LISTENING TO BLACK HOLES

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The recent discovery of gravitational waves not only confirms Albert Einstein's century old prediction, but also opens up a completely new way of observing the Universe. This article describes the exciting story of this discovery, what went behind it, and what lies ahead.

Around 1.3 billion years ago, in a distant galaxy, two massive black holes moving at speeds close to the speed of light merged to form an even more massive black hole. This powerful event released an energy equivalent to the mass of three Suns, in a fraction of a second. If this energy was converted into light, this flash of light would have outshined the entire visible universe – that is, all the stars in the universe put together – for a fraction of a second. However, this merger did not produce any light. Instead, it produced powerful ripples in spacetime, called gravitational waves.

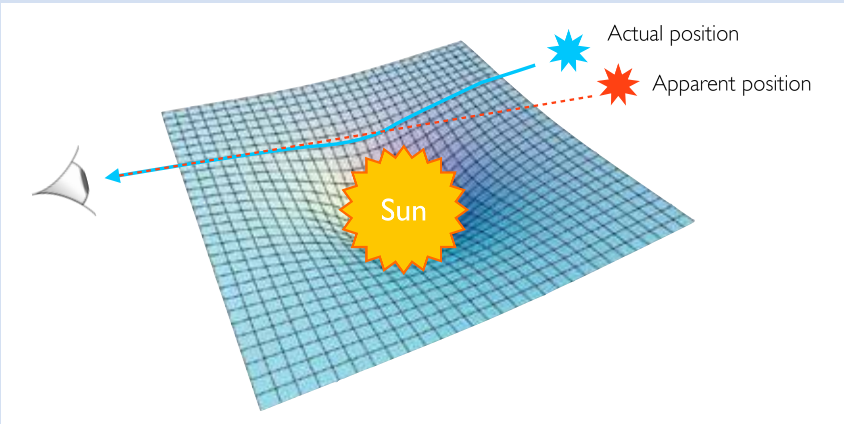
These ripples reached the Earth on 14th September 2015, having travelled a distance of 1.3 billion light years. Two marvelous instruments of the Laser Interferometric Gravitational-wave Observatory (LIGO) in the USA detected these tiny ripples in spacetime. When scientists announced this discovery on 12 February 2016, it produced even greater ripples in the popular imagination. The New York Times described it as "the chirp heard across the universe." What scientists detected in LIGO was a phenomenon called the General Theory of Relativity that was theoretically predicted by Albert Einstein, almost a century before, as a consequence of his theory of gravity.

Gravitational waves

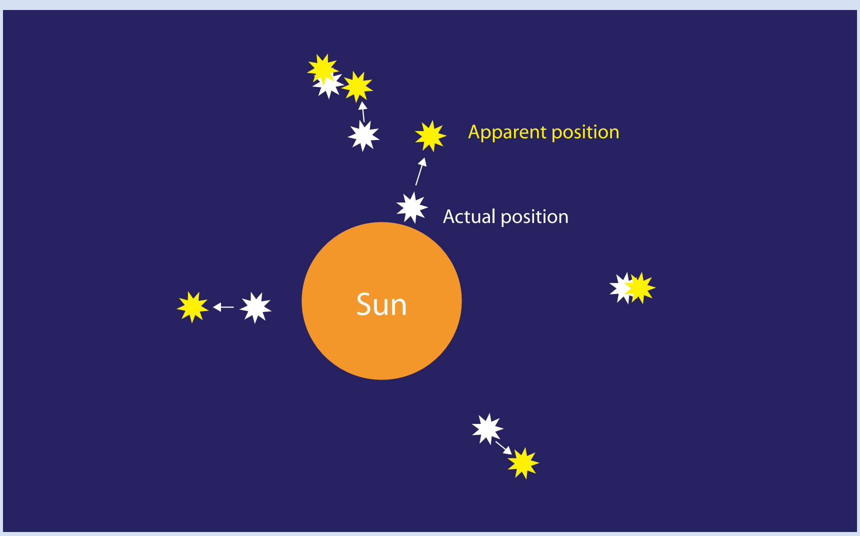
The existence of gravitational waves is one of the most intriguing theoretical predictions of Einstein's General Theory of Relativity (1915). Regarded as one of the pillars of modern physics, the General Relativity is the most accurate theoretical description of gravity available to us today. According to this theory, any massive object (or other forms of energy, such as electromagnetic radiation) curves the spacetime around it. Following this curvature of spacetime, light, which travels in a straight line in flat spacetime, starts to bend near a massive object.

