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GUEST EDITORIAL

Seeing the universe in a new light

'The gravitational waves were detected on 14 September 2015 at 5:51 a.m. Eastern Daylight Time (09:51 UTC) by both of the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors, located in Livingston, Louisiana, and Hanford, Washington, USA.'

This historic press release for the event named GW150914 from the LIGO Scientific Collaboration marks a turning point in the history of astronomy. It comes 417 years after Galileo aimed his telescope at the sky in Pisa, Italy, and 'saw' the 'seas' and highlands of our Moon and also those of Jupiter. This was the birth of modern astronomy (concurrent with the birth of modern science). The new era of gravitational wave astronomy that begins with the LIGO detection will enable us to see the universe, literally, in a new light.

Our understanding of gravity

The scientific description of gravity also begins with Galileo. He first theoretically argued and then experimentally verified that the acceleration of bodies under earth's gravity is independent of their mass. Following up on this and the extraordinary researches of Johannes Kepler, Newton arrived at the inverse square law of gravitation. This universal law applied equally well to celestial objects like the moon and apples on earth. It had the mysterious feature that if the source of gravity were to move, its effect would be felt instantaneously on objects even when they are separated by celestial distances. We now understand that this is only approximately true when the motions are slow compared to the speed of light, which is true in the solar system and hence the success of Newton's law.

Einstein's special theory of relativity, distilled from Maxwell's electrodynamics, posited that the finite speed of light (an electromagnetic wave) is the same for all observers in relative constant motion and limits the speed at which physical influences can be transmitted. Noting that this conflicted with Newton's instantaneous law, Einstein embarked on a heroic quest for the relativistic laws of gravity.

This culminated in the General Theory of Relativity (GTR) whose complete equations were announced on 25 November 1915 – a century ago. GTR was revolutionary because it changed our conception of space and time. In GTR space–time is no longer the passive stage for physical events that it was for Newton – they are equal actors in the drama of physical events. Einstein's equations tell you that matter (or energy in general) stresses and curves space–time as if it were an elastic medium.

In this framework, the sun curves the space–time around it and the earth responds to that curvature and moves in the straightest possible path in this curved geometry. It is somewhat like how a light marble moves on a trampoline, which has been curved by a heavy ball. The orbits are now corrected from the perfect ellipses of Newton though, in the solar system, this is significant only for Mercury. Einstein moreover predicted that light, having energy, would also be subject to bending and this has indeed been measured, most dramatically in the gravitational lensing by massive galaxies. Einstein's equations also form a framework for cosmology and give a quantitative understanding of the evolution and large-scale structure of the universe.

Black holes and gravitational waves

One of the most remarkable predictions of Einstein's theory are black holes. Though its interpretation as a non-rotating black hole came much later, Schwarzschild had found this exact solution shortly after Einstein's paper. The Kerr solution describing the rotating case was found only about half a century later. The astrophysical significance of these solutions gradually emerged from the work of Oppenheimer and Snyder as well as S. Chandrasekhar's work on neutron stars, which established the upper Chandrasekhar limit. It suggested that black holes might be the end point of stellar collapse. There is now astrophysical evidence for black holes, which range from a few solar masses to several million solar masses (at the centre of galaxies). Theoretically, what is remarkable about black holes are that they are pure curved geometries with no matter, yet carrying energy and angular momentum.

In 1916 Einstein himself predicted gravitational waves as solutions of the linearized version of his equations (though he, and others, kept having second thoughts about whether these were genuine solutions until the issue was settled in the mid-sixties). These are small distortions of the 'elastic medium' of space–time that travel at the speed of light and are set off by the motion of massive objects in space–time. An analogy is with ripples of water waves set off by a pebble thrown into a still pond, except that space–time is very stiff (since Newton's gravitational constant is small) and it needs large masses and violent motions to bend it and set off measurable gravitational waves. Technically, the second time derivative of the quadrupole moment of a matter system leads to gravitational radiation. Contrast this with electromagnetic radiation first time derivative of the dipole moment of a charge distribution.

Both of these novel predictions of GTR entered into the LIGO detection. What LIGO observed were gravitational waves set off by the merger of a system of binary black holes[1]. Two mutually orbiting black holes of 29 and 36 solar masses were deduced to have merged into a black hole of about 62 solar masses and spinning at 0.67 its maximal possible value. Thus, about 3 times the mass of the sun was radiated (according to Einstein's formula $m = E/c^2$) as gravitational waves in a fraction of a second with a peak power output 50 times that of the whole visible universe! This merger was an enormous gravitational dynamo. Unfortunately, from just two detectors, the exact location and time of the event have been hard to pinpoint. It happened roughly 1.3 billion years ago and has somewhere in a broad swathe of the sky in the southern hemisphere.

