Modern Physics Term Paper - Gravitational Waves

Nathan Magrogan
Department of Physics, Gonzaga University, Spokane WA 99258
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The theory of general relativity predicts the existence of gravitational waves. For nearly a century after they were predicted they were undetected. They were finally detected by the Laser Interferometer Gravitational-Wave Observatory. (LIGO) This paper will explain how LIGO detected the waves, and also what exactly gravitational waves are.

I. INTRODUCTION

The theory of general relativity has long predicted the existence of gravitational waves. For a long time direct detection eluded physicists. The theory was published at the beginning of the 20^{th} century, but they were not detected until 2015. For about century after they were first predicted they went undetected, but no one really doubted that they existed. That is because they were predicted to be very faint and thus very hard to detect. Einstein himself thought that gravitational waves may never be detected. [6]

Gravitational waves are ripples in space-time caused by the acceleration of massive objects. But what exactly does that mean, and what events actually produce gravitational waves that are measurable?

Gravitational waves have finally been detected by the Laser Interferometer Gravitational-Wave Observatory. It makes use of enormous Michelson Interferometers to measure them. What can we learn from the results of their observations and what can we hope to learn from future observations of gravitational waves in the future?

II. HISTORICAL BACKGROUND

Early indirect evidence of gravitational waves was gathered in the 1970s when a system of pulsars were found to be loosing energy at a rate that was predicted by general relativity and the energy loss was attributed to gravitational waves. This discovery won the Nobel Prize in 1993.[3]

In the 1960's a scientist named Joseph Weber developed an experiment to detect gravitational waves. And in 1969, he published an article with his findings. This caused a lot of excitement and others tried to replicate his experiment, but his results were not able to be replicated. [6]

Gravitational waves were finally detected in 2015 by the Laser Interferometer Gravitational-Wave Observatory (LIGO), about a century after they were first predicted, the source of these first detections of gravitational were the combination of 2 black holes. [1] LIGO is the largest and most sensitive interferometer that has ever been built.[6]Initially there were 2 interferometers in the LIGO system, one in Hanford Washington, and the other in Livingston Louisiana. In 2017 they were joined by Virgo, another interferometer located Italy. So now their are 3 interferometers working together to detect gravitational waves, and there are future plans to add more interferometers to this system. Having more interferometers helps filter out everything else the interferometers are detecting besides gravitational waves. Each interferometer has arms that are 4 km long. And image of one of the interferometers is shown in figure 5. They need to be this big and far apart because they are trying to measure such a faint signal, and they need to be able to filter out all the other local signals that the interferometers are detecting. [1]

III. WHAT ARE GRAVITATIONAL WAVES

So what exactly are gravitational waves? Mathematically they are described by the theory of general relativity, and the mathematics are very complicated, evolving field equations and tensors, so I will just be discussing a qualitative explanation of them.

When charged objects are accelerated they emit electromagnetic radiation, general relativity predicts that accelerating massive objects should also emits some form of wavelike radiation. When massive objects accelerate they generate disturbances in gravitational fields and space time, these disturbances will travel outwards from their source at the speed of light and are described as waves. [6] The gravitational waves are very faint because the gravitational force is relatively weak. [3] When gravitational waves were finally detected the signal was produced by the joining of 2 black holes.[1] Even those signals, produced by objects the cause the most extreme warping of space time, were still were still very small. [6]

The first step of understanding what exactly gravitational waves are is to understand a bit about the extreme warping of space time near massive objects and tendex lines. Relativistic laws state that objects moving near an massive object will try to move along a straight path, but the warped space-time of the massive object will make this not a straight path, but the objects still want to move in as straight of a lines as possible. This is depicted in figure 1.

