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Gravitational waves: A Persual

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Abstract

This paper aims to provide an updated perusal of gravitational waves science besides providing a persuasive discussion on the causes of gravitational waves, its significance, gravitational detector, and the post LIGO regime.

Keywords: Gravitational waves, LIGO regime

1. INTRODUCTION

Today the vast field of astronomy exists almost entirely within one medium of observation: electromagnetic radiation. From radio waves to gamma rays, the electromagnetic spectrum has provided us with the observational data necessary to reach our current understanding of the universe. However, this restricted view of the universe has provided us with a relatively limited knowledge of objects that emit little to no light, such as black holes and neutron stars. To better observe these bodies, we must look to an alternative cosmic messenger. The Laser Interferometer Gravitational wave Observatory (LIGO) 1 and partner observatory Virgo2 are on the verge of making the first direct detection of gravitational waves, which will provide astronomers with the most direct observations of black holes yet.

2. GRAVITATIONAL WAVE SCIENCE

A gravitational wave is an invisible (yet incredibly fast) ripple in space.

We've known about gravitational waves for a long time. More than 100 years ago, a great scientist named Albert Einstein came up with many ideas about gravity and space. Einstein predicted that something special happens when two bodies—such as planets or stars—orbit each other. He believed that this kind of movement could cause ripples in space. These ripples would spread out like the ripples in a pond when a stone is tossed in. Scientists call these ripples of space gravitational waves.

Gravitational waves are invisible. However, they are incredibly fast. They travel at the speed of light (186,000 miles per second). Gravitational waves squeeze and stretch anything in their path as they pass by.

In 2015, scientists detected gravitational waves for the very first time. They used a very sensitive instrument called LIGO (Laser Interferometer Gravitational-Wave Observatory). These first gravitational waves happened when two black holes crashed into one another. The collision happened 1.3 billion years ago. But, the ripples didn't make it to Earth until 2015!

Albert Einstein's 100-year-old theory about gravitational waves has been proved correct. And now the breakthrough has been recognised with the 2017 Nobel Prize for Physics.

Scientists working with the Laser Interferometer Gravitational Wave Observatory (Ligo) first confirmed the discovery of gravitational waves in February 2016. A second set of waves was confirmed four months later on June 15.

The first waves detected, spotted in data collected on September 14, 2015 were the result of two black holes 36 and 29 times the mass of our sun merging. The second set of gravitational waves were sent travelling through spacetime when two black holes eight and 14 times the mass of our sun collided.

This collision took place 1.4 billion years ago and created a massive spinning black hole 21 times the mass of the sun. An additional sun's worth of mass was transformed into gravitational energy. The second detection was "very strong" despite the smaller sizes of the black holes.

The scientific collaboration involved around 90 academic and scientific institutions from more than 15 countries, including MIT and Caltech. Professors Kip Thorne, Barry Barish and Rainer Weiss were award the 2017 Nobel Prize for Physics thanks to their "decisive contributions to the Ligo detector and the observation of gravitational waves".

"We're thrilled to hear that the Nobel Prize in Physics 2017 has gone to gravitational wave detection," said Professor Sheila Rowan, Director of the University of Glasgow's Institute for Gravitational Research, and one of the UK leads on Ligo. "The discovery of the existence of gravitational waves, just over two years ago, has opened up a whole new way to understand the universe."

Professor Mark Hannam, from Cardiff University's School of Physics and Astronomy, echoed the sentiment, saying: "We already knew gravitational waves existed. We already knew black holes existed. What Kip Thorne, Barry Barish and Rainer Weiss did was to build the first machine sensitive enough to be able to directly *measure* gravitational waves. It took them over forty years, and the result was the most sensitive measuring device ever made. It is an incredible new tool that has only begun to transform our understanding of the universe."

In 1905, Albert Einstein's groundbreaking work showed that the speed of light in a vacuum is independent of the motion of all observers, and the laws of physics are the same for all non-accelerating observers. This is known as the theory of special relativity.

The theory explains the behaviour of objects in space and time, and it can be used to predict everything from the existence of black holes, to light bending due to gravity and the behaviour of the planet Mercury in its orbit.

According to Einstein, who first predicted them in 1916 after forming his theory of general relativity, gravitational waves are ripples in the curvature of space-time that travel outward from the source that created them. He argued spacetime – any mathematical model that combines space and time – would create ripples that move across the universe at the speed of light.

Ligo claims the waves are "caused by some of the most powerful processes" and carry origins about the universe and the nature of gravity. "With these gravitational waves it is not another part of the electromagnetic spectrum it is a whole new spectrum in itself – it's a completely different way of getting information from things.

