Particle theorists and astronomers are investigating the bizarre properties of the densest known state of matter – quark matter – which may exist only in objects about to collapse into black holes


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Superconducting quarks

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What happens as you squeeze matter? We all know that, under pressure, substances rearrange themselves into denser forms, or phases. Gases turn into liquids, and liquids typically turn into solids. But that is nothing compared with the changes that happen when the crushing force of gravity, in the aftermath of a supernova, squeezes a massive star into a ball about 20 kilometres across.

The density of such a compact star is so high that atoms themselves cannot exist. Atomic nuclei swallow their space-wasting electron clouds and are pressed together into a liquid of protons and neutrons. But protons and neutrons still have a modicum of internal structure: in each of them, three quarks are bound together by the strong force as described by the Standard Model of Particle Physics. In the core of the compact star, at the highest densities that are known to exist in Nature, many physicists speculate that the relentless piston of gravity will finally crush these last vestiges of structure, leaving the densest form of matter that our theories can describe – quark matter.

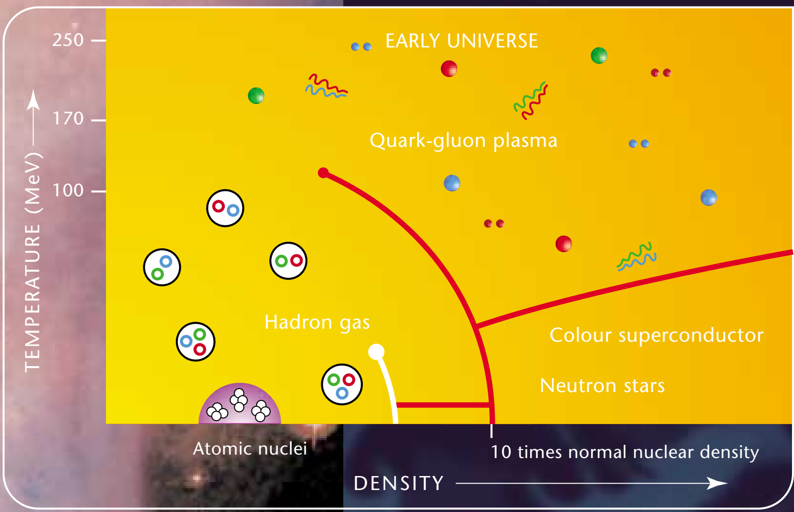
Inside a neutron star

The core of a compact, or neutron star is one of the hardest places in the Universe to study experimentally. Sheathed in nuclear matter that is still glowing from the heat of the supernova, and scattered out in space thousands of light years from Earth, compact star cores are almost as mysterious to us as the ocean floor was to primitive Man. But armed with the Standard Model, we can make some reasonable guesses about what might be found there. In the Standard Model, the ultimate constituents of matter are quarks and electrons, so at high enough pressure we expect a liquid of quarks and electrons to form, which is the quark matter.

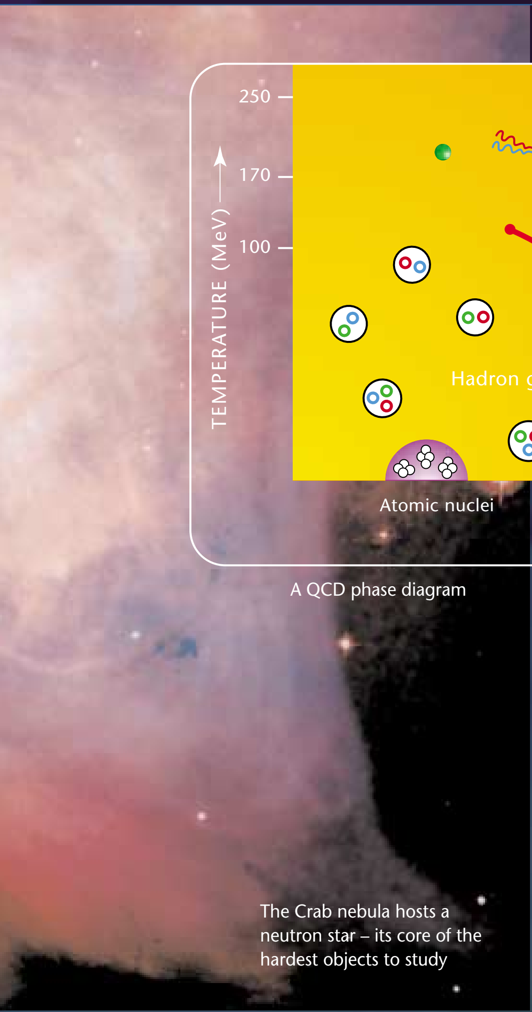
No one knows whether the core of a compact star achieves such pressures, but it certainly comes close. And in spite of the difficulties, astronomers are gradually obtaining more and more information about compact stars: their mass, rotation frequency, size, cooling rate, and so on. So theorists are beginning to ask themselves: how would quark matter be expected to behave? And building on that, could we tell from Earth-based observations of distant compact stars whether they have quark matter in their cores?

