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GRAVITATIONAL WAVES

A golden binary

The discovery of gravitational waves from a neutron-star merger and the detection of the event across the electromagnetic spectrum give insight into many aspects of gravity and astrophysics.

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Sometimes nature can be generous. Its generosity was on full display on 17 August 2017, when two compact stellar remnants called neutron stars spiralled together some 40 million parsecs (130 million light years) away[1]. The event, called GW170817, arguably provides an even greater treasure than black-hole mergers[2–5], because it produced both gravitational waves and electromagnetic radiation. GW170817 was detected in γ-rays[6] and, as reported in five papers online in *Nature*[7–11], in X-rays, optical light and infrared light. As a result, in one stroke, the event provides tests of alternative theories of gravity; a clear origin for a cosmic explosion known as a γ-ray burst; and strong evidence for the formation path of at least some of the heavy elements in the Universe (those much heavier than iron).

The detection of gravitational waves from the coalescence of a binary neutron-star system is, in itself, profoundly informative. Unlike black holes, neutron stars lack event horizons — boundaries beyond which no matter or energy can escape. Analysis of the gravitational waves from a neutron-star merger can, therefore, facilitate previously impossible tests of alternative theories of gravity that differ from Einstein's general theory of relativity only when matter is present[12].

But there is even greater excitement about GW170817, because it was accompanied by strong electromagnetic signals (Fig. 1). This means that, for the first time, it is possible to link a gravitational-wave detection to the rest of astronomy. Honours for the first-reported electromagnetic signal go to the Gamma-ray Burst Monitor aboard NASA's Fermi Gamma-ray Space Telescope, which — independently of the gravitational-wave detection — picked up a γ-ray flash formed just two seconds after the neutron-star merger[6]. The properties of the flash are generally consistent with those of short γ-ray bursts, which were long suspected of being related to neutron-star mergers[13]. The lottery-winning aspect of GW170817 can be underscored by the revelation that the event occurred more than ten times closer to Earth than any previously measured short γ-ray burst[13], which will make it easier to study.

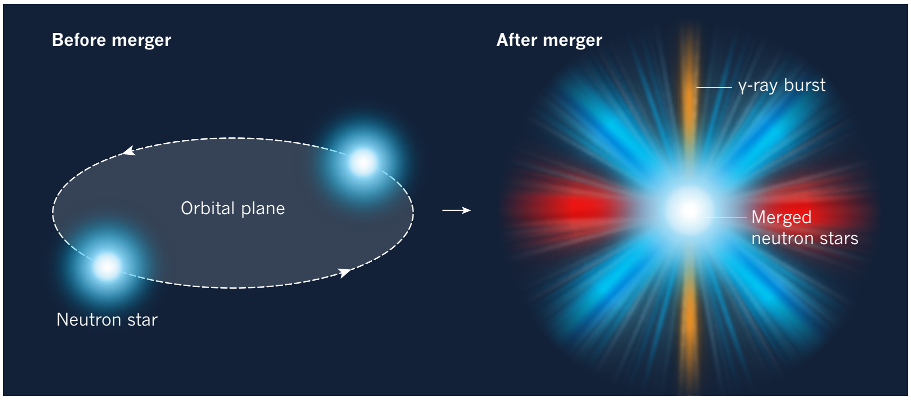

Figure 1 | The merger of a binary neutron-star system. Gravitational waves have been detected from the coalescence of two orbiting neutron stars[1]. Unlike the previous discoveries of gravitational waves[2–5], the event has been observed across the electromagnetic spectrum. The Fermi Gamma-ray Space Telescope saw a flash of γ-rays just two seconds after the neutron-star merger[6]. The flash is consistent with a cosmic explosion called a γ-ray burst, produced by a tightly collimated 'jet' of ejected material that was probably observed from a direction other than the axis of the jet. In addition, five papers[7–11] report the emission of X-rays, optical light and infrared light from the merged neutron stars. The peak X-ray and optical emission (blue) is thought to have been produced by material ejected roughly perpendicularly to the orbital plane of the original binary system. By contrast, the peak infrared emission (red) is thought to have been produced by material ejected closer to the orbital plane.

