Core 1
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What Does Gravity Sound Like?

Gravity has long been known as the silent force that pulls things to the ground, but a team of physicists, astronomers, and engineers has built an observatory that will be able to "hear" gravity. In 1916, Albert Einstein formulated the general theory of relativity, which predicted that gravitational energy could propagate through the universe in waves like light or sound. It has been almost a century since that prediction, but there have never been any direct observations of gravitational waves. The Laser Interferometer Gravitational-wave Observatory (LIGO) aims to make that first observation, perhaps even some time this year.

There are gravitational waves all around, but their effects are minimal and practically undetectable. LIGO will attempt to detect the most intense gravitational waves in the universe, which come from the interactions of star-size masses moving at speeds approaching the speed of light. These sorts of interactions are fantastic astronomical events like the collision of two black holes or supernovae explosions of stars. These phenomena produce massive gravitational ripples that travel through the universe at the speed of light. LIGO is one of the first instruments designed to be sensitive enough to "hear" these waves as they go by.

What Does it Look Like?

LIGO is an astronomical observatory, but it resembles neither the dish of a radio telescope nor the canister of an optical telescope. The LIGO detector is the most ambitious in a class of apparatuses known as interferometric gravitational wave observatories. There are two LIGO facilities, one in Hanford, Washington and the other in Livingston, Louisiana. They are each massive L-shaped structures with 4-kilometer long arms surrounded by concrete enclosures. Each arm consists of a 4-foot diameter vacuum pipe, boasting the largest high vacuum ever constructed. The vacuum system is only one of the extraordinary features of LIGO, as the project combines cutting-edge technology from many different fields. The heart of LIGO, though, is its optical configuration, which is the focus of this paper. Understanding the subtleties of the LIGO interferometer will give a deeper appreciation for what is expected to be one of the great scientific discoveries of the early 21st century.

The Michelson Interferometer: Beam splitters and Interference

The layout of LIGO is based upon a century-old optical configuration known as a Michelson Interferometer. In 1887, Albert A. Michelson and Edward Morley performed one of the most significant experiments leading up to the theory of relativity. A description of the Michelson-Morley experiment can now be found in most introductory physics textbooks: The experiment sought to confirm the existence of the "aether," an invisible medium that was believed to permeate the universe. The logic of the time was that light waves must travel through some medium, just as sound waves traveled through air, and ocean waves through water. Since the Earth is in motion around the Sun, it must move through this medium and thus experience some sort of "aether wind." In the late 19th century, Michelson came up with an ingenious way to detect this wind.

The now famous Michelson interferometer (Figure 1) has three mirrors. The light enters the interferometer from a source and hits a beam splitter, a half-silvered mirror that sends half the light in one direction and the other half in the perpendicular direction. The light then reflects off mirrors at the end of each arm and returns to the beam splitter. This returning light is then split again in two directions, one back toward the source and the other towards a detector. The split light returning from each arm interferes and combines; Michelson configured his interferometer such that the light would interfere in a very specific way.

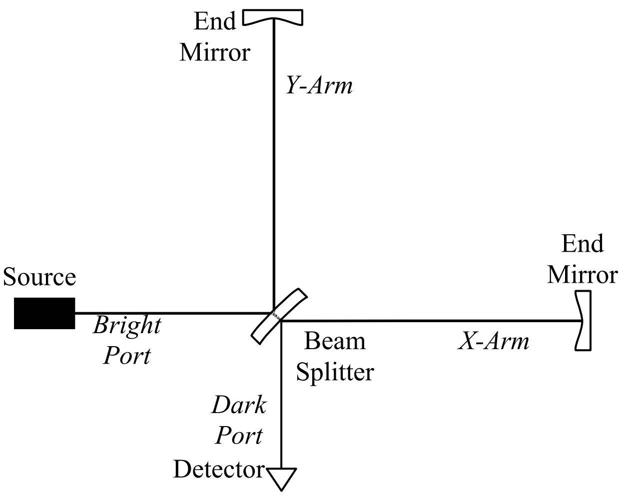

Figure 1. Michelson Interferometer[3]

The word interferometer is derived from the word interfere, and it is the precise interference of light waves in each direction that makes a Michelson interferometer work. In one direction, back toward the source, the two returning beams interfere *constructively*, summing in amplitude. This occurs when the peaks and valleys of the light waves overlap exactly (Figure 2). In the perpendicular direction, the light interferes *destructively*, canceling out to nothing. These two directions are called the *bright port* and *dark port*, respectively. The beauty of Michelson's interferometer is its extreme precision. If the difference in the speed of light in each arm causes a change in the light of only a fraction of a wavelength, the interference of the light will be disturbed. Instead of perfectly constructive or destructive, some other interference will be observed. This is most visible at the dark port; a signal will appear where there should be none.

