GRAVITATIONAL WAVES

Stellar palaeontology

A third gravitational-wave signal has been detected with confidence, produced again by the merger of two black holes. The combined data from these detections help to reveal the histories of the stars that left these black holes behind.

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Just after 2 a.m. on 4 January 2017, the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) detector located in Hanford, Washington, registered a tiny ripple in the fabric of space-time. Three milliseconds later, its twin detector, located some 3,000 kilometres away in Livingston, Louisiana, picked up an identical oscillation. Each ripple comprised a stretching and squeezing of space by less than 1 part in 1 billion trillion (10^{21}), and together they constituted the discovery of the gravitational-wave signal GW170104. The details of this observation are reported by Abbott *et al.* (the LIGO Scientific Collaboration and the Virgo Collaboration)[1] in *Physical Review Letters*, adding to a growing set of data that will help astrophysicists to discover the life stories of massive stars.

The observed signal was emitted during the merger of two black holes, as in the two previous confident detections of gravitational waves and the one further probable detection[2]. The combined mass of GW170104's black holes was about 50 times greater than the mass of the Sun, which makes it the second-heaviest merger observed so far. At a distance of 920 megaparsecs (3 billion light years) from Earth, the source of the gravitational waves is the farthest to have been detected with confidence.

The observed signal was tiny, but the energy emitted as gravitational waves was equivalent to about two solar masses: in the last second before the merger, the gravitational-wave luminosity of GW170104 exceeded the combined luminosity of all the stars in the visible Universe. Indeed, the loss of energy associated with gravitational-wave emission is what drives black holes to merge.

Gravitational-wave signals precisely probe the ultra-strong gravity that is found in the vicinity of black holes. As with the previous events, Abbott *et al.* find that their data are consistent with Albert Einstein's general theory of relativity, in both the dynamics of merging black holes and the subsequent propagation of gravitational waves through space.

As well as being a tool for testing fundamental physics, gravitational-wave astronomy holds promise for the exploration of the Universe through studies of the dramatic fates of its stellar 'fossils' — the black holes that are left behind by massive stars at the end of their lives. From the signals observed so far, Abbott *et al.* determined the rate of mergers of black-hole pairs. For a galaxy of similar size to our Milky Way, the calculated rate corresponds to about 1 to 20 mergers every million years. The observed black-hole systems show a roughly uniform spread in total mass, but this partly reflects the Advanced LIGO detectors' greater sensitivity to heavier black holes than to lighter ones. The authors infer that the underlying mass distribution of merging black holes is skewed towards lower masses, consistent with the initial mass distribution of massive stars.

To merge within the age of the Universe, the black holes responsible for GW170104 must once have been separated by a distance no greater than one-fifth that of Earth from the Sun[3]. But the massive stars that collapse to form such black holes are thought to expand to sizes much larger than this separation during their evolution. So how do they avoid merging into a single star before forming black holes?

Several possibilities have been proposed. One scenario is that the two stars are initially far apart, in a binary system that has a wide orbit. As one of the stars expands as it ages, the gravity of its companion distorts and rips off the expanding star's outer layers. This can produce a thick envelope of gas that surrounds the pair (Fig. 1a). Friction between the stars and the gas envelope then acts to bring the dense centres of the stars closer together[4,5]. Another scenario is that the stars begin close together and do not expand (Fig. 1b). Instead, rapid spinning — sustained by the energetically favourable locking of the stellar rotation period to the orbital period of the binary system — causes efficient mixing within the stars,

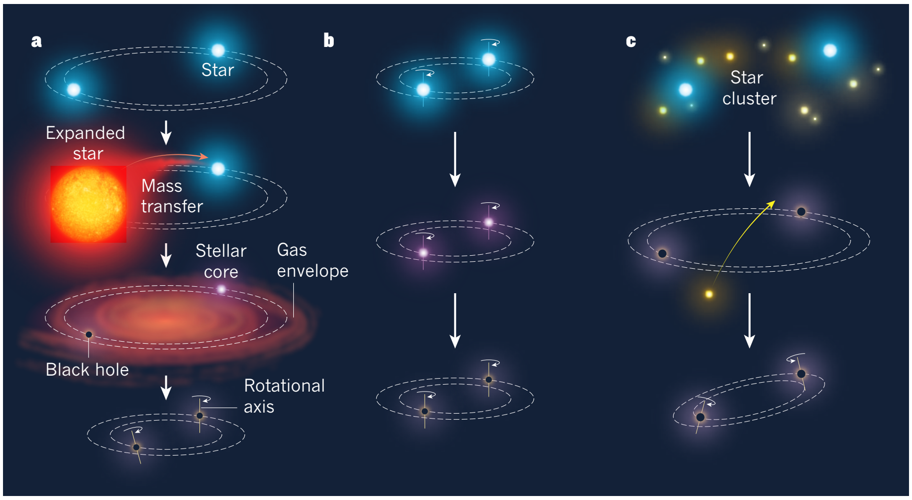

Figure 1 | Three possible mechanisms for the merger of black holes. a, In a binary star system that has a wide separation (orbit shown in broken lines), the expansion of one star as it evolves can lead to its outer layers being transferred to its companion. Further evolution of the system can lead to the formation of a gas envelope around the two objects, which are now a black hole and a stellar core. Friction between these objects and the envelope acts to bring the objects closer together. Eventually both stars collapse into black holes; the associated supernova explosions could cause misalignment of the black holes' rotation directions. **b,** Stars in close binaries can be prevented from expanding by rapid stellar rotation and efficient internal mixing, which helps to avoid the transfer of mass between the stars as they evolve. The resulting black holes are likely to have aligned rotational axes. **c,** Individual stars in dense clusters can form black holes that subsequently pair up through dynamic interactions with other stars (yellow arrow). The rotational axes of these black holes are expected to have a random orientation. Abbott and colleagues' observation[1] of a black-hole merger provides data that will help to determine how pairs of black holes form and merge.

allowing them to convert almost all of their hydrogen into helium through nuclear fusion, and to contract as they evolve[6,7].

