17.2: Candidates for Dark Energy

WHAT DO YOU THINK: WHAT IS DARK ENERGY?

Some students are discussing a recent news report about dark energy.

- **Wendy:** Did you hear the news on the radio this morning? It said that the Universe is made mostly of dark energy.
- **Xiang:** I thought the Universe is mostly dark matter .
- **Yan:** Aren't dark matter and dark energy the same thing?
- **Zack:** No, dark energy is the energy that comes from dark matter.
- **Addy:** Actually, I think we call it dark energy because we're in the dark about what it is.

Do you agree with any or all of these students and, if so, whom?

Wendy

Xiang

Yan

Zack

Addy

None

Explain.

Current measurements indicate that dark energy is about 70% of the matter-energy contained in the Universe. The remaining 30% is matter, including both baryonic (i.e., normal matter) and cold dark matter. The discovery of dark energy has given theorists much to think about, and they are busy creating models for what it might be. There are several forms the dark energy could take. Even now, more than two decades after it was first detected, scientists are still not certain which of the possible forms is the right one. As an indication of their ignorance in this matter, they have chosen a somewhat confusing placeholder name: dark energy. The name suggests to many people that there is a connection between dark energy and dark matter. Despite the superficial similarity in their names, this is not the case. The only thing dark energy and dark matter have in common is that we can detect the presence of each, but we are not certain of the form that either takes. Otherwise, there is no relationship between dark energy and dark matter. We will now discuss some of the possibilities for what dark energy might be.

17.2.1: COSMOLOGICAL CONSTANT

The idea that some aspect of the Universe acts repulsively, rather than attractively like gravity, is not new. It goes back almost 100 years to the beginning of general relativity. Albert Einstein himself proposed a cosmological constant to patch up what he believed was a flaw in his new theory.

At the time that Einstein proposed the general theory of relativity, in 1915, little was known about the Universe. In fact, astronomers of the time did not know whether what we now know are galaxies were inside or outside of the Milky Way, nor did they understand the processes that powered the stars. In 1915, the necessary physics was not yet understood, and the observational evidence of the immense size of the Universe was still more than a decade away.

In the absence of evidence to the contrary, most scientists believed that the Universe was infinite in space and time. There was no physical basis for this belief, it was just a bias that scientists brought to their understanding of the cosmos. Einstein was not immune to the biases of his time, so he shared the idea that the Universe must be unchanging and ageless.

This bias created a problem for Einstein. A static Universe is not compatible with general relativity. According to its equations, a Universe that started out static would collapse under the effect of the gravitational attraction of all the objects within it. Clearly, the Universe was not collapsing if (according to belief) it was steady and unchanging. So, Einstein assumed that his equations must be incomplete with the true nature of the world. To fix them, he added a term that counteracted the gravitational attraction: in essence he created a term that allowed space to hold up the galaxies so they would not all come crashing into one another.

Einstein's original description of gravity was quite simple and stated that the curvature of spacetime, $\mathbf{G}$, was related to the energy and mass present, represented by a term $\mathbf{T}$.

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$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

Do not confuse Newton's gravitational constant, the italic G on the right, with the spacetime curvature, the bold $\mathbf{G}$ on the left. Einstein's equation and the Friedmann equation, which is derived from it, describe the relationship between the expansion, mass-energy, and curvature of the Universe. To cancel the mass-energy and make $\mathbf{G}$ zero (so that the equations no longer predicted that the Universe would collapse), Einstein added a term to the right-hand side of his equation.

$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T} - \mathbf{\Lambda}$$

The extra term $\mathbf{\Lambda}$ (the Greek letter "lambda") is called the **cosmological constant**. It serves merely to cancel the mass-energy term represented by $\mathbf{T}$. So, the cosmological constant works in the opposite direction to the gravity (curvature) caused by the mass-energy term. The cosmological constant has the effect of making space expand rather than contract. We cannot go into the mathematics of this equation—the terms $\mathbf{G}$, $\mathbf{T}$, and $\mathbf{\Lambda}$ are tensors and require advanced mathematical methods to manipulate.

If we could explore the math, we would soon realize that $\mathbf{\Lambda}$ defined this way has a big problem. Although in principle it can cancel the gravity of the mass-energy in the Universe, it must be finely tuned to do so. Any small fluctuation to larger or smaller values will cause the Universe to collapse (if $\mathbf{\Lambda}$ is too small) or to expand (if $\mathbf{\Lambda}$ is too big). The problem is something like trying to balance a sharp pencil on its point: possible in principle, but try doing it and see what happens. So, a Universe as described by this modified Einstein equation is unstable, and it ends up collapsing (or expanding) after all. Collapse is what Einstein was attempting to avoid in the first place.

