Focus

The weirdest worlds of all

Neutron stars and white dwarfs

By Kulvinder Singh Chadha

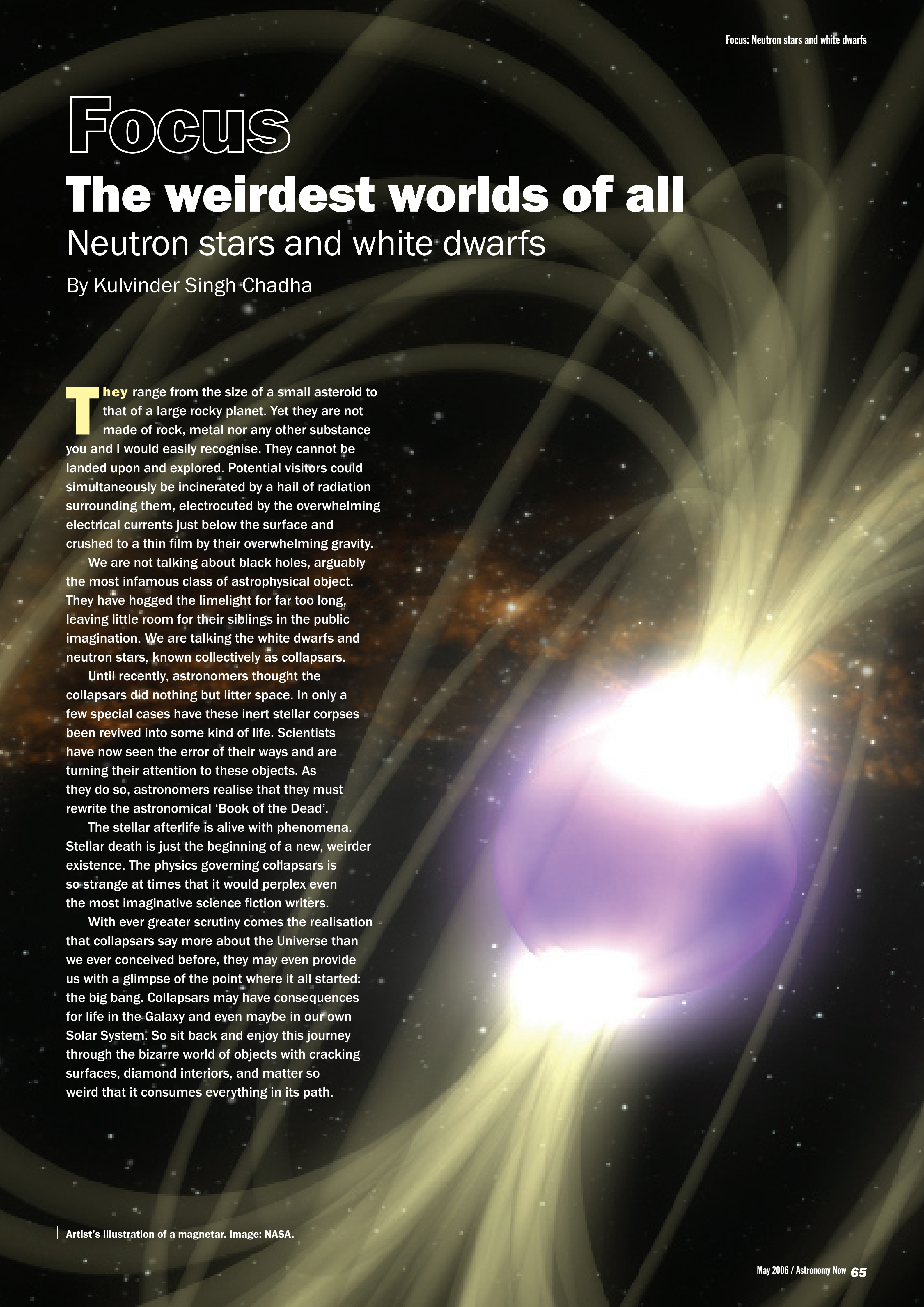
They range from the size of a small asteroid to that of a large rocky planet. Yet they are not made of rock, metal nor any other substance you and I would easily recognise. They cannot be landed upon and explored. Potential visitors could simultaneously be incinerated by a hail of radiation surrounding them, electrocuted by the overwhelming electrical currents just below the surface and crushed to a thin film by their overwhelming gravity.

We are not talking about black holes, arguably the most infamous class of astrophysical object. They have hogged the limelight for far too long, leaving little room for their siblings in the public imagination. We are talking the white dwarfs and neutron stars, known collectively as collapsars.

Until recently, astronomers thought the collapsars did nothing but litter space. In only a few special cases have these inert stellar corpses been revived into some kind of life. Scientists have now seen the error of their ways and are turning their attention to these objects. As they do so, astronomers realise that they must rewrite the astronomical ‘Book of the Dead’.

The stellar afterlife is alive with phenomena. Stellar death is just the beginning of a new, weirder existence. The physics governing collapsars is so strange at times that it would perplex even the most imaginative science fiction writers.

With ever greater scrutiny comes the realisation that collapsars say more about the Universe than we ever conceived before, they may even provide us with a glimpse of the point where it all started: the big bang. Collapsars may have consequences for life in the Galaxy and even maybe in our own Solar System. So sit back and enjoy this journey through the bizarre world of objects with cracking surfaces, diamond interiors, and matter so weird that it consumes everything in its path.



Artist’s illustration of a magnetar. Image: NASA.

The Eskimo Nebula (NGC 2392) is a beautiful example of what happens when a star dies. As the outer layers of gas are blown off to form a spectacular nebula, the core of the star collapses to form a bright, hot white dwarf. Image: NASA/Andrew Fruchter and the ERO Team [Sylvia Baggett (STScI), Richard Hook (ST-ECF), Zoltan Levay (STScI)].

