What's the difference between Dark Matter and Dark Energy?

A explanation of the frontiers of modern astronomy

By Christian Kirkham

Dark energy and dark matter are two of the most productive areas of current astrophysics, within them lie the answers to some of the most fundamental questions physicists have about how the universe works. Although their names are strikingly similar, as we will learn, the relationship is only skin-deep. In order to understand this difference, we must first learn about them separately.

Dark Matter

In 1686, Isaac Newton formulated the first ever law of gravity. Using Johannes Kepler's laws of planetary motion (which were in turn found from observing how the planets moved across the sky), Newton found that between two bodies of masses m_1 and m_2 which are separated by a distance r, the force of gravity is:

$$F_g = G\frac{m_1 m_2}{r^2} \tag{1}$$

Despite being around four hundred years old, this law holds for almost all astronomical situations (see the section on Dark Energy). One such situation is calculating how quickly stars in a galaxy orbit about its centre. To calculate this, we need an area of mechanics called rotational dynamics. This tells us that for a star of mass, m_{star} , orbiting at a radius, r, and a velocity, v, from the centre of a galaxy the force required to keep it in orbit (centripetal force) is:

$$F_c = \frac{m_{\text{star}} v^2}{r} \tag{2}$$

Given that the only force acting on the star is the gravitational pull from the rest of the galaxy, we can say that:

$$F_g = F_c \tag{3}$$

In this situation, we can find that:

$$F_g = G\frac{m_{\text{galaxy}} m_{\text{star}}}{r^2} \tag{4}$$

However, m_{galaxy} depends on the position of the star within the galaxy: if the star is further out, there is more mass inside the star's orbital radius that will exert a gravitational force upon the star. Hence, if we take the galaxy to have a uniform density, ρ, (an approximation verified by observation of galaxies) we find that:

$$m_{\text{galaxy}} = \rho V = \frac{4}{3}\pi\rho r^3 \tag{5}$$

If we substitute this into equation (4) we get:

$$F_g = \frac{4}{3}\pi G\rho m_{\text{star}} r \tag{5}$$

Now, if we substitute equations (5) and (2) into equation (3) and rearranging, we can solve for the velocity of the star:

$$v = \sqrt{\frac{4}{3}\pi G} \cdot r \tag{6}$$

Or if we define a constant, k:

$$v = kr \tag{7}$$

This tells us that we should find that the orbital velocity of a star should increase linearly with its distance from the galactic centre.

However, when we observe the orbital velocities of stars in real galaxies, we find that the velocity doesn't change with the distance from the galactic centre. Instead of a steady increase, it stays constant. This is a massive problem since observations of stars and dust tells us that the density of the galaxy should be more or less constant. Evidently there must be some mass in the galaxies that astronomers cannot see. This missing mass eventually became known as dark matter.

Dark Energy

Despite working well for almost almost all situations, Newton's Law of Gravitation starts to break down for large masses or particles moving at high velocities. For example, Newtonian gravitation fails to describe the reason for the precession of the planet Mercury's orbit around the Sun. As physics became more and more advanced, it became painfully obvious that Newtonian gravitation was not the entire picture.

In 1915, Albert Einstein first published the Einstein Field Equations. These equations defined General Relativity and was the first revolutionary development in the field of gravity since Isaac Newton, three hundred years ago. Instead of treating gravity as a force, as Newton had done, general relativity treats gravity as a result of the curvature of space and time itself. Space and time (now inextricably linked in a surface known as spacetime) is curved by mass like a rubber sheet on which a cannonball lies. This curvature of spacetime gives the illusion of a force, as in Newton's theory.

One of the major fields of physics to come out of general relativity is the field of cosmology: the study of the origin of the universe. Starting with the Big Bang, one of the main aims of cosmology is to model the rate at which the universe expands over time. One of the pioneers of this area was a Russian physicist called Alexander Friedmann who developed a set of equations which describe the expansion of the universe over time. The main focus of these equations is the scale factor, a, which is an analogue for the "radius" of the universe.

One of the Friedmann equations is as follows:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) \tag{8}$$

Where ρ is the density of the universe, and p is the pressure.

However, substituting values from observation of the universe (using the Cosmic Microwave Background Radiation, CMBR) into this equation tells us that the universe should be collapsing rather than expanding. However, in 1927, Hubble had shown by observation that the universe was expanding. Evidently something was wrong.

In order to solve this problem, a new theory was invented: Dark Energy. This is an energy which is all-pervading and fills the entire universe. This dark energy acts in the opposite direction to the gravitational pull of the matter, making the universe expand rather than contract. Incorporating dark energy into equation (8) gives us:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3} \tag{9}$$

This introduces a term, Λ, which represents the density of the dark energy.

So what's the difference between the two?

While the results found for Dark Energy may feel a bit hand wavy without a proper derivation (a proper background in General Relativity is required for that), you should be able to see that dark energy and dark matter are derived from completely different phenomenon. Dark matter was discovered from the motion of stars around the cores of galaxies and dark energy from the expansion of the universe. The only similarity between the two concepts is the word "dark".

However, both dark energy and dark matter are at the forefront of modern astrophysics, with the two being some of the most studied areas of the field. While some physicists have suggested alternatives to both dark matter and dark energy, the majority of the physics world has been unperturbed and continue these exciting fields of research.