Dark energy begone!

A simple trick of gravity could open the door to a much brighter view of the cosmos. **Amanda Gefter** reports

WHEN two teams of astronomers set out in 1998 to measure the expansion rate of the universe, it was a routine sort of mission. The cosmic backstory had already been written: the universe began with the big bang, surging rapidly outward and then continuing to expand more and more slowly, held back by the relentless pull of gravity. The astronomers were searching for supernovae, exploding stars whose precious light would confirm these details.

They didn't imagine that the supernovae would have an entirely different tale to tell. Distant supernovae turned out to be much farther away than would be expected if the expansion of the universe had been slowing all along. Both teams were stunned by the inevitable conclusion: instead of slowing down, the universe's expansion was speeding up. But why?

It has become the most troubling question in astrophysics, and 10 years on we are no closer to answering it. Most physicists think the solution lies with an elusive force known as dark energy, which lurks in the emptiness of space, accounting for more than 70 per cent of the cosmos and causing space to expand at an ever-increasing rate.

What exactly is this dark energy? It might be the energy inherent in the fabric of space itself; or an exotic field called quintessence that expands space at changing rates; or something stranger still, a phantom energy that might one day tear the universe apart. Each possibility has its share of problems (*New Scientist*, 16 February 2007, p 28).

So a small but growing number of physicists have suggested something more radical: dark energy may not exist at all. Several recent papers argue that the universe's


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expansion is in fact decelerating as expected; it's just that gravitational effects arising from the distribution of galaxies create the illusion of acceleration. This is a controversial idea, to be sure, but if proven correct it would mean far more than just rethinking our models: a whopping 70 per cent of the universe will have just turned up.

The original argument for dark energy rests on a crucial assumption. To interpret the supernova observations, researchers assume the universe operates according to the standard model of cosmology. This model uses Einstein's general theory of relativity to calculate the geometry and overall behaviour of the universe. General relativity describes gravity at large scales, but gravity depends on how matter is distributed throughout space. The standard view since Einstein has been that although the density of matter in the universe varies from place to place – a galaxy here, a bit of empty space there – overall the universe is approximately smooth and uniform.

Through recent projects like the Sloan Digital Sky Survey, however, astronomers have created 3D maps of space, and they have come to realise that the universe simply isn't smooth (see Map, page 34). While matter started out evenly spread, as can be inferred from the nearly uniform temperature of the cosmic microwave background radiation – relic heat from the nascent universe – over billions of years it has coalesced into larger and larger structures. Hundreds of billions of stars aggregate in galaxies, galaxies form clusters, clusters amass into superclusters, and superclusters string together in filaments that encircle vast voids of empty space. "Now that we have precise observations, the theoretical treatment should catch up," says Syksy Rasanen, a physicist at the University of Geneva in Switzerland.

Despite the observed lumpiness, most cosmologists still think the universe behaves, on average, as though it were uniform. The problem, first raised by George Ellis in the early 1980s, has been that they couldn't test this idea because there was no way to take an average of space-time geometry using Einstein's equations. That changed in 2000, though, when Thomas Buchert of the University of Lyon in France published a set of equations based on general relativity that allowed cosmologists to average the universe's behaviour while including the effects of an uneven matter distribution. This paved the way for physicists to try to explain the observed expansion history of the universe using models based on the lumpy distribution of matter. "There has been an explosion of research in this direction," says Buchert (see "Living in a void", page 34). "Before one invents exotic solutions like dark energy, this is the more natural approach."

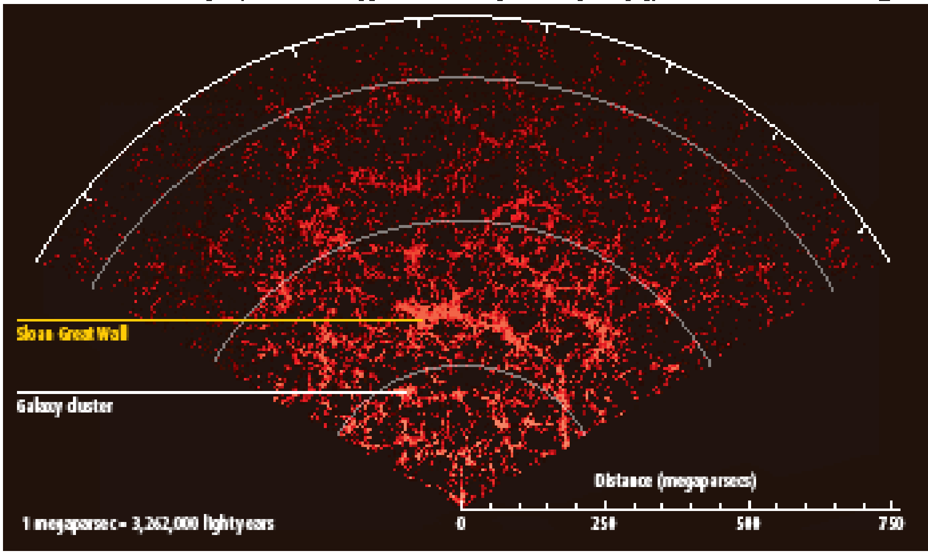
But how can the distribution of matter account for the apparent accelerated expansion? The most promising model so far has been put forward by David Wiltshire, a physicist at the University of Canterbury in New Zealand (*Physical Review Letters*, vol 99, p 251101). Wiltshire has shown that by combining Buchert's equations with some strange quirks of general relativity he can explain the supernova observations without resorting to dark energy (*New Journal of Physics*, vol 9, p 377).

