Neutron star's X-rays reveal 'photon metamorphosis'

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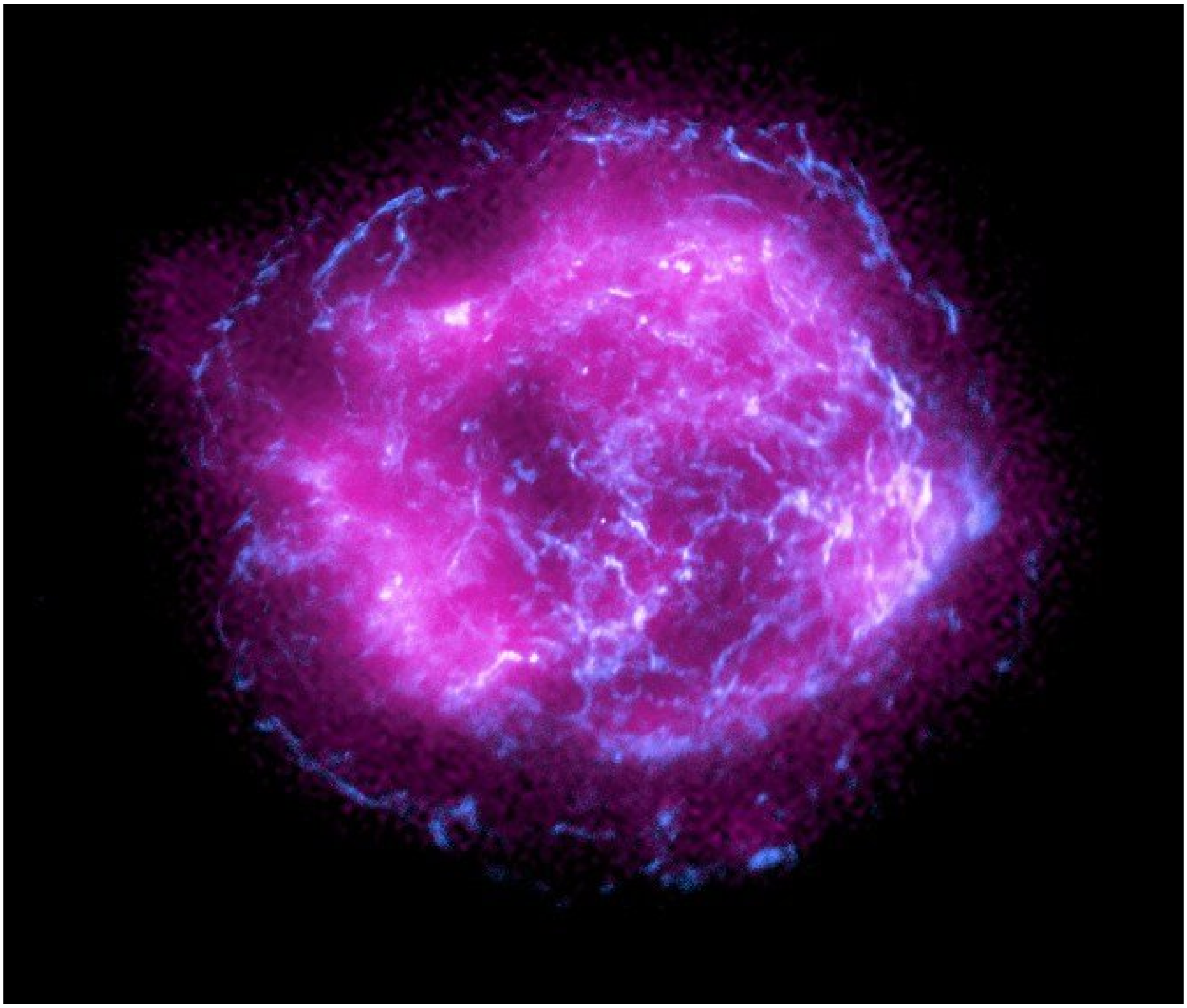

