The Most Precise Measurement in Human History: LIGO, the Detection of Gravitational Waves, and the Future of Physics

Severin Field

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I Introduction

The Laser Interferometer Gravitational Wave Observatory (LIGO) can detect gravitational waves which appear as tiny oscillations in spacetime on the order of 10^-18 meters, making it the most precise detector ever created. For reference, the radius of a proton is on the order of 10^-15 meters. Measuring such small perturbations requires unprecedented sensitivity. While they are small upon reaching us, gravitational waves are remnants of the most violent and cataclysmic events in the history of the universe that have promulgated for billions of years to reach us. In my personal research this year, I had the opportunity to access data from the detector's auxiliary channels - detectors such as accelerometers, seismometers and microphones for a project leveraging machine learning to detect anomalous noise behavior which may affect the main arm of the detector. The creativity involved in creating a detector to measure the tiny perturbations is fascinating, and the findings can confirm Einstein's general relativity and may possibly be an experimental catalyst towards finding a grand unified theory. I consider it a great embarrassment that we do not have this theory yet, we don't really know what's going on with reality... The discovery of the first gravitational wave led to a new UCR faculty member, Barry Barish, being awarded the nobel prize in 2017. The first gravitational wave measurement, recorded in 2015 by a team led by Barish, captured an event that happened 1.4 billion years ago - when life on earth was just entering the phase of multicellular life [1].

Einstein's theory of general relativity suggests the existence of gravitational waves being created by massive mass fluctuations in spacetime. These waves are analogous to simpler waves in other regimes of physics, like electromagnetic (EM) waves. One can take a positive and a negative charge and move them around each other to create EM waves - this is a dipole moment. Gravitational waves move through the medium of spacetime and require a quadrupole moment – a specific kind of motion, like that observed in the spiraling dance of merging black holes. An example of an event with a measurable gravitational quadrupole moment is a black hole merger: two black holes spinning around each other and accelerating in a well known pattern until an eventual explosive combination.

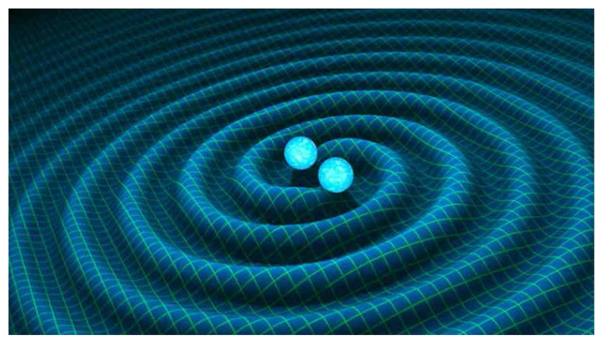

Figure 1: Black hole merger pattern [ligo.org]

An analogy often given in physics classrooms to visualize gravitation is a bowling ball on a trampoline. If you were to put a bowling ball on a trampoline and then place ping pong balls on it, the distorted trampolines dip from the bowling ball would pull the ping pong balls towards it. This is said to be analogous to gravitation over spacetime - which bends and dips around large masses. A wave passing through this medium, a gravitational wave, would push and then pull the fabric of spacetime, stretching and contracting it. Dr. Barish in an interview [2] describes what happens to you as a gravitational wave passes through you: you get slightly fatter and taller as the crest passes and then slightly shorter and skinnier as the trough passes. The distorting mirrors at carnivals or amusement parks may help visualize this phenomenon. Imagine shifting back and forth between the convex mirrors that make you appear taller and shorter.

II Measurement Devices

To quantify a passing gravitational wave, we need a device to measure fluctuations in space or time with a reference object. One of the first proposed methods was a thought experiment from Richard Feynman [3]. Feynman's Gedanken involved encircling a metal shaft with rings, where the rings would generate kinetic energy from the friction caused by a passing gravitational wave's influence. The kinetic energy should be proportional to the gravitational energy. This has only been used as a thought experiment because thermal fluctuations and thermal expansion would make such a device very difficult to use. [4]

One of the first promising devices used in an attempt to measure the gravitational wave were massive aluminum rods. A passing gravitational wave should in theory contract and expand the rod. This idea is called the Weber bar [5]. The greatest challenges in measuring a gravitational wave with a Weber bar are the various sources of noise. We can do a simple calculation [6] to find that a 10 degree change in temperature will alter a 10 meter aluminum rod by 2mm. Recall most observable gravitational waves have dissipated over the massive distance they travel to reach us and require a measurement of 10^-18m. While measuring changes in an aluminum rod could theoretically detect waves, practical challenges like thermal expansion make the Weber bar experiment problematic.