This problem soon fixed itself. Edwin Hubble announced in 1929 that the Universe is expanding. The problem of a static Universe became moot. Einstein quickly realized his mistake, and he is said to have referred to his introduction of the cosmological constant as his "biggest blunder." He understood that if he had been more trusting of his mathematics and less reliant on commonly held, but unfounded, notions of the nature of the Universe, he could have *predicted* the cosmic expansion more than a decade before any observational evidence for it was in hand. But general relativity is a theoretical tour d'force, and even Einstein was not willing (or perhaps not able) to make such a leap of faith where his new theory was concerned. One can hardly fault him for that.

The cosmological constant was mostly forgotten after the discovery of the cosmic expansion. The Hubble expansion did not disprove the existence of $\mathbf{\Lambda}$, it just made it unnecessary, at least for nearly a century. It has been invoked once again now that observations have shown the expansion to be speeding up. Perhaps Einstein's intuition was correct after all, even if his motivation was not sound. A cosmological constant could certainly cause a cosmic speedup like the one observed.

17.2.2: VACUUM ENERGY

In quantum mechanics, space can never be completely empty. That is because there is always a background bubbling and churning with virtual particles, popping in and out of existence. Any given virtual particle (or particle pair) will exist only as long as allowed by the uncertainty principle. Still, any small volume of space has many pairs coming and going all the time. As a result, if we measure the energy contained in that volume, we will not measure the classical value of zero. Instead, we will measure a small, but finite, energy content, even in "empty" space. This vacuum energy could contribute to the mass-energy of space, and it provides a possible physical reason for the cosmological constant.

In general relativity, any form of energy (not just matter) affects the curvature and expansion of spacetime. Imagine that we have a small container surrounding some volume in space, one end of which is a piston that can be used to expand or contract that space. We cannot actually perform this experiment because when we say "expand" or "contract" here, we mean that we are able to create more space, or shrink it, with our piston. We do not merely change the interior volume of the container in existing space—an important distinction.

If we use the piston handle, as in Figure 17.3, to expand our space, we will feel resistance. The resistance is directly related to the notion that the energy of the vacuum is non-zero; we must provide the energy needed to create any additional empty space. We feel that effort as a force that resists our expansion efforts. In other words, we feel that the vacuum has a negative pressure.

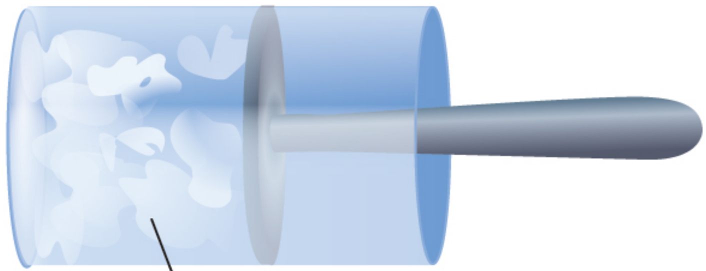

Figure 17.3 If we imagine a piston that can be used to expand or contract space, then we know that in creating additional vacuum, we create additional vacuum energy. Such a piston would resist our attempts to expand it because it would require that we furnish the additional energy in the vacuum we create. Credit: NASA/SSU/Aurore Simonnet

Pressure is different in one fundamental aspect from gravity: it can be attractive or repulsive. We generally think of pressure as being capable of imposing a push, but not a pull. That is not true for all materials. In our familiar world, gases do not produce negative pressures (tensions), but solids (like springs) can.

The existence of the negative vacuum pressure has extremely interesting gravitational ramifications. If we put the pressure into the Einstein equations, it will affect the curvature of space. Since the pressure of the vacuum is negative, not positive as in a gas, the gravity of the vacuum pressure has the opposite effect on the curvature that a gas pressure would have: it is repulsive. That means empty space tends to repel other empty space and the matter within it. This is the type of action we described earlier for the dark energy. Only general relativity provides a means to understand this kind of action. It is a completely non-Newtonian effect, and there are no Newtonian approximations or analogies we can use to help us make sense of it.

17.2.3: QUINTESSENCE

The presence of a cosmological constant or a vacuum energy is not the only possible explanation for an accelerating expansion. An accelerating expansion, known as inflation, is thought to have occurred early in the first fraction of a second of the Universe's existence. Though the inflationary period lasted for only an instant, something like 10^{-32} seconds, it expanded the scale factor of the Universe by at least 20 orders of magnitude. The current acceleration is clearly much less dramatic. It has been going on for billions of years and has had only a barely discernible effect. But could the acceleration we see now be in some way similar to the earlier inflationary event? Some cosmologists think so.