The two different color lines in the figure show 2 pairs of paths that start out parallel, but the green lines are forced apart because of the warping of space time while the pink lines are forced together because of the warp-

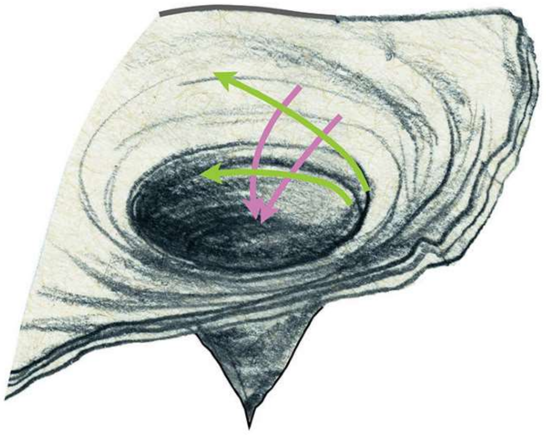

FIG. 1: Image depicting paths objects would take in the presence of the extreme space-time warping of a black hole [4]

ing. Through Einstein's general relativity theory physicists have been found lines of forces that squeeze in one direction and stretch in the other direction causing the behavior seen in figure 1. These are called tendex lines. [4] Figure 2 shows the same image as figure 1, but now with the tendex lines superimposed on the image. Along the red lines there is a stretching and along the blue lines there is a squeezing.

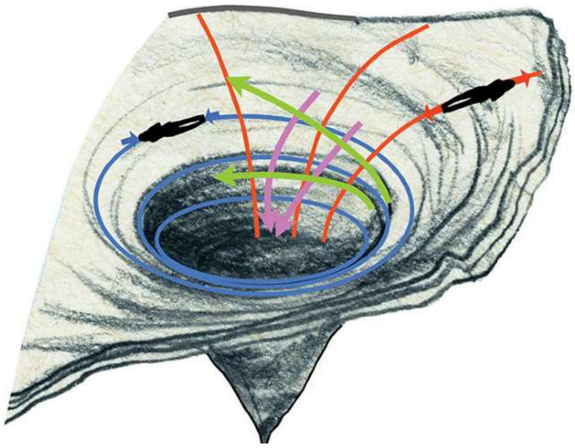

FIG. 2: Image depicting paths objects would take in the presence of the extreme space-time warping of a black hole, also tendex lines. Along the red lines there is a stretching, and along the blue lines there is a squeezing.[4]

The stretching and squeezing due to tendex lines are another way of talking about the warping of space-time. You can think of the stretching and squeezing effects as a consequence of the warping of space-time, or you can think of it as the tendex lines doing the stretching and squeezing, therefore the tendex lines represent the warping of space time. [4]

Now that we have some understanding tendex lines we can start to talk about gravitational waves. Imagine 2 black holes orbiting each other. Each hole has tendex lines extending out from themselves stretching and squeezing in different directions. As the black holes orbit they pull their tendex lines around, kind of like water coming form a sprinkler. The holes will eventually merge and the result will be a deformed black hole that is still rotating and dragging its tendex lines around that extend outwards.[4] Figure 3 depicts the tendex lines that would result from this situation. The red lines stretch, and the blue lines squeeze. The tendex lines propagate outwards as gravitational waves. They create an oscillating stretch in one direction and a squeeze in the other direction, that is orthogonal to their direction of movement.[2] In figure 3 where ever there are red stretching lines imagine that there are are blue squeezing lines coming out of the page and visa versa with the blue lines. The form of gravitational waves as they move throughout spaces is depicted better in figure 4. The black hole will become less deformed, which will cause the waves to weaken. [4] This event that I describes is the same type of event created that gravitational waves that were first detected by LIGO.

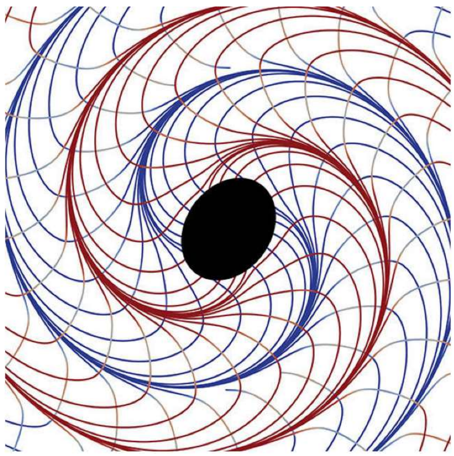

FIG. 3: Tendex lines from a 2 black holes combining [4]