It was extremely fortunate that the merger of a black hole binary sourced the first detection of gravitational waves. The entire process is described by Einstein's equations of general relativity, uncontaminated by the complications of astrophysical processes. This leads to a very clean prediction of the expected gravitational wave profile one would observe from the merger, which is in beautiful accord with what has been measured (with a signal to noise ratio of 24).

There are roughly three stages that can be seen in the observed signal (see Figures 1 and 2). There is the initial inspiral where the two black holes are mutually orbiting but rapidly spiralling in towards each other. In this regime the gravitational wave emission is modelled using the so-called post-Newtonian approximation scheme, taken to fairly high orders. Then there is the merger stage, which is a complicated non-linear regime of Einstein's equations when the two objects coalesce. Here the emission and its profile are studied using numerical relativity techniques and matching with the signal is a test of general relativity in the strong field and non-linear regime. Finally, the last stage of emission is from the small wobbles as the black hole settles into the final Kerr solution. This is called the ringdown stage like the fading chimes of a bell that has been struck, and can be studied analytically.

According to general relativity, a solar mass black hole (2×10^{30} kg) has a Schwarzschild radius of about 3 km. Since the final black hole involved in the event has a Schwarzschild radius of ~200 km the time scale associated with the ringdown is $t = R/c \sim 10^{-3}$ sec. The merger that preceded it was over a period of a few tens of milliseconds. The strong damping in the ringdown signal is a signature of it being a black hole and not a compact stellar body.

Gravitational waves and astronomy

Astrophysically, the significance of the LIGO observation lies in it providing, for the first time, strong evidence for a binary system of black holes of several tens of solar masses. Such systems were suspected to exist but had not been 'seen'. What had been seen were binaries of pulsars slowly orbiting around each other and losing energy through gravitational radiation. The expected decrease in their orbital periods had been beautifully measured by Joseph Taylor over several decades, on the binary system he had discovered with Russell Hulse, thus indirectly confirming the existence of gravitational radiation.

Our telescopes have been seeing the universe, since Galileo, with waves from the electromagnetic spectrum like light, X-rays, radio waves and gamma rays. Such waves are produced by the acceleration of electrically charged particles. However, electromagnetic waves can be shielded! The main reason being that electric charges can cancel to zero. A familiar effect is microwaves being

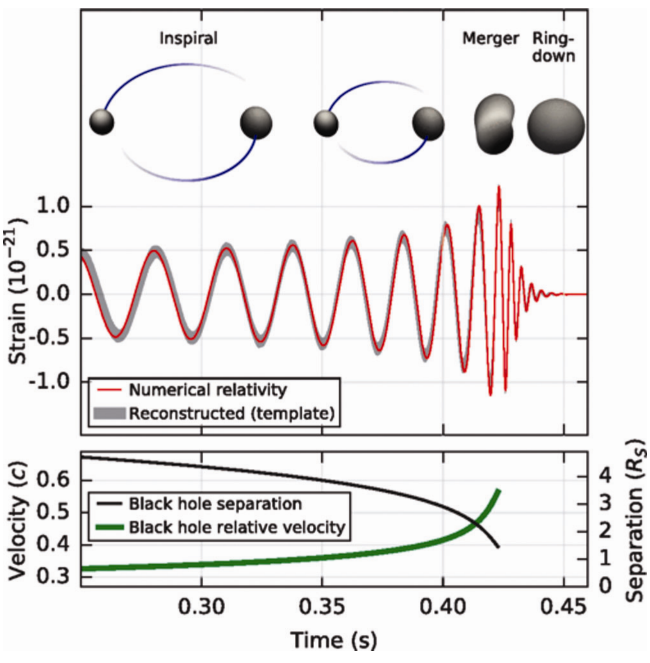

Figure 1. Schematic illustration of the three stages of black hole binary merger and the expected gravitational waveform (taken from Abbott, B. P. *et al.*[1]).