A dwarf's heavy existence

The story of collapsars begins over a century ago with the discovery of the first white dwarf star. But even in the early twentieth century one particularly eminent astronomer did not want to face up to the full implications.

On the scale of collapsar weirdness, white dwarfs are the most normal. The American astronomer Alvan Graham Clark saw the first in 1862. He was following up a prediction by the German scientist Friedrich Bessel in 1841, who, upon observing the motions of the star Sirius, noticed that something large seemed to be tugging at it. Since he could not see it himself, Bessel was forced to conclude that whatever it was had to be small, about the size of the Earth. This made Sirius B, as it was named, a perplexing puzzle. How could something the size of Earth be as massive as the Sun?

It wouldn't be for another fifty years or so that science would provide the answer. In the 1920s, British physicist Ralph Fowler, University of Cambridge, used the revolutionary new science of quantum physics to realise that under certain circumstances matter could be squeezed to enormous densities.

"Fowler discovered a limit to the compacting of electrons [see box] and both he and Eddington were satisfied that the white dwarf problem had been solved," says Arthur Miller, Professor of physics at University College London and author of *Empire of the Stars*.

Though Fowler was correct to use quantum mechanics, his answer was incomplete. One man who recognised this was the Indian-born physicist, Subramanyan Chandrasekhar. Born

The birth of a white dwarf

This is a long, protracted affair. The parent star must die, before the collapsar can live. Inside the star, the intense nuclear furnace creates successively heavier and heavier chemical elements. In stars with less than five times the mass of the Sun, fusion stops as carbon is created. The carbon sits in a sphere at the centre of the star, becoming progressively denser as gravity squeezes it relentlessly together. Eventually the core settles into an object about the size of the Earth but containing up to 1.4 times the mass of the Sun. This is known as a white dwarf star. As the outer layers of the dying star disperse into space, the white dwarf is revealed. The interior of the white dwarf is thought to be crystalline and, because the main constituent is carbon, there is a strong possibility that it is a diamond of 10^{34} carats.

This supernova remnant in Puppis hides within it the hottest white dwarf known. At more than 200,000 degrees Celsius it is thirty times hotter than the Sun and 250 times as bright. Image: NASA/The Hubble Heritage Team/H Bond (STScI) and R Ciardullo (PSU).

in Lahore, Chandra as he was known, gained a physics degree at Presidency College, Madras, India. He then left for England to work on stellar physics in Cambridge under the tutelage of the eminent British astronomer Sir Arthur Eddington, a man Chandrasekhar had admired greatly. Whilst at Cambridge, Chandrasekhar studied Eddington's work on white dwarfs, becoming ever more frustrated by the lack of a rigorous mathematical analysis.

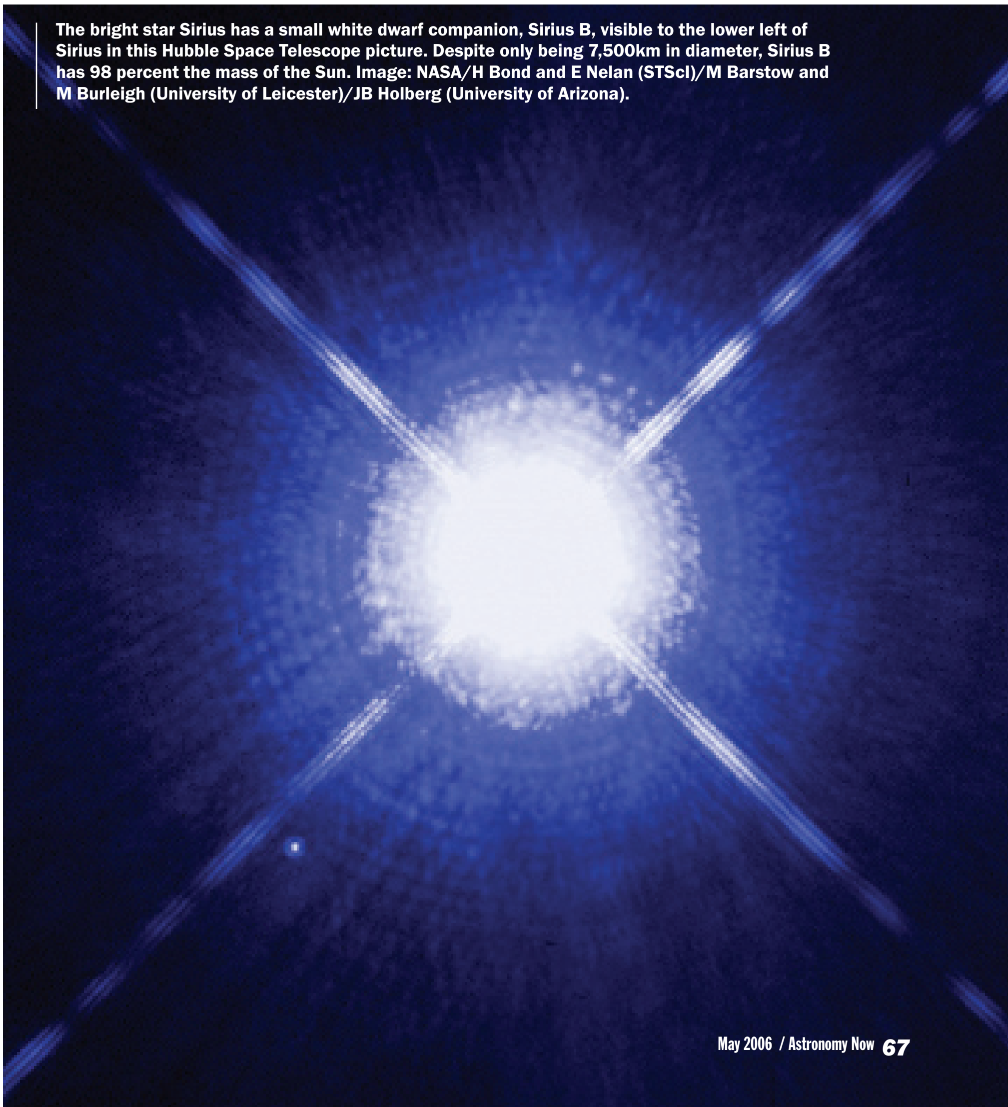
Chandra provided a fresh pair of eyes to the subject. As well as quantum physics, he also applied Einstein's theory of relativity to the solution and calculated that the maximum mass a white dwarf can have is 1.4 times that of the Sun. Any heavier, and it would collapse further into, what was thought at the time to be an indeterminate point.

