The brightest gamma ray burst ever seen came from a collapsing star

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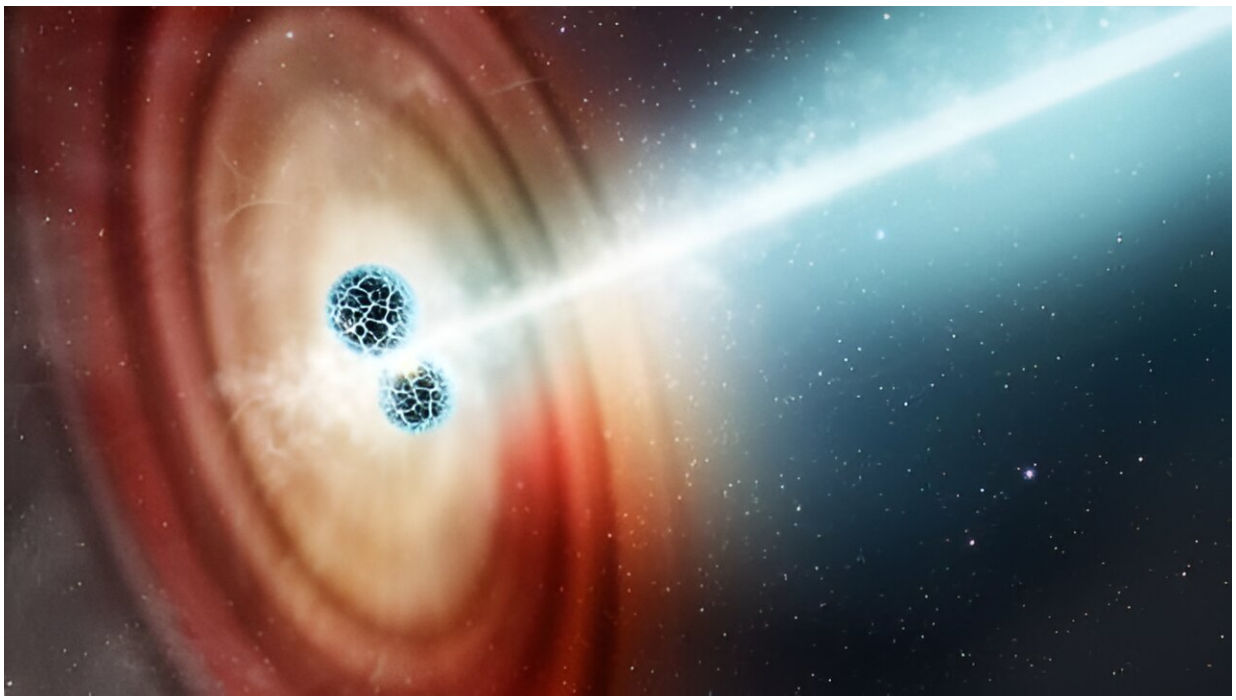

This artist's illustration shows two neutron stars colliding. Known as a "kilonova" event, they're the only confirmed location of the r-process that forges heavy elements. Credits: Elizabeth Wheatley (STScI)

After a journey lasting about two billion years, photons from an extremely energetic gamma-ray burst (GRB) struck the sensors on the Neil Gehrels Swift Observatory and the Fermi Gamma-Ray Space Telescope on October 9th, 2022. The GRB lasted seven minutes but was visible for much longer. Even amateur astronomers spotted the powerful burst in visible frequencies.

It was so powerful that it affected Earth's atmosphere, a remarkable feat for something more than two billion light-years away. It's the brightest GRB ever observed, and since then, astrophysicists have searched for its source.

NASA says GRBs are the most powerful explosions in the universe. They were first detected in the late 1960s by American satellites launched to keep an eye on the USSR. The Americans were concerned that the Russians might keep testing atomic weapons despite signing 1963's Nuclear Test Ban Treaty.

Now, we detect about one GRB daily, and they're always in distant galaxies. Astrophysicists struggled to explain them, coming up with different hypotheses. There was so much research into them that by the year 2,000, an average of 1.5 articles on GRBs were published in scientific journals daily.

There were many different proposed causes. Some thought that GRBs could be released when comets collided with neutron stars. Others thought they could come from massive stars collapsing to become black holes. In fact, scientists wondered if quasars, supernovae, pulsars, and even globular clusters could be the cause of GRBs or associated with them somehow.

GRBs are confounding because their light curves are so complex. No two are identical. But astrophysicists made progress, and they've learned a few things. Short-duration GRBs are caused by the merger of two neutron stars or the merger of a neutron star and a black hole. Longer-duration GRBs are caused by a massive star collapsing and forming a black hole.

New research in *Nature Astronomy* examined the ultra-energetic GRB 221009A, dubbed the "B.O.A.T: Brightest Of All Time," and found something surprising. When it was initially discovered, scientists said it was caused by a massive star collapsing into a black hole. The new research doesn't contradict that. But it presents a new mystery: why are there no heavy elements in the newly uncovered supernova?

The research is "JWST detection of a supernova associated with GRB 221009A without an r-process signature." The lead author is Peter Blanchard, a Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) postdoctoral fellow.

"The GRB was so bright that it obscured any potential supernova signature in the first weeks and months after the burst," Blanchard said. "At these times, the so-called afterglow of the GRB was like the headlights of a car coming straight at you, preventing you from seeing the car itself. So, we had to wait for it to fade significantly to give us a chance of seeing the supernova."

"When we confirmed that the GRB was generated by the collapse of a massive star, that gave us the opportunity to test a hypothesis for how some of the heaviest elements in the universe are formed," said lead author Blanchard.