This effect was first observed by the British astronomer Arthur Eddington during the total solar eclipse in 1919. The bending of starlight caused a shift in the apparent position of the stars near the Sun, as compared to their original position, that Eddington found to be consistent with Einstein's prediction (see Box 1). Einstein's theory also predicts that gravity warps time. That is, time runs slower near a massive object. This effect is not only observed in a number of astronomical phenomena and laboratory tests; the Global Positioning System (GPS) needs to take this effect into account for it to function (see Box 2).

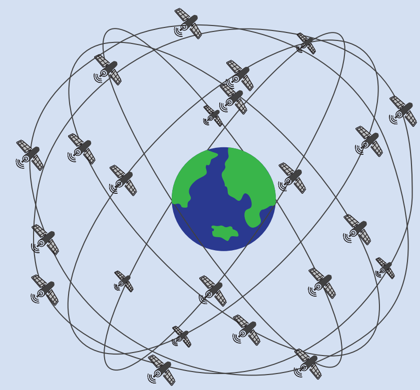
Box 1. Gravitational bending of light



In this cartoon, spacetime is schematically represented as a two-dimensional surface crisscrossed by parallel lines. The Sun curves the spacetime around it so that the shortest path between the star and the observer is no longer a straight line. Since the starlight takes the shortest path between the source and the observer, it bends in the curved spacetime, thus shifting the apparent position of the star. The starlight passing close to the limb of the Sun would be deflected most (by about 1.75/3600 degrees). Thus, stars closest to the Sun suffer the greatest shift in their apparent position.

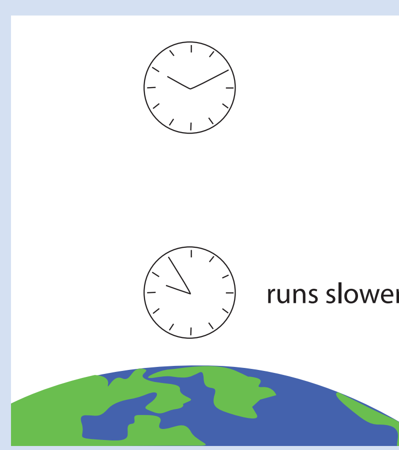


Box 2. The global positioning system and gravitational time dilation



The global positioning system (GPS) relies on a system of satellites orbiting the Earth, which acts as a reference. These satellites have precise atomic clocks onboard, and constantly transmit their location and time. If we receive radio signals from at least four satellites at a time, we can make use of the known constant speed of light to compute our three dimensional position, and the time as measured by a reference clock. The GPS allows us to locate our position on the Earth with an accuracy of up to 10 meters.

However, according to General Relativity, gravity slows time. As a result, a clock on the Earth's surface would tick slower than a similar clock onboard the satellite by about 3 microseconds per day. Note that this is much larger than the time taken by light to travel 10 meters. Thus, the GPS receivers have to factor in this subtle effect if they have to locate their position accurately.



This is one way General Relativity has made its way into our daily lives!

The amount of the warpage of the spacetime outside a gravitating object depends on its mass (or energy) and the distance from it. For example, the warpage of spacetime due to the mass of the Earth is tiny, but precision timekeeping mechanisms such as the GPS still need to account for these effects. In contrast, enormous warpage of spacetime can be observed in the neighborhood of extremely massive and compact astrophysical objects, such as black holes and neutron stars. Expected to be produced by the gravitational collapse of massive stars at the end of their lifetime (when they run out of nuclear fuel), a black hole that is as massive as the Sun, for example, has a radius of only a few kilometers (remember that the Sun's radius is about 700,000 km)!

When a massive and compact object accelerates, it not only causes the spacetime curvature to follow its movement, but also produces oscillations in this curvature that detach from the source and propagate outwards. The process of gravitational waves being produced in this way is analogous to the generation of electromagnetic waves by the acceleration of charged particles. Only, for gravitational waves, the oscillations are in the geometry of spacetime itself.

