<u>AstroTalk: Behind the news headlines; August 2023</u>

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Record-breaking flashes in the sky

In 1967, researchers exploring data obtained with the *Vela* satellite discovered a short-lived burst of gamma-rays that originated from space. The *Vela* satellite had been built to monitor the sky for possible tests of nuclear weapons, which would be a violation of the 1963 Nuclear Test Ban Treaty.

Initially, these so-called gamma-ray bursts (GRBs) were thought to originate from sources within our own Galaxy. However, since the 1990s, more sensitive space observatories revealed that they must come from far outside the Milky Way, given that they were distributed over the whole sky.

The transient nature of the bursts made them difficult to study. Not only are they transient and occur at random locations in the sky, gamma rays are also mostly absorbed by the Earth's atmosphere. To detect them, scientists have therefore used space-based gamma-ray telescopes that, when triggered, automatically send instant messages to Earth. This allows astronomers to follow up the detections with Earth-based telescopes, to look for a less energetic 'afterglow', from X-rays to optical and infrared light, that often follows the gamma-rays.

Outshining entire galaxies

On 9 October 2022, the European Space Agency's *INTEGRAL*, NASA's *Swift* and *Fermi* satellites, as well as a range of other space observatories (including the Chinese space telescopes *Insight-HXMT* and *GECAM-C*), detected a GRB which was, accordingly, named GRB 221009A. This led Daniele Bjørn Malesani, astronomer at the Radboud University in the Netherlands, to point the European Southern Observatory's Very Large Telescope in Chile in the direction of GRB 221009A.

Using the X-shooter spectrograph, the resulting spectrum allowed Malesani and his team to measure the exact distance to GRB 221009A. Although the host galaxy of the burst turned out to lie approximately 2.4 billion light-years away, in the constellation Sagitta ('the arrow'), this actually makes it one of the nearest bursts.

Short-lived flashes of gamma rays that typically last from a tenth of a second to less than an hour, GRBs may—for a brief period of time—outshine entire galaxies. Indeed, armed with a secure distance, the team was also able to calculate the total amount of energy released by GRB 221009A.

> "*Gamma-ray bursts are always energetic, but this one was absolutely astonishing: During the 290 seconds that it lasted, GRB 221009A released roughly 1000 times as much energy as our Sun has emitted during all of its lifetime of 4.5 billion years*," says Malesani.

Another way to put this is that the burst, for a brief period of time, was more luminous that the combined light of all the hundreds of billions of stars in the Milky Way. Dubbed the 'BOAT'—the 'brightest of all time'—GRB 221009A was so exceptionally powerful, 70 times brighter than ever seen before, that it actually sent shockwaves through Earth's ionosphere, the outer layer of our planet's atmosphere.

> "*If it had happened much closer, it would have been really bad*," says Brendan O'Connor from George Washington University (USA).

This calculation assumes that GRB 221009A has emitted the same amount of energy in all directions. More likely though, the energy is ‘concentrated’ in a narrow beam, in the direction of which we happen to lie. The total energy is therefore somewhat smaller, although still extremely high.

> “*Theoretically, we would expect such a powerful event to happen only once in 10,000 years*,” explains Malesani. “*This makes us wonder if our detection is just sheer luck, of if there’s something we’re misunderstanding about the nature of gamma-ray bursts*.”

Peter Veres, Michael S. Briggs and Stephen Lesage, from the University of Alabama at Huntsville (USA), operate the *Gamma-ray Burst Monitor* (*GBM*), an instrument in low-Earth orbit aboard *Fermi* that can see the entire gamma-ray sky not blocked by the Earth and hunts for GRBs as part of its main programme.

> “*We routinely detect GRBs at a rate of about five per week and keep an eye out if any of the GRBs are special in some way*,” says Dr. Veres*. This one was so bright, the instrument couldn’t keep up with the large number of incoming photons. Most of the work was to figure out how to reconstruct the lost counts*.”

GRBs come from random directions in the sky (which is how astronomers first deduced that they must be located outside the Milky Way), so the *GBM* must watch as much of the sky as possible at all times. The instrument consists of 12 detectors made of sodium iodide—for catching X-rays and low-energy gamma rays—and two detectors made of bismuth erminate (for high-energy gamma rays).

When gamma rays enter these detectors, they interact with crystals in the instrument. The more energetic the gamma ray, the more light is produced. By seeing which crystals light up, the *GBM* can tell the direction of the bursts. In all, the *Fermi* instrument has discovered more than 3500 GRBs, and 221009A is by far the brightest ever detected.

