GRAVITATIONAL WAVES, HOW CLOSE ARE WE?

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The Detection of Gravitational Waves, How Close Are We?

Since the realization that the general theory of relativity predicts gravitational waves, there have been attempts to actually detect these waves. Indirect observations have been made that support their existence but no direct measurement. This paper gives a brief explanation of gravitational waves and discusses the current condition of the experimental search for gravitational waves. It deals with the newest techniques that will enable their detection. The focus of the paper is on three experimental groups: LIGO, VIRGO, and LISA. From our research of these groups we believe that the detection of gravitational waves will occur within the next decade.

The Detection of Gravitational Waves,
How Close Are We?

Einstein's general theory of relativity was published in 1915.[1] Since that time many of the predictions derived from the theory have been experimentally observed. Three main examples are the bending of light by gravity, the red-shift of light traveling in a gravitational field, and the precession of Mercury. Einstein's theory has been credibly established because of observations like these. There are still other predictions that have yet to be observed. The detection of gravitational waves is one of these predictions.

It was discovered in 1916 that the general theory of relativity predicts the existence of gravitational waves. “Gravitational waves are perturbations in the curvature of spacetime propagating with the velocity of light. They are caused by accelerating masses.”[2] In order to understand the concept of a gravitational wave it is helpful to understand gravity as explained by the general theory of relativity. Relativity does not analyze gravity in terms of forces and acceleration as in Newtonian physics. Instead it explains gravity in terms of the geometry of spacetime.

Space time is a very difficult concept to visualize. It is made up of the three position-axes, x, y and z, but also includes the dimension of time. It is the fourth axis of time that makes spacetime difficult to conceptualize. Spacetime is all around us. It maybe helpful to think of it as a medium that encompasses everything: earth, our galaxy, the universe, etc. All planets, suns, moons and celestial bodies are “submersed” in this medium called spacetime.

According to the general theory of relativity mass bends spacetime. Larger masses bend space-time more than smaller masses, just as a more massive object would bend a trampoline more than a less massive object. If the gridlines in Figure 1 represent spacetime it can be seen how the Earth bends it. Objects that approach the Earth will be affected by this curvature around it. Specifically, an object will be moved towards the Earth. This is how general relativity pictures gravity.

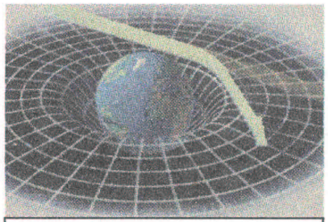


Figure 1: Earth Bends Spacetime[3]

As mentioned gravitational waves are perturbations in the curvature of spacetime, and are created by accelerated masses. A similar occurrence can be observed with water. As a fish in a bowl moves around underwater it produces movements, or waves, in the water that spread throughout the bowl. In this same way accelerated masses produce waves in spacetime. These waves travel throughout the universe affecting spacetime and other masses within it. The magnitude, or strength, of the gravitational waves is directly proportional to both the mass and the acceleration of that mass. The magnitude of the wave also depends on the distance it travels before it reaches us. The further it travels the smaller its magnitude will be. It is this fact that has made detection of the gravitational waves unsuccessful in the past. It is difficult to understand how a gravitational wave affects matter. It is best to consider the wave's effect on the spacetime around the matter. As the wave passes through spacetime it bends it, and any material in the spacetime must also bend accordingly to move with the spacetime. Gravitational waves tell spacetime how to curve, and spacetime in turn tells matter how to move.

The theoretical analysis of gravitational waves is quite difficult compared to that of a wave on a string because they are not one-dimensional. Gravitational waves have characteristics similar to both longitudinal and transverse waves. These types of waves are easily understood in one dimension but become extremely complicated in more dimensions. Gravitational waves are actually classified as both quadrupolar transverse and quadrupolar longitudinal waves. Properties of these kinds of waves are difficult to conceptualize. Figure 2 explains how gravitational waves have transverse and longitudinal components. Theoretically gravitational waves, like light waves, can be polarized, components with certain orientations could be absorbed as the wave passes through a "polarizing" medium. This means that it may be possible that as the waves move through matter in spacetime they may become polarized before they reach Earth. It would be quite possible that, of the gravitational waves that reach Earth, many are polarized in different ways. Gravitational waves are also similar to electromagnetic radiation because they can occur with different frequencies while their velocity is constant. The range of frequencies that a particular experiment attempts to detect is referred to as a detection band. It is beyond the scope of this paper to explain all the details of gravitational waves. It is sufficient that the reader understand that gravitational waves are extremely complex and thus the detection of these waves is equally complex. Scientists attempting to detect these waves must consider all the properties of the waves in order to design an experiment capable of detecting gravitational waves.[5]

