclei, called nuclear recoils [5]. Most detection is electron recoils caused by outside radiation, but occasionally nuclear recoil is detected, which could potentially be the result of an interaction with a dark matter particle. Unfortunately, the radioactive materials that exist in even the most contained experiments are a source of error, making it impossible to be certain that the interaction involved a WIMP.

![Figure 4: Illustration of energy deposited in the germanium crystal after an interaction with a WIMP. The black arrow indicates the path of the WIMP as it collides with the germanium atom shown in red.](image-url)
Within the last 10 years, there have been numerous experiments whose results contain possible dark matter interactions. Though the first cryogenic detectors were inaccurate, the margin of error has been quickly decreasing as the technology becomes more advanced and new methods are adopted. The Cyrogenic Dark Matter Search project at Stanford had two potential WIMP detections in 2007 with an estimated 25% chance of outside interaction, but the results were disregarded due to the low occurrence of these collisions. On September 4th 2011, researchers of the Cryogenic Rare Event Search with Superconducting Thermometers (CRESST) organization presented evidence of 67 particle interactions possibly caused by WIMPs. After analyzing all possible external sources of error, CRESST researchers determined that it was almost statistically impossible for these sources to be responsible for all 67 interactions [8].

Noble liquid detectors operate using a container of liquid xenon or argon to detect the flash of scintillation light produced by a particle passing through the liquid [5]. These detectors also measure the ionization energy from a particle collision by detecting the electrons ejected when a particle interacts with an atom in the liquid. The ratio of the scintillation to the ionization energy allows the detector to determine the type of particle involved in the reaction. There are many different noble liquid detection experiments in existence today but the results have not been very successful.

The results of particle accelerator experiments, as seen in figure 5, may eventually be able to prove the existence of dark matter since many of the collisions observed depict unexpected particle behavior. These behaviors could be a result of
weak force interaction between cold dark matter and regular matter in the form of radioactive decay or absorption. Current cold dark matter theory suggests that there are billions of WIMPs passing through earth every second, making interactions within a particle accelerator very likely. The problem is our understanding of particle physics is extremely limited therefore it is likely that the result of unexpected collision behavior has yet to be discovered. Since the cause of strange collision behavior is completely unknown, scientists cannot use these results to study dark matter until particle physics is better understood.

Figure 5: An image of sub-atomic particles scattering after a collision within a particle accelerator

Although we have yet to prove the existence of dark matter, the supporting evidence continues to grow as technology becomes more advanced. Once the existence of dark matter is proved, we will be able to begin studying its properties and behavior in great detail. Understanding dark matter will undoubtedly lead to
revolutionary technology that will change life as we know it. Though our civilization is still far from fully understanding the behavior and composition of space, proving the existence of dark matter would be a giant step towards unlocking the secrets of the universe.