The Dark Matter Mystery

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Abstract

Only 5% of the universe is made of ordinary matter such as atoms which make stars, planets, and us. The rest of the universe is dark and unknown, composed of dark matter and dark energy. Invisible dark matter makes up 27% of the universe, and we don't know its nature yet. Currently many experiments around the world are searching for dark matter and we hope that in the near future we will solve the mystery of dark matter and understand its properties.

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1. WHY DARK MATTER?

What is the universe made of? One immediate answer which comes to mind is that the universe is composed of all the matter which we can see or which interact with light. Galaxies, stars, planets, humans, and atoms are all made of electrons, protons, and neutrons. We call this "ordinary matter" which is visible. But is this the only component of the universe? We thought so for a long time until astronomers found that galaxies are rotating much faster than expect if they were made of ordinary matter only. This suggests that either the laws of gravity which describe many other processes very well should be modified or that the galaxy contains some other form of matter which we cannot see and haven't taken into account in our calculations. In this article, we focus on this latter hypothesis, that the mass of the galaxies may be much larger than what we see. Since we can measure the mass of the luminous part which consists of ordinary matter, we can also estimate the remaining mass which is invisible. This invisible mass component of the universe is called "dark matter", and it is estimated to be more than 5 times the ordinary matter in the universe. Dark matter is invisible because it does not emit or absorb light. However it exerts gravitational force on ordinary matter which we can see.

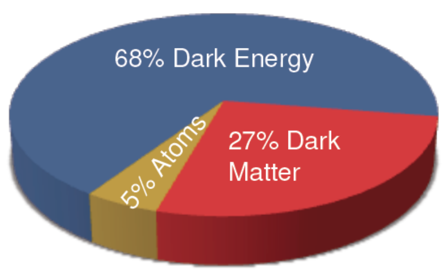

FIG. 1: Matter and energy distribution in the universe today.

Figure 1 shows the distribution of matter and energy in the universe. It is estimated that only 5% of the universe is composed of ordinary matter, and the rest is dark and invisible. 27% of the universe is composed of dark matter, and 68% is composed of a hypothetical form of energy, called "dark energy", that is responsible for the accelerated expansion of the universe. We still don't know the nature of this 95% of the universe which is dark. In this article we will discuss dark matter which makes up about 85% of the matter content of the universe.

2. A BRIEF HISTORY

The first evidences for dark matter were discovered in the 1930's. Dutch astronomer Jan Oort in 1932 studied the motion of the stars in the Milky Way galaxy and found that the stars are moving much faster than expected. In fact they were moving so fast that they should have escaped from the galaxy. So Oort came to the conclusion that there must be some unseen mass in the galaxy which is responsible for keeping the stars bound to the galaxy. In 1933 Swiss astrophysicist Fritz Zwicky (left panel of Fig. 2) reached the same

FIG. 2: Left: Swiss astrophysicist Fritz Zwicky. Right: American astronomer Vera Rubin.

conclusion when studying the galaxies in the Coma cluster. He estimated the total mass of the cluster and found that it is much larger than the visible mass. He referred to this unseen mass as *dunkle Materie* or “dark matter”.

After the first evidences for dark matter, there were many other observations indicating the presence of dark matter in the universe. But one of the strongest evidences was obtained by the American astronomer Vera Rubin (right panel of Fig. 2) in 1970. Vera Rubin in collaboration with W. K. Ford studied the rotation of the Andromeda galaxy and observed that the stars are rotating faster than expected. They studied many other spiral galaxies and reached the same conclusion that the mass of all those galaxies are larger than the visible mass.

3. EVIDENCE FOR DARK MATTER

There are many observational evidences for the existence of dark matter, although we have not detected dark matter yet. Here we summarize some of the important evidences.

One of the main evidences for dark matter comes from measuring the rotation speeds of galaxies. We can calculate the mass of a galaxy by measuring the velocities of the stars as they orbit the center of the galaxy. If the galaxies were composed of visible matter only, then most of their mass would be in their center. In this case Kepler’s Laws predict that the orbital velocities of the stars should decrease as we go to the outer edges of the galaxy, because there would be less mass there. But astronomers observe that as we go to larger distances from the center of the galaxy, the orbital velocities of the stars around the center remains constant and do not decrease even at distances where there are so few stars. This can be only explained if there is an unseen mass (or dark matter) in the galaxies well beyond the region containing most of the stars. The left panel in Fig. 3 shows a comparison between the predicted and observed orbital velocities of stars in a galaxy as a function of distance from the center of the galaxy.

The unseen hypothetical dark matter component of the galaxy makes up the “dark matter halo” which is spherical and extends beyond the galactic disc and the visible parts of the galaxy (see right panel of Fig. 3). Most of the mass of the galaxy is in the dark matter halo.