"We did not see signatures of these heavy elements, suggesting that extremely energetic GRBs like the B.O.A.T. do not produce these elements. That doesn't mean that all GRBs do not produce them, but it's a key piece of information as we continue to understand where these heavy elements come from. Future observations with JWST will determine if the B.O.A.T."s 'normal' cousins produce these elements."

Scientists know that supernova explosions forge heavy elements. They're an important source of elements from oxygen (atomic number 8) to rubidium (atomic number 37) in the interstellar medium. They also produce heavier elements than that. Heavy elements are necessary to form rocky planets like Earth and for life itself. But it's important to note that astrophysicists don't completely understand how heavy elements are produced.

"This event is particularly exciting because some had hypothesized that a luminous gamma-ray burst like the B.O.A.T. could make a lot of heavy elements like gold and platinum," said second author Ashley Villar of Harvard University and the Center for Astrophysics | Harvard & Smithsonian. "If they were correct, the B.O.A.T. should have been a goldmine. It is really striking that we didn't see any evidence for these heavy elements."

Stars forge heavy elements by nucleosynthesis. Three processes are responsible for that: the p-process, the s-process and the r-process (proton capture process, slow neutron capture process, and the rapid neutron capture process.) The r-process captures neutrons faster than the s-process and is responsible for about half of the elements heavier than iron. The r-process is also responsible for the most stable isotopes of these heavy elements.

That's all to illustrate the importance of the r-process in the universe.

The researchers used the JWST to get to the bottom of GRB 221009A. The GRB was obscured by the Milky Way, but the JWST senses infrared light and saw right through the Milky Way's gas and dust. The telescope's NIRSpec (near infrared spectrograph) senses elements like oxygen and calcium, usually found in supernovae. But the signatures weren't very bright, a surprise considering how bright the supernova was.

"It's not any brighter than previous supernovae," lead author Blanchard said. "It looks fairly normal in the context of other supernovae associated with less energetic GRBs. You might expect that the same collapsing star producing a very energetic and bright GRB would also produce a very energetic and bright supernova. But it turns out that's not the case. We have this extremely luminous GRB, but a normal supernova."

Confirming the presence of the supernova was a big step to understanding GRB 221009A. But the lack of an r-process signature is still confounding.

Scientists have only confirmed the r-process in the merger of two neutron stars, called a kilonova explosion. But there are too few neutron star mergers to explain the abundance of heavy elements.

"There is likely another source," Blanchard said. "It takes a very long time for binary neutron stars to merge. Two stars in a binary system first have to explode to leave behind neutron stars. Then, it can take billions and billions of years for the two neutron stars to slowly get closer and closer and finally merge. But observations of very old stars indicate that parts of the universe were enriched with heavy metals before most binary neutron stars would have had time to merge. That's pointing us to an alternative channel."

Researchers have wondered if luminous supernovae like this can account for the rest. Supernovae have an inner layer where more heavy elements could be synthesized. But that layer is obscured. Only after things calm down is the inner layer visible.

"The exploded material of the star is opaque at early times, so you can only see the outer layers," Blanchard said. "But once it expands and cools, it becomes transparent. Then you can see the photons coming from the inner layer of the supernova."

All elements have spectroscopic signatures, and the JWST's NIRSpec is a very capable instrument. But it couldn't detect heavier elements, even in the supernova's inner layer.

"Upon examining the B.O.A.T."s spectrum, we did not see any signature of heavy elements, suggesting extreme events like GRB 221009A are not primary sources," lead author Blanshard said. "This is crucial information as we continue to try to pin down where the heaviest elements are formed."

Scientists are still uncertain about the GRB and its lack of heavy elements. But there's another feature that might offer a clue: jets.

"A second proposed site of the r-process is in rapidly rotating cores of massive stars that collapse into an accreting black hole, producing similar conditions as the aftermath of a BNS merger," the authors write in their paper. "Theoretical simulations suggest that accretion disk outflows in these so-called 'collapsars' may reach the neutron-rich state required for the r-process to occur."

The accretion disk outflows the researchers refer to are relativistic jets. The narrower the jets are, the brighter and more focused their energy is.

Could they play a role in forging heavy elements?

"It's like focusing a flashlight's beam into a narrow column, as opposed to a broad beam that washes across a whole wall," Laskar said. "In fact, this was one of the narrowest jets seen for a gamma-ray burst so far, which gives us a hint as to why the afterglow appeared as bright as it did. There may be other factors responsible as well, a question that researchers will be studying for years to come."

The researchers also used NIRSpec to gather a spectrum from the GRB's host galaxy. It has the lowest metallicity of any galaxy known to host a

GRB. Could that be a factor?

"This is one of the lowest metallicity environments of any LGRB, which is a class of objects that prefer low-metallicity galaxies, and it is, to our knowledge, the lowest metallicity environment of a GRB-SN to date," the authors write in their research. "This may suggest that very low metallicity is required to produce a very energetic GRB."

The host galaxy is also actively forming stars. Is that another clue?

"The spectrum shows signs of star formation, hinting that the birth environment of the original star may be different than previous events," Blanshard said.

Yijia Li is a graduate student at Penn State and a co-author of the paper. "This is another unique aspect of the B.O.A.T. that may help explain its properties," Li said. "The energy released in the B.O.A.T. was completely off the charts, one of the most energetic events humans have ever seen. The fact that it also appears to be born out of near-primordial gas may be an important clue to understanding its superlative properties."

This is another case where solving one mystery leads to another unanswered one. The JWST was launched to answer some of our foundational questions about the universe. By confirming that a supernova is behind the most powerful GRB ever detected, it's done part of its job.

But it also found another mystery and has left us hanging again.

The JWST is working as intended.

More information: Peter K. Blanchard et al, JWST detection of a supernova associated with GRB 221009A without an r-process signature, *Nature Astronomy* (2024). DOI: 10.1038/s41550-024-02237-4

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