A ‘long’ GRB (a burst of gamma rays that can last several minutes) of this kind is typically the result of the death of a massive star, between 8 and 30 times the mass of our Sun. As the star runs out of fuel in its core, it contracts and then collapses to form either a neutron star or a black hole. In the process, the outer layers of the star cave in around it, forming a swirling disk of gas that powerful magnetic fields then sweep up and beam away charged particles in two fierce, magnetised jets moving at close to the speed of light.

> Dr. Veres explains, “*The black hole launches a very fast jet, close to the speed of light, and the jet will produce the gamma-ray burst. At later times, GRBs are visible at other wavelengths as well, from radio, or optical through very high-energy gamma-rays. This GRB was so bright, the afterglow showed up in the* Gamma-ray Burst Monitor*, which is very uncommon, and we could follow it for almost three hours*.”

While most GRBs of this type take place at much greater distances, GRB 221009A’s relative proximity has given astronomers an unprecedented look into its central engine. “*We knew that we would likely never get this opportunity again*,” says Gokul Srinivasaragavan from the University of Maryland (USA).

Using the Gemini South telescope, O’Connor and Srinivasaragavan examined the ‘opening angle’ of the GRB jet, which can provide information about the process that emits the gamma rays. Typically, the jets of gamma rays from a GRB are fairly narrow, which means that comparatively few are pointed towards us. This limits how many GRBs we can detect; if they're not pointed roughly towards us, we cannot detect them.

This narrow opening angle is the result of the tightly wound magnetic fields that constrain the particle jet. However, GRB 221009A was different. Using Gemini South's Multi-Object Spectrograph (GMOS), the astronomers determined that GRB 221009A's jet displayed a shape that has not been seen in the jets of other GRBs.

The jet displayed a narrow core surrounded by wide, sloping wings. These features are not generally observed, which is puzzling, because if these wing-shaped jets happened often, astronomers would expect to have detected more of them by now. Instead, these broad wings must be very rare, just as rare as GRB 221009A is bright.

> "*There has to be something in these wide jets that is unique to ultra-powerful GRBs*," says O'Connor. "*This particular shape of jet may be the signature of the most violent explosions, and explains why we kept seeing its optical and infrared glow for months after the explosion*."

Srinivasaragavan led the search for the accompanying supernova—the visible light from the stellar explosion. Using Gemini South, as well as the GROWTH-India Telescope, the Lowell Discovery Telescope in Arizona and the Liverpool Telescope in Tenerife, Spain, the team was able to find evidence for the supernova, which is now known as SN 2022xiw. It turned out to be surprisingly underwhelming, and not unlike other supernovae.

> "*We found that GRB 221009A's associated core-collapse supernova is no more energetic or brighter than the others associated with long gamma-ray bursts previously studied*," says Srinivasaragavan. "*This goes against our naïve expectations that a more powerful long gamma-ray burst will lead to a more powerful core-collapse supernova*."

From the brightness of the supernova they calculated that between 3.5 and 11.1 solar masses of material was ejected by the stellar blast. That's up to 11 Suns worth of material blown away in just seconds, and more energy liberated in those few seconds than our Sun will produce in its entire lifetime.

The detail with which astronomers were able to observe GRB 221009A will pave the way for a greater understanding of the mechanism that produces a long GRB when a massive star ends its life.

GRB 221009A was also followed up at longer wavelengths with the *James Webb Space Telescope* (*JWST*) by Andrew Levan, also at the Radboud University. The *JWST* was particularly useful because the burst happened to lie, by an unlucky chance, behind a thick layer of cosmic dust inside our Milky Way. This makes it harder to interpret the results, as dust dims the light from the burst. Webb looked at the afterglow in the mid-infrared, which is much less affected by dust, offering a better view of the event.

> Kasper Heintz, from the University of Copenhagen (Denmark), explains, "*Gamma-ray bursts like GRB 221009A are expected to explode together with a supernova whose light should 'add' to the burst itself. But for this burst, despite* Webb*'s huge mirror it couldn't find convincing evidence for a bright supernova*."

So, was the supernova just fainter than normal, or was it missing altogether? The jury is still out, and there are surely more surprises to come from this once-in-a-lifetime mysterious event.

Short is sweet?

In addition to the brightest-ever GRB, astronomers have now also discovered the shortest-ever such flash of gamma-rays. Using the Gemini Observatory, researchers identified the cause of a 0.6-second flurry of gamma rays as a supernova explosion in a distant galaxy. GRBs caused by supernovae are usually more than twice as long, which suggests that some short GRBs might actually be imposters—supernova-produced GRBs in disguise.