This isn't the only event that will produce gravitational. They are produced by accelerating massive objects whose motion is not spherically symmetric.[6] And example of this type of motion would be a dumbbell rotating around its axis orthogonal to its axis of symmetry. Rotating a dumbbell like this would produce gravitational waves, but effects would be far too minuscule to be measured. The combining of 2 black holes has an extraordinary amount of gravitational force and acceleration, creating the most extreme deformation of spacetime imaginable, and the gravitational waves produced from it are still very faint and hard to measure. Figure 4 shows some other events that happen in the universe that produce gravitational waves and may be able to be detected in the future.

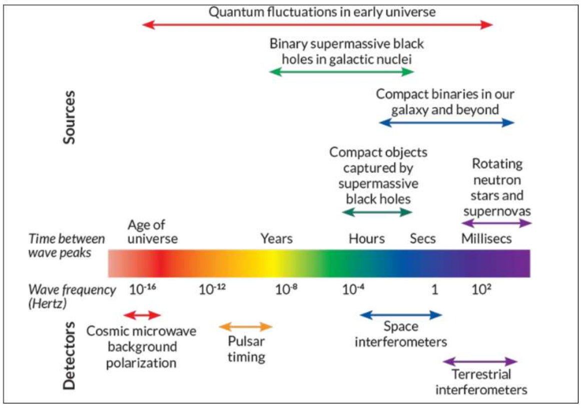

FIG. 4: Gravitational wave spectrum [6]

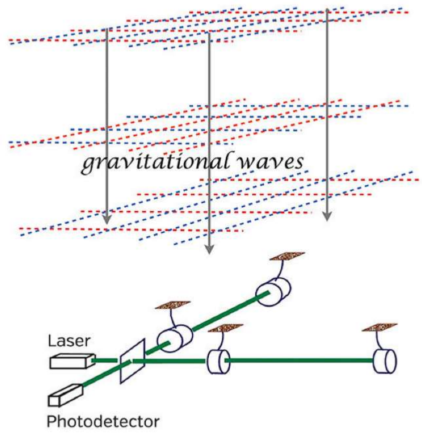

FIG. 5: How LIGO works to detect gravitational waves, waves will squeeze one arm and stretch the other, which the interferometer will be able to detect. [4]

Gravitational waves are waves in space time that are produced by accelerating massive objects. They can be thought of a changing in the warping of space time that propagates outward from its source. They cause a stretching in one direction while squeezing in the perpendicular direction. This stretching/squeezing oscillates back and forth as the waves travel. The direction of travel is orthogonal to the direction that they are squeezing and stretching in. This is depicted well in figure 5. The waves squeeze space time along the blue lines and stretch it along the red lines, and move in the direction of the black arrows. The oscillation of stretching and squeezing occurs because of the movement of the waves. Gravitational waves also move at the speed of light. [6]

The stretching and squeezing of the waves is a warping of space time, not a force that you would feel. It is similar to how length contraction works in special relativity. Along these tendex lines space time is getting stretched or squeezed causing everything along them to lengthen or contract. If they passed through a material, it is not that the molecules within the substance are just getting pulled apart or squeezed closer together, but everything about the molecule in a direction is getting deformed, kid of like when you have an image in a photo editor and drag the transform boundary and it deforms the image.

Now that we have an understanding of what gravitational waves are and how they act, we can talk about how they were first detected. And how the detectors were designed to measure the specific behavior of gravitational waves.

IV. LIGO DETECTORS

When gravitational waves reach the earth they will be more or less in the form depicted in figure 5. The waves will pass through the detectors and squeeze them in one direction and will stretch them in the other direction, and then oscillate stretching and squeezing in the opposite directions. The detectors make us of Michelson interferometers to detect and measure the waves.

