Neutron-star mergers illuminate the mysteries of quark matter

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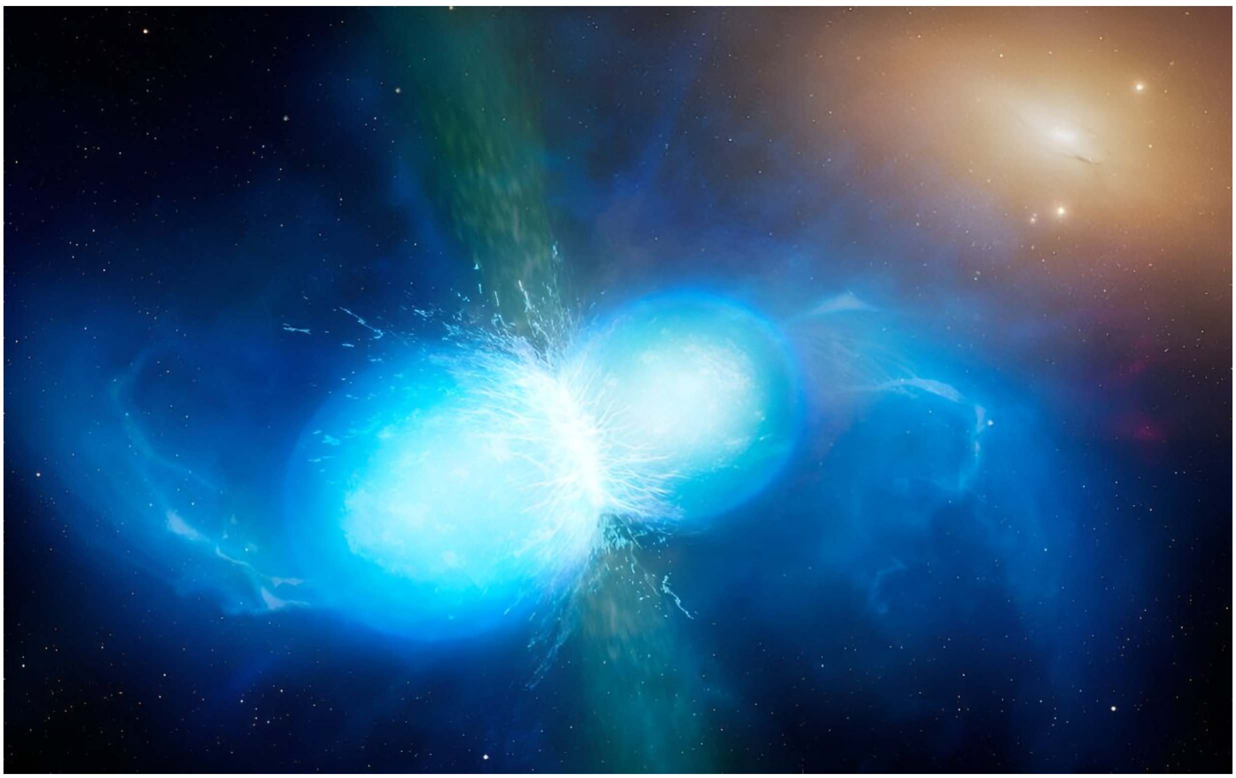

During a neutron-star merger, the stars rapidly change shape and heat up, causing changes in the state of matter inside them. The merger may also produce quark matter, where the elementary particles quarks and gluons, usually confined within protons and neutrons, are liberated and begin to move freely. According to research findings in quark matter the bulk viscosity peaks at significantly lower temperatures than in nuclear matter. Credit: University of Warwick/Mark Garlick

Neutron stars are the remnants of old stars that have run out of nuclear fuel and undergone a supernova explosion and a subsequent gravitational collapse. Although their collisions—or binary mergers—are rare, when they do occur, these violent events can perturb spacetime itself, producing gravitational waves detectable on Earth from hundreds of millions of light years away.

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Professor Aleksi Vuorinen from the University of Helsinki explains how our understanding of the properties of individual neutron stars has significantly advanced in recent years. However, we still don't fully understand what happens at the highest densities reached or in dynamic settings.

"Describing neutron-star mergers is particularly challenging for theorists because all conventional theoretical tools seem to break down in one way or another in these time-dependent and truly extreme systems," Vuorinen explains.

Determining the bulk viscosity based on string theory and perturbative QCD

One key concept in the study of neutron-star mergers is the bulk viscosity of neutron-star matter, which describes how strongly particle interactions resist flow in the system.

Together with their colleagues abroad, researchers at the University of

Helsinki successfully determined the bulk viscosity of dense quark matter by combining two different theoretical methods. One of the approaches used was based on string theory, while the other builds on perturbation theory, a classic method of quantum field theory.

In general, different viscosities describe how "sticky" the flow of a given liquid is. The most familiar example is shear viscosity, whose effects can be seen in the flow of substances like honey and water: honey flows slowly because it has high viscosity, while water flows more quickly due to its lower viscosity.

Bulk viscosity, on the other hand, describes energy loss in a system that undergoes radial oscillations, meaning that its density increases and decreases in a periodic fashion. Precisely such oscillations occur in neutron stars and their mergers, making bulk viscosity the most central transport coefficient for neutron-star mergers.

In their study, recently published in *Physical Review Letters*, the bulk viscosity of quark matter was determined in two ways: using the so-called AdS/CFT duality, commonly referred to as holography, and perturbation theory.

In holography, the properties of strongly coupled quantum field theories are determined by studying gravity in a higher-dimensional curved space. In the case of quark matter, this allows the system to be described at the densities and temperatures present in neutron star collisions, where the interactions of quantum chromodynamics (QCD), the theory of the strong nuclear force, are very strong. Due to technical reasons, however, the method cannot directly describe QCD but rather examines a phenomenological model with very similar properties.

The other method used in the new work, perturbation theory, is perhaps the most widely used tool in theoretical particle physics research. In this approach, physical quantities are determined as power series in the coupling constant of the theory, which describes the strength of the interaction. This method can describe QCD directly, but is only applicable at densities far above those found in neutron stars.

To the researchers' delight, the two methods led to very similar results, reinforcing the idea that in quark matter the bulk viscosity peaks at significantly lower temperatures than in nuclear matter.

"This information helps us understand the behavior of neutron-star matter during their binary mergers," says Academy Research Fellow Risto Paatelainen from Helsinki.

"These results may also aid the interpretation of future observations. We might, for example, look for viscous effects in future gravitational-wave data, and their absence could reveal the creation of quark matter in neutron-star mergers," adds University Lecturer Niko Jokela.

More information: Jesús Cruz Rojas et al, Estimate for the Bulk Viscosity of Strongly Coupled Quark Matter Using Perturbative QCD and Holography, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.133.071901

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