At a now infamous Royal Astronomical Society lecture in 1933, Chandra was surprised and intrigued to learn that Eddington was presenting a lecture straight after him on the topic of white dwarfs. After Chandra presented his results to the society, Eddington stepped up to deliver his own talk and his purpose become clear. His talk was an attack Chandra's results, in particular the use of relativity.

Chandrasekhar was deeply shocked that Eddington had attacked him so publicly, not having warned him privately beforehand. Had Chandra got it all wrong? He went over his calculations again and again but could not see any errors. Although he was convinced of his correctness, his superior's opinion held sway. Eddington was, after all, the most prominent astronomer of his day and a gifted mathematician, so no one would publicly challenge his viewpoint.

What happened? Had Chandrasekhar made a mistake? Why did Eddington act in such an insidious fashion that Chandrasekhar left Cambridge altogether?

As Miller explains: "The reasons for Eddington's actions that day are



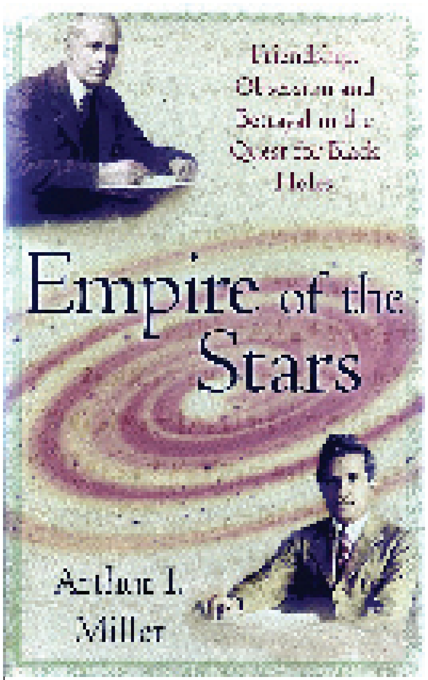
The bright star Sirius has a small white dwarf companion, Sirius B, visible to the lower left of Sirius in this Hubble Space Telescope picture. Despite only being 7,500km in diameter, Sirius B has 98 percent the mass of the Sun. Image: NASA/H Bond and E Nelan (STScI)/M Barstow and M Burleigh (University of Leicester)/JB Holberg (University of Arizona).

Influential British astronomer Arthur Eddington spoke out about his disbelief in white dwarfs. Image: Royal Astronomical Society.

How can something so small be so heavy?

There is surprisingly little to the atoms which make up most things in the Universe. An atom consists of a nucleus of protons and neutrons, surrounded by consecutive 'shells' of orbiting electrons (analogous to Russian dolls). But after taking these elementary particles into consideration, nearly all of the volume of an atom is empty space. The gravitational pull of a white dwarf is such that the atoms become compacted, like commuters on a rush-hour train filling up all the available space. In the white dwarf, this forces electrons to move closer together, creating an outward pressure that resists gravity and prevents further collapse. By this stage, however, a lot of matter has been compacted into a small volume.

This pressure can be overcome. If the star is greater than 1.4 times the mass of the Sun, gravity again becomes the dominant force and the collapse continues. The electrons are forced to merge with the protons, and turn into neutrons. Again, if the star is not too big, there comes a point where pressure from the momentum of the neutrons halts further collapse, creating a neutron star.



Arthur Miller's book *Empire of the Stars: Obsession Friendship and Betrayal in the Search for Black Holes* explores the relationship between Eddington and Chandrasekhar. The paperback edition will be out in October 2006.

long and complicated, but basically what it boils down to is that Eddington for a number of years was working on a fundamental theory." What Miller is referring to is Eddington's 'theory of everything' that had become an important part of his life. "What Eddington was trying to do was unite Einstein's theory of General Relativity with Quantum Theory. He believed that there was a single fundamental rule to describe how the Universe worked. This was not only a pivotal part of his scientific work but also of his life. Eddington had believed that the fundamental theory could explain things like consciousness, for example. Then along came Chandrasekhar with his complete description of white dwarfs."

The consequences of Chandra's work would have meant that Eddington's fundamental theory could not be true. Having invested many years on this masterwork, Eddington was not prepared to believe the results of his young protégé. What made Eddington's actions that day all the more extraordinary is that he had encouraged Chandra to continue up to the RAS meeting. It would seem that he wanted to destroy publicly any faith in the ideas that Chandra was developing.

Chandra's treatment by Eddington turned him from England and drove him to America. Although filled with self-doubt, he was encouraged to continue by trailblazing figures in quantum physics such as Wolfgang Pauli and Neils Bohr. They were convinced that Chandrasekhar was on the right lines. And they were right, although true recognition for his ideas took half a century. For solving the white dwarf problem, Chandrasekhar was awarded the 1983 Nobel Prize for physics.

Because of Chandrasekhar's insight, a crucial piece of the white dwarf puzzle had been found. Astronomers had opened the door into the weird world of the collapsars.