The way a Michelson interferometers works is by splitting a laser beam and sending it down two perpendicular arms. The laser goes down the arms and bounces of a mirror, comes back and re-combines. If there is any difference in the arm lengths of the interferometer there will be an interference in the light from the laser that can be measured.[2] The basic design of the interferometers used by LIGO is depicted in figure 5. They are very sensitive instruments and can detect very small relative differences in arm length. To detect gravitational waves they have to be sensitive enough measure 10^{-3} times the size of a proton of length difference between the two arms. [2] They can detect gravitational waves because as seen in figure 5, the waves will squish one arm and lengthen the other, causing a small difference in arm lengths. An image of one of the LIGO detectors is shown in figure 6.

The interferometer also needs to filter out all the other signals that are effecting it, like any shaking of the earth. The basic idea of how to filter out all the noise is by having multiple interferometers in different places in the world. The gravitational waves are so big that they affect the whole world in same way so by having multiple interferometers in different places in the world you can effectively filter out all the local noise by comparing the the signals from the multiple interferometers and only keeping the data that appears in both of them.

This is not as easy as it sounds. You can't just look at the 2 signals side by side and pick out the signal by eye. Interferometers are very sensitive instruments, and there is a lot of noise to filter out. I recently used a small table top interferometer in a lab class, and if you bumped

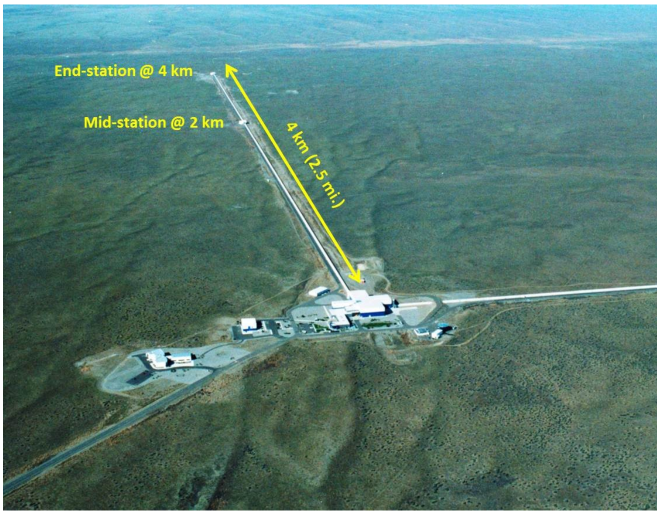

FIG. 6: Aerial view of one of the LIGO detectors

the table slightly if would cause the interference pattern to change a lot. Figure 7 shows how complex the data they they are detecting looks. So they had to develop some very sophisticated filtering algorithms to filter out the gravitational waves.

They also have done various engineering to isolate the detectors from local signals. One main way that they keep the detectors from being sensitive to local vibrations is called passive vibration isolation. This makes use of law of inertia and pendulums to keep the mirrors and detectors stable. If you imagine a pendulum with 4 weights at equidistant spacing, and you sake the top of the pendulum the bottom weight will move a lot less than the ones above it. This is because each segment above absorbs some of the vibration and prevents it from transmitting below, and the law of inertia means that objects want to stay at rest and the heavier it is the more that is needed to move it. This is basically how the detectors of LIGO are suspended very heavy masses on the ends of pendulums.[5] They also use a technique called active vibration insulation, which is basically outside the passive system and detects incoming local vibrations and creates feedback signals to try to cancel them out, kind of like how noise canceling headphones work. [5]

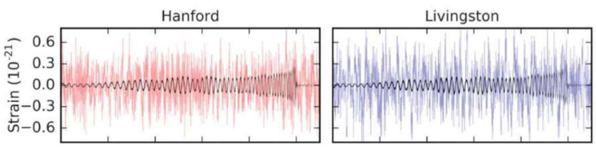

FIG. 7: Data from the LIGO detectors, dark black line their best-match for the gravitational wave that they detected. [1]

The detection of gravitational waves gives us a new way to look out in to the cosmos. In the past we have only been able to observe space through telescopes looking at electromagnetic radiation. There have been advancements to create stronger telescopes, and ones that can detect electromagnetic radiation ouside fo the visible spectrum.[2] But now with the detection of gravitational waves we have an entirely new way to observe the universe. Gravitational waves do not interact with matter in the same way that electromagnetic waves do. They pass right through matter that would absorb electromagnetic radiation, because gravitational waves are a ripples in space-time itself. Thus, they give very clean information about their sources. [2]