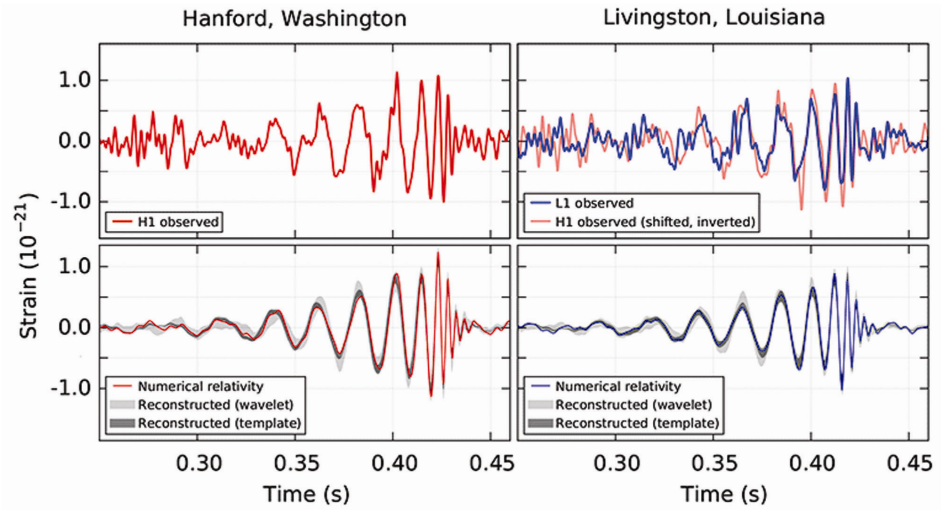

Figure 2. Comparison of the actual signals observed at the two LIGO detectors with the expected waveform (taken from Abbott, B. P. *et al.*[1]).

screened from emerging out of the microwave oven! Thus the light from the primordial universe before the era when it was an ionized plasma does not make it to us! But gravitational waves can see farther back in time and we hope to see signatures of their presence in ongoing experiments. Besides there are likely to be many dramatic phenomena like black hole mergers which are not accompanied by electromagnetic radiation and hence invisible to us. It is the prospect of overcoming both these kinds of limitations to our sight that makes gravitational wave astronomy exciting.

There are many different kinds of gravitational wave observatories, both current and planned. They range from the two LIGO detectors and the VIRGO observatory in Italy and planned ones in Japan and LIGO-India to the ambitious space-based eLISA. The instruments at these observatories are Michelson-type laser interferometers. (Alternative methods for detection exist based on pulsar timing arrays and are sensitive to very low frequencies.) Gravitational waves from realistic astrophysical sources are very weak and their wavelengths are from a few hundred to a few thousand kilometers. When they pass through the earth they distort the geometry of space–time and in particular affect the two arms of the interferometer differently and that would be presently detectable if we achieve a sensitivity that is one ten thousandth of the size of the atomic nucleus! i.e. one part in 10^{19} m. This is why the interferometers have arms that are approximately 4 km long for LIGO and up to a million km for the proposed eLISA. Because these detectors are omnidirectional instruments, it is hard to localize the sources of the gravitational waves from just one detector. This is why the presence of a third LIGO detector somewhere in the eastern hemisphere is crucial for gravitational wave astronomy. The good news is that the Govt of India has given an in-principle approval for setting up this facility in India.

The LIGO Science Collaboration is a worldwide consortium of over 1000 scientists at about 90 institutions. Scientists in various institutions in India have been involved in various aspects of gravitational waves and the analysis of the detected signal. The IndIGO consortium was formed in 2009 with B. Iyer as Chair and T. Souradeep as spokesperson, with the aim of establishing a LIGO detector in India. Guided by A. Kembhavi, a tier-2 data centre and computational laboratory has been set up at IUCAA and a similar tier-3 facility exists at ICTS-TIFR, where the estimates of the final mass and spin of the black hole were made.

It is worth mentioning the background work done by people from India in the past. The ringdown phase, that we mentioned above, with the fading chime was first calculated by C. V. Vishveshwara in 1970. Gravitational wave signals from orbiting black holes and compact objects were calculated by B. Iyer at RRI (now at ICTS-TIFR) and his collaborators in France. Sanjeev Dhurandhar working at IUCAA developed methods of data analysis to detect the weak gravitational wave signals buried in noise. More recently P. Ajith as a Ph D student (now faculty at ICTS-TIFR) developed a phenomenological method for finding the waveforms of binary coalescing black holes. It is very exciting for Indian science that, with the strong base we already have together with the bright prospect of LIGO-India, we will be able to participate in the new astronomy that the LIGO detection heralds.

1. Abbott, B. P. *et al.*, *Phys. Rev. Lett.*, 2016, **116**, 061102.

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