The star that could sit in a city

Beyond the white dwarfs are the neutron stars. Over a hundred times smaller than the white dwarfs, they are much weirder, too.

Neutron stars are not simply denser versions of white dwarfs. They exhibit strange behaviour all of their own. As scientists now know, they are not even just made of neutrons. Scientists believe that these weird bodies have kilometre thick crusts of superdense iron, superfluid interiors that flow without friction, and crystalline cores, which in some cases may even be made of the most exotic form of known matter yet: so-called 'strange matter'.

Enigmatic key players

Only a year after Sir James Chadwick discovered the 'neutral particle' (thereafter named the neutron) in 1932, American scientists Walter Baade and Fritz Zwicky proposed the existence of so-called neutron stars, each a tiny sphere of densely packed neutrons.

A neutron star forms when the core of a dying star is greater than 1.4 times the mass of the Sun. The stars from which they hail are thought themselves to be between 15 to 30 times the mass of our own Sun.

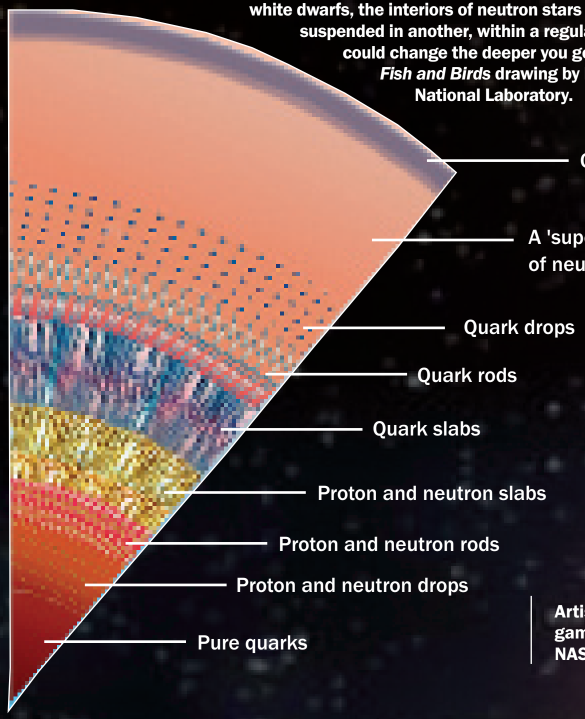
What physical properties would a neutron star have? Professor Malvin Ruderman is a scientist at the University of Columbia, New York. He says, "The crust of a neutron star is an extraordinarily good electrical conductor, many millions of times better than, say, copper. This is because the electrons are so densely packed that they're forced to move about at nearly light speed." This follows from a particularly bizarre law of physics called Heisenberg's Uncertainty Principle. It means that in the dense surroundings of a neutron star, electrical currents move with extraordinary ease, much like a skater on ice.

Einstein's legacy

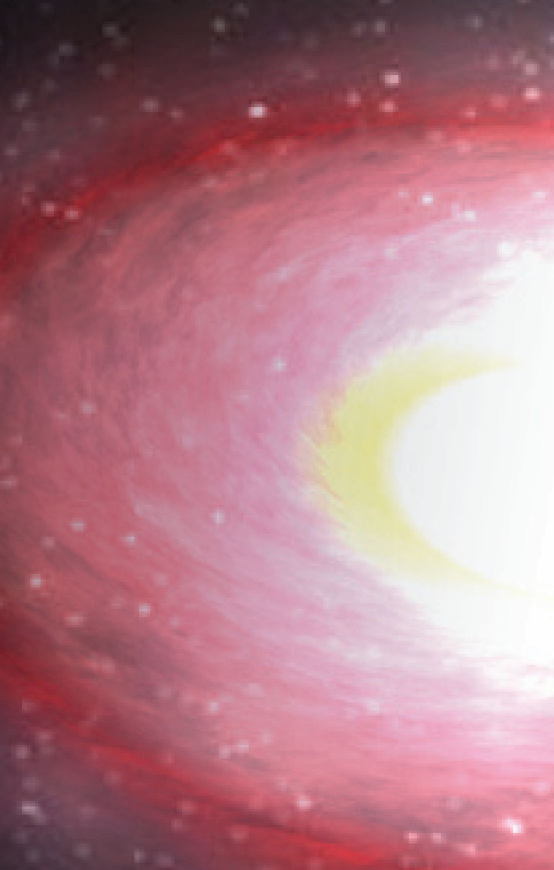
What would the surface of a neutron star look like if you could see it up close? It would be rotating anywhere between twice a minute and six hundred times a second. It would have an atmosphere just centimetres thick. The gravity of a neutron star would be up to several trillion times stronger than the Earth's and you would need to be travelling at half the speed of light to escape its pull.

Because of Einstein's theory of relativity, time would appear to slow

Neutron stars are so small they could easily fit within the confines of a city such as London.
Image: NASA/GSFC/METI/ERSDAC/JAROS and US/Japan ASTER Science Team.



A cross section of a neutron star. Neutron stars may have crystalline interiors, but unlike white dwarfs, the interiors of neutron stars are composed of one kind of matter suspended in another, within a regular geometric structure. This structuring could change the deeper you go into the star, much like the famous *Fish and Birds* drawing by Escher. Image: Lawrence Berkeley National Laboratory.



Artist's impression of a gamma-ray burst. Image: NASA/Dana Berry.

down in this strong gravitational field. Anyone caught in the field around the collapsar would see the surface become bluer. Conversely, anyone outside would see the surface get redder as they moved away. This is down to the so-called gravitational redshift and occurs because light loses energy when moving from strong gravitational regions to weaker ones.

The effect is complicated if the neutron star is rotating rapidly as it drags the fabric of the spacetime in its vicinity around with it, somewhat similar to water being dragged around a vortex or whirlpool (water escaping down a plughole being a fine example).