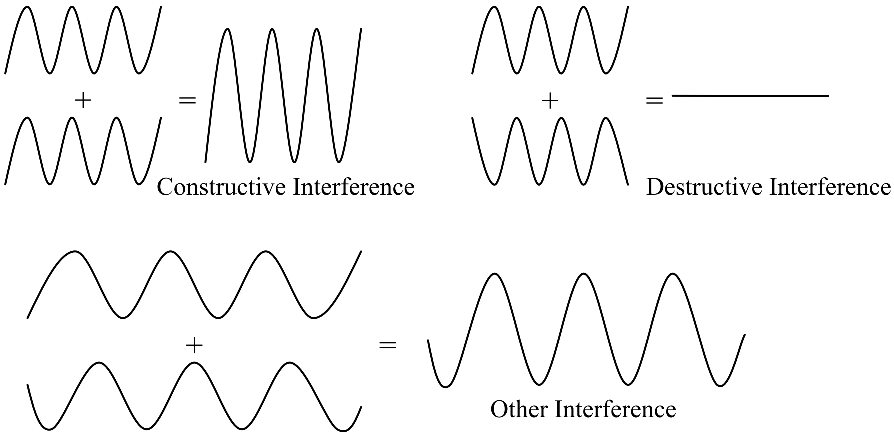

Figure 2. Interference of waves[3]

In the Michelson-Morley experiment, it was expected that as the Earth moved around the Sun and the direction of the aether wind changed, the speed of light would also change, speeding up when the Earth was moving with the aether wind and slowing down when the Earth was moving against it. Thus, if the interferometer were perfectly aligned in one direction, a signal should appear in the dark port if the interferometer were rotated. However, despite their best efforts, Michelson and Morley never detected a significant signal, implying that the speed of light was not different in different directions. Their failure became Einstein's inspiration; he formulated the special theory of relativity, which did away with the aether and whose central postulate is that the speed of light is always measured to be the same value in all directions at all times.

The Difference Between the Aether and a Gravitational Wave

In the Michelson-Morley experiment, the dark port signal was expected to originate in a difference in the speed of light in the two arms. In LIGO, the signal will originate in a *length difference* in the two arms. A Michelson interferometer is a perfect apparatus for detecting gravitational waves because the effect of a passing wave is precisely to lengthen space in one direction and contract it in the perpendicular direction (Figure 3). Just like a difference in the speed of light, this length difference will cause a signal to appear in the dark port where there should be none.

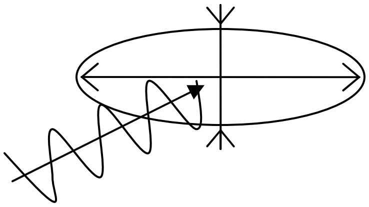

Figure 3. A gravitational wave entering the plane lengthens space in one direction and contracts it in the perpendicular direction[1]

A gravitational wave must have very large amplitude to be detected by LIGO, and there are not many things that could generate such waves. Two interacting black holes or neutron stars, the supernova collapse of a large star, or a massive pulsar are some of the phenomena that could generate gravitational waves of sufficient magnitude. However, these are very rare events in the universe and LIGO may run for many months without seeing any signal at all.

When LIGO does detect one of these phenomena, it will record the precise waveform of the passing gravitational wave. As the wave passes through the LIGO interferometer, it creates an oscillation in the distortion of space, first lengthening space along the x-axis and shortening it on the y-axis, then shortening the x-axis and lengthening the y-axis. As the distortion oscillates, so will the dark port signal, mapping out the frequency and magnitude of the gravitational wave in a manner similar to a radio telescope receiving a signal. However, unlike traditional telescopes that can map out a picture of the universe, LIGO aims to detect short-lived events and won't hear anything the vast majority of the time. When one of these events does occur, LIGO will provide a very unique perspective. In the case of black holes, where no light can escape, LIGO will provide the first picture of these mysterious entities. Just as various telescopes have expanded our view outside the visual spectrum to gamma rays or radio waves, LIGO will see the universe in the gravitational spectrum, giving astronomers the ability to make discoveries that were not previously possible.

