News & views

Astronomy

Collisions ring in a clue to extreme-matter puzzle

Paul D. Lasky

The pitch of oscillations detected in the γ-rays that are emitted when neutron stars collide could provide insight into the hottest and densest matter in the Universe — revealing physics that cannot be studied with terrestrial experiments. **See p.253**

Neutron stars have masses greater than that of the Sun, but are typically no bigger than a small city[1]. So when two of them collide, they provide some pretty exciting fireworks that can be observed from Earth, even when they are millions to billions of parsecs away. Astronomers have been recording their observations of these spectacular events for decades[2,3]. Now, on page 253, Chirenti *et al.*[4] have gone back through these archives, and made a discovery that could accelerate our understanding of physics in the most extreme regions of the Universe.

Neutron-star mergers are usually observed as short flashes of tremendously bright γ-rays that last for less than two seconds. But they can also be detected by looking at longer-lived tails of X-ray radiation that sometimes follow the flashes. Occasionally, afterglows with optical, ultraviolet and radio wavelengths follow these tails and can also signal a merger. Two neutron-star mergers have even been detected using gravitational waves, which are ripples of gravity, first detected in 2015, that the stars generate as they orbit each other[5]. One such event was simultaneously observed at wavelengths across the entire electromagnetic spectrum[6,7].

Despite this wealth of information, many aspects of neutron-star collisions still evade our understanding. And yet they provide clues to some of the most intriguing problems in theoretical physics, including how matter behaves in conditions that cannot be replicated in the laboratory. These collisions involve densities 10^{15} times that of water[1], temperatures ten million times hotter than the surface of the Sun[8] and magnetic fields ten billion times that of the strongest magnet produced on Earth[9].

Nuclear physicists cannot calculate how matter should behave during and immediately after these mergers, even with the most powerful computers. The physics of this behaviour is so bizarre that there's even the possibility that individual quarks — the fundamental particles that make up protons and neutrons — leach out of their subatomic particles and form a quark soup. The only other time this is thought to have happened in the Universe is a minuscule fraction of a second after the Big Bang.

For many neutron-star mergers, the immediate aftermath involves the birth of a new neutron star that is at least twice as massive as the Sun, has a radius of 10–15 kilometres and rotates between 1,000 and 2,000 times per second[10] (Fig. 1). The collision is so violent that this newly born neutron star undergoes frenzied oscillations as it rotates.

Evidence of these oscillations has never been found, and numerical simulations[11] suggest that they could be observable as a quasi-periodic modulation of the γ-ray signal.

Chirenti *et al.* report that they have detected signatures of these quasiperiodic oscillations in γ-ray observations from two neutron-star mergers. Although the discovery of such quasi-periodic oscillations would be fascinating in itself, it's what they might reveal about the physics of neutron stars that is of particular interest.

Hitting a drum makes a sound at a single frequency (or pitch) that is characteristic of the size of the drum: a small drum has a high pitch, and a large drum has a low pitch. Likewise, a smaller, or more compact, remnant of a neutron-star merger oscillates with a higher frequency than does a larger, less compact one. Measuring the oscillation frequency can therefore reveal the compactness of the neutron star. This compactness is key to determining which of many proposed mathematical expressions[1], known as equations of state, best describes the behaviour of matter in a neutron-star merger.

Chirenti *et al.* measured the pitch of oscillations from their two post-merger remnants, and found that it was consistent with the quasiperiodic oscillations found in the simulations[11]. Unfortunately, it's not possible to be more precise than this about the physical implications of these results. One reason is that the masses of the remnants are unknown, and this information is required for a robust conclusion to be made about the equation of state on the basis of measured oscillation frequencies.