Anyone falling onto a neutron star would immediately be crushed, releasing five times more energy than the bomb that destroyed Nagasaki. And that's if the magnetic field doesn't get you first.

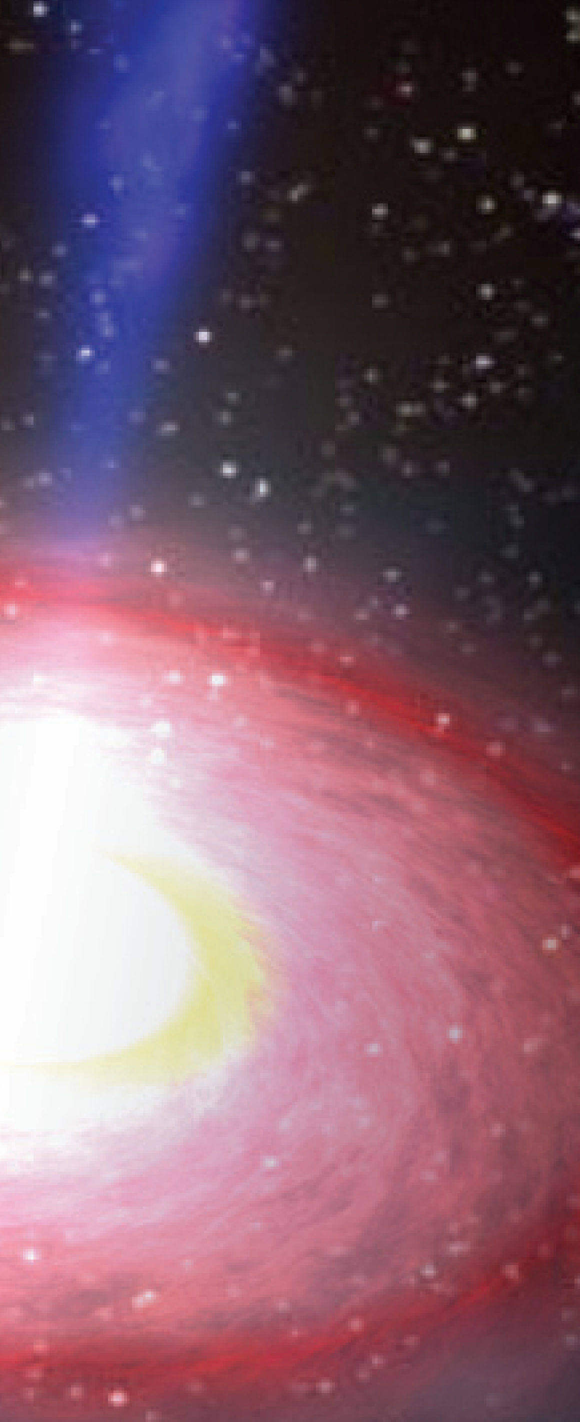
Magnetic mush

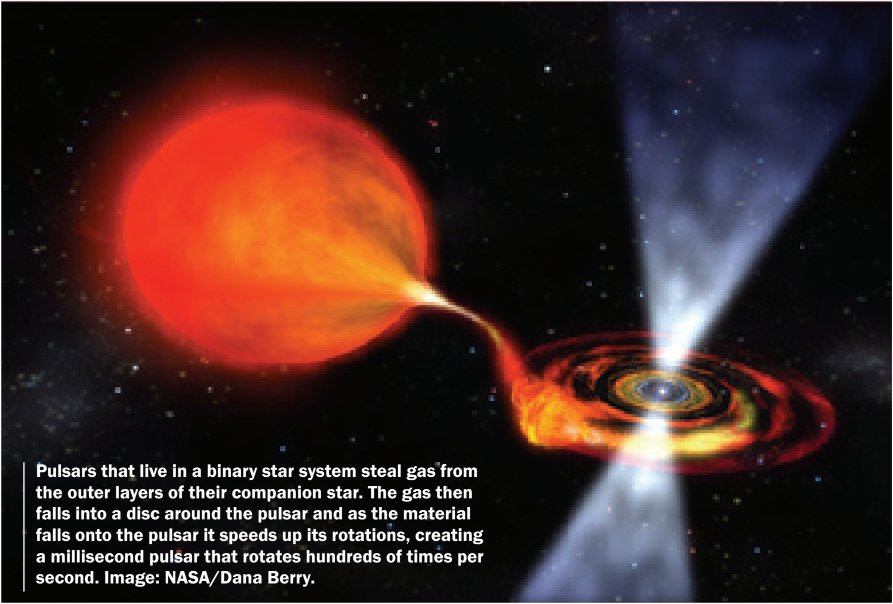
Neutron stars possess magnetic fields so powerful that there is no comparison here on Earth. A fridge magnet has a magnetic field of ten gauss. A neutron star can typically have a field of one trillion gauss. If such a neutron star were placed halfway between the Earth and the Moon, it would wipe out every credit card, videotape and floppy disk in the world. Paperclips, pins, nails, nuts, bolts, screws, staples, and all other things small and ferrous would launch themselves from the Earth, attracted by the collapsar's magnetic field.

As if that were not strong enough, some neutron stars possess magnetic fields between a hundred and a thousand times stronger than standard neutron stars. These objects are the magnetars. They have slow rotational periods because their colossal fields drag the star nearly to a halt. Magnetars have the most powerful magnetic fields known anywhere in nature. The reasons for this are not known, says Ruderman, who goes on to say, "There have been many suggestions but no agreement yet. Although the magnetic field strength of a magnetar (10^{15} gauss) is extraordinarily large, it may not be otherwise different from well known magnetic white dwarfs with magnetic fields of 10^9 gauss. If you were rapidly to squeeze one of these down to the radius of a neutron star it could end with a magnetar's field strength." Ruderman is at pains to point out that he doesn't suggest that magnetic white dwarfs may be the progenitors of magnetars, merely that they may have similarities in their evolutionary development.

