Dark Energy

Overview: Dark energy is an as-yet unexplained force that appears to be accelerating the expansion the Universe. Its unexpected and counterintuitive discovery in the late 1990s was initially met with skepticism, but further studies have independently confirmed the initial results. Unraveling the nature of dark energy will help to answer some of the most compelling questions in all of science—What makes up the universe? How does the universe work? What is the ultimate fate of the universe?

Background: In the first fraction of a second following the Big Bang, the universe grew at an exponential rate. This process, known as inflation, is an extension to the Big Bang theory, and helps explain many observations related to the structure and evolution of the Universe. Inflation theory proposes that a "vacuum energy" engorged the universe by a factor of 10^{26}.

This proposed vacuum energy at the dawn of the universe may have something in common with dark energy.

At its most basic, general relativity predicts that the universe is either expanding or contracting. At the time Albert Einstein was developing his theory of general relativity, he believed that the universe was static—neither expanding nor contracting—so he added a cosmological constant to his equations to stabilize the cosmos. After others proposed (and Edwin Hubble confirmed) that the universe was indeed expanding, Einstein regretted modifying this theory and called his cosmological constant his "greatest mistake." Even in error, however, Einstein may have glimpsed the true nature of the universe since dark energy may well be explained by a cosmological constant.

In the mid-1990s, various teams of astronomers set out to measure the expansion of the universe. The prevailing cosmic theories assumed that gravity was the predominate force in the universe, pulling on all matter and slowing down the expansion that began with the Big Bang.

This research was done by looking for a particular type of supernova, known as a Type Ia ("one-A"). These violent stellar explosions occur when matter from a companion star falling onto a white dwarf star reaches a critical mass and detonates. A white dwarf is the stellar remains of a star like the sun that has exhausted its hydrogen fuel.

Type Ia supernovae are used to study the expansion of the universe because they have an intrinsic brightness. This provides what is referred to as a "standard candle"—meaning if you know the brightness of an object (such as a standard 100 Watt light bulb), you can calculate its distance by measuring how bright it appears. The further away an object, the dimmer it will appear.

Work performed by the Supernovae Cosmology Project (headed by Saul Perlmutter) and independently by the High-Z Supernova Search Team (in a study led by Adam Riess) revealed that distant Type Ia supernovae were not behaving as theory predicted. In fact, they were much dimmer than they should have been, even taking into account intervening gas and dust in the cosmos. The implication of this startling discovery is that the universe is expanding faster now than it was in the past.

One way to explain these results is to return to Einstein's cosmological constant. In the context of modern quantum physics, the cosmological constant can be related to the vacuum of space. Rather than the vacuum having zero energy, as we would intuitively think, quantum physics tells us it has a non-zero energy that acts in a strange way, opposing gravity and causing the universe's expansion to accelerate rather than slow.

Another possible explanation for dark energy is a similar force that, rather than being constant, changes with space and time. This form of dark energy is known as "quintessence," and might well be distinguished from the constant proposed by Einstein using astronomical observations.

It is generally accepted now that dark energy dominates the universe, making up 74 percent of the total mass/energy of the cosmos, the remainder being made up by normal matter (4 percent) and dark matter (22 percent). Dark matter, though also a compelling mystery, is totally unrelated to dark energy.

As the universe expands, the density of normal matter falls, while the amount of the vacuum energy stays the same, and the vacuum energy becomes increasingly important. Cosmologists theorize that during the first 5 billion years in the history of the universe, normal matter held sway and the expansion of the universe was decelerating. As the universe continued to expand, dark energy began to dominate and the universe's expansion started to accelerate.

Studies of ever-more distant supernovae may help refine our understanding of dark energy, but scientists now believe that other measures may provide more accurate data, such as weak gravitational lensing and baryonic oscillation.

As light from distant objects travels to Earth, gravity from intervening clumps of dark matter distorts it. By studying how images of distant objects are distorted by gravitational lensing, astronomers will be able to create a 3-D model of the universe. Another possible probe of dark energy is to compare the characteristic scale of the fluctuations in the cosmic microwave background with the distribution of galaxies in the universe today (so called baryonic oscillation). Both these techniques will yield valuable information on the expansion of the universe. Questions for the next-generation of observatories include:

Is dark energy equal to the cosmological constant? Though current research is helping to confirm the existence of dark energy, scientists still need to understand exactly what it is and how the vacuum of space itself may be responsible for the accelerated expansion. Additional theories suggest that what we now see as eark energy may be the breakdown of gravity on large scales.

What is the ultimate fate of the cosmos? Current theories indicate that dark energy is the dominant force in the cosmos. If this continues, it may ultimately lead to the opposite of the Big Bang, which has been called the Big Rip, in which the fabric of space itself comes undone.