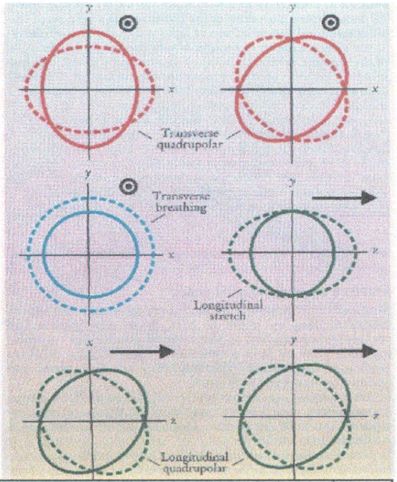


Figure 2: This diagram shows the different polarizations of a gravitational wave. The upper right corner of each polarization represents the direction of propagation. The dotted and solid lines represent the deformations of spacetime caused by the waves.[4]

Other characteristics of gravitational waves complicate their detection. Because of the expected small magnitude of gravitational waves the displacement in matter is not easily detected. "Even a strong gravitational wave signal coming from, say our own galaxy is expected to induce ... an unbelievably small effect, which would jerk masses spaced 1 km apart by a mere 10x- 18m - one thousandth of the diameter of the proton!"[6] Up until the 1970's, measurements of these magnitudes were not possible and even today the cutting edge of technology still struggles with measurements in these ranges. In order to detect these waves, experimental equipment must be extremely precise and accurate.

Since they were predicted in 1916 there has been no direct observation of gravitational waves. Experiments have been conducted but have yet to yield conclusive results. In 1974 astronomers Hulse and Taylor discovered the second pulsar to ever be observed, SR 1913 + 16. A pulsar is a cosmic source of regular and rapid pulses of radiation usually at radio frequencieS.[7] This pulsar was different than the first because it was a binary pulsar meaning it was not a singular body but two revolving around each other. The two bodies were separated by a distance a few times that from the earth to the moon.[8] This newly found binary pulsar created much excitement because it provided scientists with a means of verifying Einstein's theory that predicts that this system should loose energy by forming gravitational waves. If the system were to loose energy it would be observed that its orbit period would be reduced, the speed of the two bodies would increase and the distance between the two would also decrease. This is exactly what was observed. The decrease in the orbit period was very small, about 75 Millionths of a second per year. With their observed data Hulse and Taylor were able to calculate the rate with which the system was loosing energy. The theoretical value of the energy lose was calculated and shown to be in agreement to "within one half of a percent with the observed value."[9] Hulse and Taylor first reported their results in 1978, four years after the discovery of SR 1913 + 16. In 1993 they received the Nobel Prize in physics for their work. Their observation is strong evidence that gravitational waves exist, but it is not a direct measurement.

Pulsars like SR 1913 + 16 and other similar astronomical events are hopeful sources for detectable waves. The detection of gravitational waves ultimately depends on how often they are produced and pass through our region of spacetime. Different events send out different types of signals. Some sources emit periodic signals. By observing these sources over a period of time they can be verified to be gravitational waves can if the measurements are periodic and correspond with the expected values. Other sources emit waves in one burst. In order for these waves to be detected any data taken at one source must be verified with data from a different detector. Some sources emit waves at an increasing magnitude. This rate can be calculated by knowing the source type and by seeing that the data shows the same increase in magnitude. For the periodic and increasing waves it is necessary to know the source to do the calculations. Each source also emits waves of different frequencies. Although there is much uncertainty concerning how often different types of gravitational waves are emitted, it is believed that there are as sufficient number of these events that occur in the universe so that within a year any detector would have ample opportunity to detect and measure waves.[10]

To actually detect and measure gravitational waves, experiments must be prepared at all times. We do not know when a wave large enough to observe will perturb our region of spacetime. We have to sit and wait. Because of the small magnitude of the gravitational waves any detector must be able to verify that it has measured the disturbance from a gravitational wave instead of disturbances from other sources such seismic activity under the Earth's crust. The detectors cannot be sensitive specifically to gravitational waves. For this reason they must be isolated from all other disturbances except gravitational waves. In order to insure the detection of actual gravitational waves at last two different experiments located at very far distances from each other must confirm the data observed. To pinpoint the location of the source of the wave three detectors are required. As much distance as possible should separate the three detectors to enable the triangulation of the incoming data and to calculate the wave's origin in space. This is similar to the methods used to locate the epicenter of earthquakes.

