Nobel Prize winners in the area of physiology or medicine, physics, chemistry, literature, peace and economics for the year 2017 have been announced. The Nobel Prize in Physiology/Medicine was shared by Jeffrey C. Hall (University of Maine, Maine, ME, USA), Michael Rosbash (Brandeis University, Waltham, MA, USA and Howard Hughes Medical Institute, USA) and Michael W. Young (Rockefeller University, New York, NY, USA) for their 'discoveries of molecular mechanisms controlling the circadian rhythm'. The Nobel Prize in Physics was shared by Rainer Weiss (LIGO/VIRGO Collaboration, Massachusetts Institute of Technology, Cambridge, MA, USA), Barry C. Barish and Kip S. Thorne (LIGO/VIRGO Collaboration, California Institute of Technology, Pasadena, CA, USA) for 'decisive contributions to the LIGO detector and the observation of gravitational waves'. The Nobel Prize in Chemistry was awarded to three scientists for 'developing cryo-electron microscopy for the high-resolution structure determination of biomolecules in solution'. The three scientists are Jacques Dubochet (University of Lausanne, Lausanne, Switzerland), Joachim Frank (Columbia University, New York, NY, USA) and Richard Henderson (MRC Laboratory of Molecular Biology, Cambridge, United Kingdom). Current Science is publishing more detailed accounts of some of these prizes in this issue.

–Editor

Nobel for gravitational waves

This year's Physics Nobel prize was awarded to American physicists Rainer Weiss, Barry Barish and Kip S. Thorne 'for decisive contributions to the LIGO detector and the observation of gravitational waves'. Half of the prize has been awarded to Weiss, with the other half split between Barish and Thorne. The laureates are the prime architects of the Laser Interferometer Gravitational-wave Observatory (LIGO) that made the first direct detection of gravitational waves in 2015 – a century after Albert Einstein's theory predicted their existence.

Gravitational waves

The existence of gravitational waves is one of the most intriguing predictions of Einstein's General Theory of Relativity. One of the cornerstones of modern physics, this theory describes gravity as the curvature of spacetime. Any massive object (and other forms of energy) would curve the spacetime around it, resulting in a number of observable effects. The astonishing and profound predictions of Einstein's theory include the gravitational bending of light, gravitational time dilation (or, red shift), expanding universe, and the existence of neutron stars and black holes – all of which have been confirmed by a variety of astronomical observations and laboratory tests over the last century. Gravitational waves were the only phenomenon that evaded a direct observation until recently, although their existence was confirmed by a strong body of indirect evidence through radio observations of binary pulsars starting from 1970s.

Rainer Weiss Barry Barish Kip S. Thorne

General relativity predicts that whenever massive objects (or energy concentrations) move with acceleration, the spacetime curvature not only follows them, but also decouples from the source and propagates outwards at the speed of light. Such freely propagating oscillations in spacetime are called gravitational waves. Generation of gravitational waves through the acceleration of masses is analogous to the generation of electromagnetic waves through the acceleration of charges. Although any motions of masses produce gravitational waves, most of the time these are too weak to be detected by any conceivable technology. However, astrophysical phenomena involving massive and compact objects moving with *relativistic* speeds (i.e. speeds close to that of light) can generate enormous amounts of gravitational radiation that can travel through cosmic distances unaffected by the intervening matter.

Catching the wave

At large distance from the source gravitational waves can be thought as oscillations in the geometry of space. These oscillations have a characteristic *quadrupolar* nature, i.e. orthogonal directions (both perpendicular to the direction of propagation) get stretched and squeezed as the wave passes. These deformations can be detected by means of sensitive laser interferometers (Figure 1). LIGO consists of four-kilometer long interferometers at the two observatories in Hanford, Washington and Livingston, Louisiana in the USA. Interferometer mirrors act as test masses and the passage of gravitational waves induces differential arm-length change proportional to the gravitational-wave strain amplitude. This generates power fluctuations in the interferometer readout port that is measured by photodiodes.

Even the strongest of astrophysical sources would produce displacements of the order of 10^{-18} m; hence a simple Michelson interferometer is not sensitive enough. Fabry–Pérot cavities allow light to bounce back and forth along the arms about 100 times, increasing the sensitivity a 100 fold. Further, by *power recycling*, i.e. by reflecting the light coming out of the interferometer by about 50 times, fringe sensing is further improved. By *signal recycling*, which involves reflecting the signal back into interferometer, one can tailor the frequency response. As a result of these, the photodetectors can finally sense 10^{-11} of a fringe. One needs to beat a number of fundamental and technical noise sources that affect measurement at this sub-nuclear length scales. LIGO detectors achieve their incredible sensitivities making use of highly stable, high-power lasers, optical components with very low thermal noise, and superior vibration isolation systems.

LIGO detectors, which have been operational for a decade underwent a major upgrade in 2015, graduating to a configuration called Advanced LIGO. As soon as they started operating, they detected the first gravitational-wave signal on 14 September 2015. The signal was produced by the merger of two massive black holes at a distance of a 1.3 billion light years away from the earth (Figure 2). This observation was followed by three other confirmed detections of binary black hole mergers over the last two years by LIGO and its sister observatory Virgo in Europe. These observations not only confirm the century-old prediction of Einstein's theory, but also opens up a fundamentally new branch of astronomy.

