Physics for the 21st Century

Unit 11: Dark Energy

Robert Kirshner and David Spergel

In 1998, astrophysicists made a shocking discovery. They uncovered an anti-gravity-like force controlling the fate of our universe. Cosmologists are still struggling to understand this force they call dark energy.

> ROBERT KIRSHNER: *This is really the biggest mystery in all of physics that turns out to be 3/4 of the stuff in the universe and we don't know what it is.*

Robert Kirshner, at the Harvard-Smithsonian Center for Astrophysics, is investigating what this dark energy may be. He studies distant supernovae to gain a better understanding of how this force has shaped our universe over time. At Princeton University, David Spergel is looking back even further in time, into remnants of light emitted only 300,000 years after the Big Bang, searching for clues about dark energy.

> DAVID SPERGEL: *Whatever it is, it's something completely different from anything else we've ever encountered.*

Through examining these different lines of evidence for dark energy, both scientists hope to understand how our universe has evolved and what its ultimate fate may be.

Part I: Evidence for an Accelerating Universe

Robert Kirshner

Robert Kirshner and his team at the Harvard-Smithsonian Center for Astrophysics hope to get a better understanding of how dark energy has shaped our universe.

> ROBERT KIRSHNER: *Well, we're trying to find out what the universe is made of. And the way we're doing it is by looking at the history of cosmic expansion.*

In the early 20th century, the universe was thought to be static. Astronomers did not know of anything beyond our Milky Way Galaxy. But in the 1920s, astronomer Edwin Hubble showed through his observations that there were other galaxies outside our own. And he profoundly altered our understanding of the cosmos when his research led him to the

conclusion that our universe was expanding. By charting velocities of galaxies with his own observations of their distances from the Milky Way, he found that galaxies were receding from us with speeds proportional to their distances. The further away a galaxy, the faster it was traveling away from us. We call this Hubble's law.

Cosmologists concluded that our universe had been expanding since the Big Bang, 13.7 billion years ago. They hypothesized that the expansion would slow over time due to gravity.

> RK: *What we used to say was that there was the Big Bang, and expansion in all directions, in all parts of the universe, but with gravity trying to slow it down. Stars pull on each other; the galaxies pull on each other. And in the whole universe, all of that stuff is pulling on each other, trying to help it slow down.*

In the 1990s, Robert Kirshner was a member of one of two teams, who set out to determine how much the expansion of our universe had slowed down over time. To test this hypothesis, they needed to collect data to create a more complete Hubble plot.

But instead of galaxies, Kirshner's team turned to a rare, but well-studied exploding star called a Type 1a supernova. These supernovae have an inherent brightness, which gives astrophysicists a powerful tool for measuring cosmic distances.

> RK: *There's a certain kind of supernova, which we can recognize, that seems to have fairly nearly the same brightness. They're not all exactly the same, and we have to make other measurements that allow us to tell which are a little bit brighter, and which are a little bit dimmer, but those are details. If they were all the same brightness intrinsically, then you could tell how far away they are, or were, from how bright they appear.*
>
> *Doing it really accurately, though, is not so simple.*
>
> *And so you have to recognize which ones are a little bit brighter, and which ones are a little dimmer. It turns out you do that from the shape of their light curve, the time it takes to get bright and dim. And you need to make corrections for dust along the line of sight, because we're trying to judge the distance of things by their brightness. If there's something else that's affecting how bright they look, then we could make a mistake.*

In addition to calculating the distance of a supernova, the team must determine its redshift, which is a measure of how much the universe expanded as the light traveled from the supernova to our telescope.

If the universe is expanding, the wavelength of light from the supernova is stretched out and appears more red. If the universe were contracting, the wavelength of light would be compressed and the light would appear more blue.

When Kirshner's team looks at the spectrum of a supernova, they can measure this change in wavelength.

There are characteristic patterns of absorption lines in a star's spectrum due to the elements present in that star. When the spectral lines shift towards the red end of the spectrum, we infer that the wavelength has stretched. This is called a redshift. Measuring a supernova's redshift determines how much the universe has expanded since it exploded. The bigger the shift, the greater the cumulative expansion since the light left the supernova.

