Space oddity

When neutron stars melt, what's left behind is truly strange. Anil Ananthaswamy reports

ON 22 September last year, the website of The Astronomer's Telegram alerted researchers to a supernova explosion in a spiral galaxy about 84 million light years away. There was just one problem. The same object, SN 2009ip, had blown up in a similarly spectacular fashion just weeks earlier. Such stars shouldn't go supernova twice, let alone in quick succession. The thing was, it wasn't the only one, the next year another supernova, SN 2010mc, did the same.

One of the few people not to be bamboozled was Rachid Ouyed. "When I looked at those explosions, they were talking to me right away," he says. Ouyed, an astrophysicist at the University of Calgary in Alberta, Canada, thinks that these double explosions are not the signature of a supernova, but something stranger. They may mark the violent birth of a quark star, a cosmic oddity that has only existed so far in the imaginations and equations of a few physicists. If so they would be the strongest hints yet that these celestial creatures exist in the cosmic wild.

The implications would be enormous. These stars would take pride of place alongside the other heavenly heavyweights: neutron stars and black holes. They could help solve some puzzling mysteries related to gamma-ray bursts and the formation of the heftiest elements in the universe. Back on Earth, quark stars would help us better understand the fundamental building blocks of matter in ways that even machines like the Large Hadron Collider cannot.

MATT MURPHY

Astrophysicists can thank string theorist Edward Witten for quark stars. In 1984, he hypothesised that protons and neutrons may not be the most stable forms of matter.

Both are made of two types of smaller entities, known as quarks: protons are comprised of two "up" quarks and one "down" quark, whereas neutrons are made of two downs and one up. Up and down are the lightest of six distinct "flavours" of quark. Add the third lightest to the mix and you get something called strange quark matter. Witten argued that this kind of matter may have lower net energy and hence be more stable than nuclear matter made of protons and neutrons.

Quark nova

If so, we might all start decaying into strange matter. But don't fret. You either need to wait around longer than the age of the universe for the stuff to form spontaneously, or find somewhere with the right conditions to start the process. One place this could happen is inside neutron stars, the dense remnants of certain types of supernovae.

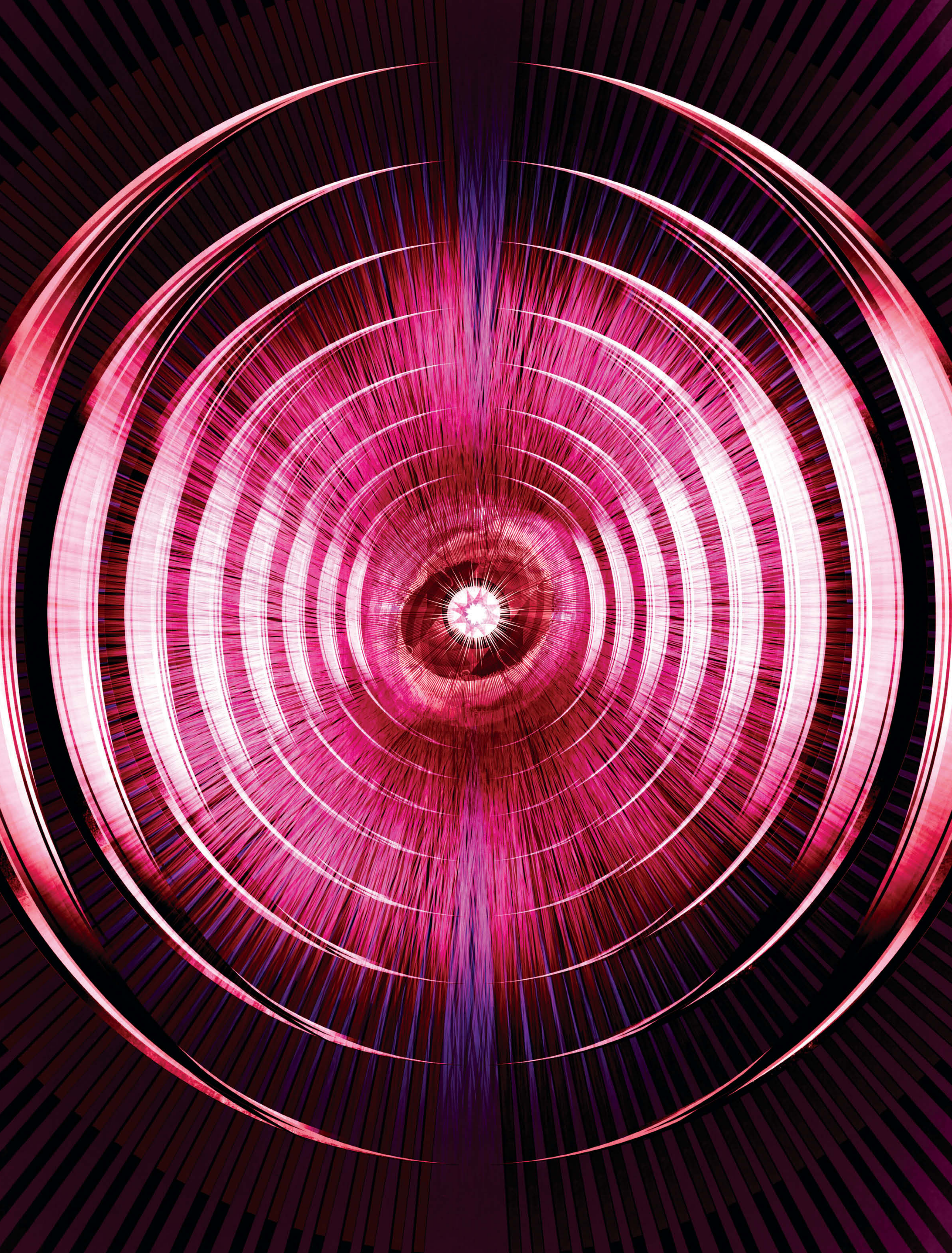
When a star many times more massive than the sun runs out of fuel, its inner core implodes. The outer layers are cast off in a spectacular explosion. What's left behind is a rapidly spinning neutron star, which as the name implies is made mainly of neutrons, with a crust of iron. Whirling up to 1000 times per second, a neutron star is constantly shedding magnetic fields. Over time, this loss of energy causes the star to spin slower and slower. As it spins down, the centrifugal forces that kept gravity at bay start weakening, allowing gravity to squish the star still further.