This kind of star is obviously not something you would want halfway between you and the Moon. The strongest magnetic field the human body is likely to experience is in a magnetic resonance imager in a hospital (10^6 gauss). Experiencing a field of 10^9 gauss is lethal because at these strengths, magnetism affects every kind of material, not just magnetic ones. Atoms change from being round into being cigar shaped as they align themselves in the strong field. Because the electrons are trapped in the magnetic flux lines, they do not interact with those of other atoms. This has the effect of isolating each atom from its neighbour. Because of this there would no longer be any molecules (collections of different atoms joined together) and the chemistry of life would cease. You would, in effect, become a 'magnetic mush' of atoms, retained only by the field.

A magnetar's field is so huge that anything in its vicinity will have their atoms





Pulsars that live in a binary star system steal gas from the outer layers of their companion star. The gas then falls into a disc around the pulsar and as the material falls onto the pulsar it speeds up its rotations, creating a millisecond pulsar that rotates hundreds of times per second. Image: NASA/Dana Berry.

turned into useless needles, aligned in the field. It could be thought of as a 'head of hair' with each filament being one atom thick. In fact, this is what occurs at the magnetar's surface at the regions where the magnetic field is particularly strong.

A glitch in the system

Magnetars also have surfaces that ripple and crack, releasing huge amounts of energy in a 'starquake'. Sometimes there is an abrupt change in the rotation of a body, and this is thought to be due to a change in the surface of amazingly, only a centimetre. This effect holds true for standard neutron stars as well.

Magnetars could be a candidate for the biggest bangs in the solar system, the gamma-ray burst (GRB). Robert Chapman of the University of Hertfordshire is part of a team looking at gamma-ray bursts. He says, "Magnetars have a very short lifespan of around 10,000 years and have thus been dismissed by most people as possible GRB candidates. What we're saying is that this dismissal is possibly a bit premature."

Chapman goes on to say how there are two kinds of GRBs, the long duration single events (associated with hypernovae), and the periodic short duration burst, the so-called soft gamma repeaters (SGRs). "What we see from the energy spectrum of an SGR is a brief, intense spike, followed by a receding tail. On a magnetar, a twisted magnetic field snapping back in place can cause the kind of spike we've seen. The high-speed charged particles trapped on the surface can cause a fireball, resulting in the 'tail' we see. Because their lifetimes are so short, these magnetars must exist in regions of star formation. Others have dismissed star-forming regions but we think this warrants another look." Previously, the favoured explanation for SGRs has been collisions between white dwarfs, or between neutron stars.

Some even believe that the long duration GRBs can be explained by single neutron stars. Louis Clavelli is a professor of astrophysics at the University of Alabama. He shook up the astronomical world by suggesting that quantum bubbles could tear apart collapsars, causing GRB events.

Quantum bubbles are predicted by quantum theory. They can occur in the emptiness of space, are usually incredibly small, and last for the briefest moment before they collapse. It is possible for a large bubble to form in space, in which case it would expand, potentially engulfing the Universe. There is little need to panic however, as the chances of this happening are next to zero. But things don't look quite so rosy for the collapsars.

The extreme density of collapsar material could endow it with the ideal conditions for a quantum bubble to expand, and so the likelihood of a randomly formed quantum bubble expanding to engulf a collapsar is not as remote as it is for the rest of the Universe.

According to Clavelli's theory, a bubble that formed and expanded would turn the normal particles in the collapsar into denser versions, as yet undetected from Earth. The resultant effect would be that the collapsar could support itself no further, and would undergo an ultimate collapse into a black hole. This event would release energy in the form of a massive burst of gamma rays.

Clavelli's original theory is based on white dwarfs. As he says, "I'm still thinking about the possibility [of it happening] in neutron stars or elsewhere. The volume of a neutron star is so small that the probability of bubbles forming there would be small compared to white dwarfs unless the surface tension of the bubble was quite high."

Clavelli continues, saying that his extraordinary idea hasn't yet gained much acceptance, despite being based

The swirling mass of gas surrounding the Crab Nebula pulsar. Combination Image: NASA/CXC/ASU/J. Hester et al and NASA/HST/ASU/J. Hester et al.

on sound physics. The problem is that (as Clavelli himself would admit) there is at present no way of testing this theory. Clavelli though originally formulated his theory because he was dissatisfied with the standard GRB models.

