The dark side of the universe

Scientists are trying to understand why the universe is running away from them
The dark side of the universe - Cosmology

AT FIVE tonnes and 520 megapixels, it is the biggest digital camera ever built—which is fitting, because it is designed to tackle the biggest problem in the universe. On February 20th researchers at the Cerro Tololo Inter-American Observatory (pictured), which sits 2,200 metres (7,200 feet) above sea level in the Atacama desert of northern Chile, will begin installing this behemoth on a telescope called Blanco. It is the centrepiece of the Dark Energy Survey (DES), the most ambitious attempt yet to understand a mystery as perplexing as any that faces physics: what is driving the universe to expand at an ever greater rate.

It has been known since the late 1920s that the universe is getting bigger. But it was thought that the expansion was slowing. When in 1998 two independent studies reached the opposite conclusion, cosmology was knocked head over heels. Since then, 5,000 papers have been written to try to explain (or explain away) this result. “That’s more than one a day,” marvels Saul Perlmutter, of the Lawrence Berkeley National Laboratory, who led the Supernova Cosmology Project—one of the studies that was responsible for dropping the bombshell. Last October that work earned Dr Perlmutter the Nobel prize for physics, which he shared with Brian Schmidt and Adam Riess, who led the other study, the High-Z Supernova Search.
Many of those 5,000 papers deal with something that has come to be known as dark energy. One reason for its popularity is that, at one fell swoop, it explains another big cosmological find of recent years. In the early 1990s studies of the cosmic microwave background (CMB), an all-pervading sea of microwaves which reveals what the universe looked like when it was just 380,000 years old, showed that the universe, then and now, was “flat”. However big a triangle you draw on it—the corners could be billions of light years apart—the angles in it would add up to 180°, just as they do in a school exercise book.

That might not surprise people whose geometrical endeavours have never gone beyond such books. But it surprised many physicists. At some scales space is not at all flat: the power of Albert Einstein's theory of general relativity lies in its interpretation of gravity in terms of curved space. Cosmologists were quite prepared for it to be curved at the grandest of scales, and intrigued to discover that it was not.

**Dark thoughts**

Relativity says that for the universe to be flat, it has to have a very particular density—which in relativity is a measure not just of the mass contained in a certain volume, but also of the energy. The puzzle was that various lines of evidence showed that the universe's endowment of ordinary matter (the stuff that people, planets and stars are made of) would give it just 4% of that density. Adding in extraordinary matter—“dark matter”, not made of atoms, that interacts with the rest of the universe almost only by means of gravity—gets at most an extra 22%. That left almost three-quarters of the critical density unaccounted for. Theorists such as Michael Turner, of the University of Chicago, became convinced that there was something big missing from their picture of the universe.

Whatever it is that is driving the universe's accelerating expansion fits the bill rather well. Add the amount of energy needed to keep cosmic acceleration going to the amount of matter and energy in the universe already accounted for and you have more or less exactly the density of matter and energy needed to make the universe flat. But there is a catch; for the sums to tally, that “dark energy”—Dr Turner is thought to have coined the term— must be very strange stuff indeed. According to Einstein's theory of relativity, energy in the form of radiation has the same sort of gravitational effect as matter does—the photons of which light is made exert a pressure, and this in turn gives rise to a gravitational attraction. In order to drive its acceleration, then, dark energy must instead have a repulsive effect. It must, in other words, exert a negative pressure.

Divide dark energy's pressure (negative) by its energy density (positive) and you get something cosmologists label “w”. It is easy to see that w must be negative. Observations made since 1998 suggest that w is pretty close to -1. If it were found to be exactly -1, that would make dark energy something physicists call a cosmological constant. A cosmological constant is the same no matter where in the universe you look—an inherent, unchanging feature of the fabric of creation, however much it expands, twists or ties itself in knots.

The cosmological constant is another thing first dreamed up by Einstein. On realising that the equations of general relativity allowed for the universe's expansion (or, indeed, contraction), he added a parameter describing just such a constant in order to keep it from doing either. For all his notoriously counterintuitive predictions, an expanding universe was one he was not prepared to countenance, at least not in 1917, when he published his theory. After Edwin Hubble's discovery 12 years later that other galaxies were indeed streaming away from Earth's Milky Way backyard, Einstein dropped the tweak. No doubt miffed that he had not trusted his maths in the first place, he later called the cosmological constant his "biggest blunder".

By then, though, the cosmological constant had been seized upon by quantum theorists, themselves in the midst of turning physics on its head. Quantum theory says that the seemingly empty vacuum of space is, in fact, not empty at all. Instead it is constantly abuzz with "virtual" particles flitting in and out of existence. The energy resulting from all this buzzing—vacuum energy—should be a fixed feature of space—in other words, a cosmological constant.

**Stringing it all together**
And, in principle, it could also propel the universe's expansion. Thus vacuum energy and dark energy might be the same thing. But this theoretical neatness runs into a practical problem. A naive approach to quantum theory says that vacuum energy should be a whopping $10^{60}$ to $10^{120}$ times bigger than dark energy's estimated energy density. Some physicists call this "the worst prediction ever". Working out why vacuum energy is not so vast has been a problem for physics ever since.

