AstroSat Catches Nuclear Reactions Spreading Across a Neutron Star

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- *Occasionally, the radiation emitted by neutron stars in a binary increases by about 10x within a few seconds and decays sharply to the average intensity within a couple of minutes.*
- *Scientists from IISER Mohali have shed important new light on the astrophysics of these thermonuclear bursts, using data collected by India's AstroSat space telescope.*
- *AstroSat's specialty is being able to use its five instruments to observe radiation emitted by the same astronomical source in multiple frequencies at the same time.*

Neutron stars are natural laboratories of physics unlike any on Earth. But for all the power and spectacle that they can muster, physicists have had a tough time making full sense of them because of a gap in observations.

Now, a new study indicates that India's first and only space telescope, AstroSat, could bridge this gap and lend a hand in resolving a cosmic mystery.

All ordinary matter is made up of atoms, and at the centres all these atoms are nuclei made of protons and neutrons. But neutron stars consist only of neutrons, packed against each other. This makes them extremely dense: a neutron star could be as massive as the Sun but only have a radius of about 10 km. As such, they could be more than 100,000,000,000,000-times as dense as the Sun.

Only quantum mechanics can describe the properties and behaviour of such ultra-dense matter. At the same time, the high density also offers a glimpse into the behaviour of strong gravitational fields.

There is only one kind of cosmological object that is more dense than neutron stars – black holes. And like neutron stars, their properties also combine quantum mechanics and gravity in mysterious ways.

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them directly.

A neutron star's gravity warps nearby space-time. The distortion is strong enough to redirect light from the star's far side toward us. Illustration: NASA GSFC/Chris Smith (USRA/GESTAR)

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Sometimes, neutron stars are gravitationally bound with other stars, orbiting each other in a stellar dance. Scientists call such systems binaries, and study them using the X-ray radiation they emit.

Occasionally, the radiation emitted by neutron stars in a binary increases by about 10x within a few seconds and decays sharply to the average intensity within a couple of minutes. Astrophysicists call these flashes *thermonuclear bursts*.

A new study has shed light on the astrophysics of thermonuclear bursts. Scientists from India extracted data about a neutron star called 4U 1636-536 from the archives of AstroSat, the space-telescope that India launched in 2015.

AstroSat's specialty is being able to use its five instruments to observe radiation emitted by the same astronomical source in multiple frequencies at the same time.

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The wavelength and energy coverage of AstroSat's instruments. Image: ISRO

Earlier, astronomers studied 4U 1636-536 with the Rossi X-Ray Timing Explorer (RXTE), a NASA space telescope that observes X-ray radiation emitted by astronomical sources. RXTE detected photons in the range of energy 2-60 keV – about 1,000-times more energetic than typical yellow light.

By studying photons emitted by the neutron star every *micro*second, astronomers detected high-frequency oscillations in the intensity of the radiation during the burst, in the range of 300-600 times per second.

Experts haven't yet been able to agree on what could be causing these oscillations.

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neutron star rotates.

Since neutron stars could revolve around a few hundred times a second, the frequency of the oscillations of X-rays coming from the hotspot could be similar, the model suggests.

The RXTE ceased operations in 2012. Since then, only one other telescope, NASA's Neutron Star Interior Composition Explorer (NICER), has been studying the rapid variability of X-ray light coming from neutron stars.

But NICER can detect photons of energy only up to 12 keV, whereas astronomers need to understand X-ray emissions of up to 80 keV.

Scientists have now found that AstroSat can bridge this gap. And using its data, they have reason to believe the flame-spreading model could be valid.

"Detection of burst oscillations requires X-ray telescopes with a large collecting area and a fine timing resolution – features not many instruments are endowed with," Navin Sridhar, an astrophysics graduate student at Columbia University, New York, said. He was not involved in the present study.

One such instrument is on board AstroSat, called the Large Area X-ray Proportional Counter (LAXPC). It detects photons of energy 3-80 keV every 10 microseconds.

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The location of LAXPC on AstroSat (stowed view). Image: ISRO

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The scientists behind the new study obtained LAXPC data pertaining to 12 thermonuclear bursts in six separate observations of the 4U 1636-536 neutron star.

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When they analysed this data more closely, they detected high-frequency oscillations in three of these bursts, at about 581 oscillations per second. This is an important achievement because it signals that AstroSat can step in where RXTE left off.

"We have observed bursts oscillations using [around 46 hours'] archival data of this well-studied neutron star, collected between 2016 and 2018," Pinaki Roy, of the Indian Institute of Science Education and Research Mohali (IISER), Mohali, and one of the authors of the study.

Aru Beri, also of IISER-Mohali and another author of the study, added, "The results extend the timeline of the neutron star's behaviour from earlier RXTE observations and present an excellent benchmark for further similar studies with AstroSat."

Sridhar agreed. "The fact that observations with AstroSat–LAXPC could confirm burst oscillations in this source … further bolsters the capability of the instrument," he said.

"The detection enables scientists to reliably use AstroSat for future observations and discoveries associated with thermonuclear bursts and burst oscillations, with higher confidence."

Next, the IISER Mohali team investigated how the *strength* of the burst oscillations – measured by their amplitude – changed according to the energy of each oscillation.

By studying how burst oscillations vary, astronomers can understand how a burst is born, spreads and fizzes out, according to Sridhar.

The flame-spreading model predicts how the energy distribution of radiation from the neutron star source evolves during the rising phase of bursts. The researchers set out to check if these predictions matched with AstroSat observations.

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They did. They also found that the speed of a hotspot's spread depends on its distance from the neutron star's equator. This is the study's second major finding.

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While the study boosts the prospects of the flame-spreading model, it's still not a perfect model: it hasn't been able to explain all thermonuclear-burst observations till date, only some.

In many cases, observational biases have got in the way of understanding how thermonuclear bursts spread over the neutron star's surface.

"There are lots of questions regarding the model," said Manoneeta Chakraborty, an astrophysicist at IIT Indore who was not also involved in the study. "For example, what are the physical conditions governing the propagation of the heat flame?"

She explained that multiple parameters determine what the X-ray emission looks like during a burst, including the neutron star's spin frequency, surface temperature and where the hotspot originates.

"It is an important conclusion," Chakraborty said, referring to the IISER team's claim of a relationship between a burst's spreading speed and its location on the surface.

For now, the flame-spreading model fits the data from one more neutron star.

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