Actually detecting a gravitational wave, however, is no easy feat. Although the astronomical phenomena involve huge masses, the expected effect on the LIGO detector is a length change of about 10^{-18} meters (1000th of the diameter of a proton, 100 million times smaller than the diameter of an atom). The Michelson-Morley interferometer could only have detected a 10^{-8} meter difference, so there are drastic improvements that need to be made. Luckily, over a century has passed since their experiment and technology has progressed dramatically.

The 21st Century Update of a 19th Century Apparatus

Michelson's 1887 interferometer fit in a standard physics lab, but the LIGO detectors are over 2000 times bigger. Michelson-Morley used a standard sodium lamp, but LIGO uses a high-powered infrared laser. The 1887 experiment was done in air, but LIGO is enclosed in a 16,000 cubic-meter high vacuum. The differences between LIGO and the Michelson-Morley interferometer are more than just scale, however. The optical layout has several additional complexities, most obviously three extra mirrors (Recycling Mirror and two Input Test Masses as shown in Figure 4).

A recycling mirror is inserted at the bright port to recycle unused light back into the interferometer. In the Michelson configuration, the beam splitter combines the light returning from the arms and sends it back towards the bright port. In the 1887 interferometer, this light is essentially lost, but the addition of a recycling mirror multiplies the amount of light available inside the interferometer, and thus multiplies the final gravitational wave signal. This technique is formally known as power recycling, so the LIGO interferometer is categorized as a power-recycled Michelson interferometer.

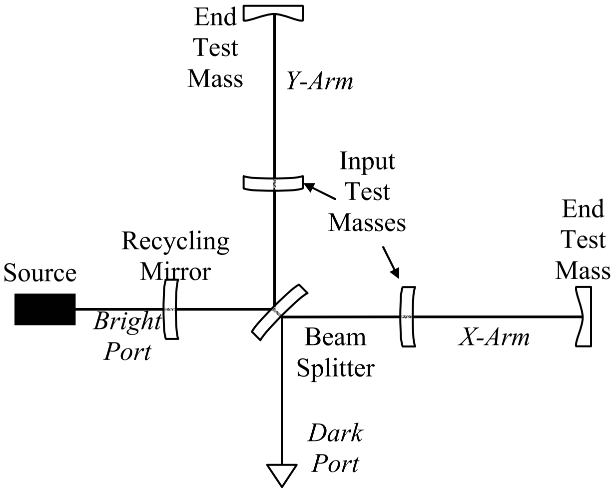

Figure 4. LIGO Interferometer[1]

The longer the arms of an interferometric gravitational wave observatory, the more sensitive it is. This is the reason the LIGO interferometer has 4-kilometer arms, but with optical tricks, the effective length can be multiplied dramatically. In the Michelson-Morley interferometer, several mirrors were used in each arm so that the light would bounce several times. LIGO takes this one step further by placing a mirror directly in the path of the light at the input of each arm (Input Test Masses in Figure 4). They are only

3% transmissive, but 97% reflective. When light passes through these input mirrors, it will bounce back and forth across the entire length of the arm many times before returning to the beam splitter. This lengthens the optical path traveled by the light considerably by folding it on top of itself. Michelson and Morley used four mirrors in each arm to multiply the length four times, but with just two mirrors in LIGO, the length of the arms is effectively multiplied several hundred times.

This configuration, where light bounces many times between two mirrors, is known as a Fabry-Perot cavity, named for Charles Fabry and Albert Perot, who were contemporaries of Michelson and Morley. Fabry and Perot were French physicists who made numerous contributions to optics and astrophysics in the early twentieth century. Today, their research is a vital part of the LIGO interferometer, which can be fully described as a power-recycled Michelson interferometer with Fabry-Perot arms.

A Fabry-Perot cavity is not simply the space between two mirrors however; the spacing of the mirrors must be precise to take full advantage of a phenomenon called *optical resonance*. Just as Michelson aligned his interferometer so that the light returning from each arm interfered constructively at the bright port, Fabry and Perot made their cavity the exact length such that the light would interfere constructively with itself on successive bounces. This occurs when the peaks and valleys of the light wave overlap with each other exactly, which will happen if the length of the cavity is an exact multiple of half of the light's wavelength. With this property of resonance, not only does the light travel a distance that is many times the length of the arm, but the intensity of light within the arm is many times that of the input light.

