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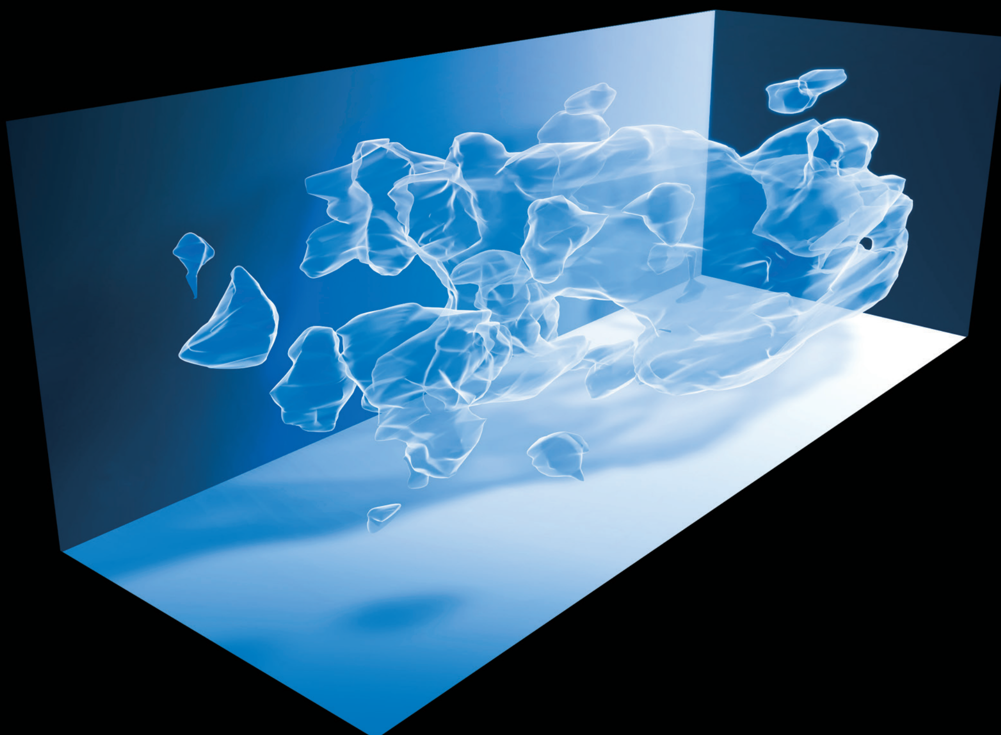

01 Perimeter Explorations

The Mystery of Dark Matter

DARK SIDE OF THE UNIVERSE:

A PRIMER ON DARK MATTER

Dark Side of the Universe:
A Primer on Dark Matter

In 1967, astronomer Vera Rubin trained her telescope on the Andromeda galaxy hoping to learn about the distribution of its stars. However, her observations ended up revealing far more. Over time, they played a key role in shattering our existing understanding of the entire physical universe. In its place emerged a new theory in which around 90% of the mass of every galaxy is made of an unseen material known as dark matter.

Vera Rubin

Andromeda's Stars

Like the stars in all other spiral galaxies, the stars in Andromeda orbit the galaxy's centre in uniform circular motion, as in Figure 1. Andromeda also contains a vast cloud of hydrogen gas, and the hydrogen orbits at the same speed as the stars in its immediate vicinity. Rubin was able to find the speeds of stars by measuring the Doppler shift of radio waves emitted by the hydrogen.

Within the Solar System, the orbital speeds of the planets decrease the farther the planet is from the Sun. Rubin expected to see the same relationship between the orbital speeds of Andromeda's outer stars and their distance from the centre of the galaxy. However, she found that the speeds of these stars were constant with distance, as in Figure 2.

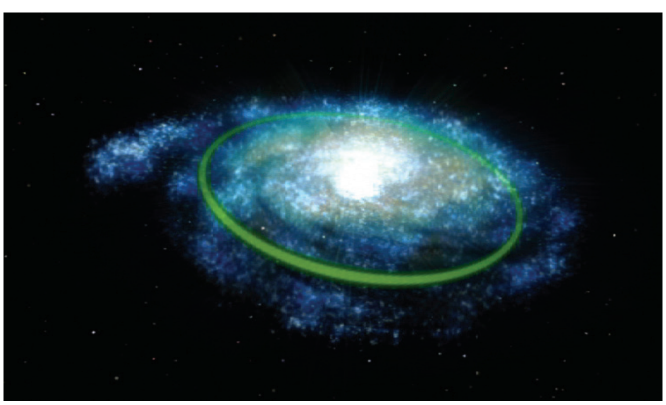

Figure 1 The stars and hydrogen gas in Andromeda orbit the centre in uniform circular motion.