A new astronomy

This discovery could be compared with Galileo's first observations using the newly discovered astronomical telescope, or the detection of the cosmic microwave background radiation in the 1960s – what was originally just a hiss recorded by a microwave antenna eventually turned into an astonishing set of observations that revolutionized our understanding of the origin and structure of the universe. The very first detections of gravitational waves brought out many surprises. Apart from being the first direct detections of binary black hole systems that merge within the age of the universe, these provide us the first evidence of stellar-mass black holes that are much more massive than 20 solar masses – something that most of the astronomers did not imagine to exist.

Based on the rate of observed signals, LIGO and its sister observatories are expected to detect hundreds of binary black hole mergers over the next few years. A large number of such mergers happening at different parts of the universe is expected to produce a stochastic background of gravitational waves which might be detected in the next several years. In addition, we anticipate the detection of merging binaries involving neutron stars, and possible detection of spinning neutron stars and supernovae. Indeed, the 'holy grail' of gravitational-wave astronomy is to directly detect the stochastic gravitational-wave background from the early universe. Such an observation, analogous to the cosmic microwave background radiation, would provide us a direct access to the so-called *inflationary epoch* following the Big Bang, which is inaccessible to current astronomical observations. Gravitational-wave astronomy is opening up a unique new window to the cosmos.

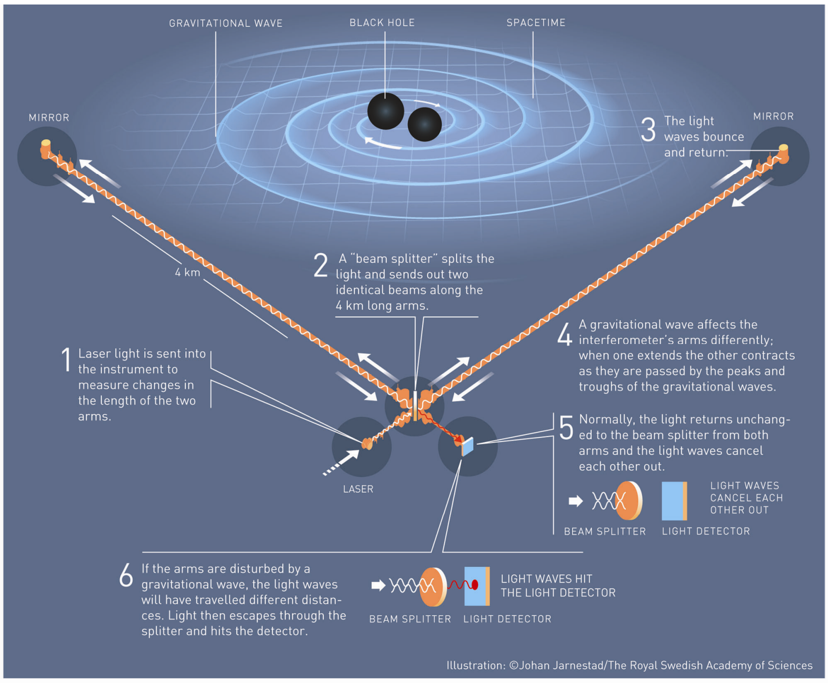

Figure 1. The LIGO interferometer is the most sensitive length-measurement device constructed by the humankind.

Exceptional leaders

Rainer Weiss's family fled the Nazi Germany and emigrated to the United States in 1939, when he was seven. Weiss grew up in post-war New York making money by repairing broken radios and building high-fidelity audio systems using war-surplus electronic components that was flooding the streets of New York. He graduated from the MIT (with some difficulty) and landed up in a faculty position at MIT after a postdoc stint at Princeton with Robert Dicke, a remarkable experimental physicist. Story has it that he developed the idea of using interferometers as gravitational-wave detectors in the 1970s while he was teaching a course on General Relativity at MIT. Weiss performed a comprehensive investigation of the fundamental noises that would limit such a measurement and worked on a small prototype interferometer. In 1975, he discussed his ideas of the interferometric detection of gravitational waves with Kip

