Expert insight into current research

News & views

Astronomy

Strange flashes linked to stars merging, not dying

Luigi Piro

Long bursts of γ-rays usually signal the death of massive stars, but an emission detected last year suggests that a long burst with peculiar properties originated from the merger of stars in a compact binary system. **See p.223, p.228, p.232 & p.236**

Brief, intense flashes known as γ-ray bursts appear every day at random locations in the sky. These bursts are classified according to their duration. Short γ-ray bursts, lasting less than one second, are thought to derive from the merging of two neutron stars in a binary system, whereas long γ-ray bursts are active for a few seconds or more, and result from the collapse of a massive star. Four papers published in this issue of *Nature* by Troja *et al.*[1], Rastinejad *et al.*[2], Mei *et al.*[3] and Yang *et al.*[4] now challenge this long-standing paradigm, by providing evidence of a long γ-ray burst that seems to have been produced by the merger of a compact binary system.

Over the past 25 years, astronomers have studied emissions at wavelengths longer than γ-rays to pinpoint the source of these bursts, and have deduced that the two classes of burst come from distinct progenitor systems (Fig. 1). Long γ-ray bursts take place in galaxies with irregular or spiral-shaped geometries, occurring preferentially in bright star-forming regions in the central part of the galaxy. The spectra of these bursts contain features consistent with supernovae, which are considered indisputable proof of the connection between long γ-ray bursts and the collapse of massive stars[5].

By contrast, short γ-ray bursts can come from both spiral-shaped galaxies and more-regular elliptical galaxies, but always originate in isolated regions that are often far from the centres of their host galaxies. These properties are consistent with the idea that short γ-ray bursts originate in old stellar populations from progenitors comprising either two neutron stars or a neutron star and a black hole. The orbit of such systems shrinks over tens to hundreds of millions of years, owing to energy lost through gravitational waves, until eventually the two bodies merge. The remnant is a black hole, or perhaps a rapidly spinning neutron star, that accretes matter quickly from a disk of debris that powers the γ-ray burst. The kick from the supernova explosion that formed the neutron star is responsible for having flung the system to the outskirts of the galaxy – or even beyond.

This scenario was confirmed in August 2017 when gravitational waves from the merger of two neutron stars (labelled GW170817) were detected at the same time that a short γ-ray burst was observed[6], revealing a cosmic event known as a kilonova, as the electromagnetic fingerprint of such a merger[7]. The neutron-rich matter that is ejected during the merger generates heavy radioactive elements, the decay of which powers a flash in the optical infrared spectrum that lasts a few days. So just as a supernova links long γ-ray bursts to the collapse of massive stars, a kilonova is the smoking gun for a compact binary merger.

But this neat picture was disturbed in 2006, when NASA's Neil Gehrels Swift observatory identified a few long γ-ray bursts with no trace of a supernova, nor convincing evidence of a stellar progenitor[8]. The data reported by the four papers in this issue constitute indisputable evidence that these unusual events are