There are quite a few organizations around the world that are preparing to detect gravitational waves and many different methods are being prepared. This paper will focus on what we feel are the three most promising groups. Coincidentally, these three experiments are based on similar concepts. We will first discuss the theory behind these projects and then examine the specifics of the organizations. With this information we will be able to compare the groups and their capabilities.

Interferometer

The three experiments we will discuss make use of an interferometer in their research, to detect gravitational waves. The interferometers, are designed similar to the one Michelson and Morley constructed to detect the ether, see Figure 3. Just as in the Michelson-Morley interferometer the original laser beam splits and travels down two different arms. The interferometers used for gravitational wave detection are designed so the two split beams destructively interfere upon recombining with each other. In normal conditions, without gravitational waves present, the photodetector will not read anything. If for any reason the arm lengths of the interferometer were to fluctuate the recombined beams would not perfectly interfere and the photodetector would detect a change in intensity from the laser. This is how gravitational waves will be detected. As they pass through the interferometer the arms lengths will fluctuate and it will be noted by the photodetector.

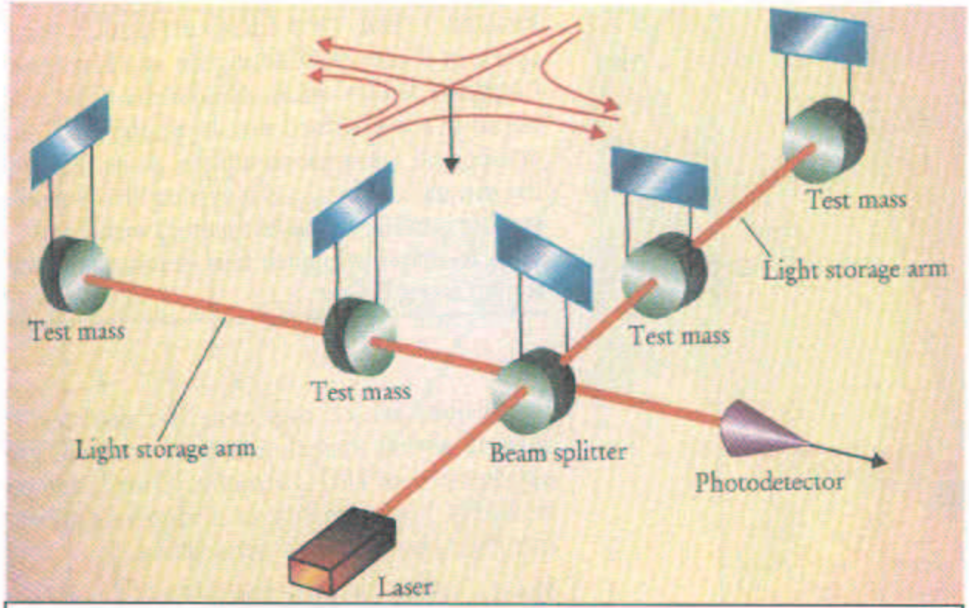


Figure 3: A Michelson interferometer[11]

The ability to measure gravitational waves is proportional to the length of the arms of the interferometer. If two masses, separated by a given distance, experience a distortion due to a gravitational wave, then two identical masses at twice that distance will experience a distortion twice as great. For example, if a meter stick is contracted expanded by 1% then a 2-meter stick will also be affected by 1%. However, this same percentage in the 2-meter stick will be twice as much as the stretch of the meter stick. Thus for the detection of gravitational waves, longer arms allow for more sensitive interferometers.

There are other factors that could cause the arm lengths to fluctuate or appear to fluctuate, such as, thermal expansion, a non-stable laser source, or a poor vacuum. Anything that interferes with the detection of a gravitational waves signal is referred to as noise. If the laser source does not emit a constant, or stable, frequency of light the photodetector will detect a change in the intensity. Thermal expansion will change the arm lengths of the interferometer, thus changing the detected interference of the recombined beams. If the vacuum environment in the system is not low enough the particles in the air can interact with the laser beam, changing the interference of the recombined beams. These are just some of the factors that could hinder the ability of the interferometer to detect gravitational waves. For this reason the interferometer must be isolated from these and other noise sources.

