NEWS & VIEWS

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GRAVITATIONAL WAVES

Dawn of a new astronomy

The discovery of gravitational waves from a merging black-hole system opens a window on the Universe that promises to test gravity at its strongest, and to reveal many surprises about black holes and other astrophysical systems.

M. COLEMAN MILLER

Shortly after Albert Einstein delivered his theory of gravity — general relativity — to the world in 1915, he discovered that binary stars and other sources should generate gravitational waves[1,2]. Unfortunately, he also found that any imaginable source would produce gravitational waves so weak that detection was inconceivable using the technology of the day. But this inconceivable detection has now been reported by Abbott *et al.* (the LIGO Scientific Collaboration and the Virgo Collaboration) in *Physical Review Letters*[3].

The authors describe the detection of the signal GW150914 from gravitational waves generated by the merger of two black holes (Fig. 1). These waves were detected from the temporary, tiny changes that they induced in the lengths of the two detectors of the US-based Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO). The consequences of this detection are difficult to overstate, as is its promise for future advances and discoveries. Before this discovery, astronomers had only three types of messenger from space beyond our Solar System: photons, neutrinos and high-energy cosmic rays. Gravitational waves can now be added to this short list.

Moreover, some of the most violent events in the Universe can be seen only in gravitational waves. Consider, for example, the inspiral and merger of two black holes, such as the one that caused GW150914. During the last moments of coalescence, the energy emitted in gravitational waves was tens of times larger than the energy emitted in those moments by all the stars in the Universe combined. But such an event is expected to be undetectable using any of the other messengers. Opening the gravitational-wave window will thus reveal events that had previously only been hypothesized.

This window will also enable tests of general relativity in realms that were previously inaccessible. We can get an idea of the domain that can now be explored by considering a dimensionless quantity, GM/Rc^2, that measures the importance of gravity for an object of mass M and radius R (G is Newton's gravitational constant and c is the speed of light). For Earth, GM/Rc^2 at the surface is approximately 7×10^{-10}. For a star such as the Sun, GM/Rc^2 is still only about 2×10^{-6}. Previous tests of general relativity have therefore been restricted to systems that have weak gravity.

But at the event horizon of a black hole (the boundary beyond which nothing can escape the hole's gravitational field), GM/Rc^2 is roughly 1, many orders of magnitude larger than for planets and stars. Gravity can thus be tested directly at its greatest strength for the first time, by analysing GW150914 and any other signals detected for similar mergers in the future. General relativity has passed the tests set by GW150914 with flying colours[4]. This signal has also provided the most direct confirmation yet of the existence of event horizons, which are unique to black holes.

The discovery of GW150914 has profound consequences for astronomy. Previously known black holes that formed from a single star have quite a restricted mass range: the highest mass that was definitively established was found to be only about 15 times the mass of the Sun[5]. Analysis of GW150914 has doubled this mass record at a stroke (the merging black holes had masses 29 and 36 times that of the Sun[6]), and then doubled it again (the final merged black hole is inferred to have a mass 62 times that of the Sun[6]). The spins of black holes are notoriously difficult to measure, but Abbott *et al.* were able to infer the spin of the final black hole from their data: the 160-kilometre-radius black hole spins completely around 100 times per second, which is roughly 70% of the maximum possible rate for a black hole of this mass.

None of this could have happened without spectacular developments in instrumentation. Gravitational waves distort space and time only slightly at our distance from any likely sources. The distortion is characterized by a dimensionless quantity called strain, which is the fractional change in distances produced by the waves. Even for a fairly strong event such as