Astronomers divide GRBs into two broad categories based on their duration. Short GRBs blaze into life in less than two seconds and are thought to be caused by the merging of binary neutron stars, or by the merger of a neutron star and a black hole. Those that last longer are classified as long GRBs, and have been associated with supernova explosions caused by the implosions of massive stars. However, the recent discovery of the shortest-ever GRB produced during a supernova shows that GRBs don't fit neatly into boxes.

> "*This discovery represents the shortest gamma-ray emission caused by a supernova during the collapse of a massive star*," commented Tomás Ahumada from the University of Maryland and NASA's Goddard Space Flight Center. "*It lasted for only 0.6 second, and it sits on the brink between a successful and a failed gamma-ray burst*."

The team believes that this and some other supernova-related GRBs are appearing short because the jets of gamma rays that emerge from the collapsing star's poles aren't strong enough to completely escape the star—almost failing to produce a GRB—and that other collapsing stars have such weak jets that they don't produce GRBs at all.

This discovery could also help explain an astronomical mystery. Long GRBs are associated with a specific type of supernova, known as 'Type Ic-BL'. However, astronomers usually observe many more of these supernovae than long GRBs. This discovery of the shortest GRB associated with a supernova suggests that some of these supernova-caused GRBs are masquerading as short GRBs and are, therefore, not getting counted as the supernova kind.

> "*Our discovery suggests that, since we observe many more of these supernovae than long gamma-ray bursts, most collapsing stars fail to produce a GRB jet that breaks through the outer envelope of the collapsing star*," explains Ahumada. "*We think this event was effectively a fizzle, one that was close to not happening at all*."

The team was able to determine that this GRB—GRB 200826A—originated from a supernova explosion thanks to the imaging capabilities of GMOS on Gemini North in Hawai'i. The researchers used Gemini North to obtain images of the GRB's host galaxy 28, 45, and 80 days after the GRB was first detected on 26 August 2020 by a network of observatories that included NASA's *Fermi Gamma-ray Space Telescope*. Gemini's observations allowed the team to spot the tell-tale rise in energy that signifies a supernova, despite the blast's location in a galaxy 6.6 billion light-years away.

> "*This was a complicated endeavour as we needed to separate the light of an already faint galaxy from the light of a supernova*," says Ahumada. "*Gemini is the only ground-based telescope that can do follow-up observations like this with a flexible-enough schedule to let us squeeze in our observations*."

This result shows that classifying GRBs based solely on their duration may not be the best approach, and that additional observations are needed to determine a GRB's cause.

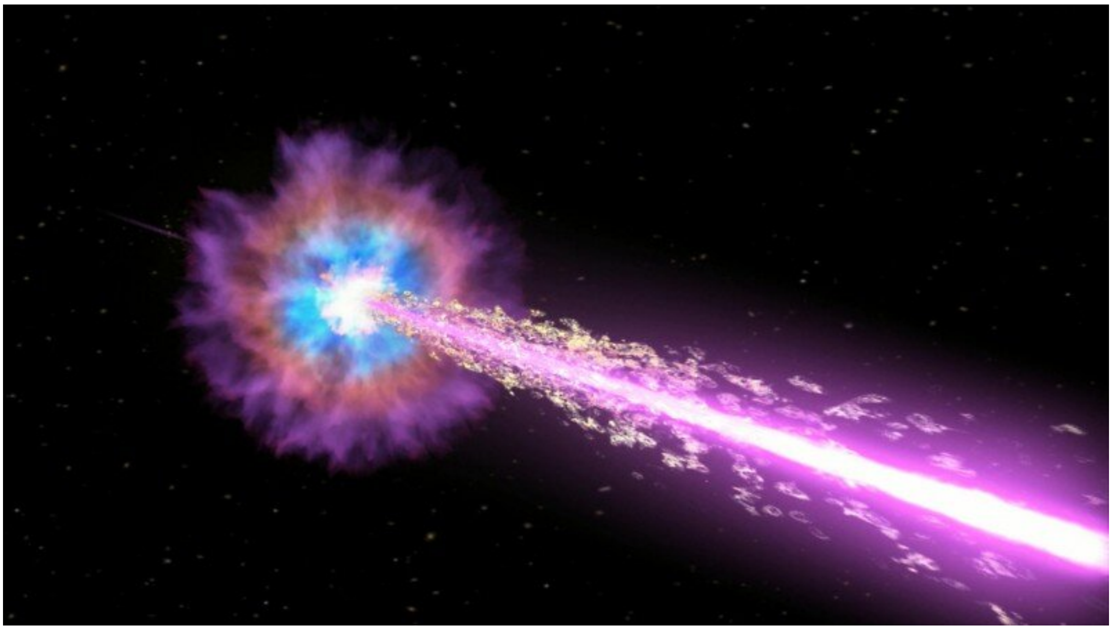

Figure 1: Astronomers believe GRB 221009A represents the birth of a new black hole formed within the heart of a collapsing star. In this illustration, the black hole drives powerful jets of particles traveling near the speed of light. The jets pierce through the star, emitting X-rays and gamma rays as they stream into space. Credit: NASA.