Cliff Burgess, from Perimeter Institute for Theoretical Physics in Waterloo, Ontario, and the author of a handful of the 5,000 papers Dr Perlmutter has dug up, thinks he has a solution; the vacuum energy is vast, but it is almost all hidden away in extra spatial dimensions. Unlike the familiar three of length, breadth and height, these extra dimensions are curled up so tightly that they elude detection (though scientists are trying to prise them open in particle accelerators like the Large Hadron Collider near Geneva). Extra dimensions are of interest because string theory, a class of mathematical models based on quantum theory that seeks to describe reality in the most fundamental way, requires that there be at least six of them, maybe more.

What makes Dr Burgess's proposal unusual is that he went out on a limb and suggested that these energy-sapping, curled-up extra dimensions should be as big as a few microns across, gargantuan by string-theory standards. The reason they have not been noticed by chipmakers, virologists and others who pay attention to things on the micron scale, he contends, is that, like dark matter, they are sensitive only to gravity, and relatively oblivious to the other three of nature's fundamental interactions: electromagnetism and the weak and strong nuclear forces. This may sound like a cheap excuse but it makes robust mathematical sense. And it makes predictions; at micron scales the attraction between two masses will no longer depend on the square of the distance between them in the way that physicists since Newton have required it to.

An experiment under way at the University of Washington, led by Eric Adelberger, tests this idea using the world's most sensitive torsion balance, a souped-up version of the kit Henry Cavendish, an English physicist, used to measure gravity directly for the first time in the late 18th century. It consists of a disk with holes around its edge hanging horizontally from a cord, microns above another, similarly perforated plate. When the bottom disk is rotated the material between its holes exerts a tiny gravitational tug on the material between the holes of the top disk, causing it to rotate, albeit only by billionths of a degree. So far, Sir Isaac is winning. Dr Adelberger has confirmed that Newton's predictions are correct down to 44 microns. But the experiment continues, and Dr Burgess is taking bets that Newton's winning streak will not last much longer.

If Dr Burgess is right, vacuum energy and dark energy are the same thing, a cosmological constant, and $w$ is exactly equal to -1. What, though, if it is not? Then dark energy would have to be something that varies in space, time, or both, and is close to -1 today just by coincidence. Names applied to this something else include quintessence, k-essence, phantom energy and a bunch more, depending on which theorist you ask and what properties you think likely. It would be a new fundamental force, one that rears its head only at vast cosmic distances.

An alternative is to monkey with one of the existing forces. Some physicists would rather fiddle with Einstein's theory of relativity, for instance by making gravity weaker at extremely long ranges. This is tricky. It is notoriously hard to modify the equations of general relativity without damaging the theory beyond repair. That is one reason for their enduring appeal. Another is that they have been confirmed time and again by tests that range from minute measurements of bodies circling the solar system to observations of the farthest known light sources, quasars, billions of light years from Earth. Any new theory, then, has its work cut out—which has not, of course, stopped theorists trying.

The more precisely $w$ comes to look like -1, the more enthusiasm there will be for cosmological constant theories, which require that value, and the less enthusiasm there will be for fifth forces and modified gravity, part of the charm of which is that they can work with other values. This is where telescopes like Cerro Tololo come in. Existing data from ground-based and space telescopes put $w$ at between -1.1 and -0.9. DES will aim to narrow the margin of uncertainty down to just 0.01. To
do so, it will take 400 one-gigabyte snaps a night for 525 nights over five years (the remaining telescope time will be split between other science projects). And it will use an array of clever techniques to analyse the data.

The first is a time-honoured method borrowed from Dr Perlmutter, Dr Schmidt and Dr Riess and used to study exploding stars called supernovae. These come in different varieties. Some, called type Ia, always explode with almost exactly the same energy. They are, therefore, equally bright. Since brightness decreases in a predictable way with distance, type Ia supernovae make excellent cosmic yardsticks. Since the speed of light is constant, knowing how far away such a “standard candle” is (calculated from its apparent brightness seen from Earth) is to know how long ago it exploded. The rate at which stars and galaxies are moving away from Earth, meanwhile, can be worked out from their redshift. As light travels across space, which is stretching, its wavelength, too, is stretched and its frequency shifts towards the red end of the spectrum. The faster the expansion, the greater the redshift.

What the Supernova Cosmology Project and the High-z Supernova Search both found, and what others have later confirmed, is that distant exploding stars are dimmer, and so farther away, than their redshift implies they should be if the universe has been expanding at a steady clip throughout. The expansion must therefore have sped up recently.

The two groups originally based this conclusion on data from a mere 50-odd supernovae. The number has since grown tenfold, but it still leaves plenty of wriggle room for the cosmological constant to prove, well, not so constant after all. Joshua Frieman, who heads DES, hopes his team will eventually analyse over 4,000 exploding stars, some as far away as 7 billion light years. They exploded when the universe was half its current age and, researchers now reckon, still dominated by the gravity of the matter it contained, which was putting the brakes on expansion. Dark energy, it is thought, revved things up some 5 billion years ago. A better estimate of the time at which one gave way to the other helps determine $w$.