> RK: *We've also measured the redshift, the expansion of the universe that's taking place at the site where the supernova exploded. This allows us to construct the history of cosmic expansion. That is, how fast the universe was expanding at each time. We can find out whether it's slowing down or speeding up.*

To get a more accurate picture of the expansion history of the universe, it is important to look at supernovae at a range of distances. Finding distant supernovae proved to be a challenge for Kirshner's group.

> RK: *To find them you need to take a big chunk of the sky. Make a very, very deep image that lets you see very distant objects. These are digital images. So you put all of that into a computer. You come back the next month and subtract one picture from the other. The idea is that anything that's new in the second picture will be left over. Anything that stayed the same will just get subtracted away. Well, it's easier to say than to do, like a lot of these things. And getting the computer to do the right thing to the data is something that people on our team work very, very hard to make so that it worked well.*

Finally, in 1998, Kirshner and his team finished analyzing their data...and were confounded by the results.

> RK: *So we set out to find out how much the galaxies had slowed down over time. And, of course, to our surprise we found that they hadn't slowed down, but instead were speeding up!*

Both Kirshner's team and their rivals found the same result and combined their data into one updated Hubble plot with redshift along the x-axis and distance on the y-axis.

> *RK: And you can see that nearby and at small velocities, everything lies along this line, which is just what you'd expect in a universe that is expanding. But, what you see out here, if you ignore the points but just look at the lines for a second, these are meant to represent different universes that have acceleration or don't, or a universe that might be slowing down due to gravity. And you can see that as you go farther away, those lines begin to separate a little tiny bit.*

To get a better picture of this separation, the group created another plot.

> RK: *What we've done here in the next panel is to subtract out that 45 degree line and just show you the difference from the ordinary expansion to show you whether things are speeding up or slowing down. If the universe were slowing down, decelerating, the points would lie along this line as you got farther and farther away. If the universe were slowing down just a little bit due to the matter that we know is present, that would lie along this horizontal line. And while the points are pretty messy, you can see that the data lie above this horizontal line, and because they do that means that the supernovae are a little fainter than you would otherwise expect. It means the light has had to travel a longer distance than you would otherwise expect. It means that the universe is accelerating.*

At higher redshifts, the supernovae are further away than predicted. The teams determined that the universe is expanding faster than predicted – that it is in fact, speeding up.

Discovery of an accelerating universe has changed our understanding of the cosmos. To account for this finding, astrophysicists now hypothesize the existence of an inexplicable repulsive force.

> RK: *We don't really know what it is, but we have a name for it, and we call it "the dark energy." It's very surprising, just like it would be surprising to throw a ball up, and see it fly up into the sky, to see this other thing, this sort of antigravity-like quality that the dark energy has.*

Currently, Kirshner is trying to unlock the mystery of dark energy. Surprisingly, one hypothesis that may help describe dark energy is found in a discarded idea of Albert Einstein's.

Einstein's theory of general relativity had predicted that the universe would either be expanding or contracting. But at the time, in 1917, the universe was thought to be static, so Einstein had to adjust his equations to agree with this observation. He added an anti-gravity force to his equations, denoted as lambda, called the "cosmological constant."

> RK: *What Einstein found was that he could make up a theory, which had gravity pulling in, and some other thing, which he called the cosmological term, pushing back out to make a static universe, something that would not change over time.*

A decade later, when Hubble concluded that the universe was not static, but was expanding, Einstein gave up on his cosmological constant, calling it the greatest blunder of his life. But, the supernovae results imply that there is an anti-gravity force, which may be similar to Einstein's cosmological constant.

> RK: *So far what we find is the thing that's powering this cosmic expansion could be the cosmological constant. So what we ought to do is find out whether there's any departure, no matter how small, from the predictions of the cosmological constant.*

Kirshner and his team continue to gather data to get a clearer picture of the history of cosmic expansion and to determine if the dark energy is in fact the cosmological constant.

> RK: *This is a Hubble diagram for supernovae from 2009. The things that you notice compared to the previous diagram is first of all there are a lot more points. Secondly, the scatter in them is actually smaller, and the diagram is better populated. We've gone from a few dozen supernovae at low redshift to a few hundred and from a few dozen supernovae at high redshift to a few hundred. And we've been able to pin down with better precision the fact that the universe is accelerating. And we're beginning to be able to answer the question: What is the dark energy? Is it the cosmological constant or is it something else?*
>
> *So far we can say that the dark energy can't be more than 10 percent different from the cosmological constant. But, of course, it could be 2 percent, or 1 percent, or some other number. So, it seems like we ought to try to do better.*

To obtain more accurate results, over the next several years, the team hopes to gather bigger supernova samples with better sky surveys and more precise measurements.

