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Astrophysics

Rare isotopes formed in prelude to γ-ray burst

Daniel Kasen

The afterglow of a long burst of γ-rays suggests that the events leading to these explosions can be sizeable sources of some of the Universe's rare isotopes – and that classifications of γ-ray bursts are too simplistic. **See p.737 & p.742**

In March 2023, an astrophysical blast of γ-rays named GRB 230307A was registered as the second-brightest known burst of its kind. Astronomers, however, became entranced by the faint, colourful glow of its aftermath, which turned from an ordinary blue to a deep red over several weeks. On pages 737 and 742, respectively, Levan *et al.*[1] and Yang *et al.*[2] conclude that this red colour was the radioactive glow of rare isotopes synthesized in the event that triggered the burst. The discovery is another step towards understanding the cosmic origins of the heaviest elements. But it also muddies the waters of a question that was thought to have been answered: what causes γ-ray bursts (GRBs)?

Short GRBs, which have average durations of around 0.3 seconds, are generally thought to arise from mergers of compact objects, particularly the coalescence of two neutron stars in a binary system. By contrast, long GRBs, which have average durations of about 30 s, are considered to be derived from the collapse of a massive star (a collapsar).

GRBs originating from either progenitor should evolve to a similar final configuration: a central black hole with an orbiting disk of debris. Accretion of disk material by the black hole can produce a jet that accelerates particles close to the speed of light, which, in turn, powers a GRB. The debris disks formed in compact-object mergers are small in radius (approximately tens of kilometres)[3], and should accrete quickly, producing 'engines' that probably power up a GRB quickly[4].

Various observations have supported the idea that long and short GRBs have different progenitors. Astronomers have seen the bright lights from supernovae in the afterglows of long GRBs, indicating that massive stars had exploded[5]. By contrast, short GRBs are often found in regions of space that are devoid of massive stars, and they have never been observed with an accompanying supernova[4]. Clear-cut evidence about the origins of short GRBs came in 2017, when a short burst was found to coincide with a source of gravitational waves (GW170817) – definitively identifying the progenitor of this GRB as the merger of a binary neutron star[6].

Just six years after the confirmation of the progenitor of GW170817, the dichotomy of long and short GRBs was called into question by GRB 230307A. With a duration of around 35 s, this burst is classified as a long GRB. But it was found in a lonely part of space, with no young, massive stars in its vicinity, and around 40,000 parsecs (about 130,000 light years) away from the host galaxy (Fig. 1). That environment implies that GRB 230307A arose from a compact-object merger – from binary neutron stars that formed eons ago and drifted into the outskirts of the galaxy before merging.

But even more intriguing is the GRB's red afterglow. Amid the violent dynamics of a merger, matter is ejected from the neutron stars and transformed into heavy nuclei as a result of the copious free neutrons rapidly attaching to 'seed' nuclei (an isotope-formation pathway known as the r-process)[7,8]. The resulting mushroom cloud is radioactive and produces an observable glow known as a kilonova. The distinctive red colour of some kilonovae reflects their chemical make-up, and, in particular, tends to be indicative of the presence of nuclei from the lanthanide series of elements[9,10]. Just such a radioactive glow was observed for GW170817.

Observations made by Levan *et al.* and Yang *et al.* showed that the colour, brightness and temporal evolution of the afterglow of GRB 230307A contained kilonova signatures that were remarkably similar to those of GW170817. Levan *et al.* therefore requested observations with the James Webb Space Telescope (JWST), which provided unprecedented emission spectra of a kilonova long after the burst (29 and

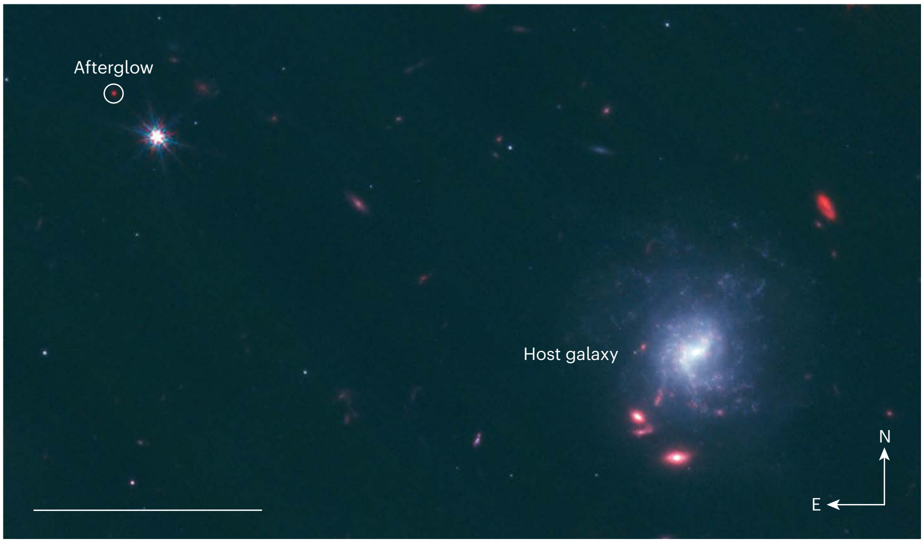

Figure 1 | The afterglow of the γ-ray burst GRB 230307A. GRB 20307A originated from a remote part of space, with no young, massive stars in its vicinity, and around 40,000 parsecs (about 130,000 light years) away from its host galaxy. This suggests that the burst arose from the merger of two neutron stars that formed eons ago and had drifted to the outskirts of the galaxy. Levan *et al.*[1] and Yang *et al.*[2] report analyses of observational data that support that model. A red hue seen in the afterglow indicates that lanthanide elements were produced in the event that formed the γ-ray burst. This JWST image combines images taken at three different wavelengths. Scale bar, 10 arcseconds. (Adapted from Fig. 2a of ref. 1.)