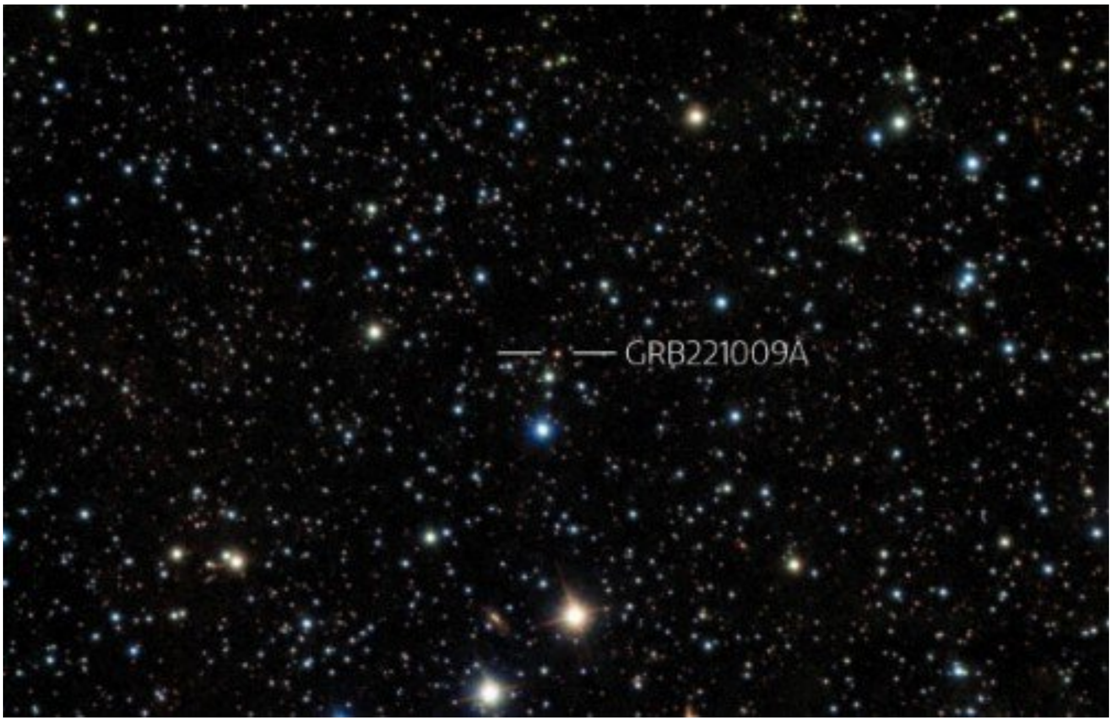

Figure 2: GRB 221009A occurred approximately 2.4 billion light-years away in the direction of the constellation Sagitta. Credit: International Gemini Observatory.

Figure 3: Artist's illustration depicting a collapsing star that is producing two short gamma-ray jets. Credit: International Gemini Observatory/NOIRLab/NSF/AURA/J. da Silva. Image processing: M. Zamani (NSF's NOIRLab).

Figure 4: Artist's illustration of a GRB resulting from a collapsing stars, ejecting particles and radiation in a narrow jet. Credit: Soheb Mandhai.

