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Serendipitous signal

The first direct observation of gravitational waves occurred on 14 September 2015. We look back at ten years of gravitational wave science.

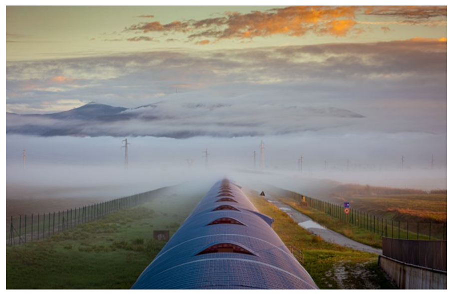
Albert Einstein proposed the existence of gravitational waves almost 100 years ago[1,2]. However, he was not fully convinced that they existed – or, if they did, that they could ever be detected. It was not until the late 1950s that Einstein's proposal was placed on firm theoretical ground, followed shortly after by experiments searching for gravitational wave signals.

The first detection of gravitational waves was initially claimed in experiments with resonant mass detectors located at the University of Maryland and Argonne National Laboratory – separated by around 1,000 kilometres (ref. 3). Networks of similar resonant mass detectors began operating soon after, but none could reproduce this finding; the last such detectors seem to have been shut down in 2016.

Therefore, the first indirect observation of gravitational waves is credited to Russell Hulse and Joseph Taylor Jr. In 1974, they observed that the orbit period of the binary pulsar PSR 1913+16 declined over time, suggesting that the pulsar and its companion rotated faster and faster around each other, consistent with the emission of gravitational waves. This "discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation" would later earn Hulse and Taylor the Nobel Prize in Physics.

These new possibilities culminated in the first direct discovery of gravitational waves on 14 September 2015 by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and this prompted another Nobel Prize in Physics, awarded to Rainer Weiss, Barry Barish and Kip Thorne in 2017 "for decisive contributions to the LIGO detector and the observation of gravitational waves". This achievement was the result of perseverance and a bit of luck.

Weiss put forward a proposal for an interferometer with a baseline on the kilometre-scale in 1972 (ref. 4), followed by a design study, which was published in the so-called Blue Book. The construction of LIGO was approved in 1990, and data-taking began in 2002 at the two sites in the states of Louisiana and Washington, roughly



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3,000 km apart. Its upgrade, known as Advanced LIGO, began operations in September 2015.

When alerted to the detection of a possible gravitational wave event in both LIGO detectors on 14 September 2015, Marco Drago, who was overseeing the automated data pipelines that day, assumed it was an artificially injected signal. But not all detector components were ready for data taking – among them the injection system[5]. This turned out to be a real gravitational wave event, and following thorough verification, the news was made public on 11 February 2016[6].

Ten years after this first event, the network of gravitational wave interferometers – the two LIGO detectors in the USA, GEO600 in Germany, Virgo in Italy and the Kamioka Gravitational Wave Detector (KAGRA) in Japan – have reported the detection of more than 200 signals, mostly from binary black hole mergers. Event GW170817, the first – and so far one of the few – neutron star merger, had an electromagnetic counterpart, which was observed by many different instruments. This opened the door for multi-messenger astronomy with gravitational waves.

Exciting results keep coming. For example, LIGO, Virgo and KAGRA announced the observation of GW231123 (ref. 7), a merger of the most massive black holes observed to date, with masses corresponding to around 137 and 103 solar masses, respectively. The lower-mass one lies in the range between (roughly) 60 to 130 solar masses, where black holes are predicted not to form.

Another interesting preliminary result is GW230529, which is probably a signal from the neutron star–black hole merger, with the latter object's mass in the mass range that is believed to separate neutron star and stellar-mass black hole populations[8]. Additional data from the first part of the fourth observing run was released at the end of August this year, and more results are expected soon.

Whereas gravitational wave interferometers are sensitive to frequencies from a few tens of Hz to a few kHz, pulsar timing arrays search for signals in the nHz range. In 2023, pulsar timing arrays reported evidence for the presence of a stochastic gravitational wave background[9]. The members of the International Pulsar Timing Array consortium are currently working on a combination of their most recent data – and their results are awaited with anticipation.

In addition to data releases and experimental upgrades, the field will welcome new players in the coming decades. Earlier this year, construction of LIGO-India got the green light, following the formal approval of the budget by the Indian government. The detector is expected to commence operations in the early 2030s and will substantially improve sky coverage and gravitational wave source localization of the current LIGO–Virgo–KAGRA network. Furthermore, gravitational wave interferometers Cosmic Explorer and Einstein Telescope have been proposed in the USA and Europe.

But as the saying goes, the sky is the limit. For example, the TianQin and Laser Interferometer Space Antenna (LISA) missions are currently expected to launch in the 2030s, bringing gravitational wave interferometers to space. Both interferometers will consist of three satellites, with interferometer armlengths of 170,000 km and 2,500,000 km, respectively. They will be sensitive to gravitational wave signals in the frequency ranges of 0.1 mHz–1 Hz and 0.1 mHz–0.1 Hz, for TianQin and LISA, respectively. If the satellites – and the stars – align, more discoveries might be on the cards.

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