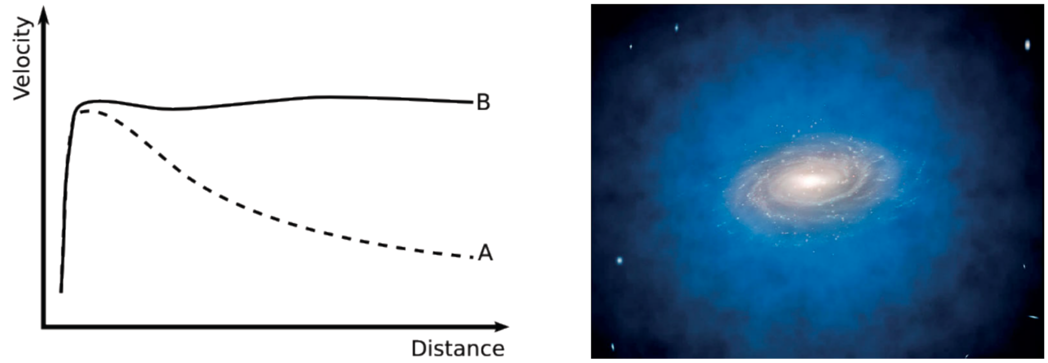

FIG. 3: Left: comparison between the predicted (A) and observed (B) rotation curves of a galaxy. If we include the dark matter component of the galaxy, our predicted rotation curve would match the observed one. Right: artist's concept of the Milky Way embedded in a spherical dark matter halo shown in blue (Image credit: ESO/L Calçada).

Another important observational evidence of dark matter comes from studying galaxy clusters. One way to estimate the mass of a galaxy cluster is through an effect called "gravitational lensing". According to Einstein's theory of relativity, a massive object like a galaxy cluster can bend the light coming towards us from a distance bright source. So the massive object acts as a "gravitational lens" by bending light. This method can be used to measure the total mass of the cluster by measuring the distortion of light. In many clusters this method has been used and it is estimated that a large fraction of the mass of the clusters is composed of dark matter. The left panel of Fig. 4 shows the Hubble Space Telescope image of galaxy cluster Abell 1689 where gravitational lensing effects can be seen from the lensing arcs in the image. The estimated dark matter distribution is shown in blue in the image.

One of the direct observational evidences for dark matter comes from the Bullet Cluster which is composed of two clusters of galaxies passing through each other. When the two galaxy clusters pass each other, their visible matter components collide and slow down. On the other hand, the dark matter components of the two clusters pass each other without interaction and slowing down. This causes a separation between the dark matter and ordinary matter components of each cluster. Right panel of Fig. 4 shows the separation of the dark matter and luminous matter in the Bullet cluster. This separation was detected by comparing X-ray images of the luminous matter taken with the Chandra X-ray Observatory with measurements of the cluster's total mass from gravitational lensing observations. In this way it was possible to find the locations of the dark matter and luminous matter in the cluster. It was discovered that two large clumps of dark matter are moving away from the center of the collision with high speeds, while the two smaller clumps of ordinary luminous matter are moving with slower speeds behind them. What is interesting is that this evidence for dark matter is independent from the details of Newtonian gravitational laws, so it can be counted as a direct evidence for dark matter.

FIG. 4: Left: Hubble Space Telescope image of the galaxy cluster Abell 1689 which is located 2.2 billion light years away. The dark matter distribution is shown in blue. Dark matter cannot be photographed, but we infer its existence from its gravitational effects. Right: Separation of dark matter (blue) from luminous matter (red) in the Bullet Cluster. Image courtesy of Chandra X-ray Observatory.

4. DARK MATTER SEARCHES

One of the preferred candidates of dark matter is a particle which interacts weakly with ordinary matter. Millions of such dark matter particles could be passing through Earth each second, but because of their weak interactions they are very hard to detect. There are three different complementary ways to detect dark matter:

Direct detection: There are many experiments deep underground searching for the effect of a dark matter particle passing through the detector. The dark matter particle can collide with an atom in the detector and produce heat or light which can be measured.

Indirect detection: Indirect detectors look for the product of dark matter annihilation or decays. For example two dark matter particles can annihilate and produce gamma rays which can be detected by space or ground-based gamma ray telescopes.

Production in laboratory: Another way to detect dark matter is to produce it in the laboratory. Experiments in the Large Hadron Collider (LHC) at CERN will look for dark matter produced after protons coming from opposite directions collide at high energies and speeds.

Direct detection is currently the most promising method to search for dark matter, and there are several direct dark matter experiments running all over the world. These detectors are built deep underground to avoid the background from cosmic rays. Cosmic rays which are constantly coming towards the Earth collide with the upper atmosphere and create a shower of particles reaching the surface of the Earth. Thus it is important to built the dark matter detectors deep underground to avoid such backgrounds.

So far four experiments (DAMA, CoGeNT, CRESST, and CDMS) which use different materials in their detectors and different detection techniques have found hints for a dark matter particle. Their hints are not completely consistent with each other, and also are in disagreement with results from several other experiments which have not found any signals.

The nature of dark matter is still unknown, but with the current level of sensitivity reached by the experiments, we are hopeful to detect dark matter soon and shed light on this dark mystery.