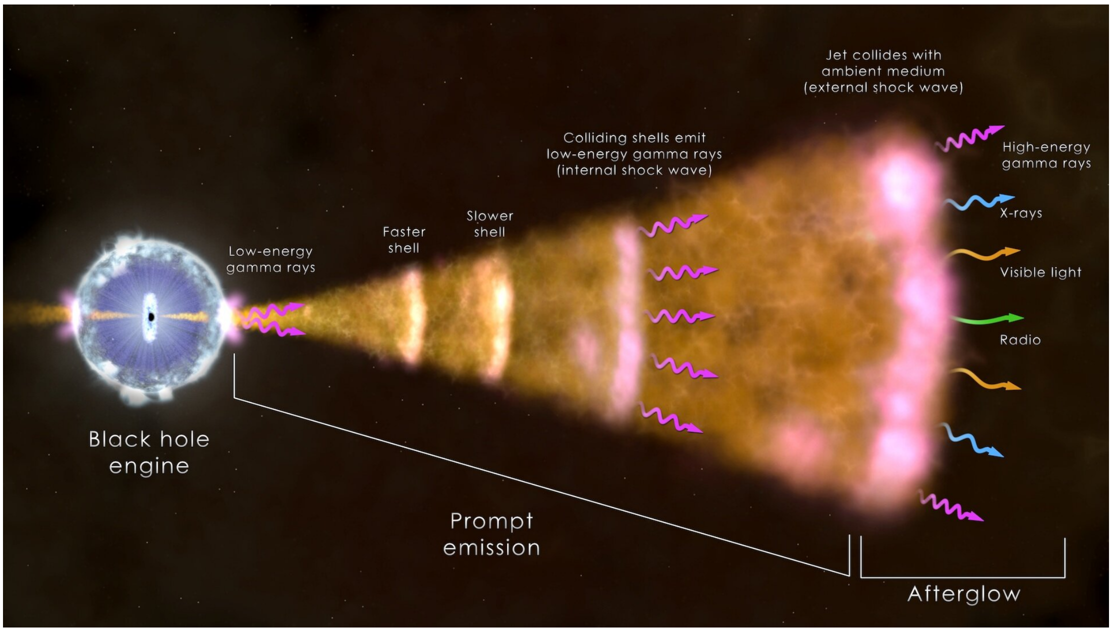

Figure 5: This illustration shows the ingredients of a long GRB, the most common type. The core of a massive star (*left*) has collapsed, forming a black hole that sends a jet of particles moving through the collapsing star and out into space at nearly the speed of light. Radiation across the spectrum arises from hot ionised gas (plasma) in the vicinity of the newborn black hole, collisions among shells of fast-moving gas within the jet (internal shock waves), and from the leading edge of the jet as it sweeps up and interacts with its surroundings (external shock). Credit: NASA's Goddard Space Flight Center.

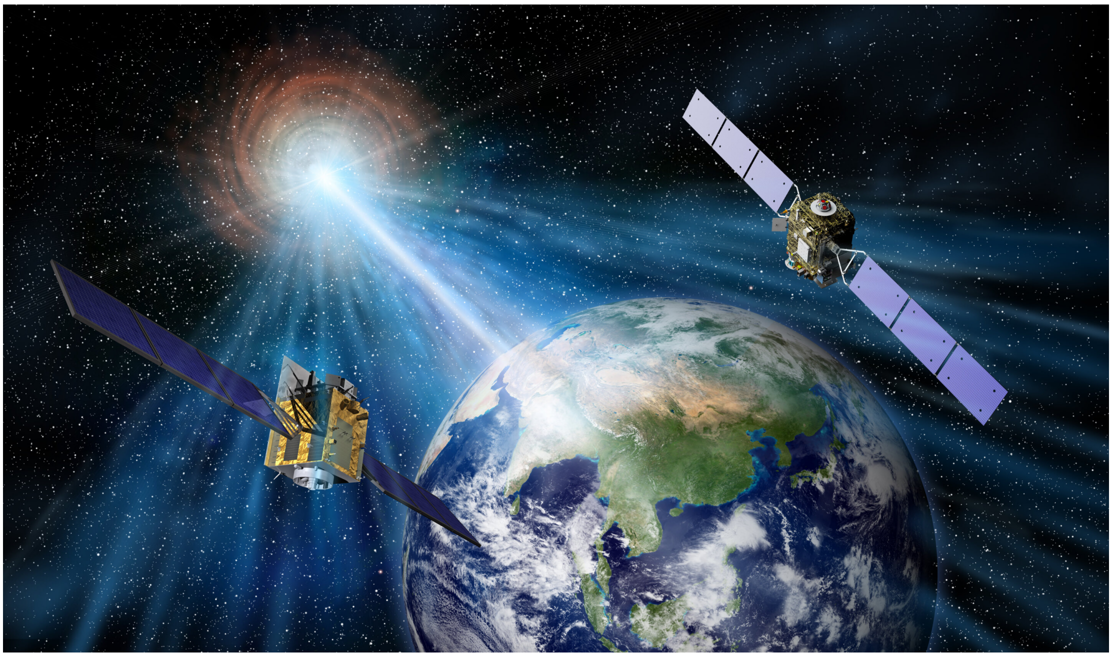

Figure 6: Illustration of the *Insight-HXMT* and *GECAM-C* observations of GRB 221009A. Credit: IHEP/HXMT & GECAM Team.

Figure 7: Illustration of the brightest GRB 221009A. Credit: IHEP/HXMT & GECAM Team