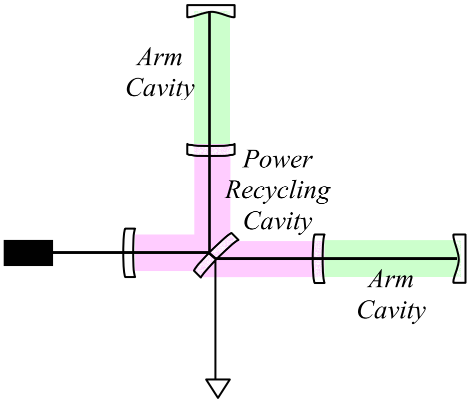

Figure 5. Fabry-Perot Cavities in LIGO[2]

This resonance property is also behind the effect of power recycling, and the space from the recycling mirror to the input test masses is referred to as the power recycling cavity (Figure 5). In this way, the LIGO interferometer can be thought of not as a collection of six mirrors, but a combination of three Fabry-Perot cavities, the power recycling cavity and two arm cavities. The gains in light intensity from compounding these cavities significantly amplify the gravitational wave signal at the dark port, which is already magnified by the multiplying effect of lengthening the optical path in the arms. By creating these Fabry-Perot cavities, adding just three mirrors makes LIGO several orders of magnitude more sensitive than Michelson's interferometer.

Hearing a Pin Drop

In addition to amplifying the signal with optics, LIGO engineers have to worry about many noise sources that can obscure the signal. Michelson and Morley dealt with this by floating their interferometer on a bed of mercury. LIGO takes this many steps further, using a vast array of technology to filter out noise from seismic vibrations, collisions with air molecules, the gravitational effects of the Moon and Sun, and a host of other sources. The effect of a gravitational wave on LIGO is miniscule, and it is crucial to silence the room before trying to hear a pin drop.

The mirrors are all suspended by thin wires and hung from a complex suspension system of springs and pendulums. Not only does this isolate the interferometer from seismic vibrations, but it is actually an active system, with servos that move the mirrors to cancel out predictable effects such as the gravitational pull of the moon. The entire interferometer is held in high vacuum (10^{-9} torr, about one trillionth of standard atmospheric pressure), which involves a complex computer-controlled system of valves, gauges, and pumps. This reduces collisions of air molecules with the optics as well as refractive effects on the beam itself. Unlike Michelson and Morley's crude sodium lamp, the light source in LIGO is a precision laser, with an array of optics to stabilize its frequency and intensity. The mirrors used in LIGO are also very special; they are high-quality fused silica *supermirrors* designed to absorb very little light as it passes through or reflects. Each mirror weighs 10 kilograms so they are massive enough to suppress quantum-level fluctuations. These are just some of the advanced technologies that allow LIGO to achieve its extreme level of sensitivity.

However, a passing gravitational wave does not manifest itself in the suspension system, the vacuum system, or even in the optics. A gravitational wave will do just one thing: change the lengths of the arms. All the other systems of LIGO simply work to reduce noise that might obscure this length change. The part of LIGO that actually measures this length is the length sensing and control (LSC) system; understanding this system is the key to understanding how LIGO really works.

What Exactly is Length Sensing and Control?

A gravitational wave will simultaneously lengthen one arm of the LIGO interferometer and shorten the other by the same amount. The basic purpose of the observatory is to detect this phenomenon, but noise sources will cause movements in the mirrors that obscure the gravitational wave signal. Damping out these movements and accurately measuring the length changes caused by gravitational waves is the purpose of the LSC system.

In order for the system to work at all, all the optics must be held at fixed distances apart in the absence of a gravitational wave. Michelson affixed his mirrors to a solid surface, so he did not need to worry about the distances between his mirrors changing. LIGO’s mirrors are each suspended by wires and are actually in no way physically attached to each other. Hanging the optics reduces high-frequency noise, isolating the optics from the Earth and allowing the mirrors to move freely when a gravitational wave does pass through. However, if the mirrors are free to swing, the distances between them will change. Thus, the LSC system must actively sense the length between each mirror and if it is incorrect, move the mirrors to correct that length.