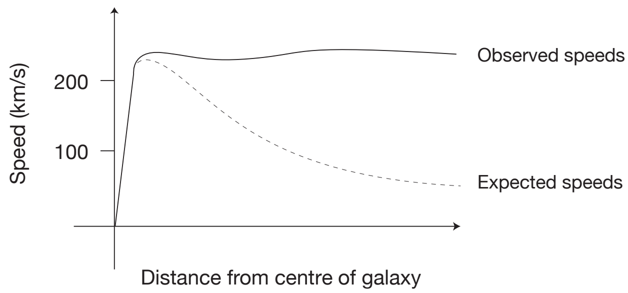

Figure 2 Expected and observed orbital speeds for stars within Andromeda

Orbital Speeds of the Planets in the Solar System

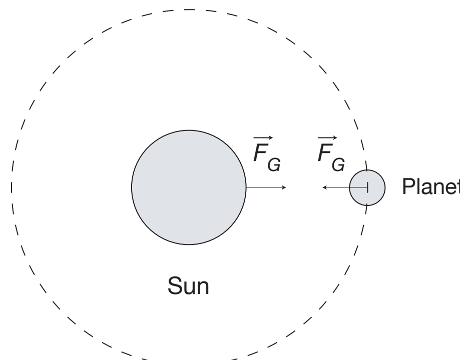

Figure 3

Consider a planet in orbit around the Sun (Figure 3). Applying Newton's second law of motion

$$\vec{F}_{\text{net}} = m\vec{a} \qquad (1)$$

to the planet, we find that the only force acting on it is the Sun's gravitational attraction. The magnitude of this force is given by

$$F_G = \frac{Gm_P M_S}{r^2} \qquad (2)$$

where G is the universal gravitational constant, m_P, is the mass of the planet, M_S is the mass of the Sun, and r is the distance between the centres of mass of the two objects.

For a planet orbiting in uniform circular motion, the magnitude of the planet's acceleration a is

$$a = \frac{v^2}{r} \qquad (3)$$

where v is the planet's orbital speed. Substituting equations 2 and 3 into equation 1, we obtain

$$\frac{Gm_P M_S}{r^2} = m_P \frac{v^2}{r} \tag{4}$$

Solving for M_S

$$M_S = \frac{v^2 r}{G} \tag{5}$$

Rearranging, we obtain

$$v = \sqrt{\frac{GM_S}{r}} \tag{6}$$

So, the orbital speed of a planet varies inversely with the square root of its orbital radius.

Measuring the Mass of a Galaxy: Orbital Method

To see how Rubin's unexpected observations led to the acceptance of dark matter, let us return to the Solar System. The mass of the Sun, M_S, is related to the orbit of any planet by the following formula:

$$M_S = \frac{v^2 r}{G} \tag{7}$$

where v is the orbital speed of the planet, r is the radius of its orbit, and G is the universal gravitational constant

(See Figure 3 for details). We can therefore calculate the Sun's mass simply by measuring the orbital speed and orbital radius of any planet.

We can also use the same principle to calculate mass within a galaxy from the orbits of its stars. If a galaxy's mass is distributed in a spherically symmetric fashion, then its mass M_{gal} contained within a radius r is

$$M_{gal} = \frac{v^2 r}{G} \tag{8}$$

where v is the orbital speed of a star at radius r. We will call this approach to measuring mass the Orbital Method. Note that it relies on the fact that the gravitational force outside any spherically symmetric distribution of mass is the same as if the mass was concentrated at the centre.

Applying the Orbital Method to the Triangulum Galaxy

Now that we have described the Orbital Method, let us apply it to the nearby galaxy Triangulum (M33), as shown in Figure 4. As in Andromeda, physicists have observed stars within this galaxy moving at higher than expected speeds. From careful observations, we know that stars within Triangulum orbiting at a radius of $r = 4.0 \times 10^{20}$ m move with a speed of $v = 123$ km/s.

Substituting v and r into equation 8, we obtain

$$\begin{aligned} M_{gal} &= \frac{(123 \times 10^3 \text{m})^2 \left(4.0 \times 10^{20} \text{m}\right)}{6.67 \times 10^{-11} \text{Nm}^2/\text{kg}^2} \\ &= 9.1 \times 10^{40} \text{kg} \end{aligned} \tag{9}$$

This mass is equal to 46 billion Suns.