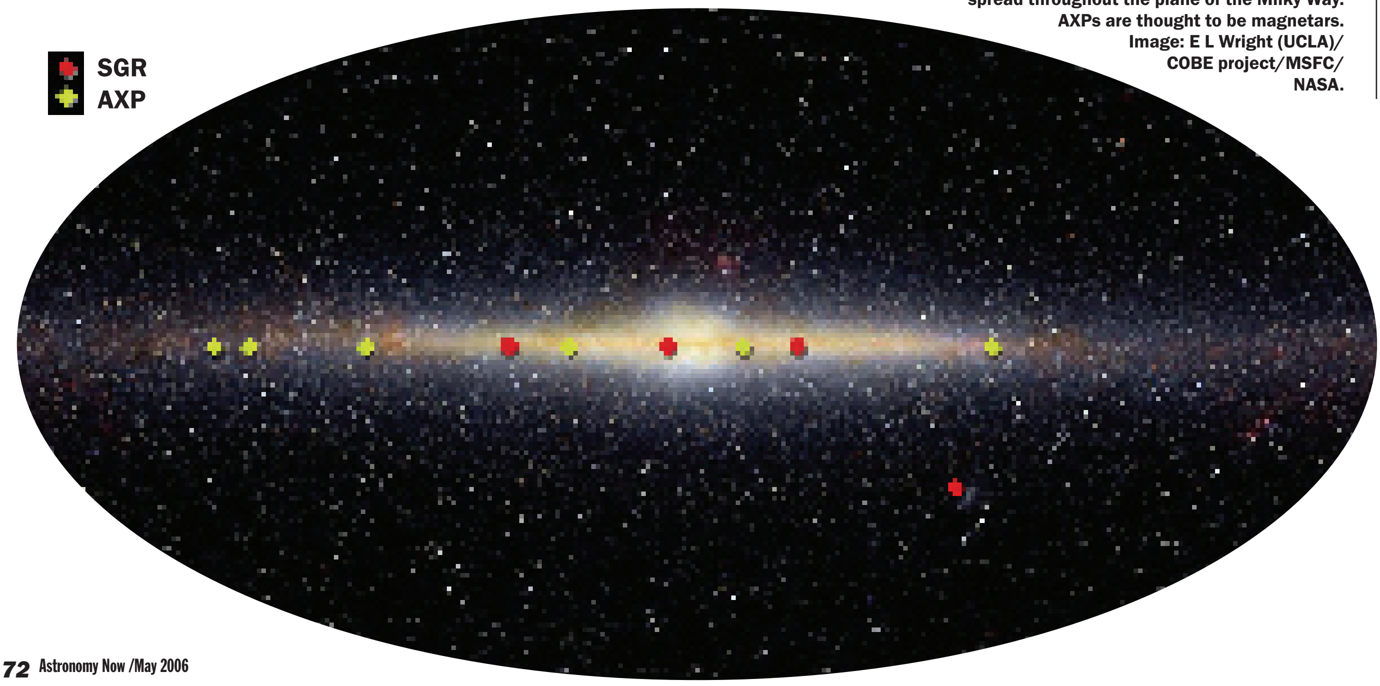
"The quantum bubble idea accounts for the broad features of the gamma-ray burst. But so far there is no compelling evidence that would force everyone to drop alternative theories. Most astronomers are still hoping for a standard model explanation, which, for the short bursts, would require a fast moving disc of material falling onto a neutron star or black hole. The relative absence of telltale afterglows suggests to me that this isn't the sole mechanism. The standard approaches aren't really successful when it comes to producing the jet structures expected from gamma-ray bursts either, or for the extreme energy release, which would be necessary if the bursts are not highly collimated.

The popular collapsar model for the long bursts does not really provide a good model for the 'central engine' but finds its major successes in modelling the consequences of such a sudden energy release. Thus, there might be room for a combination of the quantum bubble idea with the standard collapsar models."

Stellar clocks

Ordinary stars rotate about their axis. The more massive they are, the faster they spin. Neutron stars, being much smaller but just as massive, can rotate at an astonishing six hundred times a second. Gradually, they slow down as the energy of rotation transforms into radiation and escapes into space. The neutron star's powerful magnetic field funnels the radiation into a cone, which, if orientated just right, can be detected as a series of pulses here on Earth. Neutron stars of this type are called pulsars. The timing of the pulses varies from several seconds to 1.5 thousandths of a second. Nothing faster than that has yet been detected. Very gradually, the rotation rate of the neutron star slows down. Typically, a neutron star's rotation can expect to slow by just over a second in a million years. Although the latest atomic clock is a hundred times more accurate, a neutron star pulsar would still keep time 175 million times more precisely than a quartz wrist watch.

The discovery of these pulses from Cambridge in 1967 was the first direct evidence of the existence of neutron stars since they were first proposed by Baade and Zwicky. It turned out that the extremely regular pulses weren't coming from alien machinery as some had initially thought. Controversially, although graduate student Jocelyn Bell made the discovery, her supervisor Anthony Hewish received the Nobel Prize.



Soft Gamma Repeaters (SGRs) and objects called Anomalous X-ray Pulsars (AXPs) are spread throughout the plane of the Milky Way. AXPs are thought to be magnetars. Image: E L Wright (UCLA)/ COBE project/MSFC/ NASA.

The strangelet that time forgot

What lies beyond the neutron stars? Conventionally, astronomers thought it was the black holes but now they are considering another stopgap collapsar, the aptly named strange star.

Neutron stars are difficult to spot unless they have a nebula around them. This particular neutron star is RX J185635-3754, and may actually turn out to be a quark star.
Image: Fred Walter (State University of New York at Stony Brook) and NASA.

If you crush a neutron star, it would become a black hole, right? Well maybe not. It may become something even weirder, a quark star. It's believed that the neutrons would break down into their individual quarks (protons and neutrons are each made of three 'up' or 'down' quarks). In effect, the star would become a giant nucleon, that is, it could be thought of as a single atomic particle several miles across. Due to quantum theory, some of these quarks would be massive, so-called 'strange' quarks, which last for only fractions of a second in particle accelerators on Earth.

Dr Jeremy Drake of the Harvard Smithsonian Center for Astrophysics Research may well be the discoverer of this new kind of object. Using the results from the Chandra X-ray orbiting observatory, Drake found that the temperature of the unimaginatively named

RX J1856.5-3754 meant it could not be a neutron star. Though some have cast doubt on the actual measurements, Drake thinks that this could be a strange matter star. However, he admits that more evidence is needed, and does not hold any firm conclusions.

He says, "In a neutron star, you could have stable clumps of strange matter, composed of some several hundred quarks. It isn't certain whether a quark star could be stable. If it was, the star would possess a strong electric charge, and the resulting field would likely repel anything in its vicinity." Drake then goes on to explain how some theories suggest a solid crust for a quark star, over a layer of strange matter. This would have the bizarre effect of there being a gap between the two all around the star because of the latter's repulsion of the crust by electrostatic forces.