Measuring the distance between two freely swinging mirrors is no easy task. There is no stable, external place to put a measuring device, so LIGO engineers can’t just put a ruler next to each mirror and see how far it moves. The ruler must swing along with the mirrors to accurately measure lengths in the interferometer. Four-kilometer long swinging rulers in the traditional sense would not be very feasible but fortunately, the needed rulers are already built into the interferometer.

Using Lasers as Rulers

The initial LIGO configuration uses a technique developed by S. Whitcomb in 1991[2] to perform length sensing and control. This scheme uses the laser itself as a ruler and measures lengths by utilizing the optical properties of the interferometer. A way to measure one length in the interferometer has already been discussed in this paper: the signal at the dark port corresponds to the difference in the lengths of the two arms. This is done by design, aligning the interferometer precisely so that the light interferes in a specific way. Other length variables in the interferometer can be measured in the same way, by careful alignment of the interferometer and an observation of interference patterns in the light.

The basic idea of the scheme is to use frequencies of light that are different (but derived) from the main laser. The frequencies are chosen so that the light is not resonant in the arms. This effectively makes the light bounce off the input test masses so it will only be affected by the length of the power recycling cavity. The main laser is generally referred to as the carrier and, since they differ from the carrier by radio frequencies, the other frequencies are called RF sidebands. Three photodiodes monitor the carrier and sideband light at different locations in the interferometer. The Symmetric and Asymmetric photodiodes monitor the bright and dark ports, respectively. An additional Pickoff photodiode monitors the light inside the power recycling cavity.

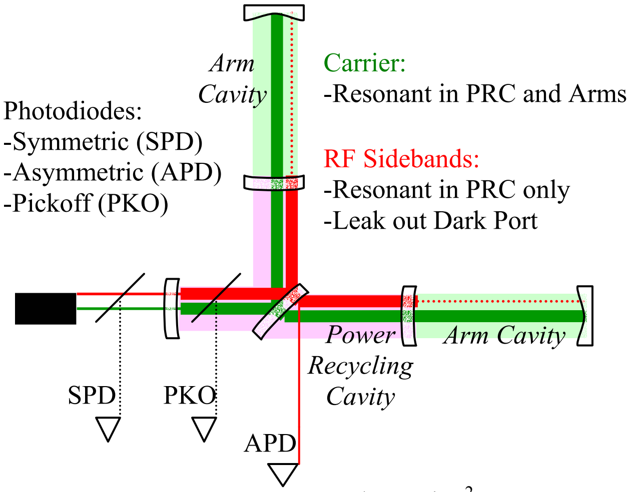

Figure 6. LIGO Length Sensing[2]

Since light is being used as a ruler, the lengths that can be measured are closely related to the Fabry-Perot cavities in the interferometer. As already discussed, the difference in the lengths of the arm cavities is measured in a change in the carrier light at the Asymmetric photodiode. Using different combinations of the three photodiodes, the length of the power recycling cavity and each arm cavity can be measured. These lengths define the relative positions of the four most important mirrors (the test masses) and are all the LSC system needs to keep the interferometer in perfect alignment.

When the system detects a deviation in any of these lengths, it sends a signal to servos that move the mirrors back to alignment. An instrument that maintains its initial configuration in this way is called a “null instrument.” Even when a gravitational wave passes through the LIGO interferometer and changes the arm lengths, the LSC system will counteract the movement. In fact, the gravitational wave signal will not come from the exact physical movement of the mirrors; the servo signals pushing against this effect will be the data recorded as the first direct observation of a gravitational wave.

This is a Telescope?

Although it looks and behaves in a unique way, LIGO is still fundamentally an observatory like any other. Just as astronomers have mapped the universe in the radio, microwave, infrared, visual, ultraviolet, x-ray, and gamma ray ranges, LIGO will be able to see the sky in a brand new regime, likely discovering astronomical features that have never previously been observed. The initial LIGO configuration can detect gravitational wave events as far as 20 MPc, which is 400 times the diameter of the Milky Way. However, colliding black holes and exploding stars are very rare, even in such a large range; over its first year LIGO is expected to detect few if any gravitational wave events. However, when the advanced LIGO configuration is implemented in a few years, 1000 times more of the universe will be visible and LIGO can be reasonably expected to make the momentous first-ever direct observation of a gravitational wave.

It's just a matter of lasers and mirrors, but using Michelson's 19th-century techniques and LIGO's 21st-century technology, scientists will soon "hear" a phenomenon first predicted by Einstein's famous 20th-century theory.

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