Because the universe is not smooth, says Wiltshire, observers need to take into account their own position in order to properly interpret cosmological measurements. In relativity, distance and time measurements are made in terms of an observer's rods and clocks. Cosmologists usually assume that rods and clocks across the universe are all identically calibrated, but for Wiltshire this is where they have gone wrong. Clocks that were in sync in the smooth, early universe become mismatched as the matter distribution grows increasingly lumpy. That's because gravity slows time, a proven relativistic effect. So a clock in a galaxy will tick more slowly than a clock in empty space. By now, Wiltshire says, the time told by a clock in our galaxy and the time told by one floating in a void could differ by as much as 38 per cent.

It is this mismatch that can explain the supernova data, he says. Back in 1998, the two teams, led by Saul Perlmutter of the ▶

STRUCTURE IN THE COSMOS

Mapping projects such as the Sloan Digital Sky Survey reveal that matter is distributed unevenly on large scales, with gigantic clusters of galaxies, such as the Sloan Great Wall. This challenges the standard model of cosmology, which assumes the universe is smooth and uniform. With this assumption, observations imply the universe's expansion is speeding up, which is attributed to dark energy



Lawrence Berkeley National Laboratory in California and Brian Schmidt of the Australian National University in Canberra, looked at type 1a supernovae, which burn with a known brightness. Comparing a supernova's apparent brightness with its intrinsic brightness reveals its distance. Its red shift – the stretching of the light's wavelength – reveals how much the intervening space has expanded from the time the light left the supernova to the time it reached our telescopes. When the teams looked at distant supernovae, they found that they were much farther away, for their measured red shift, than they would be if the universe's expansion had always been decelerating.

This interpretation, however, assumes the standard cosmological model is correct. The standard model, because it is based on a uniform space with no distinct physical structures, describes us observers as floating in a freely expanding space, rather than confined to a galaxy. If our rods measure smaller volumes and our clocks are ticking more slowly than those of an observer in a void, as Wiltshire contends, then the simplification can lead to wrong conclusions.

For instance, the calculated expansion rate of the space between the Earth and the supernovae depends in part on the density of the intervening matter, because gravity slows expansion. Density is the amount of mass in a given volume, but volume depends on the way in which space is curved. In voids, space is negatively curved, so the volume for a given radius is larger than in the relatively flat space in which we live. Buchert had realised that taking the changing volumes into account alters what we calculate to be the universe's expansion history. This change alone is not enough, however, to account for the apparent acceleration.

Wiltshire's key realisation was that in addition to these volume corrections, the lumpiness of matter also requires corrections to clocks. Because we live in a gravitationally bound system – our galaxy – our clocks run more slowly than they would in a void. This means our calculations of how fast space is expanding will be wrong too. Together, Wiltshire says, the corrections to volumes and times do away with the apparent acceleration. "It is not really that the expansion of space is accelerating," he says. "Rather, our estimates of volume are too small and our estimates of time are too slow." Wiltshire's conclusion? The universe's expansion is slowing down, as originally thought (see Diagram, right).

His model challenges other basics of standard cosmology as well. According to Wiltshire's calculations, the age of the universe from our point of view should be 14.7 billion years, rather than the standard 13.7 billion. For hypothetical observers in voids, the situation is even more dramatic: for them the universe is 18.6 billion years old. Wiltshire thinks this can help account for some of the advanced structures that appear to have existed far earlier in the history of the universe than they

Living in a void

Several researchers are trying to explain away dark energy using the idea of voids in space. Subir Sarkar of the University of Oxford has suggested that if our local cluster of galaxies is surrounded by an enormous void, its gravitational effects would explain the appearance of accelerated expansion (*General Relativity and Gravitation*, vol 40, p 269). Perhaps our galaxy lies within an atypically sparse portion of the universe, he says, and the area outside our bubble is much denser. This denser region would exert a gravitational pull on our cosmic neighbourhood, so the galaxies around us would be flying away at an ever-increasing rate.

The catch is that Sarkar's void would have to be a staggering 1.6 billion light years across – larger than any void ever observed. Still, we can't rule it out, as astronomers are discovering bigger voids all the time. In August last year, they found a void nearly 1 billion light years across, about 6 to 10 billion light years away in the direction of the constellation Eridanus. The void was far larger than anyone had expected might exist.

According to Sarkar, astronomers can test his idea by measuring how fast space is expanding in different places, starting locally and then moving further out. He says that galaxy catalogues such as the Two Micron All Sky Survey suggest we live in an underdense region. The Sloan Digital Sky Survey's upcoming supernova project will provide a more definitive test.