For theorists, one of the surprising results of their calculations is that quark matter has its own rich set of distinct forms. Quarks, like electrons, belong to a discrete set of quantum particles with half-integer spin, and since the 1950s we have known that such particles in a metal can become superconducting by forming pairs in which two spins cancel. In the past few years a growing number of nuclear and particle theorists have become convinced that something similar will happen in quark matter. Since the strong interaction between quarks is associated with their so-called colour charge (red, green or blue), and described by a theory called quantum chromodynamics (QCD), this special quark state is known as a colour superconductor.

Unlike an electrical superconductor, however, colour-superconducting quark matter comes in many varieties, each of which is a separate phase of matter. This is because quarks, unlike electrons, come in many species. They can have one of three different colours, and in the core of a compact star we expect three different flavours of quark (up, down and strange) to exist. This means that in pairing up there are many choices: will the red down quarks pair with the green up quarks, or



A QCD phase diagram



The Crab nebula hosts a neutron star – its core of the hardest objects to study

the blue strange quarks?

It is very hard to answer this question definitively, because lattice QCD – the usual brute-force computational approach – is unusable at high quark density. Physicists are currently trying to get a rough idea of the special properties of each phase, and the signatures by which experimental observations can tell us which is favoured. This is a worldwide effort involving researchers in Germany, Italy, Japan, the US, and many other countries. The UK is involved too. At the University of Wales Swansea, Simon Hands is finding ways to apply lattice QCD methods to quark matter. And at Glasgow University and Washington University, St Louis in the US, with Jürgen Berges of the ITP at Heidelberg University, we are exploring new methods for dense-matter calculations. We investigate the lowest-density forms of colour superconductivity that have the best chance of existing in Nature, and we try to envisage how these phases might manifest themselves in observable signatures.

Although compact stars are remote and hard to observe, theorists and astronomers are now optimistic that such signatures exist. One example is simply the rate at which a compact star cools. The compact star starts out, freshly created by a supernova, 10,000 times hotter than the core of our Sun. Its surface glows with X-rays, which can be observed by telescopes such as NASA's Chandra.

Signatures of quark matter

Over thousands of years a compact star gradually cools, and, by measuring the spectra and ages of such stars in our Galaxy, observers can construct a temperature-versus-time cooling curve. The crucial point is that the star cools not via the radiation from its surface, but mainly by emitting neutrinos from its interior. The exact rate of the cooling therefore depends on the heat capacity and neutrino emissivity of the star's interior, and it turns out that the existence of a colour superconducting phase in the core can greatly influence these properties. Colour superconducting quark matter cools very slowly, in a way that is consistent with observed cooling curves.

A more exotic signature is connected with the dynamics of the rotating compact star. If its interior has low enough viscosity, then unstable flows ('r-modes') can occur, and these would rapidly carry off the angular momentum, causing its spin to slow down very quickly. Most forms of colour superconducting quark matter are actually superfluids (superfluidity is when a fluid loses all viscosity). They would, therefore, permit rapid spindown via r-modes. But we see plenty of fast-spinning neutron stars, such as millisecond pulsars, indicating that the matter inside these neutron stars is too viscous to allow r-mode flows. So we may soon be able to rule out some of these superfluid phases. To do this definitively will require better r-mode calculations, such as those being performed by Peter Jones at Oxford and Nils Andersson at Southampton University.

All this work on high-density quark matter fits into a more general quest to build the 'phase diagram' for QCD – a road map of the behaviour of matter under extreme conditions of ultra-high density and/or ultra-high temperature. At sufficiently high temperatures, nuclei 'ionise' into a plasma of quarks – the quark-gluon plasma (QGP). This happens at about a million million degrees (170 MeV in particle-physics units).

Surprisingly, it is easier to produce such temperatures, albeit briefly, in the laboratory, than it is to achieve the densities required to make colour superconducting quark matter. Accelerators such as RHIC at Brookhaven National Laboratory and the Large Hadron Collider being constructed at CERN can collide heavy nuclei to make tiny flashes of QGP whose products can be studied to learn more about that state. However, it is hard to make a cool lump of high-density matter this way, so observations of compact stars still have a vital role to play. Together, particle physicists and astronomers hope to collect enough data to allow them to draw the phase boundaries in the QCD phase diagram, and see whether they match theorists' predictions. F

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Inside a neutron star