Or perhaps the two black holes don't start out as a pair at all. Long after the stars have collapsed into black holes, interactions with other stars in a dense stellar cluster might bring them into an orbit close enough to enable a merger that is driven by the emission of gravitational waves[8,9] (Fig. 1c). Even more extraordinary possibilities exist, including a proposal that the two black holes have a non-stellar origin. Could they instead have formed from the direct collapse of density perturbations in the early Universe[10]?

GW170104, together with the previously observed signals, provides tantalizing hints as to which mechanisms of formation are most probable. Merger rates alone do not narrow down the possibilities much at present, because of uncertainties in all of the formation models. But the mass distribution of merging black holes will provide more-stringent constraints after further detections have been made.

A particularly interesting piece of evidence from GW170104 relates to the rotation of its black holes. Although the individual rotation frequencies and directions of the two black holes are difficult to measure, Abbott *et al.* report that there was no significant net rotation in the same direction as the binary system's orbit. The black holes were therefore spinning very slowly, or their spins were considerably misaligned with the orbit. Misaligned spins could point to the mechanism in which the black holes formed separately (Fig. 1c), because the spins of the black holes are expected to show a random orientation relative to the orbit in such a scenario. However, the isolated evolution of a binary that has an initially wide orbit (Fig. 1a) might yield low rotation rates[11], or could produce misalignments when the stars undergo supernova explosions.

One thing is clear: mergers of pairs of dense objects will be observed in ever greater numbers as the sensitivity of the Advanced LIGO detectors increases. Such observations will provide a rich and fascinating astrophysical data set. Just as palaeontologists use fossilized skeletons to make inferences about the appearance, diet and behaviour of dinosaurs, astrophysicists are beginning to use gravitational waves from compact stellar remnants to explore the lives — and deaths — of massive stars. ■

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ARCHAEOLOGY

Early signs of human presence in Australia

It emerges that people reached Australia earlier than was thought. This finding casts light on the technology used by the travellers, and their possible interactions with animal species that became extinct. **SEE ARTICLE P.306**

CURTIS W. MAREAN

When did ancient humans, dispersed from Africa, reach some of the most distant corners of the world? And which technologies were associated with these early travellers? On page 306, Clarkson *et al.*[1] report an analysis of archaeological fieldwork in Australia, and propose a revised timeline for the peopling of this continent.

Around 70,000 years ago[2], a group of African people moved into Asia, probably through the Sinai peninsula in Egypt and into the Negev Desert, as part of a journey that was the most consequential dispersal event of our species in the history of our planet. The descendants of these early travellers pushed into Europe, eastern Asia, Australia and the Americas, and eventually reached the remaining unpopulated islands such as Madagascar and New Zealand. This diaspora resulted in altered environments, was associated with the eventual disappearance of related species from the family tree of humans, such as the Neanderthals, and set the stage for the formation of the main human genetic lineages that have given rise to different ethnic and linguistic groups. Moreover, the dispersal also overlapped in time with the extinction of many animal species.

Hunter-gatherers, using nothing more than

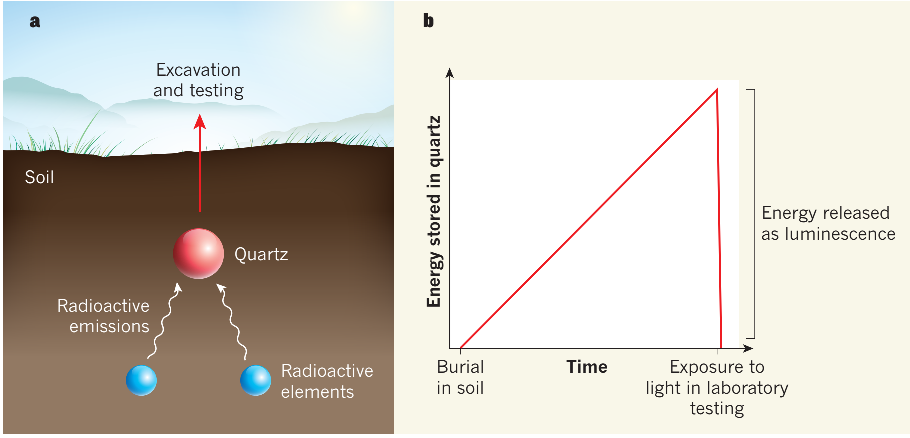

Figure 1 | The optically stimulated luminescence dating technique. **a**, When sediments containing minerals such as quartz are buried underground, they can be exposed to radioactive emissions that result in energy being stored in the mineral grains. This energy remains trapped, provided that the quartz grains are not exposed to light during excavation. **b**, Over time, the amount of trapped energy that is stored in buried quartz grains increases. When excavated quartz grains are exposed to light under laboratory conditions, the stored energy is released in the form of luminescence. After calibration, the amount of luminescence released can indicate how long the sediment sample has been buried. Clarkson *et al.*[1] used this technique, known as optically stimulated luminescence, to provide a revised timeline for human occupation at the archaeological site Madjedbebe in Australia, revealing that humans reached the continent earlier than previously thought.