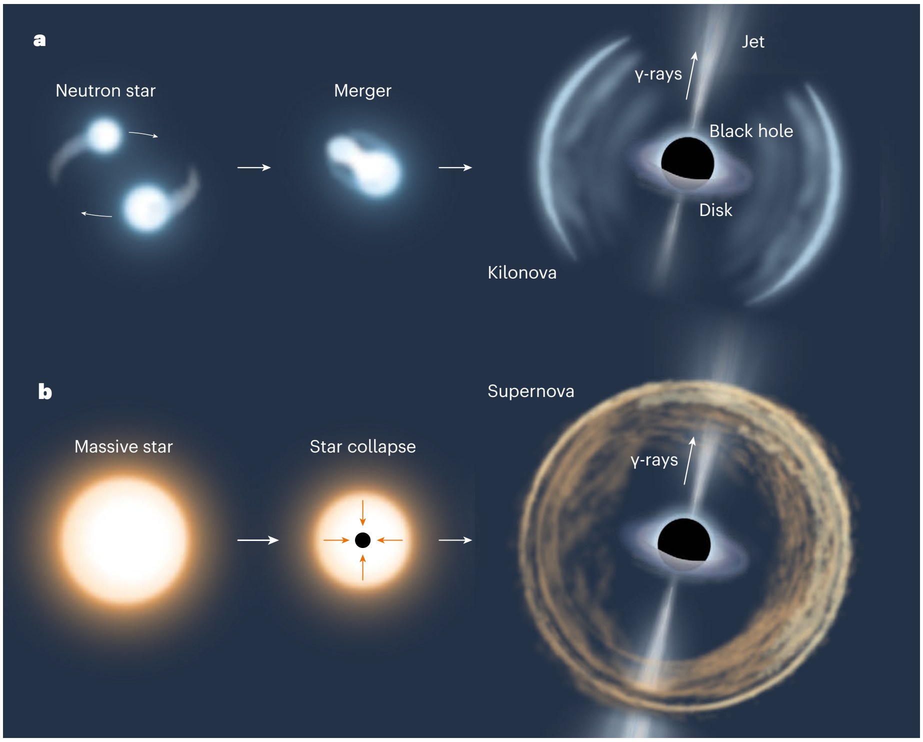

Figure 1 | Cosmic events that result in bursts of γ-rays. Bright flashes known as γ-ray bursts either last less than one second, or more than a few seconds. **a**, Short γ-ray bursts are thought to derive from the merging of two neutron stars in a binary system, which leaves a black hole, or a spinning neutron star, that accretes matter from a disk of debris to power a jet that emits γ-rays. A cosmic event called a kilonova, produced by neutron-rich ejecta, is evident in the electromagnetic spectra associated with these mergers. **b**, Long γ-ray bursts are linked to the collapse of a massive star, with spectral features that are consistent with a supernova. Troja *et al.*[1], Rastinejad *et al.*[2], Mei *et al.*[3] and Yang *et al.*[4] report that a long γ-ray burst detected on 11 December 2021 exhibits strange properties (including those characteristic of a kilonova) that suggest it originated in a stellar merger, rather than in stellar death.

connected to mergers of compact objects, rather than to the collapse of massive stars.

On 11 December 2021, the Swift observatory detected another bright, long γ-ray burst with high intensity at all wavelengths, the source of which was a relatively close 350 megaparsecs away from Earth. The optical and infrared light emitted far exceeded that expected from the standard afterglow of the γ-ray burst. This afterglow is produced by a jet of relativistic particles, which are particles travelling at close to the speed of light, interacting with the surrounding medium. Troja *et al.* and Rastinejad *et al.* attribute this excess to a kilonova, because it is consistent with theoretical models of mergers, and its luminosity, duration and colours are similar to those of GW170817. In fact, this burst resembles a short γ-ray burst in all aspects except its duration.

This discovery begs the question of how the merger of two neutron stars could have given rise to such a long emission – a pulse of 13 seconds, followed by a pulse of lower intensity lasting another 55 seconds. One possibility is that a compact remnant of the merger (a black hole) powered a jet by accreting material from a temporary disk of debris from the collision. But the larger the disk, the longer the burst, and neutron-star mergers produce small, compact disks that are unable to sustain γ-ray bursts lasting longer than a second[9].

Yang *et al.* propose that the duration of the first pulse is long because it is associated with a large accretion disk surrounding a spinning neutron star with a very strong magnetic field (a proto-magnetar) that formed when a white dwarf merged with a neutron star. By contrast, the extended emission shows a different spectrum that suggests it was powered by a relativistic wind that extracted the rotational energy of the proto-magnetar. This scenario is not uncommon and has been proposed to explain the extended emission observed in a substantial fraction of short γ-ray bursts[10]. Indeed, the idea that a proto-magnetar is involved in GW170817 has not been ruled out[11,12].

Previously, the only known electromagnetic signature of a kilonova was the optical infrared flash. But Mei *et al.* found that the kilonova is also evident in the appearance of more photons than expected in the gigaelectronvolt energy range. This excess is produced by the same population of relativistic electrons that emits the afterglow of the γ-ray burst and that boosts the optical photons of the kilonova at high energies.

Other distinctive features of kilonovae have been proposed in the past, but have so far eluded detection. For example, ejecta from the merger are expected to produce shocks when they interact with the interstellar material, leading to faint emissions at radio to X-ray wavelengths that peak several years after the merger[13]. Ongoing monitoring of GW170817 (ref. 14) with existing observatories and a sample of short γ-ray bursts[15] has not detected such components. The low luminosity of the expected emission would require observatories with improved sensitivity, such as that promised by the Advanced Telescope for High-ENergy Astrophysics (Athena), the European Space Agency's X-ray observatory mission[16].