LIGO

Laser Interferometer Gravitational-Wave Observatory, LIGO, is a collaboration of MIT, Caltech, and many other universities in the United States. The LIGO project is building detectors at two different sites. One is in Livingston, Louisiana, and the other is some 2000 miles away in Hanford, Washington.[12] This should provide sufficient distance between the sites to validate the detection of the

Figure 4: A recent photograph of the Hanford, WA site.[12]

waves. In fact, the Washington site houses two interferometers in the same vacuum tube. One is 4 km long and the other is 2 km long. As mentioned above the length of the longer interferometer will be distorted twice as mush as the smaller interferometer. Signals due to seismic activity, thermal expansion, etc. will not cause this regular 2:1 ratio. Thus, these two interferometers authenticate the detection of gravitational waves. This correlation as well as conformation from the independent Louisiana site will solidify the researcher's confidence in gravitational wave detection.[13]

Because the magnitude of gravitational waves is expected to be very small, the LIGO detector must be one of the most precise instruments. Due to their expected polarizations, as gravitational waves pass through the interferometer, one of its arms will shrink as the other elongates, creating a phase difference in the laser beam. LIGO has an “ultra stable” laser reflecting many times down the 4 kilometer long arms of the interferometer.

To isolate the interferometer from atmospheric noise the tubes inside the arms will be evacuated to one-trillionth the earth's atmosphere. The effects of seismic activity have been reduced through a complex system of 20 suspended mirrors. The first part, of the isolation system stabilizes the mirrors by using “four stages of springs and masses.”[14] This part alone reduces the seismic motion a million fold.[15] The last stage of seismic isolation involves the mirrors being suspended from pendulums. To avoid having to account for the motion of the pendulums, the natural modes of oscillation of the mirror-pendulums are chosen to be outside the “detection band” for LIGO. LIGO's detection band will measure gravitational waves ranging from 10 Hz to 10 kHz. And hence, the natural modes of oscillation of the suspended mirrors will not be within this range. LIGO's design will allow it to detect changes in length on the order of 10^{-21} meters.[16]

This is very precise, as was stated earlier, gravitational waves are expected to move masses l km apart by less than 10^{-18} meters.

LIGO is designed to be upgradeable. It is scheduled to be upgraded in 2006 and again in 2010. These two improvements will increase LIGO's sensitivity by 15 times and increase the detection rate by 3000 times. LIGO is completed and is expected to begin to acquire data in 2002. Its first data run is scheduled to last for three yearS.[17] LIGO is ultimately designed to function as a telescope watching the gravitational disturbances of the universe. To accomplish this the two LIGO sites will need to compare their data with a third gravitational wave detector that is located as far as possible from the LIGO sites. In order to do this LIGO will need international cooperation.[18]

VIRGO

The VIRGO project, named after the Virgo cluster, consists of efforts from the Istituto Nazionale di Fisica Nucleare (INFN) of Italy and the Centre National de la Recherche Scientifique (CNRS) of France. The VIRGO interferometer is based in Cascina, Italy, 10 km from Pisa.

Unlike the LIGO project, there is only one interferometer in VIRGO.[19] Like the LIGO project, VIRGO also uses an ultra-stable laser. The arms of the interferometer are each 3 km long. Multiple mirrors within each arm reflect the laser beam such that the total length traveled is 120 km [20] As mentioned above, this increased distance will allow for a more accurate measurement of gravitational waves passing through it.

VIRGO will also take great measures to eliminate noise. VIRGO's interferometer will be kept at a very high vacuum level similar to that of the LIGO project. In order to reduce the effects of seismic motion of the earth, both of these interferometer arms are suspended by a 10 meter-high

Figure 5: Recent photograph of the VIRGO interferometer in Cascina, Italy.[22]

system of compound pendulums, called a "super attenuator." VIRGO detection band will measure gravitational waves ranging from 10 Hz to 6 KHz. Once VIRGO is operational it will run continuously year in and year out. These signals will be detected, registered, and analyzed by a computer center that will run continuously. This data will then be available to the entire international scientific community for further studies.[21] Construction of the VIRGO interferometer began on May 6, 1996, and it should be fully operational by the end of 2001.

LISA

The Laser Interferometer Space Antenna, LISA, is another future detector that is sponsored by NASA and the European Space Agency. Like the LIGO and VIRGO projects it will use a laser interferometer to detect changes in the length of the arms. However, this interferometer is going to be put into orbit.