**Music of the spheres**

In addition to supernova searches, which will train the telescope at ten patches of the sky where Dr Frieman and his colleagues hope to spot and track the explosions, DES will be scouring one-eighth of the night sky for other clues, using three other methods. These all rely on throwing cartloads of computing power at seemingly random data in order to tease out tiny statistical anomalies.

One method looks for the effects of sound waves which originated in the Big Bang: baryon-acoustic oscillations (BAO). In the Big Bang's primordial soup of particles, known as a baryon-photon fluid, there were density waves like the sound waves in air, though far vaster. When the fluid cooled down enough, though, the baryons (particles from which atomic nuclei are made) and photons parted company. The photons became what is now the CMB; it is the fact that they have had nothing to do with matter since the Big Bang that makes the CMB such a remarkable window into the early universe.

With the photons no longer willing to play, there could be no more baryon-photon fluid. The baryons were stuck in position. Where the oscillations in the fluid had bunched the baryons tightly, they remained bunched; where they had been rarefied they remained sparse. The higher density regions became the seeds of galaxies—and the average separation of those galaxies thus reveals the wavelength of the oscillations in the primordial fluid. That characteristic scale has been stretched out to around 450m light years; measuring it at earlier times is another way to show how quickly the universe has been expanding.

The last two of DES's techniques measure not just rates of expansion, as supernovae and BAO searches do, but also the growth of cosmic structures like clusters of galaxies. Tracking the size and shape of clusters through time gives an idea of the tug-of-war between gravity, pulling them together, and dark energy, pushing them apart. This could help answer the question whether expansion is down to dark energy alone, in which case physicists expect a correlation between results from all four techniques, or to modified gravity, if the last two do not square with the first two.
One way to probe structure is to count the number of clusters of a given mass in a given volume of space at different redshifts. This is harder than it sounds because 85% of the mass is invisible dark matter. But it can be measured indirectly, for instance by looking at how hot clouds of gas get as they are pulled towards the cluster's dark-matter core by its gravity.

Alternatively, the distribution of matter, both dark and humdrum, can be gleaned from the effect it has on light. Relativity requires the path of light to be bent by massive objects. The heavier the object, the more an image of something behind it is warped. Most of the time, this warping is tiny—images of galaxies are typically stretched by 2% or so by the clumps of matter they pass on their way to telescopes on Earth. To complicate matters further, few galaxies are perfectly round to start with, so it is hard to tell whether stretching has taken place by looking at any particular galaxy. Fortunately, light from all the galaxies in a given region of the sky passes by the same clumps of matter on the way to Earth. So galaxies as seen from Earth ought all to be distorted in a preferred direction. Observe enough of them, 300m in DES's case, and a pattern should emerge, allowing astronomers to model the structures responsible for the bending.

Combine all four techniques and a clearer picture of the causes of cosmic acceleration will emerge. That, at least, is the hope. Ofer Lahav from University College, London, who is in charge of DES’s science programme, says the odds are that DES will home in on \( w \) being equal to -1—some sort of a cosmological constant.

**Saving the best 'til LSST**

Other, even more ambitious projects, will strive to increase the precision of the measurement of \( W \). Last year ground was broken on the Large Synoptic Survey Telescope (LSST), a much bigger instrument which will be perched atop Cerro Pachón, 10km (6 miles) from Cerro Tololo. Though its $620m budget awaits final approval from America’s National Science Foundation and Department of Energy, scientists hope to have it up and running by 2021. The LSST’s mammoth camera will boast 3.2 gigapixels.

Then there are two space telescopes, each with a price tag of $1 billion or so. The European Space Agency plans to launch *Euclid* in 2019 and NASA hopes to put WFIRST in orbit three years later.

These projects are not solely dedicated to probing the nature of dark energy. LSST, for example, will discover asteroids by the bushel—including some that might be hazardous to Earth. But one way or another it is cosmic expansion that they, and all sorts of other astronomical ventures, will be addressing.

The rub is that no amount of observations can ever pin down the figure for \( W \) with perfect accuracy. That would require infinite precision, something impossible to achieve even in an ever-expanding universe. And the whole constant idea falls to pieces if \( W \) is even a smidgen off -1.
More than any other scientific problem the cosmic-expansion conundrum presents scientists with an existential quandary. “It could be a 22nd-century problem we stumbled upon in the 20th century,” says Dr Turner. Some researchers may begin to feel time would be better spent on other scientific pursuits.

Many astronomers, including Dr Perlmutter, are quietly hoping that as DES and the host of other acronyms come online, they will spring another surprise, like the one that first propelled cosmic acceleration into the limelight in 1998. Whether they do or not, though, dark energy—or whatever else is causing the universe to speed up—is probably too big a conundrum for one generation to crack. It will cause boffins to rack their brains for years to come.
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