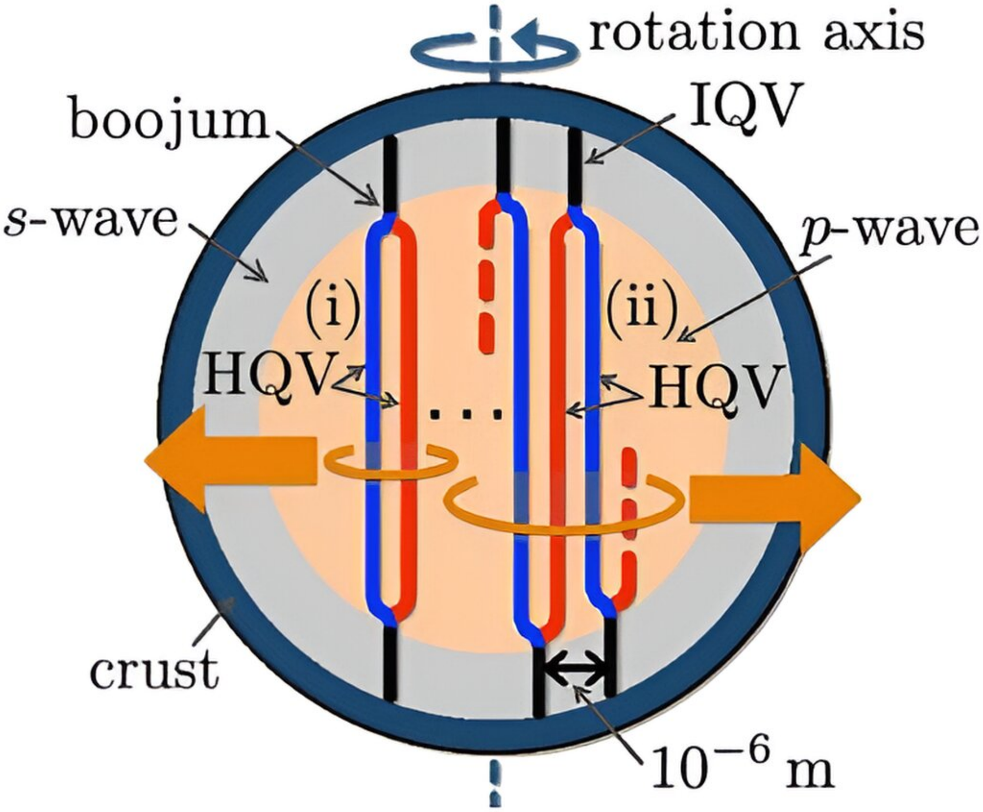
Study reveals twisted origin of dead stars' mysterious 'heartbeats'

June 26 2024, by Mikas Matsuzawa



The quantum vortex network model proposed by the study authors. The p-wave inner core (pink) surrounds the s-wave outer core (gray). Credit: Muneto Nitta and Shigehiro Yasui

Stars blinking code in Netflix's "3 Body Problem" might be science fiction, but by deciphering neutron stars' erratic flickers, a new study has revealed the twisted origin of these dead stars' mysterious "heartbeats."