From the first detection of gravitational waves by LIGO, they proved the existence of binary black holes which had only been theorized in the past, and discovered black holes with masses 30 times that of our sun, and physicists are now working to understand how such black holes were formed. [5] The first two waves they detected were both produced by the coalescence of 2 black holes. From the waves that they detected they were able to calculate the masses of the 2 black holes $(m_1, m)_2)$ and the mass m_f and dimensionless spin angular momentum $|\vec{S}|/m_f^2$ of the black hole after the coalescence of the 2 black holes. For their first detection they found:

$$\begin{aligned} (m_1, m_2) &\approx (36.2, 29.1)M_\odot \\ m_f &\approx 62.3M_\odot \\ |\vec{S}|/m_f^2 &\approx 0.68 \end{aligned}$$

Where $M_\odot$ is the mass of our sun. [2] And for the second detection of gravitational waves they found:

$$\begin{aligned} (m_1, m_2) &\approx (14.2, 7.5)M_\odot \\ m_f &\approx 20.8M_\odot \\ |\vec{S}|/m_f^2 &\approx 0.74 \end{aligned}$$

In both cases detected the peak luminosity radiated from these coalescence was $10^{56} ergs/s$, the first system effectively lost $3M_\odot$ and the second lost $1M_\odot$ both did this in less that 0.1 seconds. This means that for a very short time these two events produced more energy than all the stars in the observable universe put together.[2]

LIGO has more recently made a detection of merging neutron stars. From that we have learned that one source of short gamma ray bursts is from merging neutron stars, and that merging of neutron stars is responsible for generating the quantities of heavy elements that we observe in the universe. [5]

The LIGO observations proved the existence of binary black holes. And has provided more information in support of general relativity. Future observations will hopefully help to verify more parts of general relativity. There are hopes that more detection of gravitational waves will lead to information that can be used to develop further the theory of quantum gravity [2] And hopes that knowledge gained from these observations could help improve our understanding of space,time,matter, energy and their interactions. [5] Gravitational waves mark a new step in exploring the universe. As detectors get better and more gravitational waves are detected we will hopefully be able to discover new information that was previously undetectable using the tools we are currently using to look at the universe.

V. CONCLUSION

Gravitational waves are a phenomenon that was predicted by the theory of general relativity. After they were predicted it took nearly a century to actually measure one. Gravitational waves are an oscillation of the warping of space time that are produced by accelerating massive objects. Similar to how accelerating a charged object will produce electromagnetic radiation. Tendex lines extend out from massive objects. These lines describe the warping of space-time. Figure 2 shows these tendex lines. They squeeze in one direction and stretch in the other direction. When massive objects are accelerated they are changing these tendex lines and they propagate outwards as gravitational waves. The effects are very faint because gravity is a relatively weak force, the first gravitational waves that were been detected were ones that were created by the combination of black holes.

Gravitational waves have been detected by the Laser Interferometer Gravitation-Wave Observatory(LIGO), using a system of huge Michelson interferometers in different parts of the world. Gravitational waves will squish the interferometer in one direction and stretch them in the other direction, causing a small difference in arm length of the interferometers. This is depicted in figure 4. The first gravitational waves were measured in 2015 and in 2017 the Nobel prize was awarded to Rainer Weiss, Barry C. Baris and Kip S. Thorne for contributions to the LIGO detector and observation of gravitational waves. [6]

Gravitational waves are a new way to look out into the universe. In the past we have only been able to detect electromagnetic radiation. However electromagnetic radiation does not reach us from the furthest parts of the universe. [6] Gravitational waves can give us a clearer picture of the universe than electromagnetic radiation can. [2] As gravitational wave detectors get better we will be able to discover new things in our universe, we have a lot to learn from future observations of gravitational waves. There are plans to further upgrade the detectors of the LIGO system and plans for other interferometers to be built in different parts of the world. [6]

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