

Three cosmic enigmas, one audacious answer

- 09 March 2006
- Exclusive from New Scientist Print Edition
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DARK energy and dark matter, two of the greatest mysteries confronting physicists, may be two sides of the same coin. A new and as yet undiscovered kind of star could explain both phenomena and, in turn, remove black holes from the lexicon of cosmology.

The audacious idea comes from George Chapline, a physicist at Lawrence Livermore National Laboratory in California, and Nobel laureate Robert Laughlin of Stanford University and their colleagues. Last week at the 22nd Pacific Coast Gravity Meeting in Santa Barbara, California, Chapline suggested that the objects that till now have been thought of as black holes could in fact be dead stars that form as a result of an obscure quantum phenomenon. These stars could explain both dark energy and dark matter.

This radical suggestion would get round some fundamental problems posed by the existence of black holes. One such problem arises from the idea that once matter crosses a black hole's event horizon - the point beyond which not even light can escape - it will be destroyed by the space-time "singularity" at the centre of the black hole. Because information about the matter is lost forever, this conflicts with the laws of quantum mechanics, which state that information can never disappear from the universe.

Another problem is that light from an object falling into a black hole is stretched so dramatically by the immense gravity there that observers outside will see time freeze: the object will appear to sit at the event horizon for ever. This freezing of time also violates quantum mechanics. "People have been vaguely uncomfortable about these problems for a while, but they figured they'd get solved someday," says Chapline. "But that hasn't happened and I'm sure when historians look back, they'll wonder why people didn't question these contradictions."

While looking for ways to avoid these physical paradoxes, Chapline and Laughlin found some answers in an unrelated phenomenon: the bizarre behaviour of superconducting crystals as they go through something called "quantum critical phase transition" (*New Scientist*, 28 January, p 40). During this transition, the spin of the electrons in the crystals is predicted to fluctuate wildly, but this prediction is not borne out by observation. Instead, the fluctuations appear to slow down, and even become still, as if time itself has slowed down.

"That was when we had our epiphany," Chapline says. He and Laughlin realised that if a quantum critical phase transition happened on the surface of a star, it would slow down time and the surface would behave just like a black hole's event horizon. Quantum mechanics would not be violated because in this scenario time would never

freeze entirely. "We start with effects actually seen in the lab, which I think gives it more credibility than black holes," says Chapline.

With this idea in mind, they - along with Emil Mottola at the Los Alamos National Laboratory in New Mexico, Pawel Mazur of the University of South Carolina in Columbia and colleagues - analysed the collapse of massive stars in a way that did not allow any violation of quantum mechanics. Sure enough, in place of black holes their analysis predicts a phase transition that creates a thin quantum critical shell. The size of this shell is determined by the star's mass and, crucially, does not contain a space-time singularity. Instead, the shell contains a vacuum, just like the energy-containing vacuum of free space. As the star's mass collapses through the shell, it is converted to energy that contributes to the energy of the vacuum.

The team's calculations show that the vacuum energy inside the shell has a powerful anti-gravity effect, just like the dark energy that appears to be causing the expansion of the universe to accelerate. Chapline has dubbed the objects produced this way "dark energy stars".

Though this anti-gravity effect might be expected to blow the star's shell apart, calculations by Francisco Lobo of the University of Lisbon in Portugal have shown that stable dark energy stars can exist for a number of different models of vacuum energy. What's more, these stable stars would have shells that lie near the region where a black hole's event horizon would form (*Classical Quantum Gravity*, vol 23, p 1525).

"Dark energy stars and black holes would have identical external geometries, so it will be very difficult to tell them apart," Lobo says. "All observations used as evidence for black holes - their gravitational pull on objects and the formation of accretion discs of matter around them - could also work as evidence for dark energy stars."

That does not mean they are completely indistinguishable. While black holes supposedly swallow anything that gets past the event horizon, quantum critical shells are a two-way street, Chapline says. Matter crossing the shell decays, and the anti-gravity should spit some of the remnants back out again. Also, quark particles crossing the shell should decay by releasing positrons and gamma rays, which would pop out of the surface. This could explain the excess positrons that are seen at the centre of our galaxy, around the region that was hitherto thought to harbour a massive black hole. Conventional models cannot adequately explain these positrons, Chapline says.

He and his colleagues have also calculated the energy spectrum of the released gamma rays. "It is very similar to the spectrum observed in gamma-ray bursts," says Chapline. The team also predicts that matter falling into a dark energy star will heat up the star, causing it to emit infrared radiation. "As telescopes improve over the next decade, we'll be able to search for this light," says Chapline. "This is a theory that should be proved one way or the other in five to ten years."

Black hole expert Marek Abramowicz at Gothenburg University in Sweden agrees that the idea of dark energy stars is worth pursuing. "We really don't have proof that black holes exist," he says. "This is a very interesting alternative."

The most intriguing fallout from this idea has to do with the strength of the vacuum energy inside the dark energy star. This energy is related to the star's size, and for a star as big as our universe the calculated vacuum energy inside its shell matches the value of dark energy seen in the universe today. "It's like we are living inside a giant dark energy star," Chapline says. There is, of course, no explanation yet for how a universe-sized star could come into being.

At the other end of the size scale, small versions of these stars could explain dark matter. "The big bang would have created zillions of tiny dark energy stars out of the vacuum," says Chapline, who worked on this idea with Mazur. "Our universe is pervaded by dark energy, with tiny dark energy stars peppered across it." These small dark energy stars would behave just like dark matter particles: their gravity would tug on the matter around them, but they would otherwise be invisible.

Abramowicz says we know too little about dark energy and dark matter to judge Chapline and Laughlin's idea, but he is not dismissing it out of hand. "At the very least we can say the idea isn't impossible."