Fig 1:

3. CAUSES OF GRAVITATIONAL WAVES

The most powerful gravitational waves are created when objects move at very high speeds. Some examples of events that could cause a gravitational wave are:

- when a star explodes asymmetrically (called a supernova)
- when two big stars orbit each other
- when two black holes orbit each other and merge

But these types of objects that create gravitational waves are far away. And sometimes, these events only cause small, weak gravitational waves. The waves are then very weak by the time they reach Earth. This makes gravitational waves hard to detect.

Gravitational waves have been detected for a second time. They're information carrying and they can tell us about aspects of astrophysical forces and principle things like the early universe that you just wouldn't be able to get in any other way.

Gravitational waves should not be confused with gravity waves. Atmospheric gravity waves form when buoyancy pushes air up, and gravity pulls it back down. As it drops into the low-point of the wave, also known as the trough, the air touches the surface of the ocean. This 'roughens' the water.

This creates long, vertical dark lines that can be seen in satellite images that show where the troughs of gravity waves have roughened the surface. Crests of the atmospheric waves can then be seen as bright areas on the same satellite images. By comparison, water beneath a crest is calm and reflects light towards the sensor. Clouds commonly form at the crests of the waves.

4. SIGNIFICANCE OF GRAVITATIONAL WAVES

The discovery of the waves is "profound," Lasenby said, The reason? They create systems that allow us to look at the universe in ways that have not been possible until now. In the same way that infrared and X-ray spectrums have allowed humans to look into the depths of space, gravitational waves open up new possibilities for research. The existence of the waves is almost universally agreed upon by scientists but until February 2016, they were elusive.

As gravitational waves pass through the universe, their interaction with everything around them is "minuscule" when compared to other types of waves. According to "a supernova explosion in our own galaxy would emit pretty strong gravitational radiation, yet a 1 km ring would deform no more than a one thousandth the size of an atomic nucleus."

Gravitational waves emitted from the collision of two black holes have been identified by scientists for a second time.

The gravitational waves, which are ripples in the fabric of spacetime, were observed by researchers using data collected from the Laser Interferometer Gravitational Wave Observatory (Ligo). The research team, involving more than 90 institutions around the world, has now confirmed the finding. The news follows the breakthrough discovery of gravitational waves in February.

The gravitational waves were sent travelling through spacetime when two black holes eight and 14 times the mass of our sun collided. The collision, which took place 1.4 billion years ago, created a more massive spinning black hole that is 21 times the mass of the sun. An additional sun's worth of mass was transformed into gravitational energy.

The first detection, found in data collected on September 14, 2015, resulted from the merger of black holes 36 and 29 times the mass of our sun. Gabriela González, professor of physics and astronomy at the Louisiana State University and part of the Ligo team, said the latest detection was "very strong" despite the smaller sizes of the black holes.

The nice thing about this detection is that because the black holes are smaller, they merge at a higher frequency. "Our detected signal has a lot more cycles in the specific part of the Ligo detectors. For the first detection we could only see a few cycles.

It shows that black holes have diversity too. This is telling us there's a big spectrum of masses out there." The black holes colliding, as detailed in the journal *Physical Review Letters* journal, were smaller than the previous collision observed by scientists.

The work was a starting point for being able to map the populations of black holes in the universe. The signals were produced from the final 27 orbits of the black holes before they merged. By looking at the arrival time of the waves' signals at both of the Ligo detectors it was possible for the scientists to roughly be able to position the source in the sky.

"In the near future, Virgo, the European interferometer, will join a growing network of gravitational wave detectors, which work together with ground-based telescopes that follow-up on the signals. The three interferometers together will permit a far better localisation in the sky of the signals."

Albert Einstein first predicted gravitational waves in 1916, following his theory of general relativity. He said gravitational waves were ripples in the curvature of spacetime that travel outward from the source that created them (in this case the merging of the black holes). He argued that spacetime – which is any mathematical model that combines space and time – would create ripples that move across the universe at the speed of light.

When the gravitational waves were discovered for the first time the Ligo scientists were able to listen to the waves by converting the distortions into sound. This time, they heard a series of 'chips' as the recorded frequency was shifted by the waves. "It was different in a sense that it was not as loud," said González. "With the first one we were very surprised that you could clearly see it in the data."

The second detection of the waves also makes it more likely that scientists looking at Ligo data will be able to forecast waves discovered in the future. The machine will be turned back on for six months later this year after its detection sensitivities have been improved.

The improvements of the machines will mean that Ligo is able to reach between 1.5 and two times more of the volume of the universe than it was previously able to.

5. LIGO

The research project is one of the largest gravitational wave observatories in the world and is spread across two sites in the US – one in Washington and the other in Louisiana.

It is the world's largest gravitational wave observatory and it studies the properties of light and of space to detect the origins of gravitational waves.