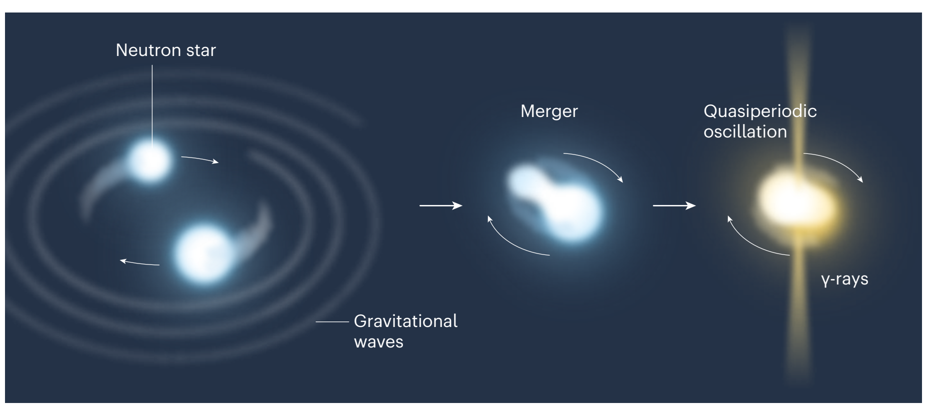

Figure 1 | Signals from a neutron-star merger. When two neutron stars collide and merge, the new neutron star that forms undergoes oscillations that have been predicted to be quasiperiodic[11]. Chirenti *et al.*[4] detected signatures of quasiperiodic oscillations in γ-rays from two neutron-star mergers. The discovery could help us to understand how matter behaves under the extreme conditions that these events generate. But this knowledge would require estimates of the distance from the detector to the binary system, and the masses of the neutron stars before they collided. Gravitational-wave observatories could provide this missing information, because they measure ripples of the gravity that the stars generated while still in orbit.

This uncertainty is exacerbated by the fact that it's also unclear how far away these mergers occurred. The expansion of the Universe implies that the measured oscillation frequencies differ from those that are emitted at the source, but inferring one from the other requires knowledge of the separation between source and detector. And it's impossible to determine the equation of state accurately without knowing the emitted frequencies.

Although bold statements about the equation of state are not immediately forthcoming from this work, Chirenti and colleagues' findings are certainly cause for excitement. Binary neutron-star mergers are prime candidates for being detected through the gravitational waves they generate. Observations of these waves would provide precisely the details that are missing from the authors' study. Gravitational-wave observatories, such as the United States' Laser Interferometer Gravitational-Wave Observatory, Europe's Virgo interferometer and Japan's Kamioka Gravitational Wave Detector (KAGRA), measure the signal before the collision, which should enable estimates of both the distance to the source and the masses of the neutron stars before they collided. Combining these measurements with Chirenti and colleagues' γ-ray observations would allow extremely precise inferences to be made about the nuclear equation of state.

But the future is even brighter. If confirmed independently through observations with a higher signal-to-noise ratio than those reported, these quasiperiodic oscillations would offer a new focus for gravitational-wave observatories. Although the first binary neutron-star merger[6] observed in gravitational waves was whoppingly 'loud', it wasn't loud enough to guarantee that the gravitational waves from these post-merger oscillations will be detectable. But they should be there, and they should be observable by dedicated next-generation observatories, such as Australia's newly proposed Neutron Star Extreme Matter Observatory[12], or third-generation gravitational-wave detectors, such as Cosmic Explorer[13] in the United States, or Europe's Einstein Telescope[14]. Chirenti and colleagues' savvy discovery will help these instruments to analyse matter that is key to one of the great unsolved problems in nuclear physics.

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1. Lattimer, J. M. *Annu. Rev. Nucl. Part. Sci.* **71**, 433 (2021).
2. Klebesadel, R. W., Strong, I. B. & Olson, R. A. *Astrophys. J.* **182**, L85–L88 (1973).
3. Goodman, J. *Astrophys. J.* **308**, L47–L50 (1986).
4. Chirenti, C., Dichiara, S., Lien, A., Miller, M. C. & Preece, R. *Nature* **613**, 253–256 (2023).
5. Abbott, B. P. *et al. Phys. Rev. Lett.* **116**, 061102 (2016).
6. Abbott, B. P. *et al. Phys. Rev. Lett.* **119**, 161101 (2017).
7. Abbott, B. P. *et al. Astrophys. J.* **848**, L12 (2017).
8. Sekiguchi, Y., Kiuchi, K., Kyutoku, K. & Shibata, M. *Phys. Rev. Lett.* **107**, 211101 (2011).
9. Kiuchi, K., Kyutoku, K., Sekiguchi, Y., Shibata, M. & Wada, T. *Phys. Rev. D* **90**, 041502 (2014).
10. Sarin, N. & Lasky, P. D. *Gen. Relativ. Grav.* **53**, 59 (2021).
11. Chirenti, C., Miller, M. C., Strohmayer, T. & Camp, J. *Astrophys. J.* **884**, L16 (2019).
12. Ackley, K. *et al. Publ. Astron. Soc. Aust.* **37**, e047 (2020).
13. Abbott, B. P. *et al. Class. Quantum Gravity* **34**, 044001 (2017).
14. Punturo, M. *et al. Class. Quantum Gravity* **27**, 194002 (2010).

