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UCSB researcher bridges the worlds of general relativity and supernova astrophysics

For decades, astronomers have used distant supernovae as cosmic lighthouses to test fundamental physics and to measure the universe. For Joseph Farah, a fifth-year graduate student at UC Santa Barbara, one particular supernova began to signal something never seen before: a “chirp.”

In a groundbreaking paper accepted to the journal Nature, Farah and a team of international researchers, including his advisor Andy Howell, who leads the supernova group at Las Cumbres Observatory (LCO), announce the discovery of a superluminous supernova (SN 2024afav) whose erratic behavior has confirmed a long-standing theory of stellar death. By applying the principles of general relativity to the explosive death of a massive star, the team has provided an explanation for the unusual behavior of these ultra-bright events.

The mystery of the bumps

When a massive star runs out of fuel, its core collapses and the star dies in a spectacular explosion called a supernova. Most supernovae follow a predictable evolution, brightening and fading in a smooth arc. While ordinary supernovae are already bright enough to outshine their host galaxies, a rare class of supernovae has been discovered in recent years which are 10 to 100 times brighter: superluminous supernova whose power mechanism remains unknown. These hyper-bright explosions often have mysterious undulations, temporary surges that defy expectations and point to hidden physics inside the expanding supernova.

The origin of the overbrightness and bumps is hotly debated. One possibility is that superluminous supernovae are powered from within. The violent core collapse is theorized to forge a neutron star, an ultra-dense stellar remnant, which pours energy into the expanding supernova, increasing its brightness. Another school of thought suggests that the unusual characteristics stem from the supernova shock slamming into layers of gas clumped around the star. As the blast wave crashes into this surrounding material, it might briefly brighten the supernova again.

Scientists at LCO observed that SN 2024afav — located roughly a billion light-years away — displayed a strange sequence of “bumps” or modulations in its brightness. With SN 2024afav, Farah noticed a pattern that no random interactions could explain: The bumps had a clearly sinusoidal, periodic shape — and that period was getting rapidly shorter. For the first time, a supernova was displaying a quasi-periodic signal with an increasing frequency, generating a “chirp” reminiscent of the gravitational wave signals produced by merging black holes.

"There was just no existing model that could explain a pattern of bumps that get faster in time,” said Farah. “I started thinking about ways this could happen, because the signal seemed too structured to be due to random interactions.”

A magnetar under the hood

Farah’s breakthrough thinking came from an unlikely source: a General Relativity class he was auditing at the time with leading relativist and UCSB Professor Gary Horowitz. Farah hypothesized that the supernova had left behind a magnetar, a rapidly spinning neutron star with a massive magnetic field. In the existing theory, a magnetar can power a supernova like a battery, pumping in energy from within, leading to an ultra-bright and smooth rise and fall. But this theory can’t explain the bumps, which could be caused by anything from interactions with surrounding material to unexplained deviations in the power output of the magnetar.

According to Farah’s model, some material from the explosion fell back toward the magnetar, forming a tilted accretion disk. Because of a General Relativity effect known as Lense-Thirring precession, the fabric of space-time itself is twisted by the spinning magnetar, causing the disk to wobble. As the disk precessed, it periodically blocked and reflected light from the magnetar, turning the whole system into a strobing cosmic lighthouse. The precession timescale decreases with the radius of the disk; so as the disk slides inward towards the magnetar, the disk wobbles faster, creating the “chirp” observed by telescopes on Earth.

Lense-Thirring precession isn’t the only effect that can make a disk wobble. Working with theorist Logan Prust (a former postdoctoral scholar at UCSB’s Kavli Institute for Theoretical Physics), Farah and his team investigated several alternatives. What makes SN 2024afav unique — and a particularly effective test bed for these theories — is that any model needs to explain both the period and the period rate-of-change observed in the data. “We tested several ideas, including purely Newtonian effects and precession driven by the magnetar’s magnetic fields, but only Lense-Thirring precession matched the timing perfectly,” Farah explained. “It is the first time General Relativity has been invoked to describe the mechanics of a supernova.”

A Victory for Global Observation

The discovery was a “mad dash” involving a global network of telescopes. While the ATLAS survey discovered the initial flash in December 2024, the LCO in Goleta played a pivotal role, tracking the event for over 200 days. During this extended campaign, the team took maximal advantage of the full suite of LCO’s instruments and ability to near-continuously survey any target. Observation parameters were adjusted on-the-fly to capture even the faintest bumps in SN 2024afav’s evolution.

“This is a major victory for LCO,” said Farah. “The uniquely pristine and high-cadence LCO data allowed us to predict future bumps and the ability to dynamically adjust the campaign on a dime let us check our predictions in real-time. When the predictions started coming true, we knew we were watching something special.”

The paper is being hailed as a breakthrough for two reasons. As the first observed “chirp” in a supernova, it identifies a new class of observational phenomena in exploding stars. It also provides the first unambiguous confirmation of the magnetar model for superluminous supernovae, transforming the model from one of several competing hypotheses into an observationally confirmed mechanism.

The Next Frontier

Farah, who is set to defend his Ph.D. thesis at UCSB this May, will continue his work as a Miller Fellow of the Miller Institute for Basic Science at UC Berkeley

Farah's advisor, Andy Howell, emphasized the importance of the breakthrough: "I was part of the discovery of superluminous supernovae almost 20 years ago, and at first we didn't know what they were. Then the magnetar model was developed and it seemed like it could explain the astounding energies needed, but not the bumps.

"Now, I think Joseph has found the smoking gun," Howell continued, "and he's tied the bumps into the magnetar model, and explained everything with the best-tested theory in astrophysics – General Relativity. It is incredibly elegant."

Farah expects to find dozens more of these "chirping" supernovae as the Vera C. Rubin Observatory in Chile prepares to come online and begin the most comprehensive survey of the night sky. The new facility will produce 10 terabytes of data every night throughout a ten-year initiative. "This is the most exciting thing I have ever had the privilege to be a part of. This is the science I dreamed of as a kid," Farah said. "It's the universe telling us out loud and in our face that we don't fully understand it yet, and challenging us to explain it."

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