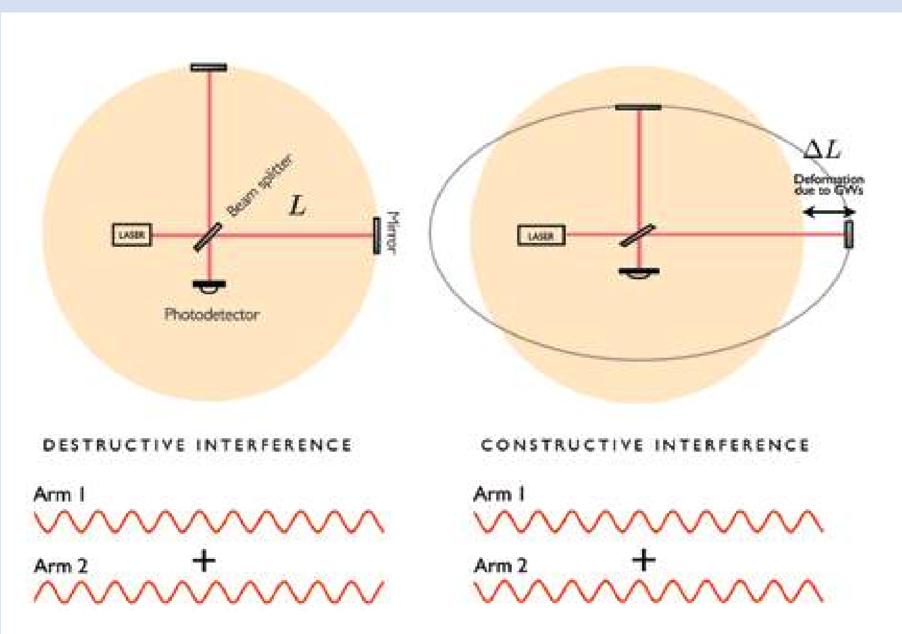
While examining field equations of General Relativity in 1916, Einstein discovered that they admitted mathematical solutions that describe waves travelling at the speed of light. However, whether these are phenomena that exist in the physical world or not remained controversial until the 1950s. There were times when Einstein, himself, doubted their existence. However, a large body of theoretical work from the 1950s and 1960s established that gravitational waves have real physical existence. They could, for instance, carry away energy from their source, much like electromagnetic waves. Then, in 1975, Russell Hulse and Joseph Taylor discovered a binary pulsar system through radio observations. This is a system of two neutron stars orbiting each other with a period of about 8 hours. If the system radiated gravitational waves, the loss of energy would cause the orbital separation to decrease. Measurements using a few years of radio observations showed a corresponding decrease in the orbital period, agreeing precisely with the prediction of General Relativity. This was a remarkable triumph of the theory and settled, beyond any reasonable doubt, that gravitational waves are real. Hulse and Taylor were awarded the 1993 Nobel Prize in Physics for the discovery of this binary pulsar.

Catching the wave

While binary pulsars allow us to observe the effect of gravitational waves, we have not observed the gravitational waves from them. The success of binary pulsar observations prompted scientists to give serious thought to the possibility of directly detecting gravitational waves.

Theoretical calculations showed that astrophysical phenomena involving massive and compact objects moving with very high velocities will produce gravitational waves that are potentially detectable from the Earth. Examples include the collapse of massive stars at the end of their lifetime, binary systems of black holes or neutron stars, fast rotating deformed neutron stars, and the Big Bang itself. There was also compelling observational evidence of the existence of such phenomena. Experimental efforts to detect gravitational waves started in the 1960s itself, with Joseph Weber using resonant bar detectors. However, what revolutionized this endeavor was the idea of using large-scale laser interferometers as gravitational wave antennas.

Far away from their source, gravitational waves can be thought of as time-dependent distortions in the curvature of space. They distort space in a way that is characteristic of tidal forces. Just like the Moon creates tides, deforming the Earth from its spherical shape, gravitational waves would deform a ring of "test particles" into ellipses (except that the tidal deformation produced by gravitational waves is purely transverse, i.e., perpendicular to the direction of wave propagation). It is this key idea that makes a laser interferometer the ideal instrument for detecting gravitational waves (see Box 3).



Box 3. Detecting gravitational waves using laser interferometers:

In a Michelson interferometer, a laser beam is split and sent to two orthogonal arms, which are reflected by two mirrors, and then allowed to recombine.

Initially the length of the two arms are adjusted in such a way that the two light beams interfere destructively (left). When a gravitational wave passes perpendicular to the plane of the interferometer, it will lengthen one arm and shorten the other. Since the speed of light is a universal constant, this will introduce a relative change in the time taken by light to make this round trip in the two arms. The interference between the two light beams will change the output power of the light, which can be read out using a photo-detector.