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Microbiology

Asgard archaeal microbes reveal their inner secrets

Jan Löwe

A microorganism that is a proposed relative of our cellular ancestors has been grown successfully in the laboratory. Its internal architecture offers clues to the early evolution of eukaryotic cells. **See p.332**

The nucleus-containing cells of animals, plants and fungi, called eukaryotic cells, arose during evolution through the merging of cells of two types of microorganism – archaea and bacteria – in a process termed eukaryogenesis. How exactly this happened remains enigmatic. The discovery of DNA sequences from a group of microbes called Asgard archaea revealed them to be the best candidates for the archaeal lineage related to the one involved in eukaryogenesis[1]. However, Asgard archaea have proved very difficult to grow in the laboratory. On page 332, Rodrigues-Oliviera *et al.*[2] report successful culture of the Asgard organism *Lokiarchaeum ossiferum*, the second to have been grown in a laboratory so far. *Prometheoarchaeum syntrophicum* was the first[3], but certain details of the intracellular organization of those archaea could not be established.

The cells reported by Rodrigues-Oliviera and colleagues have many surface protrusions and constrictions (Fig. 1), something that is predicted by arguably the most compelling theory of eukaryogenesis, called the inside-out model[4], which proposes that eukaryogenesis occurred through the engulfment of a bacterium by the cell membrane of an archaeal cell. Rodrigues-Oliviera *et al.* used atomic-structure determination of large molecules analysed directly in cells by electron microscopy to identify the *Lokiarchaeum ossiferum* in samples of a culture enriched for these Asgard archaea.

The authors also visualized intracellular protein filaments, which are very similar to key F-actin protein filaments of a eukaryotic internal structure called the cytoskeleton. Although it had been predicted[5] that Asgard archaea would contain a more-complex cytoskeleton than those of bacteria and other archaea, seeing these filaments in cells is nevertheless a triumph made possible by genomics, painstaking microbiology and the advancing field of structural cell biology that uses imaging by cryo-electron tomography (cryo-ET). An understanding of eukaryogenesis might not be as far off as was once thought.

The evolution of complex life from simpler forms is an important feature of biology. Eukaryotes are the most complex multicellular organisms on Earth. Their cells contain a DNA-filled nucleus, energy-providing organelles such as mitochondria, an intracellular membrane network that includes the endoplasmic reticulum and a complex cytoskeleton, which at its core has filaments made of the proteins actin and tubulin. Mitochondrial origins have been traced to a group of bacteria called alphaproteobacteria[6]. Analysis using a phylogenetic approach revealed that the cell that took up the alphaproteobacterium was of archaeal origin[7].

The discovery of Asgard archaea only seven years ago[1] revealed non-eukaryotic organisms that are the most closely related in DNA sequence to eukaryotes. In fact, the relationship is so close that we cannot exclude the possibility that eukaryotes emerged directly from one of the Asgard lineages[5]. Or, in other words, the tree of life might have only two branches, bacteria and archaea[7] – with us humans merely a twig on the archaeal branch.

The closeness is reflected by Asgard archaea having many eukaryotic signature proteins (ESPs), proteins that are found almost exclusively in eukaryotes and are often associated with uniquely eukaryotic processes such as intracellular trafficking – the movement of cargo between membrane-bound