> RK: *Well we can see what to do next. We have Pan-STARRS, which is this searching for objects, searching for changing objects program that's underway in Hawaii. And we're going to find a lot of supernova. We're going to make a much better measurement than we've done so far. We're learning to make observations in the infrared and that means we're getting away from the optical where dust can affect us and maybe give us slightly misleading or anyway inaccurate results. So we're learning how to use that to make more precise measurements. And we have this idea of getting above the earth's atmosphere, building a satellite, making a beautiful sample of extremely well calibrated measurements with the JDEM, the joint dark energy mission satellite. So we can see a whole big program of things to do over the next 10 or 15 years that will really help us understand better what the dark energy is.*

Part II: Dark Energy in the Early Universe

David Spergel

While the supernova data provided the first hint of the existence of dark energy, currently astrophysicists such as David Spergel at Princeton University are pursuing other lines of evidence.

> DAVID SPERGEL: *One of the most bizarre results in cosmology and maybe in all of physics is the observation that the universe is accelerating. This is a tremendous challenge for physicists. It implies there's a big piece of physics we're missing.*

To unlock this mystery and find corroborating evidence of dark energy, Spergel looks back in time to examine remnants of light emitted only 300,000 years after the Big Bang. Scientists call this the cosmic microwave background, or CMB.

> DS: *The cosmic microwave background is the leftover heat from the Big Bang. We say it's microwave because it's a microwave wavelength, so relatively long wavelengths compared to optical.*

Since the CMB is not observable to the naked eye, special equipment is needed to detect it. In the 1960s, astronomers Arno Penzias and Robert Wilson stumbled upon the first evidence of the cosmic microwave background. They were using a highly sensitive microwave receiving system to study radio emissions from the Milky Way. But what they found was an unexpected background of radio noise with no obvious explanation.

> ROBERT WILSON: *Some radiation was coming from somewhere that we didn't expect. We were sort of seeing this effect every time we turned it on -- everywhere we pointed, and we were puzzled.*

Penzias and Wilson consulted with Princeton physicist Robert Dicke. Dicke had predicted that if the universe was created according to the Big Bang model, a background radiation at three Kelvin would exist throughout the universe.

> RW: *He and a couple of post docs were setting up to make a measurement to see if they could see radiation left over. But unfortunately for them, we had already found it.*

Penzias and Wilson uncovered the cosmic microwave background – light from very early in the evolution of our universe, just 300,000 years after the Big Bang or roughly 13.7 billion years ago.

Decades after this breakthrough discovery, David Spergel uses the cosmic microwave background to find more clues about the existence of dark energy.

> DAVID SPERGEL: *The reason why I'm interested in the cosmic microwave background is it gives us a snapshot of what the universe was like 300,000 years after the Big Bang. It lets us do two things. By seeing kind of the universe's baby picture, we can go back in time and figure out what happened in the first moments of the Big Bang and test our ideas about the very early universe. We could also use it as an anchor to go forward in time and understand the evolution of the universe and use as a probe to measure the geometry and composition of the universe. So, the microwave background is a tremendous tool for studying the physics of the universe.*

One key characteristic of the CMB is that it contains extremely small temperature variations. To bring these patterns of fluctuation into sharper focus, Spergel and a team of scientists developed a satellite that measures these differences in temperature, or anisotropies, called the Wilkinson Microwave Anisotropy Probe, or WMAP.

> DS: *The temperature variations that WMAP measures is one part in 100,000. So that means at that region in the sky the temperature might be 2.73001 Kelvin and it's 2.73000 over there.*

In 2001 WMAP was launched to four times the distance of the moon, looking out into space. Using data collected by WMAP, the team constructs a map of these tiny variations in temperature. The average brightness

corresponds to a temperature of 2.725 Kelvin. The red regions are warmer than average by a mere two 10,000ths of a degree and the blue regions are colder by two 10,000ths of a degree

> DS: *With WMAP what we did was a differential experiment. What we actually measure when we go out and look at the sky is temperature difference between two points. These small variations in temperature from place to place, or strength of the microwave signal in our case, reflect small variations in the density of the universe.*

These fluctuations in density are believed to have been created in the first fraction of a second after the Big Bang. As our universe cooled and expanded, the denser regions became the structures we know today, such as stars and galaxies.