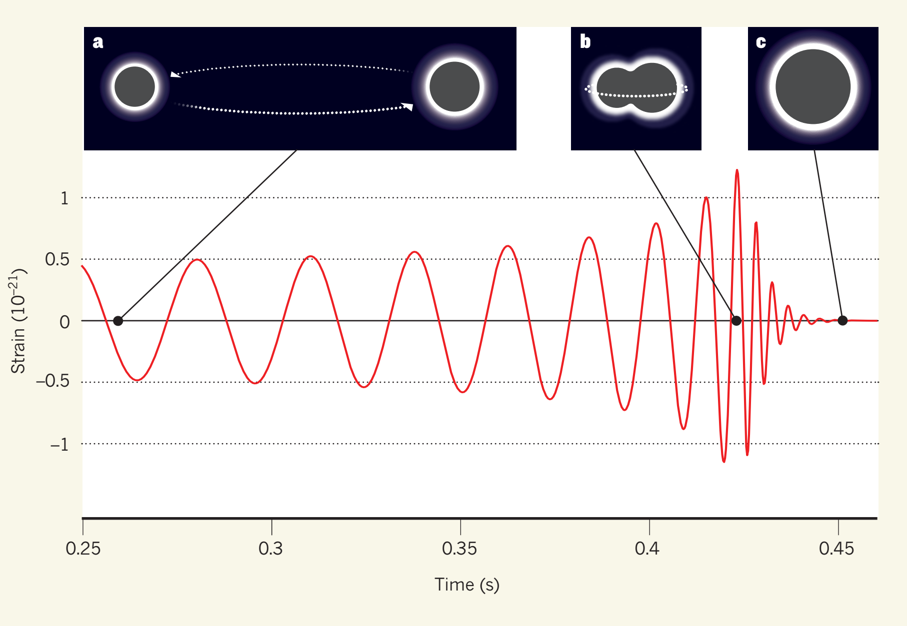

Figure 1 | A gravitational wave from merging black holes. Abbott *et al.*[3] report the detection of a gravitational wave, which they attribute to the coalescence of two black holes. **a**, The wave was first detected at approximately 35 Hz, as it reached the sensitivity range of Advanced LIGO (the detecting observatory). At this point, the black holes were spiralling in towards each other. The depicted radii are proportional to the black-holes' masses. **b**, The wave frequency increased as the black holes coalesced — at the point of merger, the black-hole horizons overlapped, but had not settled down to their final state. **c**, The wave dissipated as the merged black hole attained its final, simple configuration. The wave depicted here is based on observational data, but has been smoothed and fitted to a numerical model based on general relativity; strain represents the fractional changes in distance that are produced by the waves. (Adapted from ref. 1.)

the black-hole merger, the change is tiny: the authors find a maximum value of just 10^{-21}. This means that the 4-kilometre-long, L-shaped arms of Advanced LIGO change in length by about 1/200 of the radius of a proton. Such changes can nonetheless be seen because of the exquisite precision of the optics of Advanced LIGO, the delicacy of its suspension and the power of its lasers, which all result from years of development — the LIGO detector has improved in all respects by orders of magnitude since its first conception more than 40 years ago.

Even more encouragingly, further major improvements are just around the corner. During its next run in 2016, Advanced LIGO will be able to observe about three times the volume of space that it could in 2015, and in the next year or two the Advanced Virgo detector in Italy will join the search for gravitational waves. A few years later, the Japanese Kamioka Gravitational Wave Detector will come online, and it is hoped that LIGO-India will join the hunt before 2025. This international network will also benefit from technological developments in light manipulation such as those at the GEO600 detector in Germany. The resulting volume of space that can be explored will be tens of times greater than could be seen during the GW150914 detection, and will allow the direction of future events to be determined much more accurately than was possible for GW150914.

Surprises undoubtedly await, particularly given that the ability to detect gravitational waves at new frequency ranges is being developed in facilities such as the space-based Evolved Laser Interferometer Space Antenna and the ground-based International Pulsar Timing Array, and for various experiments that are studying the polarization of the cosmic microwave background (the oldest light in the Universe). Just as when Galileo turned his telescope to the heavens for the first time, everything will be new. It is truly a privilege to be present at the dawn of gravitational-wave astronomy. ■

M. Coleman Miller *is in the Department of Astronomy and Joint Space-Science Institute, University of Maryland, College Park, Maryland 20742-2421, USA.*
e-mail: miller@astro.umd.edu

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The author declares competing interests. See go.nature.com/wfoqkb for details.