Syksy Rasanen of the University of Geneva, Switzerland, thinks that as the universe expands and voids become a larger portion of its volume – with a smaller proportion of matter to put the brakes on cosmic expansion – the overall pace of expansion actually does speed up, even though there is no anti-gravity force or dark energy at work (*Journal of Cosmology and Astroparticle Physics*, vol 0611, p 003). So far, however, he has not been able to get his model to match the observed acceleration. "Calculating these effects is involved," he says, "and one is not yet at the stage where it could be confirmed or ruled out."

should. "A return to thinking about observers and measurements in the manner Einstein taught us is what is going to solve a lot of puzzles in cosmology," he says.

Other researchers think it is a step in the right direction, but that the assumption of dense regions and voids, with nothing in between, may be unrealistic. "This is already very interesting," says physicist Luciano Pietronero of the University of Rome in Italy, "but I wonder what would be the result for a more realistic model." Nevertheless, he says that Wiltshire's work could ultimately lead to new insights into how to devise more realistic cosmological models.

Physicist Yurij Baryshev of St Petersburg State University in Russia agrees that the uneven matter distribution requires a new cosmological model, but he thinks Wiltshire's is too simplistic. "It is interesting, but only as the beginning of a discussion of the problem," Baryshev says.

Though intrigued by Wiltshire's approach, most of the community has yet to be convinced. "The argument is important," says Buchert, "and his model is one way to interpret these equations. But it's not the only way to do it." Mainstream cosmologists caution that the approach is still too speculative to seriously challenge the concept of dark energy. "This idea is probably the longest shot right now," says Sean Carroll of the California Institute of Technology in Pasadena. The majority of his peers would still put their money on vacuum energy, often referred to as the cosmological constant, as being the driver of the universe's expansion. "That's the most popular scenario," says Carroll, "but a puzzle because the energy should be much larger than it is."

With so many theories vying to explain dark energy, how are we to decide between them? Perlmutter thinks we need more data. "It has been 10 years now and you might have expected that someone would have had a real 'a-ha' moment. If they haven't then it tends to mean we need more clues," he says.

To that end, Perlmutter is leading an upcoming project called SNAP (SuperNova Acceleration Probe), a near-infrared space telescope that will examine supernovae from as far back as 10 billion years, giving us a more detailed history of the universe's expansion. If all goes well, the satellite should be up and running within seven years. Experiments with SNAP, more detailed measurements of the cosmic microwave background by the forthcoming Planck satellite and larger galaxy maps will all help decide which model of dark energy is correct. "I'm excited to hear new ideas like Wiltshire's," says Perlmutter. "I'd like the measurements that we're about to make to be able to distinguish among a huge number of theories."

For now, physicists are literally placing bets. At a symposium in Texas last year, Wiltshire made a wager with Thanu Padmanabhan, a physicist at the Inter-University Center for Astronomy and Astrophysics in Pune, India. Padmanabhan wagered that within 10 years dark energy would be revealed as a true cosmological constant and not as an artefact of matter distribution. The terms of the bet are telling. If Padmanabhan wins, Wiltshire has to buy him a lamp "to help him better illuminate his calculations of the darkness of the universe". If Wiltshire wins, he gets a clock, "to help him better keep track of the lack of constancy of cosmological ideas". ●

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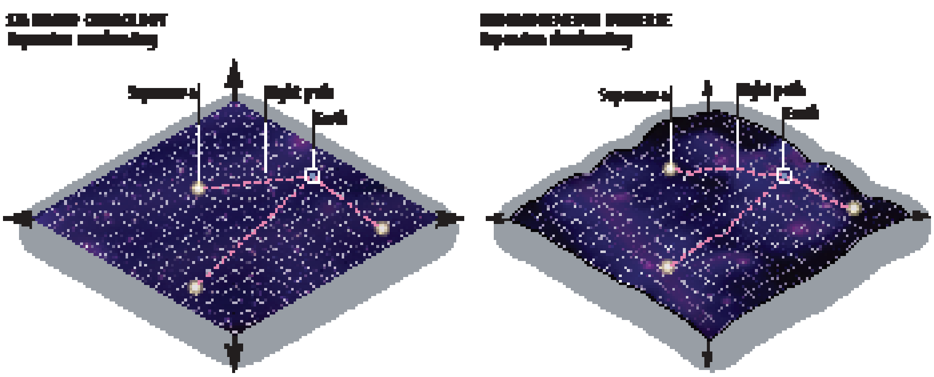
DO WE NEED DARK ENERGY?



ASSUMPTIONS

Matter is evenly distributed in the universe on average

Time runs at about the same rate everywhere

CONCLUSION

Expansion of the universe is speeding up, due to repulsive dark energy

ASSUMPTIONS

Universe is lumpy and curved because of uneven matter distribution

Time runs faster in voids than in regions where matter clumps

CONCLUSION

Expansion of the universe is slowing down due to gravity, so no need for dark energy