In what is a blink of an eye in cosmic time, the neutrons can be converted to strange quark matter, which is a soup of up, down and strange quarks. In theory, this unusual change happens when the density inside the neutron star starts increasing. New particles called hyperons begin forming that contain at least one strange quark bound to others.

However, the appearance of hyperons marks the beginning of the end of the neutron star. "Once you start to form hyperons, then you can start the nucleation of the first droplet of strange quark matter," says Giuseppe Pagliara of the University of Ferrara in Italy. As the density in the core continues to increase, the star's innards "melt", freeing quarks from their bound state. In fact, a single droplet of strange matter is enough to trigger a runaway process that converts all the neutrons. What was a neutron star turns into a quark star.

Of course, this assumes that Witten is correct about strange quark matter being more stable than neutrons. No one has yet proved him wrong, but it is a tough idea for some to swallow. "More conservative thinkers are just not open to the idea that free quarks exist in neutron stars," says Fridolin Weber, an astrophysicist at the San Diego State University in California.

Not so the daring ones. Ouyed, for instance, has been trying to convince his fellow astrophysicists of the existence of quark stars for more than a decade. Not only do these intrepid few think that quarks can exist ›



"Quark stars can help us understand the fundamental building blocks of matter in ways that even the Large Hadron Collider cannot"

freely inside neutron stars, they have even thought about what comes next. "We all agree that if quark stars exist, then the conversion of normal, ordinary matter into a quark star will be a very exothermic process, a lot of energy will be released," says Pagliara. "How this energy is released is a matter of debate."

On one hand, Pagliara and his colleagues have done extensive simulations to show that this conversion will happen in a matter of milliseconds. In what he calls a "strong deflagration", the neutron star burns up as it turns into a quark star. There is no explosion.

Ouyed, on the other hand, begs to differ. His team's simulations show that the conversion is most likely to be an extremely violent process. The seed of strange quark matter spreads until it reaches the outer crust of the neutron star. As the part of the star that has been turned into quark matter separates from the iron-rich crust, it collapses. The collapse halts when the inner core becomes incredibly dense and rebounds, creating a shock wave. Much as in a supernova, the iron-rich crust and leftover neutrons are ejected in another spectacular explosion – a "quark nova".

Hurtling through space, the quark nova ejecta then slam into the earlier supernova remnants, causing them to light up again, as they did after the explosion of the original, conventional star. What's left behind is a quark star. "It was very hard to find solutions where the entire neutron star turned into a quark star, in just a puff with no explosion," says Ouyed.

Double explosion

Depending on the mass of the star before its first explosion, the second blast could occur anywhere from seconds to years after the original supernova. Too soon, and the two explosions would merge, appearing as one blast, smeared out in time. Too late, and the supernova ejecta would have dispersed long before the detonation of the quark nova, and there would be no re-brightening.

But if the timing is just right, the outcome should be observable. In 2009, Ouyed's team predicted that if the quark nova goes off days or weeks after the supernova, there should be two peaks in energy: the first being the supernova explosion itself, and the second being the reheating of the supernova ejecta. The objects SN 2009ip and SN 2010mc matched predictions in ways almost too good to be true.