The Advanced Ligo project, which started being used in October 2015 after a seven-year redesign, was designed by California Institute of Technology and Massachusetts Institute of Technology staff but involves researchers from 80 worldwide institutions. "What Ligo is specialising in is looking at these pretty rapid frequencies from 10 hertz up to 1,000 hertz events which correspond to extreme astrophysical things," Lasenby said.

To do this, the interferometer has two 4km long arms which laser beams are shone along, reflecting off mirrors at each end. "Ligo scientists can look for the pattern of arm length changes that we expect from different types of gravitational wave source: if they see the pattern, they'll know a gravitational wave has passed by," says the project.

The system is looking for four different categories of gravitational waves, each of which has their own patterns that could be sensed by the equipment.

In addition to Ligo, the world's largest radio telescope in China was completed in September 2016. Dubbed, Five-hundred-meter Aperture Spherical Telescope (Fast), the telescope features the world's largest aperture, at 500 metres, and has a total area equal to 30 football fields. It not only surpasses the Arecibo Observatory – once the world’s largest single-aperture telescope – in size, but also in sensitivity and overall performance.

Once in full operation, Fast will search space for gravitational waves, galaxies and the origin of life.
Research from last year into the Ligo-Virgo collaboration discovered that the binary black holes it found, and were said to be responsible for the gravitational waves, may be primordial entities that formed just after the Big Bang.

Based on general relativity, the research team from Kyoto University studied how often black holes merge. The binary black holes found by the Ligo-Virgo team would match this theory if they were primordial, and if they made up one thousandth of all dark matter in the universe.

Primordial black hole binaries were heavily discussed in the 1990s but observations suggested they were limited. At present, no-one has found any primordial black holes, possibly making the Ligo-Virgo observations the first of their kind.

If further data support this observation, it could mark the first confirmed finding of a primordial black hole, guiding theories about the beginnings of the universe.

6. GRAVITATIONAL WAVE SCIENCE

Gravitational wave science is the study of small ripples in space and time emitted by the acceleration of massive bodies. In the following sections, we provide background information on the physics underlying the emission of gravitational waves, the main detection methods, the astronomical phenomena our gravitational wave detectors are sensitive to, and the main methods for data analysis. Gravitational waves with his general theory of relativity, Einstein triggered the most significant advancement in our understanding of gravity since Newton. Einstein's theory proposes that the dimension of time can be treated much like our three spatial dimensions, which together constitute spacetime. This spacetime is influenced by the presence of mass in a way similar to a stretched fabric holding a heavy object. When other massive bodies travel through this curved region of space, their motions deviate from the normally straight paths, like a ball rolling on a curved fabric. This analogy can be extended further by considering the rapid movement of very massive objects on the fabric, which produces ripples traveling outward from the bodies, as also happens in spacetime. These ripples produced by the acceleration of massive objects traveling through spacetime are gravitational waves, and they carry with them a wealth of information about their source. As these gravitational waves propagate, they exert a periodic expansion and contraction of the spacetime they pass through in directions perpendicular to the direction of travel. To examine the effects of these waves locally, consider a ring of particles floating in space, free of any external forces. As the wave passes, the distance along each axis undergoes periodic expansion and contraction in a fashion exactly opposite to that of the perpendicular axis. The goal of gravitational wave detectors is to measure these minuscule vibrations, with the hope of learning more about their sources.

7. GRAVITATIONAL WAVE DETECTORS

Currently, the most sensitive operational gravitational wave detectors are based on the Michelson interferometer, which uses the interference properties of light to make incredibly precise measurements of distances. As shown in Fig. 2, these detectors split a coherent light beam from a single laser into two beams. These two beams travel along different paths before recombining and entering the photodetector. More specifically, the detector is set up in an "L" formation, with a mirror suspended at the end of each arm. A laser emits a beam of light that is in phase, meaning the peaks and troughs of each light wave are aligned. This original beam of light is split by the beam splitter. One beam is reflected off of one mirror while the other beam is reflected off of the other mirror. Once the two beams return to the beam splitter they recombine, with some light going back toward the laser while the rest passes to the photo detector. The beam splitter has a reflective coating on one side of it, which means that of the two possible paths the light could take to the photodetector, one has reflected from the glass side of the coating, and the other from the vacuum side.

These two different cases of reflection will result in a 180 phase difference. If the distances traveled by each half of the beam are equal (i.e., the arms are equal in length), the two light beams will be exactly out of phase and cancel each other out, resulting in all light traveling back toward the laser and none reaching the photodetector. If instead one arm is slightly shorter than the other, the light no longer exactly cancels out, and a nonzero light intensity is measured by the photodetector. The intensity of this light measured at the detector depends very sensitively on the phase difference of the two halves of the beam. Thus by monitoring the fluctuations in the intensity of exiting light, the difference in arm lengths can be determined with incredible accuracy. This is the underlying principle for the detection of gravitational waves. The three largest detectors in the world based on this design make up the LIGO–Virgo Collaboration (LVC).