61 days afterwards) and at long wavelengths (up to 5 micrometres). The emission spectra contain a line feature near 2 µm, similar to one seen in the GW170817 event. Building on a previously reported theoretical study[11], the authors suggest (but do not prove) that this line arises from tellurium, an r-process element.

Levan *et al.* and Yang *et al.* carried out modelling of the kilonova signatures, which suggested that a mass equivalent to one-twentieth to one-tenth of the mass of the Sun was ejected from the source of the GRB, and that this ejecta contained heavy elements (lanthanides) produced by the r-process. This corroborates what was indicated by studies of GW170817 – that kilonovas were a substantial, and possibly dominant, contributor to the production of r-process elements in the Universe.

The idea that a long GRB such as GRB 230307A could be produced by a compact-object merger was suggested in 2021, when another long GRB (GRB 211211A) showed possible signatures of a kilonova[12,13]. So what is going on in these events? There are three possible explanations. First, it could be that GRB 230307A was derived from the collapse of a massive star, as expected for long GRBs, but that it happened to make a kilonova, rather than a brighter supernova. Some simulations suggest that a collapsar can produce and expel r-process elements[14], but the yields would probably be about tenfold more than what was observed for GRB 230307A.

A more compelling argument – which both Levan *et al.* and Yang *et al.* favour – is that GRB 230307A arose from a compact-object merger that somehow resulted in a long GRB. Although the small disks produced in such mergers should rapidly accrete onto the resulting black hole, simulations[15] published in 2023 suggest that the power of a GRB engine might initially depend not only on the amount of mass that accretes on the black hole, but also on the magnetic field of the accreted debris. The mass feeding the black hole might dwindle quickly, but the magnetic field of the mass inflow might increase, and provide a relatively constant power to the engine over timescales that match the durations of long GRBs. If this theory is correct, then compact-object mergers could produce either long or short GRBs, depending on the magnetic-field geometry and whether the merger produces a black hole or a hypermassive neutron star.

Finally, an overlooked scenario could be responsible. One possibility is a white dwarf merging with a black hole or a neutron star. White dwarfs have a much bigger radius than do neutron stars, and so their debris disks are large and the characteristic accretion timescales would be roughly consistent with the duration of long GRBs[16]. Material ejected from a disrupted white dwarf might produce a radioactive afterglow[17], but this ejecta would probably lack the peculiar heavy elements that give rise to a distinctive red hue. This scenario has not yet been investigated in detail, and further modelling of such white-dwarf mergers might resolve the contradiction.

The puzzles posed by GRB 230307A will inspire continuing theoretical and observational studies. Fortunately, it might be only a matter of time before gravitational waves from an unusually long GRB are detected, which would definitively tell us whether or not the burst arose from a compact-object merger – and, if it did, what the masses of the component objects were. In the meantime, the misbehaviour of GRB 230307A is a reminder that the Universe is more interesting than the pedantic classifications of humans suggest.

> **“The JWST observations provided unprecedented emission spectra of a kilonova.”**

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Neuroscience

A neural circuit that keeps flies on target

Katherine Nagel

Studies reveal how neuronal populations in the fruit fly brain work together to compare the direction of a goal with the direction that the fly is facing, and convert this into a signal that steers the fly towards its target. **See p.808 & p.819**

Animals of all kinds show a remarkable ability to navigate, whether it is to the location of a remembered food source or back to the safety of a nest. To accomplish this kind of goal-directed movement, brains have evolved specialized navigation centres – the hippocampus in vertebrates and the central complex in insects – that allow each animal to build an internal map or compass of its environment. Although the way in which these maps are built by neural circuits has been studied for many years, neuroscientists are still trying to understand how the maps allow an animal to orient towards a goal. On pages 808 and 819, respectively, Mussells Pires *et al.*[1] and Westeinde *et al.*[2] reveal the detailed mechanisms by which the insect brain converts a map-like representation of direction into goal-oriented steering.

The essence of a map is that it stays the same as an animal moves through space – the map is tied to coordinates of the animal's spatial environment (for example, north, south, east and west) rather than to the animal's left or right. Turning such a map into a steering command requires some form of comparison. For example, if a map tells you that treasure is northeast and you are currently pointing north, you can compare these two directions and determine that your best course of action is to turn right by a few degrees.

How might a neural circuit make this comparison? A possible answer first emerged from reconstructions of the brains of sweat bees (*Megalopta genalis*)[3] and, later, fruit flies (*Drosophila melanogaster*)[4]. By painstakingly tracing and reconstructing neurons and their synaptic connections using electron microscopy images, researchers revealed surprisingly precise and selective connectivity