Even more fortunate was that, unlike for the first three gravitational-wave discoveries[2–4], the Virgo gravitational-wave detector, as well as the Laser Interferometer Gravitational-Wave Observatory (LIGO), was operating during GW170817. The Virgo detector is situated outside Pisa in Italy, and its distance from the US-based LIGO detectors — at sites in Hanford, Washington, and Livingston, Louisiana — allowed the location of GW170817 on the sky to be determined with an uncertainty of about 30 square degrees[1], compared with 600 square degrees or more for the first three detections[2–4].

The discovery of GW170817 led to a tremendously successful follow-up campaign, the results of which are reported in the current papers. For example, some γ-ray bursts seem to be extremely intense given their distance from Earth, and well-established models indicate that we see such intensity because our line of sight is close to the axis of a tightly collimated 'jet' of material moving at close to the speed of light. By contrast, the γ-rays from GW170817 are remarkably weak. Troja *et al.*[9] (see also ref. 14) use data from the space-based Chandra X-ray Observatory to show that this can be understood if we are off-axis observers of the jet associated with GW170817. This opens up the intriguing possibility that we see many γ-ray bursts as dim not because they are distant, but because we view them from an unfavourable angle.

Over the past few years, there has been a growing body of theoretical work predicting that mergers of binary neutron-star systems generate an outflow of matter that radiates optical and infrared light in a characteristic way. This is because such mergers are messy: a small fraction of the neutron-rich matter in the stars is thought to be ejected along the system's orbital plane, where the neutrons and protons combine to form heavy elements, and in doing so, produce a signature glow. Arcavi *et al.*[7], Pian *et al.*[8] and Smartt *et al.*[10] report that they have found this signature associated with GW170817.

As discussed by Kasen *et al.*[11], previous predictions had been that the outflow of matter along the orbital plane would lead to emission that rises and then falls over many days, and that peaks in the infrared region of the electromagnetic spectrum[15]. But some work had suggested that, for outflow roughly perpendicular to the orbital plane, neutrinos produced in the merger would interact with the outflow and reduce the number of neutrons. Compared to the case of orbital-plane outflow, this would lead to the production of lighter elements such as iron[16], and, in turn, would result in emission that rises and falls more quickly, and would be seen by some observers to peak in the optical range.

What Arcavi *et al.*, Pian *et al.* and Smartt *et al.* find is something of a hybrid of these two scenarios. A fast rise and fall, and an optical peak, are seen. Furthermore, the ejecta speed (roughly 20% of the speed of light) and mass (a few per cent of the Sun's mass) are consistent with numerical simulations of double-neutron-star mergers. All three papers therefore agree that at least the early stage of the observed outflow is dominated by lighter elements. For the later development, however, consensus has not yet been reached. Smartt *et al.* find that, until about two weeks after the merger, the entire optical and near-infrared spectrum can be explained by the formation of lighter elements. Conversely, Pian *et al.* and Kasen *et al.* (see also refs. 17,18) favour the emergence of a heavy-element composition during this time.

One of the issues at stake is the origin of the 'r-process' elements (the most enticing of which to most people is gold). These elements are so named because they can be produced only in environments that are so rich in neutrons that the neutrons combine with nuclei more rapidly (hence the 'r') than the nuclei decay into stable isotopes. Early work favoured supernovae as the origin of these elements, but over the past few years, analyses have leaned towards the merger of compact objects, such as neutron stars, as the prime r-process factories (an idea first suggested in ref. 19).

For all of these reasons, GW170817 represents a remarkable opportunity to make major progress in multiple fields of physics and astrophysics, and it whets our appetite for the many expected observations of neutron-star mergers in future campaigns. Let's see what nature has in store for us next. ■

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