8. SOURCES

According to the theory of general relativity, any mass that is accelerating in a way that is not perfectly spherically or cylindrically symmetric will produce gravitational waves. Though this excludes some processes like the spherically symmetric pulsations of stars, it does include countless other events, ranging from the energetic collision of stars and black holes to the less spectacular toss of a ball. Consider a system of two bodies, each about as massive as the Sun, orbiting about one another. As the bodies orbit, gravitational waves are emitted with a period that is closely related to that of the orbit. These waves carry energy away from the system. As the orbit loses energy, the separation between the two objects must shrink, thereby decreasing the orbital period. Furthermore, as the bodies get closer together, the second time derivative of the quadrupole moment varies more rapidly, resulting in an increase in the gravitational wave amplitude. This increase in frequency and amplitude continues until the orbital radius decreases to the point of merger, where the two objects physically combine to form a single body. Until the time of merger the system is said to be in its inspiral phase, which is modeled fairly accurately by making small corrections to the non-general relativistic equations of motion. An example of a gravitational wave produced during the inspiral phase of such a system is shown in. As discussed earlier, when presenting this in a high school classroom setting, the explanation for why the amplitude increases is more qualitative. The focus is on the students appreciating the connection between the more extreme curvature of spacetime as the bodies get closer together and the increase in amplitude of the signal. If we were to take the same system, but compress each object's mass into a smaller radius, the inspiral phase would be prolonged. In this case, the orbital radius is able to reach even smaller values before these denser objects merge, thereby increasing the amplitude and frequency reached by the gravitational wave before merger. Consequently, only binary systems containing the densest objects in the universe, namely neutron stars and black holes, are capable of producing gravitational waves at amplitudes and frequencies detectable by current detectors. The fact that we have yet to detect a gravitational wave, despite being surrounded by sources, is due primarily to the "stiffness" of space time. The stiffness of space time refers to the incredible amounts of energy in gravitational waves that are required to distort space time to a degree we can measure with our detectors. A second major factor is the relatively low amount of energy emitted in gravitational waves by systems in the first place. As an example of the latter, the amount of energy per second (power) radiated in gravitational waves by the orbit of Jupiter around the Sun is 5200W. Even though this is the most energetic source of gravitational waves in our solar system, the energy radiated in all directions each year by the orbit of Jupiter would only be enough to power a single average household in India. To detect gravitational waves, we must look for much more energetic sources, outside of our solar system. The stiffness of space time is apparent if we consider a gravitational wave just barely detectable with current detectors, which periodically changes the difference in the distances along the arms of the detector by at most 10^{-19} m with a frequency of 100 Hz. Such a signal has a flux (power per unit area) of about 10^{-5} W/m^2. This is approximately the same flux in visible light measured 300m away from a standard 60 W light bulb. Thus even though these fluxes are equivalent, in the case of gravitational waves, the signal is barely detectable with state of the art detectors, whereas with electromagnetic radiation, the signal is easily detected by the human eye.

9. DATA ANALYSIS

The LVC detectors are measuring changes in the difference of the distances along the arms that are orders of magnitude smaller than the diameter of a proton (approximately 10^{-15} m), reaching sensitivities of 10^{-18} to 10^{-19} m. In addition to gravitational waves, such minute fluctuations in arm length can also be caused by many uninteresting sources, including seismic vibrations, local highway traffic, etc. With so many noise sources causing signals at comparable levels to those we are trying to detect, advanced data analysis techniques are necessary. Many of these techniques rely on having a reasonably accurate theoretical model for the system emitting the gravitational waves, which provide the hypothesized signal that is then looked for in the data. As described in Sec. IIC, the LVC network is particularly sensitive to the mergers of black holes and neutron stars. The main search algorithm for merger signals in the LVC uses the technique of matched filtering, in which we first construct a bank of possible signals, and then search the data for instances of a statistically significant match to a signal in the bank. This method is very efficient at detecting possible signals in large amounts of data but does a poor job of determining source properties of individual signals, such as the masses of the merging objects and where in the sky waves must be losing energy. This situation is analogous to what they had just seen in the fabric sheet demonstration, where instead of losing energy through gravitational waves the orbit lost energy due to friction. This loss of energy resulted in the orbital radius shrinking and the orbital velocity increasing, just as it does during binary evolution. The last part of the activity had students hypothesize what they believed a gravitational wave from an inspiraling binary system should look like, then compare that to a more rigorous computational model.15 The applet used to interface with the computational model (provided for free by Wolfram Demonstrations16) displays the gravitational wave for a given set of parameters describing the binary system. Slider bars then allow students to manipulate various parameters in the model (e.g., inclination, component masses, etc.), to investigate how these parameters can affect the modeled waveform.

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