Rather than posit the existence of a constant vacuum energy that exists everywhere in space for the entire history of the Universe, an alternative is to suggest that the Universe contains an energy field, similar to the one that caused inflation. However, rather than decaying in 10^{-32} seconds, the current acceleration is caused by a field with a much slower rate of decay, one that is taking billions of years to evolve. Just as with inflation, the field is currently decaying from a quasi-stable state of false vacuum to its ground state. As it does so it mimics a cosmological constant, except it is changing in strength. To distinguish this decaying field model for the acceleration from the cosmological constant model, it is given its own name: **quintessence**.

Quintessence models are attractive for several reasons. First, the field is changing over time and we might be able to discern this change if we look at higher redshift parts of the Universe. The cosmological constant does not change in time, so its effects should not depend on redshift at all, but quintessence would. Quintessence is also more physically motivated than a cosmological constant, which is literally just a constant number added to the equations of relativity. An aspect of quintessence that makes it more attractive than vacuum energy has to do with a disturbing inconsistency. Quantum theory can be used to compute how big we expect the vacuum energy to be, but when those computations are done we find to our great surprise and embarrassment that the calculations disagree with the measured value by 120 orders of magnitude, or in other words, by a factor of 10^{120}. Quintessence models alleviate some of this problem, but we are going to need to learn a lot more about the Universe, on both its largest and smallest scales, before we solve this puzzle.

17.2.4: OTHER IDEAS

The leading ideas for understanding the apparent acceleration of cosmic expansion are the cosmological constant (perhaps in the form of vacuum energy) and quintessence. However, some other explanations of an even more exotic nature have also been put forth.

One idea is the existence of energy fields, distinct from the quintessence idea, that couple to other fields. These so-called chameleon particles might interact with the recently discovered Higgs field (or other fields) in a manner that would create an effect similar to the cosmological constant.

Another idea is that on large scales, general relativity is not a correct description of gravity and the apparent acceleration is an artifact of using an incorrect theory of gravity that produces the wrong redshift—distance relation for supernovae. However, a self-consistent theory of modified gravity has proven elusive so far.

Some cosmologists do not accept the notion of accelerating expansion at all. Instead, they suggest, the entire idea is due to an illusion caused by the fact that we reside in a region of the Universe with slightly lower than typical density, a condition that could mimic the effects of acceleration on the supernova data that provided the primary evidence of the acceleration in the first place.

Even interactions of our Universe with speculative higher dimensions in which it might be embedded have been suggested as the origin of the acceleration.

Which of these ideas, if any, is the correct one? We still do not know. For this reason, most scientists refer to whatever is causing the apparent acceleration of the expansion as dark energy. Only further observational and theoretical studies, and probably some new physics, are likely to lead to an eventual understanding of the cause and nature of dark energy.

GOING FURTHER 17.1: PARAMETERIZING DARK ENERGY

For the various models of dark energy, there is a mathematical relationship between the pressure (P) and density (ρ) called the equation of state, which has the form below.

$$\rho = Pwc^2$$

As usual, c is the speed of light. The parameter w is a different number for each type of dark energy model. From the equations of general relativity, we can find a relationship between the overall density (ρ), the scale factor (S), and w:

$$\rho \sim S^{-3(1+w)}$$

In terms of redshift (z), this can be written:

$$\rho \sim (1+z)^{3(1+w)}$$

For the case of constant dark energy (such as a vacuum energy) we would have $w=-1$, but other values of w are possible for different hypothetical forms of dark energy. For example, w could be larger or smaller than -1. Those cases lead to radically different evolutionary paths for the Universe. It is not even known if w remains constant in time. There is no reason that it should do so, but making the assumption of a constant w leads to simpler models. Lacking any compelling observational reason to adopt a more complex scenario, cosmologists usually assume that w is constant. We will do the same. In the future, if observational evidence warrants, it might be necessary to abandon this assumption. Table B.15.1 shows the equation of state and density as a function of scale factor or redshift for various substances.

TABLE B.17.1 EQUATION OF STATE FOR VARIOUS SUBSTANCES

Substance	w	Density and Pressure	Density and scale factor	Density and redshift
Cosmological constant (vacuum energy)	-1	P ~ -ρ	ρ = constant	ρ = constant
Matter	0	P ~ 0	$\rho \sim 1/S^3$	$\rho \sim (1+z)^3$
Radiation	+1/3	P ~ ρ/3	$\rho \sim 1/S^4$	$\rho \sim (1+z)^4$
Quintessence	-2/3	P ~ -2ρ/3	ρ ~ 1/S	ρ ~ (1+z)

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