Drake then explained, "The physics is indeterminate, but for reasons I couldn't fathom, some [scientists] were vehemently opposed to the possibility of quark stars, though others were open and supportive." It seems that Drake's situation has some parallels with Chandrasekhar's.

Ed Whitten, of Princeton University, New Jersey, was the first scientist to suggest the possibility of quark stars. Some were quick to dismiss his ideas as ludicrous. Their reasoning was that if strange stars had always existed, strange matter would be released in quark star collisions, spreading the material through space, which we would then detect in our own Solar System as well as elsewhere in the Galaxy. But as Drake says, "The reason this argument is flawed is because you're assuming that there are lots and lots of these collisions, and we are just not detecting any."

This is probably a good thing too, because if strange matter collided with normal matter at high speed, there is the possibility that the normal matter would become quark matter too. Unlike neutron star or white dwarf material, which will change its structure if removed from the crushing gravitational field of the collapsar, it is theoretically possible that chunks of quark matter, or strangelets as small quantities of the stuff are known, can be stable on their own. Indeed, scientists at CERN think they may have created this very exotic material.

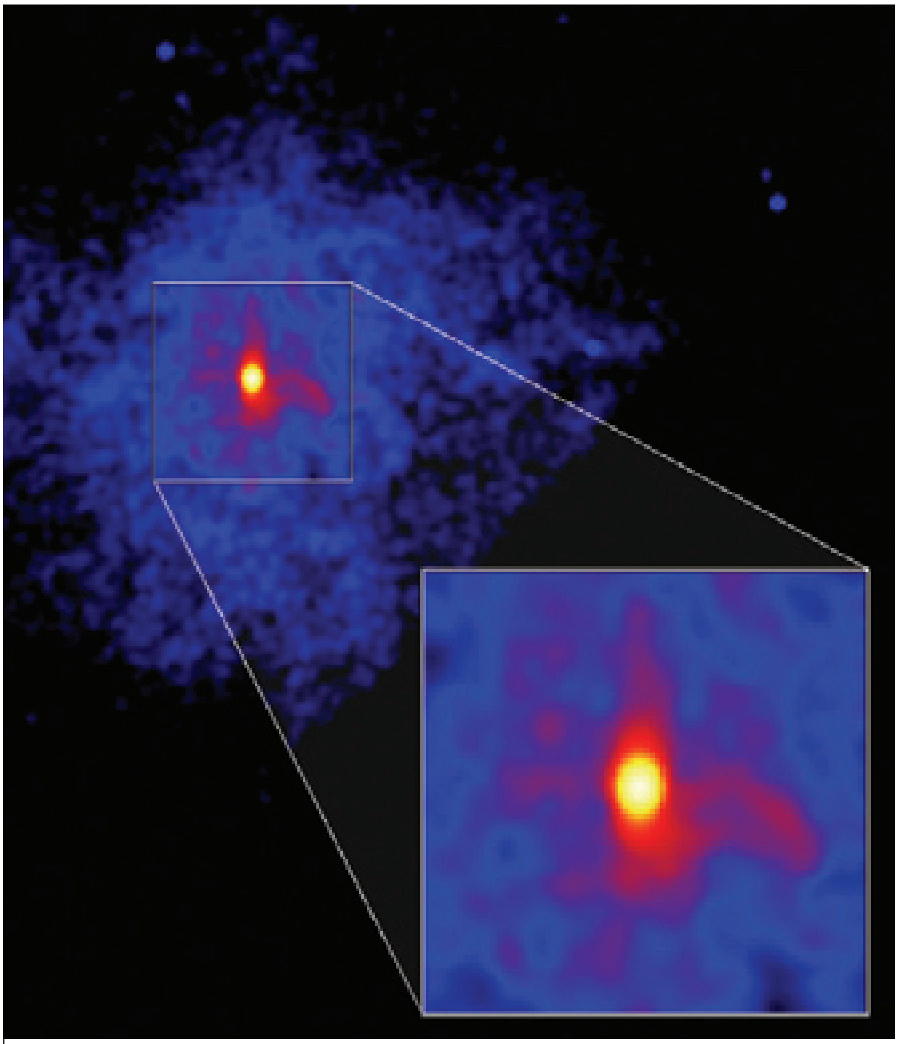
How could we be certain that

some of the collapsars out there could in fact be quark stars? Dr Maura McLaughlin is an astrophysicist at Jodrell Bank radio observatory in Macclesfield. She intends to perform pulsar searches using the proposed Square Kilometre Array (SKA). SKA will be a revolutionary radio telescope (of obvious size) utilizing a bank of separate aerials. Its location will be decided this year. The great thing about SKA is that it uses existing off-the-shelf components, greatly reducing costs. As McLaughlin explains, "It'll be able to see several degrees of sky, compared with the much tinier areas of its predecessors. SKA is ten times more sensitive than the radio telescope at Arecibo, and will be able to see about ten different pulsars simultaneously." Although McLaughlin and her team did not specifically mention strange stars, if the discovery of these objects is real then some of them are bound to turn out to be quark stars.

If the rotation rates of any detected strange stars are faster than 1.5 milliseconds, this would be good evidence, as it would point to an object heavier that a neutron star. Some astronomers even believe that strange stars will be found that were formed during the big bang. If so, astronomers might glimpse a living fossil of the birth of the Universe.

Whatever we discover, the truth is certain to be weirder than we can imagine.

Kulvinder Singh Chadha* is Astronomy Now's *staff writer.



The supposed pulsar 3c58, buried in the middle of this X-ray emission, is a little too cold for comfort. Some believe the temperatures mean it is a quark star. Image: X-ray: NASA/CXC/SAO/P.Slane et al.

On the trail of the quark stars. The Square Kilometre Array will begin its search during the next decade. Image: SKA.