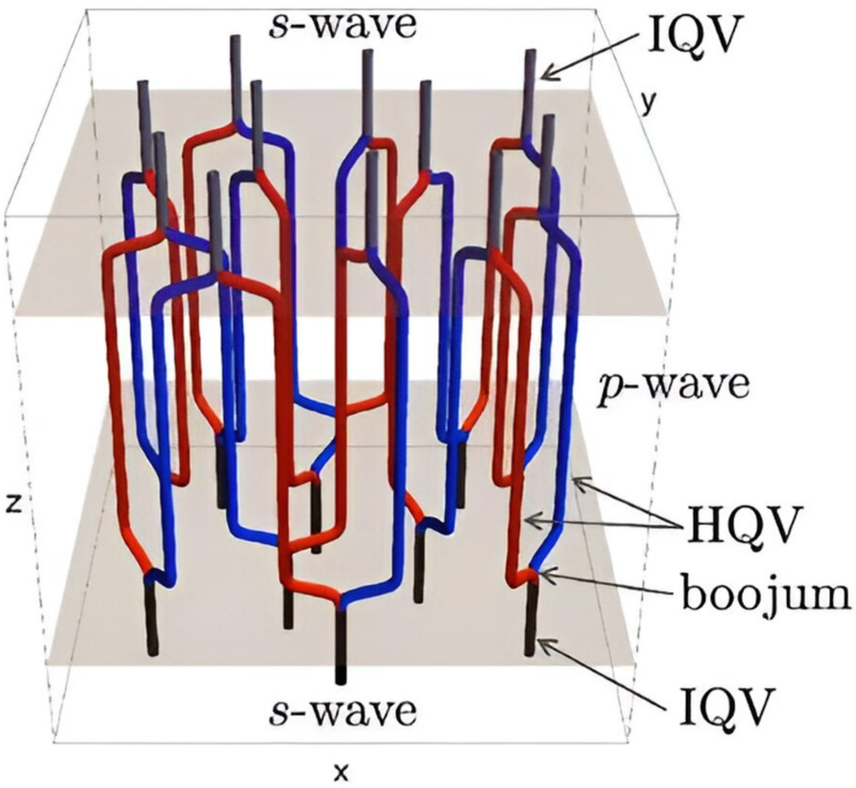
When neutron stars—ultra-dense remnants of massive stars that exploded in supernovae—were first discovered in 1967, astronomers thought their strange periodic pulses could be signals from an alien civilization. Although we now know these "heartbeats" originate from radiation beams of stellar corpses, not extraterrestrial life, their precision makes them excellent cosmic clocks for studying astrophysical phenomena, such as the rotation speeds and internal dynamics of celestial bodies.

At times, however, their clockwork accuracy is disrupted by pulses inexplicably arriving earlier, signaling a glitch or a sudden speed-up in the neutron stars' spins. While their exact causes remain unclear, glitch energies have been observed to follow the power law (also known as scaling law)—a mathematical relationship reflected in many complex systems from wealth inequality to frequency-magnitude patterns in earthquakes. Just as smaller earthquakes occur more frequently than larger ones, low-energy glitches are more common than high-energy ones in neutron stars.

Re-analyzing 533 up-to-date data sets from observations of rapidly spinning neutron stars, called pulsars, a team of physicists found that their proposed quantum vortex network naturally aligns with calculations on the power law behavior of glitch energies without needing extra tuning, unlike past models. Their findings are published in the journal Scientific Reports.

"More than half a century has passed since the discovery of neutron stars, but the mechanism of why glitches happen is not yet understood. So we proposed a model to explain this phenomenon," said study corresponding author Muneto Nitta, a specially appointed professor and co-principal investigator at Hiroshima University's International Institute for Sustainability with Knotted Chiral Meta Matter (WPI-SKCM^2).

Superfluid vortices get a new twist



3D configuration of the quantum vortex network. Credit: Muneto Nitta and Shigehiro Yasui

Previous studies have proposed two main theories to explain these glitches: starquakes and superfluid vortex avalanches. While starquakes, which behave like earthquakes, might explain the observed power law pattern, they could not account for all types of glitches. Superfluid vortices are the widely invoked explanation.