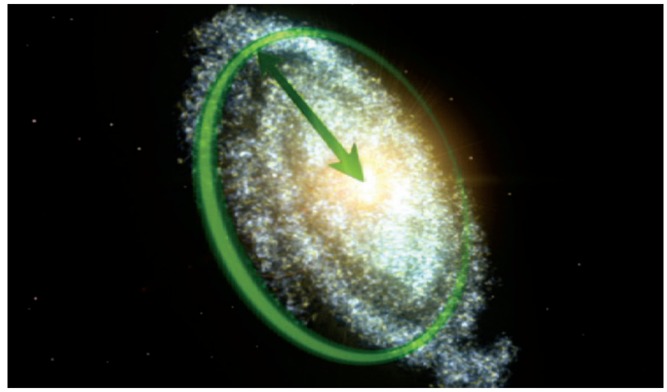

Figure 4 Orbital speed and radius for a star in the Triangulum galaxy

Measuring the Mass of a Galaxy: Brightness Method

Another way to measure the mass of a galaxy is from its brightness (or luminosity). Galaxies with more mass tend to emit more light and thus tend to be brighter. To understand the Brightness Method, it helps to realize that if all the stars within a galaxy were identical, then we could measure its mass by comparing the brightness of the galaxy to the brightness of a single star, and then finding the galaxy's mass from the following formula:

$$M^B_{gal} = \text{mass of one star}\left(\frac{\text{total brightness}}{\text{brightness of one star}}\right) \tag{10}$$

where M^B_{gal} is the galaxy's mass as calculated by the Brightness Method. However, this approach is overly simplistic because galaxies are populated by stars with widely varying brightnesses and masses. Nevertheless, we can account for this variation by using knowledge about the relative numbers of different types of stars found within galaxies.

Physicists have used the Brightness Method with Triangulum to calculate that the mass of this galaxy within a radius of 4.0×10^{20} m is equivalent to 7 billion Suns. As the Orbital Method gave a mass of 46 billion Suns, there is a discrepancy of 39 billion Suns of mass between the two methods. Similar discrepancies have been found in over 1000 galaxies

Unseen Mass

The discrepancies between the Orbital and Brightness methods imply that Triangulum and the other galaxies in which such discrepancies have been observed contain vast quantities of unseen mass that does not emit or reflect any light. This unseen mass explains the higher-than-expected orbital speeds observed in Triangulum and these other galaxies, as we can see by rearranging the galaxy mass formula (equation 8) to solve for v

$$M_{gal} = \frac{v^2 r}{G}$$

$$v = \sqrt{\frac{M_{gal} G}{r}} \tag{11}$$

In particular, the unseen mass accounts for the unexpectedly high orbital speeds Vera Rubin observed in Andromeda.

Faced with vast discrepancies in mass, many physicists are convinced that every single galaxy in the universe contains vast quantities of unseen mass. As it does not emit or reflect any light, the unseen mass is called "dark matter."

Further Evidence: Gravitational Lensing

Additional evidence for the existence of dark matter comes from Einstein's theory of general relativity. This theory predicts that large masses in outer space, such as clusters of galaxies, bend light that travels near them, an effect known as "gravitational lensing".

Gravitational Lensing distorts the images of objects lying beyond the large mass, and the distortion occurs whether or not we can see the mass causing it. In many clusters of galaxies, the amount of distortion seen is far greater than would be produced by just the visible stars and hydrogen gas. This strongly suggests the existence of vast quantities of dark matter within these clusters.

Is Dark Matter Really There?

Although the vast majority of physicists think that the evidence for dark matter is overwhelming, not everyone is convinced. A small minority of physicists think that our current theories of gravity do not apply on scales as large as a galaxy and so need to be replaced by a new theory. Some have proposed theories that, to date, can explain some (but not all) astronomical observations without assuming the existence of dark matter.

What is Dark Matter?

Initially, physicists thought dark matter was composed of relatively large known celestial objects such as planets, brown dwarfs, asteroids, and the like. Collectively, these items are known as massive astrophysical compact halo objects (MACHOs). However, physicists have searched for MACHOs using sensitive gravitational lensing experiments and the number found is not anywhere near enough to make up all of dark matter.

New Subatomic Particles

Currently, most physicists think that the bulk of dark matter is made up of vast clouds composed of a currently undiscovered particle. The two main candidates are hypothetical subatomic particles known as weakly interacting massive particles (WIMPs) and axions. WIMPs are many times heavier than axions, but both particles share the property that they do not emit or reflect electromagnetic radiation, including visible light, of any frequency.

If dark matter is made of subatomic particles then, as Earth lies within the Milky Way galaxy (which is dominated by dark matter), billions of dark matter particles are streaming down onto the surface of our planet every second. Because of this, physicists have set up a number of highly sensitive experiments to try to detect these elusive hypothetical particles. Some of the most promising experiments are taking place at SNOLAB in Sudbury, Ontario, Canada.

Conclusion

Over the last few decades, physicists have observed stars within many galaxies orbiting with speeds far higher than expected. This has led them to the conclusion that these galaxies contain vast quantities of unseen matter that does not emit or reflect any light (dark matter) and is responsible for the speeds. Currently, experiments worldwide are trying to directly detect dark matter.

If one of the experiments succeeds in doing so, then for the first time ever, we will "see" the dominant material making up our galaxy and all other galaxies. It would represent a massive leap in our understanding of the universe and Nobel Prizes would be sure to follow