Spergel and his team analyze these density, or temperature, fluctuations in the WMAP data to find further evidence of the existence of dark energy.

While the amount of dark energy cannot be directly measured from these fluctuations, it can be inferred. By measuring the total density of our universe and the density of matter, the WMAP team can calculate the amount of dark energy.

> DS: *The microwave background provides additional evidence for dark energy by measuring the total density of the universe and the density of matter and showing us there has to be an additional component like this.*

The density of our universe is related to its geometry or curvature. In the current model of cosmology, if the density of our universe is equal to one, or the critical density, then our universe is flat. If it is less than one, it is negatively curved like a saddle, and if it is greater than one, it is positively curved like the surface of a sphere.

According to general relativity, the curvature of space determines how light travels. So these various geometries predict different results in the size and pattern of hot and cold spots in the Cosmic Microwave Background.

To calculate the geometry, the WMAP team measures the observed angular size of the hot and cold spots of the CMB and compares these to the predictions.

The team found that the characteristic observed size of the spots is one degree, which is consistent with a flat universe.

> DS: *If the universe is flat, light moves on straight lines and the characteristic size of hot and cold spots in the microwave sky would be a degree. By measuring the size of these hot and cold spots, we can measure the geometry of the universe; hence measure its total density.*

According to the model, in a flat universe the total density is equal to 1.

Next the team must determine the amount of matter in our universe.

The amount of matter is determined by measuring the overall height and pattern of the temperature fluctuations. These fluctuations are analogous to ripples in a lake.

> DS: *The kind of ripples I get depends on what the lake is made of. A lake of water will give different ripples than a lake made of mercury. So, by looking at the amplitude of the waves, so the pattern of hot and cold spots, in more detail I can measure the density of atoms. I can also measure the density of matter. These ripples are affected by their own gravity. And how those ripples grow and behave, how they get amplified, depends upon the matter density. So, by looking at the amplitude of the fluctuations as a function of scale, how big the hot spots are on this scale and this scale and that scale, I can measure the atomic density and the matter density and the total density.*

Spergel and his team fit their data to a model and found that atomic matter, the matter we are familiar with, makes up less than 5% of the total density of the universe and an unidentified dark matter makes up 23%, leaving almost 3/4 of our universe unaccounted for. These results provide corroborating evidence for the existence of dark energy.

Without dark energy, there is not enough matter to equal the total density. The total density would be less than 1.

> DS: *If there was no dark energy, there was just the matter we know, the geometry of the universe would be different. The universe would be negatively curved. These spots would be 1/3 the size we see. So we would see a very different pattern here. So the fact that we see across the sky about 40,000 of these spots, hot and cold spots. If the universe didn't have any dark energy in it, instead of seeing 40,000 we'd see 400,000.*

The WMAP team's results support the initial supernova evidence for dark energy.

> DS: *When you see something as bizarre as dark energy, when you first hear about the evidence for it, the right reaction as a scientist is to say, "This is crazy;" there must be something wrong with the measurements. That's why it has been so important to have many lines of evidence pointing in the same direction.*

In 2009, Spergel is studying the cosmic microwave background in finer detail using the Atacama Cosmology Telescope in Chile. Its resolution is ten times finer than WMAP. This finer resolution will reveal subtle details of how certain structures in our universe evolved under the influence of dark energy.

> DS: *So, rather than just see what happened 300,000 years after the Big Bang, we'll observe what happened to those microwave photons as they got from there to our telescopes. That will give us another handle on how density fluctuations grow, which will give us another piece of the story for what are the effects of dark energy.*

Both Spergel and Kirshner hope to get a better understanding of dark energy to unravel clues about our past and open a small window into the future of our universe.

> ROBERT KIRSHNER: *Even though we see a universe that is accelerating, expanding faster and faster over time now, we don't know enough about the dark energy to know whether it's really going to keep doing that. Or, whether the acceleration that we see today could turn around and there could be a big crunch at some very distant time in the future. So we need to learn more*.