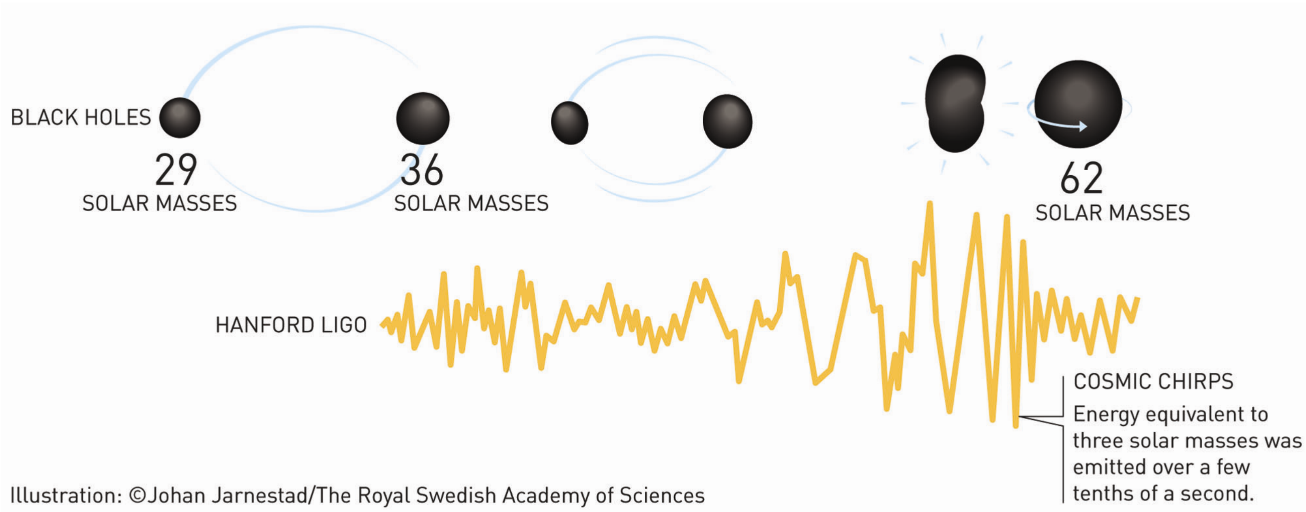

Figure 2. LIGO made the first observation of gravitational waves from merging block holes in 2015.

Thorne – the charismatic young theoretical physicist at Caltech, who has been in the forefront of the astrophysical applications of Einstein's theory.

Thorne managed to convince the Caltech administration to start an experimental gravity program by hiring Ron Drever, an experimental physicist at the University of Glasgow. Drever came up with innovative ideas like the use of Fabry–Pérot cavities to improve the detector sensitivity. Under the directive of the National Science Foundation (NSF), LIGO was set up as a collaboration between Caltech and MIT, led by the troika of Thorne, Weiss and Drever. At NSF, among others, visionaries like Marcel Bardon and Richard Isaacson strongly argued for support to this endeavour in which about 1.1 billion dollars were invested over four decades. Thorne's group at Caltech identified key challenges related to the theory and data analysis required for gravitational-wave observations and engaged with an international community of exceptional physicists to push the frontiers of the fundamental physics of astrophysical sources as well as detectors. This international community of theorists played an important role in enabling the discovery.

The project run by the 'troika' had problems even though it was successful in being funded under the leadership of Rochus Vogt. It required the vision of Barry Barish, a high-energy physicist with vast experience in managing big projects who took over the leadership of LIGO in 1994. Realizing the scale of the effort needed, Barish re-engineered LIGO from being a small laboratory activity into a large project and by complementing the LIGO Laboratory by a global community under the aegis of the LIGO Scientific Collaboration. This international collaboration of about thousand scientists from 20 countries was able to build an efficient and robust infrastructure to analyse data, extract astrophysics and to plan for upgrades. 'I view this more as a thing that recognizes the work of about 1,000 people, a really dedicated effort that's been going on for – I hate to tell you – as long as 40 years,' said Weiss in an interview with the Nobel Committee just after winning the prize.

Indian contribution

Indian scientists have made significant contributions to the gravitational-wave science over the last three decades. The research group led by Sanjeev Dhurandhar at IUCAA, with notable contributions from B. S. Sathyaprakash, initiated foundational work on developing data-analysis techniques to detect weak gravitational-wave signals buried in noisy data. The group led by one of the authors (Iyer) at the Raman Research Institute, in collaboration with scientists in France in groups around Thibault Damour and Luc Blanchet, actively contributed to the analytical calculations to model gravitational-wave signals from orbiting black holes and neutron stars. Theoretical work on the quasi-normal modes of black holes was published by C. V. Vishveshwara in 1970.

The Indian participation in the LIGO Scientific Collaboration, under the umbrella of the Indian Initiative in Gravitational-Wave Observations (IndIGO), involves sixty-six scientists from thirteen institutions – CMI Chennai, ICTS-TIFR Bengaluru, IISER Kolkata, IISER Thiruvananthapuram, IIT Bombay, IIT Hyderabad, IIT Madras, IIT Gandhinagar, IPR Gandhinagar, IUCAA Pune, RRCAT Indore, TIFR Mumbai and UAIR Gandhinagar. Indian groups have made several direct contributions to deciphering the gravitational-wave discovery – the discovery paper has 35 authors from Indian institutions. IndIGO was formed in 2009 by a group of researchers with expertise in theoretical and experimental gravity, cosmology and optical metrology, with a dream of realizing a gravitational-wave detector in India. The planned *LIGO-India* detector will substantially improve the ability of the international gravitational-wave network to localize the sources, enabling the efficient and prompt follow-up of gravitational-wave observations with electromagnetic telescopes. The Indian community aspires to play a major role in this upcoming research frontier.

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