Future observatories might also reveal the spectral features produced by the decay of the radioactive nuclei that are generated in mergers[16,17]. Understanding the signatures of kilonovae at different wavelengths would enable an increase in the number of mergers detected through both gravitational waves and electromagnetic signals. Such joint efforts would hone the many merger models used to estimate the mass, composition and velocity of ejecta – data that are key to theories touting neutron-star mergers as the main source of heavy metals in the Universe.

Yang and colleagues' proposed scenario suggests that the kilonova emission is powered by a large amount of energy from the proto-magnetar, because mergers between neutron stars and white dwarfs are not expected to yield much neutron-rich material[18]. By contrast, a neutron-star merger requires limited, if any, energy from a magnetar[1,2]. It remains to be seen which scenario is correct, but any extra energy should boost the long-term radio emission in a way that might soon be detectable[15]. Another means of distinguishing the most plausible scenario involves the effectiveness of the accretion disk in supporting a long γ-ray burst, because the disk associated with the merger of a white dwarf and a black hole might not be capable of doing so[19].

The next campaign for the Earth-based gravitational wave laboratories Laser Interferometer Gravitational-Wave Observatory (LIGO), the Virgo interferometer and the Kamioka Gravitational Wave Detector (KAGRA) is planned for 2023 and 2026, and is expected to uncover tens to hundreds of neutron-star mergers[20]. About 10% of these mergers could be associated[1] with the strange hybrid γ-ray bursts reported in the four papers. This would mean that these events had been detected by both gravitational waves and electromagnetic emission, at least in cases in which the progenitor comprises two neutron stars. The gravitational-wave emission for the merger of a white dwarf and a neutron star would be too low for LIGO and Virgo to detect. But with so many pieces of the puzzle coming together, it won't be long before the origin of these peculiar flashes is revealed.

Luigi Piro is at the Istituto di Astrofisica e Planetologia Spaziali, INAF, 00133 Rome, Italy.
e-mail:luigi.piro@inaf.it

1. Troja, E. *et al. Nature* **612**, 228–231 (2022).
2. Rastinejad, J. C. *et al. Nature* **612**, 223–227 (2022).
3. Mei, A. *et al. Nature* **612**, 236–239 (2022).
4. Yang, J. *et al. Nature* **612**, 232–235 (2022).
5. Galama, T. J. *et al. Nature* **395**, 670 (1998).
6. Abbott, B. P. *et al. Astrophys. J.* **848**, L13 (2017).
7. Pian, E. *et al. Nature* **551**, 67–70 (2017).
8. Gehrels, N. *et al. Nature* **444**, 1044–1046 (2006).
9. Fryer C. L. *et al. Eur. Phys. J. A* **55**, 132 (2019).
10. Metzger, B. D., Quataert, E. & Thompson, T. A. *Mon. Notices R. Astron. Soc.* **385**, 1455–1460 (2008).
11. Metzger, B. D. *et al. Astrophys. J.* **856**, 101 (2018).
12. Piro, L. *et al. Mon. Notices R. Astron. Soc.* **483**, 1912–1921 (2019).
13. Nakar, E. & Piran, T. *Nature* **478**, 82 (2011).
14. Troja, E. *et al. Mon. Notices R. Astron. Soc.* **510**, 1902–1909 (2022).
15. Ricci, R. *et al. Mon. Notices R. Astron. Soc.* **500**, 1708–1720 (2021).
16. Piro, L. *et al. Exp. Astron.* **54**, 23–117 (2022).
17. Korobkin, O. *et al. Astrophys. J.* **889**, 168 (2020).
18. Bobrick, A. *et al. Mon. Notices R. Astron. Soc.* **510**, 3758–3777 (2022).
19. Narayan, R. *et al. Astrophys. J.* **557**, 949 (2001).
20. Petrov, P. *et al. Astrophys. J.* **924**, 54 (2022).

The author declares no competing interests.

Climate change

A plastic container for carbon emissions

Sangwon Suh & André Bardow

Modelling reveals that the carbon emissions associated with plastics could be negative by 2100 under a strict set of technological and socio-economic conditions – including increased recycling and plant-derived production. **See p.272**

The direct effect of plastics on the marine ecosystem has attracted global attention. However, the production and disposal of plastics are also a concern, because these processes release more climate-warming gases annually than does global aviation[1]. And these emissions are increasing: the growing global appetite for plastics is expected to result in a doubling of their associated carbon emissions by 2050. Such an increase would prevent us from achieving net-zero emissions, a target that is widely held to be necessary to protect the planet's ability to