SN 2009ip had its first major explosion in early August 2012, and 40 days later flared up again. SN 2010mc was eerily similar in its outbursts, showing a double explosion in which the peaks were about 40 days apart. While other researchers continue trying to explain these unusual observations using their tried-and-tested models of supernovae, Ouyed is convinced that we have witnessed quark stars being born.

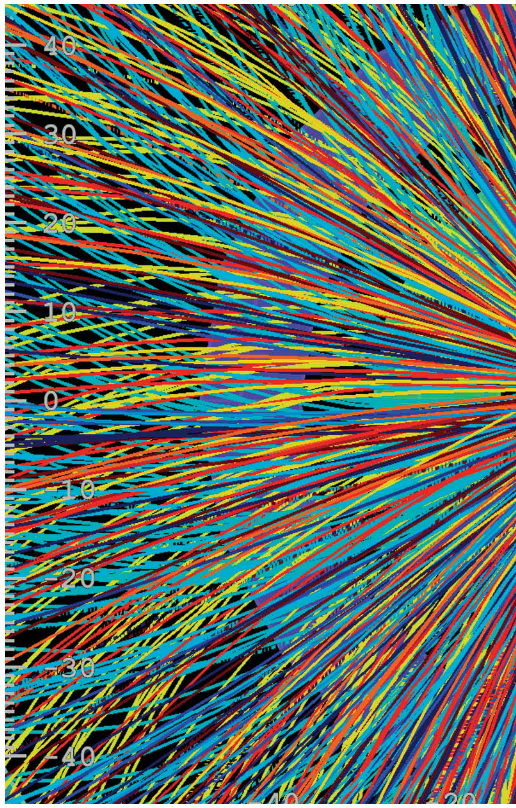
Oddly, it is the first peak in both events that convinces him. If these have all the characteristics of a regular supernova, it makes the second boom harder to explain using conventional arguments. "When you look at the first ejecta, it looks like a duck and walks like a duck: it's a supernova," says Ouyed. "Then what's the second one?"

He points the finger at quark novae. "We just applied our model of the dual shock quark nova, and it was actually easy to fit," he says. "That's the beauty of it."

While Pagliara and Ouyed's teams disagree on whether the transition from a neutron star to a quark star is explosive, they do agree that space should be littered with quark stars. How should we look for them?

We might be mistaking some of them for neutron stars, says Pagliara. Most neutron stars weigh as much as 1.4 suns or slightly more. The best studied examples, orbiting each other in systems called Hulse-Taylor binary pulsars, certainly follow this pattern. Both neutron stars involved weigh in at 1.4 solar masses. However, Pagliara is bothered by two discoveries of neutron stars that tip the scales at 2 solar masses each. "It's difficult to reach this mass with normal particle components like neutrons, protons and hyperons," he says.

This has to do with a property of matter called its equation of state. Equations of state describe how matter behaves under changes in physical conditions, such as pressure and temperature. Hyperons, which are precursors to strange quark matter, have a "soft" equation of state. Their existence in the dense core of a neutron star makes the star more compressible, causing it to shrink in size.



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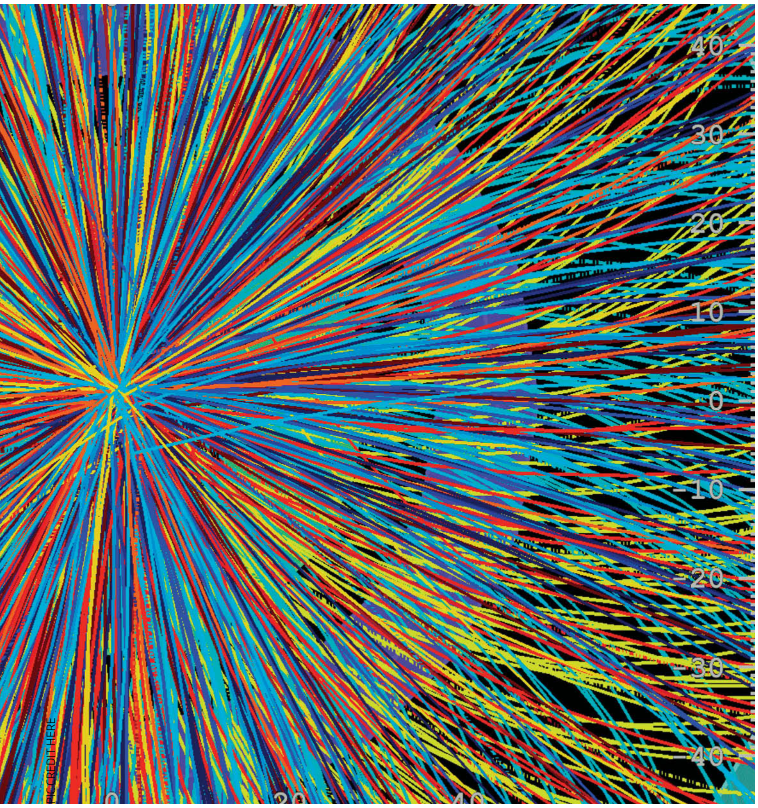
Astronomers estimate that neutron stars are about 10 kilometres across – but squeezing 2 solar masses into an object of such size would end up creating a black hole. Pagliara says that compact stars weighing 2 solar masses or more have to be bigger, or put another way, the matter has to be "stiffer" so that gravity cannot compress it as much. There is one candidate with a stiffer equation of state: strange quark matter.