Invented by Albert Michelson in the late nineteenth century, interferometry is a well-established technique. The problem with using it as a gravitational wave detector is that the distortions in the arm-length of the interferometer due to the passage of gravitational waves are tiny. For example, the merger of two neutron stars in Virgo, a neighboring galaxy cluster, will only make a fractional change of ~ 10^{-21} in the arm length of the interferometer! This means that to detect this phenomenon, we will need to measure length changes as small as 10^{-21} meters. No wonder, then, that detecting gravitational waves is a difficult task! One way of addressing this problem is by using interferometers with arms much longer than that of a 1-meter table-top device – with longer arms, the absolute change in the arm length produced by the gravitational wave would be larger. Thus, modern gravitational wave detectors are kilometer-scale Michelson interferometers. However, we still have to measure changes in their arm length that are much smaller than 10^{-18} meters – much smaller than the size of an atomic nucleus! Interferometers are nominally designed to measure the distance between the 'dark' and 'bright' fringes, that is, length scales comparable to the wavelength of light used. However, with advances in the last three decades, modern gravitational wave detectors measure a much smaller fraction (~10^{-12}) of the wavelength by detecting tiny changes in the brightness of the light coming out of the interferometer.

Although an interferometer is most sensitive to gravitational waves arriving perpendicular to its plane, it is also sensitive to signals coming from almost all other directions. It is an antenna that can detect signals coming from essentially the full sky. This is different from a telescope, which can be pointed to a small part in the sky to observe a star or a galaxy. On the one hand, this allows us to observe the full sky using a small number of antennas. On the other hand, this makes it difficult to identify the location of the source using a single antenna. Instead, the location of the source is identified by combining data from multiple, geographically-separated detectors. Since gravitational waves travel at the speed of light, the difference in the arrival time of the signal in multiple detectors across the globe allows us to reconstruct the location of the source in the sky. This is analogous to an owl identifying its prey by processing the time of arrival of the sound in its two ears. This makes it evident that the larger the distance between different detectors, the better is the accuracy with which the source of a gravitational wave can be localized. In this context, current plans to establish a LIGO observatory in India will be an important addition to the existing international network of gravitational wave detectors. Since the site for LIGO-India is at a significant distance from the existing detectors in USA and Europe, it will greatly improve the accuracy with which gravitational wave sources can be localized in the sky.

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A new "sense" to perceive the universe

Large interferometric gravitational wave detectors have been constructed at many different parts of the globe.

After a major upgrade over the past few years, two of these detectors, at the LIGO observatory in the USA, started operating with a significantly improved sensitivity since September 2015. On 14th September, 2015, both these Advanced LIGO detectors, separated by about 3000 kilometers, observed a coincident gravitational wave signal. A careful analysis of this data revealed that the signal was produced by the merger of two massive black holes that were about 1.3 billion light years away. Apart from being the first direct detection of gravitational waves, this is the first discovery of a binary system consisting of two black holes. These black holes were significantly more massive than any other stellar-mass black holes that astronomers have observed so far – in fact, each of these black holes were about 30 times more massive than our Sun! The merger produced an energy equivalent to the mass of three Suns ($E = 3 Mc^2$) that was radiated as gravitational waves over a fraction of a second, reaching a peak power emission of 10^{49} watts! This is the most powerful astronomical phenomena ever observed by humankind. On 26th December 2015, a second signal, from yet another black hole merger was observed. Based on the rate of observed signals, scientists expect observations of gravitational waves from black hole binaries to become routine in the coming years.

The history of astronomy presents a story full of surprises. Looking at the heavens through his telescope, Galileo saw that far from being a translucent and perfect sphere as thought by the ancients, the Moon was full of large mountains and deep craters; Venus had phases like that of the Moon; and Jupiter had satellites orbiting it. Since then, radio, microwave, infrared, ultraviolet, x-ray and gamma-ray telescopes have extended astronomy to invisible wavelengths of the electromagnetic spectrum and presented different windows to the universe. Cosmic ray and neutrino observations have extended astronomy to messengers that are entirely different from electromagnetic waves. LIGO has opened up the newest branch of observational astronomy – its observations of gravitational wave signals have frequencies in the audio band. Thus, gravitational wave astronomy is more like listening to the Universe rather than looking at the Universe. One may say that gravitational wave observations gave astronomy yet another "sense" with which to perceive the Universe.

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Further reading

1. Bernard F Schutz, Gravity from the Ground Up: An Introductory Guide to Gravity and General Relativity, Cambridge University Press (2003). URL: http://www.gravityfromthegroundup.org/
2. Kip S Thorne, Black Holes & Time Warps - Einstein's Outrageous Legacy, W. W. Norton & Company (1995).
3. Web resources on gravitational waves https://www.ligo.caltech.edu/page/learn-more.
4. Resources for students, teachers and the public: http://ligo.org/public.php.
5. Web portal on General Relativity and its applications: http://www.einstein-online.info/

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