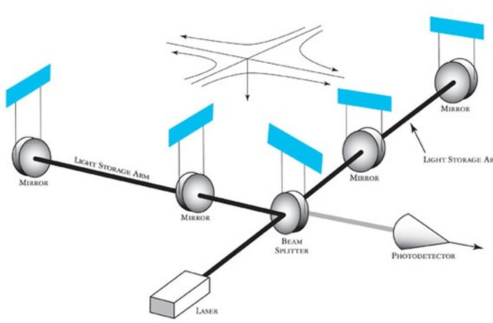

Figure 2: A Michelson Interferometer [ligo.org]

The method used by LIGO to detect waves is two massive Michelson interferometers. In a Michelson interferometer, a laser is split by a beam splitter and reflects off two mirrors, one for each beam emitted from the beam splitter at 90 degrees from each other. The mirrors at each end reflect the light back towards the beam splitter. Because gravitational waves cause bending of space itself, one arm of the interferometer may shrink while the other expands. Then at the interference pattern of the laser is a measure of the phase difference between the two arms - how far the laser traveled in each direction. With this information we can see when contractions and expansions happen and in which direction. But because the waves are so small in amplitude, the detector's arms must be many kilometers in length to detect a phase change. Since the change in space is on the order of 10^-18m, a contraction would only appear in the 4 kilometer tube as a contraction of 10^-15m. To confirm the signal is not just noise, a second detector with the equivalent setup of two 4km arms was created half way across the country to avoid picking up some sort of local noise. The combined strain information can subtract out local noise information by isolating frequencies that appear in both detectors. The two detectors operate in Livingston, Louisiana and Hanford Washington.

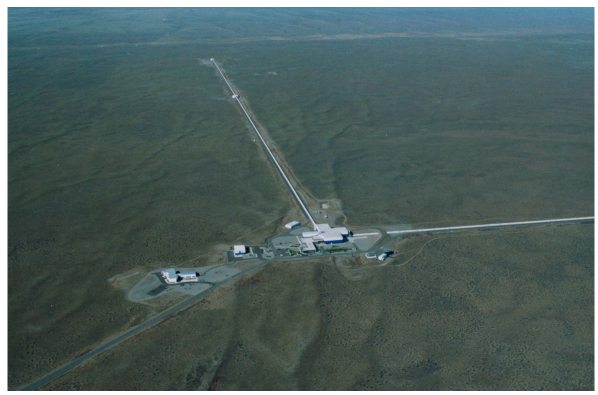

Figure 3: The 4km arms of the Hanford interferometer [ligo.org]

Sensitivity is the greatest hurdle at LIGO. Improving sensitivity is the main goal of the detector because being able to see smaller perturbations equates to being able to see gravitational events further into space and time. To get such a sensitive measurement, many precautions are taken. There are many sources of noise which get in the way of recording the phase difference with just a simple interferometer setup. Firstly, the laser must go through a vacuum tube, because quantum noise and bouncing off of random suspended particles slightly alters the phase losing precision. Another source of noise is seismic activity - this can be filtered out by attaching seismometers along the tube and subtracting out relevant signals. To help minimize this type of noise in the output signal, the laser, mirrors, beam splitter and optics are all suspended and hang from the top of the tube as opposed to being mounted on the bottom. Finally, among their engineering feats is a particularly interesting use of a new technology, active canceling.

The same technology in your wireless headphones that cancels out ambient sound but can pick up on a human voice. LIGO uses shock absorbers and noise canceling to filter out lower frequency noise

III Future Direction

The discovery isn't just a landmark in engineering - creating the most precise detector in history, it also has important implications for the future of physics and possibly life in the cosmos. The ultimate goal of physics, as most academics will suggest, is the disconnect between quantum field theory and general relativity. Quantum field theory is true in the regime of the very small. It's mathematics can be used to describe nuclear decay and quantum effects but includes the embarrassing issue of failing to describe large scale events in the universe. Quantum field theory equations cannot be used to model supernovae or galaxy collisions. Similarly, the mathematics of Einstein's general relativity fail to explain the super small. Though accurate in describing the physics of large scale events and masses, it cannot explain small phenomena such as quantum superposition. This should all be able to be described under one theory: a theory of physics. Dr. Barish believes that we are at a brick wall in terms of progress towards the grand unified theory and need some sort of catalyst. Observations of black holes and gravitational wave emitting events may be the cure to this stagnation in physics, he thinks, as the physics in black holes is theorized to behave similarly to both quantum field theory and relativity. After having the privilege of talking to Dr. Barish a few times this quarter, I agree that there's a possibility of LIGO research unifying the great theories of physics. Even if this discovery doesn't lead to the grand unification theory, mapping the gravitational history of the universe may be a more powerful and descriptive biography of the universe's past than the famed cosmic microwave background discovery. As sensitivity improves and the archives of data grows, the future of gravitational wave physics seems very promising.

References

[1] B. Barish, "Ligo detects gravitational waves," *Physics Today*, vol. 69, 2017.

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[5] Wikipedia, "Weber bar."

[6] Wikipedia, "Thermal expansion."