Pagliara and his colleague Alessandro Drago and others claim that the compact stars we have spotted come from two families. The smaller ones must be the run-of-the-mill neutron stars. The larger ones must be quark stars. The only way to verify this claim is to measure their masses and also measure their radii to the nearest kilometre. A proposed European satellite mission called the Large Observatory for X-ray Timing could do just that. Its aim is to measure the equation of state for compact objects – and thus differentiate between neutron stars and quark stars.

Meanwhile, Ouyed's team is concentrating on predictions based on their quark nova model. One prediction has to do with the



Cosmic wild: particles containing strange quarks emerge from collisions of heavy ions

creation of heavy elements in the universe. Once a massive star goes supernova, weighty elements are synthesised in a matter of milliseconds, when neutrons are absorbed into iron nuclei. These neutron-rich nuclei are unstable and decay into elements further up in the periodic table when neutrons get converted to protons. "But the challenge with supernovae has always been to go to really heavy elements," says Ouyed. The iron and neutrons needed for the process are in short supply because most of them are left behind in the remnant neutron star.

The quark nova solves that problem. Its ejecta are a potent mix of neutrons and iron from the neutron star's crust, providing just the laboratory for synthesising the heaviest elements. Ouyed is urging astronomers to study double explosions carefully. His team predicts that the second blast should show the presence of elements heavier than atomic mass 130, elements which should be missing from the first explosion.

The conversion of a neutron star to a quark star could also solve another problem plaguing astrophysics: the source of some long-duration gamma-ray bursts, which are among the brightest events in the universe. On 9 July 2011, NASA's SWIFT gamma-ray satellite saw a burst with two spectacular peaks of emission, spaced 11 minutes apart. And the second was the stronger of the two. The traditional "collapsar" model of gamma-ray bursts relies on a star collapsing to a black hole. As the last remnants of the doomed star fall in, it is thought to result in such an emission. But 11 minutes is an eternity for a black hole – it's hard to make sense of the second peak.

Pagliara thinks his team has the answer. According to their model, a neutron star converts to a quark star without an explosion. Yet there is still a tremendous release of energy, which Pagliara suspects goes into gamma rays. This could explain the second peak. "At the moment, and it's speculation, we think that this second event could be related to quark stars," he says. "If you want to see a possible signature of formation of quark matter, you should probably look at those gamma-ray bursts that have an activity long after the main event."

"Space should be littered with quark stars. How should we look for them? We may be mistaking some of them for neutron stars"

Quark world

Confirming the existence of quark stars and verifying their properties could have a huge impact on particle physics. Colliders like the LHC and the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory in New York have been smashing heavy ions head-on to create a state of matter called a quark-gluon plasma, where quarks are essentially free.

The best way to study this phase of matter is using a method called lattice quantum chromodynamics. But physicists have only been able to solve the equations of lattice QCD for high temperatures and low density – the conditions created at the LHC and the RHIC. The equations are intractable for other conditions. For instance, it is impossible to calculate the density at which protons and neutrons can melt into their constituent quarks at low temperatures.

Enter quark stars. First, if their existence is confirmed, it proves that quarks can exist freely at high densities and low temperatures, rather than bound up in hadrons – the catch-all name given to any particle made of quarks. Second, for the explosive quark nova model Ouyed's team has shown that the density at which quarks get freed is intimately linked to the time lag between the supernova and the quark nova. Measure the timing of the double explosion and you will glean important clues about conditions at the transition. "The quark nova is a very beautiful bridge that straddles the hadronic world and the quark world," says Ouyed. "It'd be a very nice tool to use for physics and astrophysics."

Weber agrees that quark stars, if they exist, would be a unique astrophysical laboratory. They would help us probe properties of matter in ways that we cannot do with the best colliders on Earth – in the domain of high densities and low temperatures. "This is a regime that is only accessible to stars, and only stars can tell us what will happen." ■

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