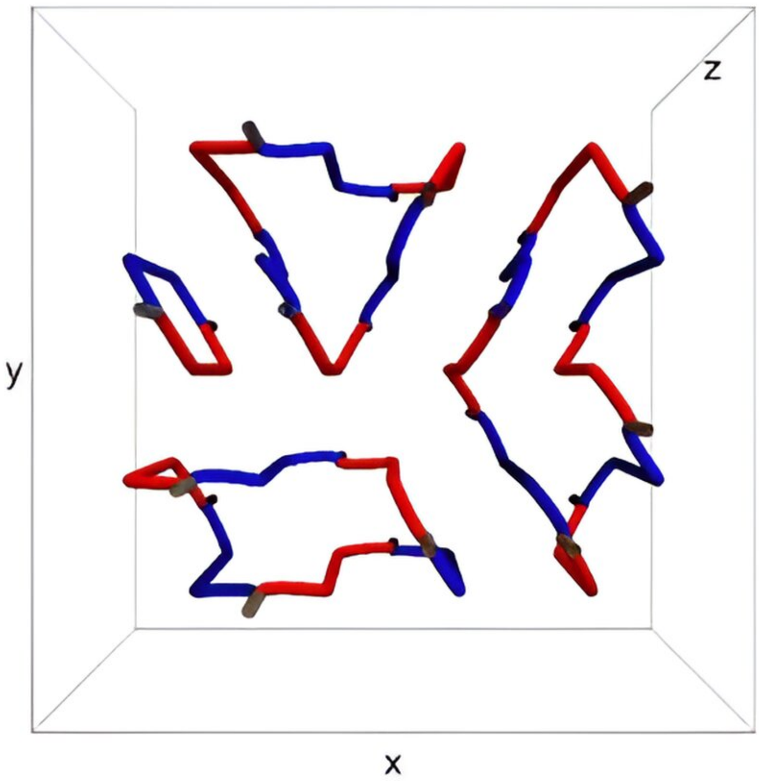
"In the standard scenario, researchers consider that avalanche of unpinned vortices could explain the origin of glitches," Nitta said.

However, there has been no consensus on what might trigger vortices to avalanche catastrophically.

"If there would be no pinning, it means the superfluid releases vortices one by one, allowing for a smooth adjustment in rotation speed. There would be no avalanches and no glitches," Nitta said.

"But in our case, we didn't need any mechanism of pinning or additional parameters. We only needed to consider the structure of p-wave and s-wave superfluids. In this structure, all vortices are connected to each other in each cluster, so they cannot be released one by one. Instead, the neutron star has to release a large number of vortices simultaneously. That is the key point of our model."

While a neutron star's superfluid core spins at a constant pace, its ordinary component lowers its rotation speed by releasing [gravitational waves] and electromagnetic pulses. Over time, their speed discrepancy grows so the star expels superfluid vortices, which carry a fraction of angular momentum, to regain balance. However, as superfluid vortices are entangled they drag others with them, explaining the glitches.



Top view of a quantum vortex network. Credit: Muneto Nitta and Shigehiro Yasui

To explain how vortices form twisted clusters, researchers proposed the existence of two types of superfluids in neutron stars. S-wave superfluidity, which dominates the outer core's relatively tamer environment, supports the formation of integer-quantized vortices (IQVs). In contrast, p-wave superfluidity prevailing in the inner core's extreme conditions favors half-quantized vortices (HQVs).

As a result, each IQV in the s-wave outer core splits into two HQVs upon entering the p-wave inner core, forming a cactus-like superfluid structure known as a boojum. As more HQVs split from IQVs and connect through boojums, the dynamics of vortex clusters become increasingly complex, much like cacti arms sprouting and intertwining with neighboring branches, creating intricate patterns.

The researchers ran simulations and found that the exponent for the power-law behavior of glitch energies in their model (0.8±0.2) closely matched the observed data (0.88±0.03). This indicates that their proposed framework accurately reflects real-world neutron star glitches.

"Our argument, while simple, is very powerful. Even though we cannot directly observe the p-wave superfluid inside, the logical consequence of its existence is the power-law behavior of the cluster sizes obtained from simulations. Translating this into a corresponding power-law distribution for glitch energies showed it matches the observations," said co-author Shigehiro Yasui, a postdoctoral researcher at WPI-SKCM^2 and associate professor at Nishogakusha University.

"A neutron star is a very particular situation because the three fields of astrophysics, nuclear physics, and condensed matter physics meet at one point. It's very difficult to observe directly because neutron stars exist far away from us, therefore, we need to make a deep connection between the interior structure and some observation data from the neutron star."

Yasui and Nitta are also affiliated with Keio University's Department of Physics and Research and Education Center for Natural Sciences. Another collaborator in the study is Giacomo Marmorini from the Department of Physics of both Nihon University and Aoyama Gakuin University.

More information: Giacomo Marmorini et al, Pulsar glitches from quantum vortex networks, *Scientific Reports* (2024). DOI: 10.1038/s41598-024-56383-w

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