This image of the supernova remnant Cassiopeia A, the first object observed by NASA’s Imaging X-ray Polarimetry Explorer (IXPE) satellite, combines some of the first X-ray data collected by IXPE, shown in magenta, with high-energy X-ray data from NASA's Chandra X-Ray Observatory, in blue. The satellite later detected polarized X-rays from 4U 0142+61, a highly magnetized neutron star located in the Cassiopeia constellation. Credit: NASA/CXC/SAO/IXPE

A "beautiful effect" predicted by quantum electrodynamics (QED) can explain the puzzling first observations of polarized X-rays emitted by a magnetar—a neutron star featuring a powerful magnetic field, according to a Cornell astrophysicist.

The extremely dense and hot remnant of a massive star, boasting a magnetic field 100 trillion times stronger than Earth's, was expected to generate highly polarized X-rays, meaning that the radiation's electromagnetic field did not vibrate randomly but had a preferred direction.

But scientists were surprised when NASA's Imaging X-ray Polarimetry Explorer (IXPE) satellite last year detected that lower- and higher-energy X-rays were polarized differently, with electromagnetic fields oriented at right angles to each other.

The phenomenon can be naturally explained as a result of "photon metamorphosis"—a transformation of X-ray photons that has been theorized but never directly observed, said Dong Lai, Ph.D. '94, the Benson Jay Simon '59, MBA '62, and Mary Ellen Simon, M.A. '63, Professor of Astrophysics in the College of Arts and Sciences.

"In this observation of radiation from a faraway celestial object, we see a beautiful effect that is a manifestation of intricate, fundamental physics," Lai said. "QED is one of the most successful physics theories, but it had not been tested in such strong magnetic field conditions."

Lai is the author of "IXPE Detection of Polarized X-rays from Magnetars and Photon Mode Conversion at QED Vacuum Resonance," published in *Proceedings of the National Academy of Sciences*.

The research builds on calculations Lai and Wynn Ho, Ph.D. '03, published 20 years ago, incorporating observations NASA reported last November of the magnetar 4U 0142+61, located 13,000 light-years away in the Cassiopeia constellation.

Quantum electrodynamics, which describes microscopic interactions between electrons and photons, predicts that as X-ray photons exit the neutron star's thin atmosphere of hot, magnetized gas, or plasma, they pass through a phase called vacuum resonance.

There, Lai said, photons, which have no charge, can temporarily convert into pairs of "virtual" electrons and positrons that are influenced by the magnetar's super-strong magnetic field even in vacuum, a process called "vacuum birefringence." Combined with a related process, plasma birefringence, conditions are created for the polarity of high-energy X-rays to swing 90 degrees relative to low-energy X-rays, according to Lai's analysis.

"You can think about the polarization as two flavors of photons," he said. "A photon suddenly converting from one flavor to another—you don't usually see this kind of thing. But it's a natural consequence of the physics if you apply the theory under these extreme conditions."

The IXPE mission did not see the polarization swing in observations of another magnetar, called 1RXS J170849.0-400910, with an even stronger magnetic field. Lai said that's consistent with his calculations, which suggest vacuum resonance and photon metamorphosis would occur very deep inside such a neutron star.

Lai said his interpretation of IXPE's observations of the magnetar 4U 0142+61 helped constrain its magnetic field and rotation, and suggested that its atmosphere was likely composed of partially ionized heavy elements.

Ongoing study of X-rays from some of the universe's most extreme objects, including neutron stars and black holes, he said, enables scientists to probe the behavior of matter in conditions that can't be replicated in labs, and adds to understanding of the universe's beauty and diversity.

"The observations by IXPE have opened a new window for studying the surface environment of neutron stars," Lai said. "This will lead to new insights into these enigmatic objects."

More information: Dong Lai, IXPE detection of polarized X-rays from magnetars and photon mode conversion at QED vacuum resonance, *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2216534120

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