Putting satellites in space has a number of advantages. The arm length can be much longer than would be possible here on Earth. Space provides a ready-made vacuum environment that is isolated from seismic activity and other noise. The vacuum in this region of space is slightly better than those obtained by LIGO and VIRGO. It is being built to detect gravitational waves with lower frequencies than those detected by LIGO and VIRGO. LISA will have a detection band from 10^{-4} Hz to 10^{-1} Hz. Many of the waves expected to be measured are in this range. These are frequencies that VIRGO and LIGO cannot detect.

The LISA design will also be based on a Michelson interferometer. However, LISA has some fundamental design differences. As envisioned right now, LISA will consist of three identical satellites put into a solar orbit 20° behind the Earth. As seen in Figure 6, the three satellites will form an equilateral triangle with sides of length 5x10^{6} kilometers.[24] Rather than having one laser beam, each satellite will have two separate lasers. One laser will be aimed at the other two satellites. One of the satellites will be chosen as the central satellite. The two beams from the central satellite will be in phase with each other. This is similar to the beams traveling the two arms of the Michelson interferometer. Unlike the Michelson interferometer the beams are not reflected in the LISA system. Instead, the other satellite will detect the incoming laser beam and send a new beam, in phase with the original, back to the source. The central satellite compares the phase difference of the two received signals. Based on this information, its computer will recognize phase shifts caused by gravitational waves.[25]

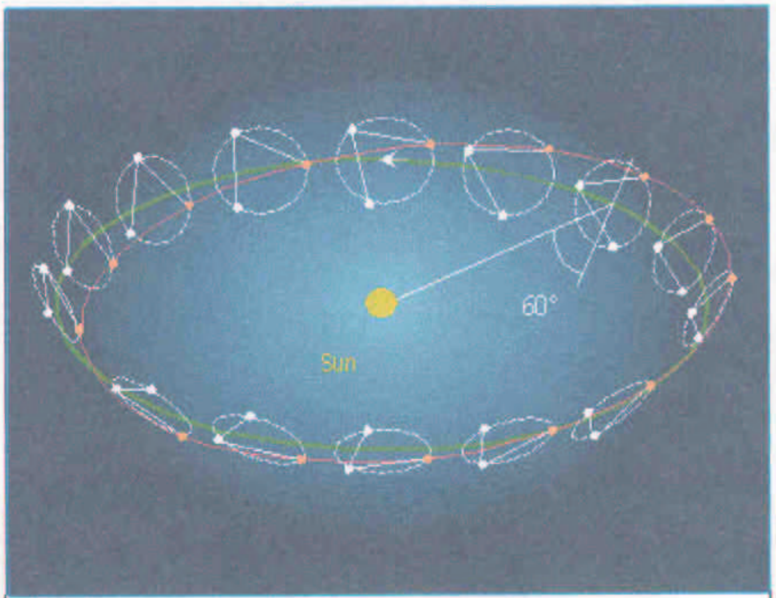
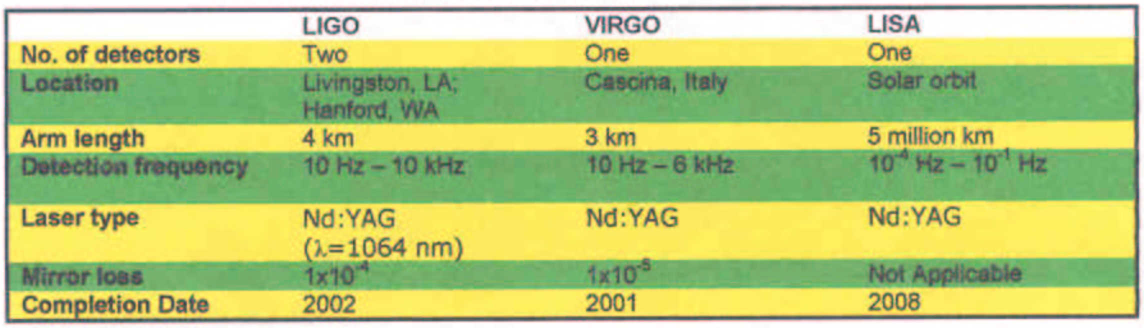


Figure 6: A diagram of LISA's proposed orbit.[23]

LISA is designed to reduce noise in a variety of ways. Thrusters will be built into the satellites to counteract forces such as light from the sun which would accelerate them from their normal positions. The satellites will be shielded from sunlight to limit thermal expansion which could misalign the lasers. In space LISA must carry its own power supply. This power constraint will not allow LISA to have a very strong laser.[26] LISA will use a one-watt laser. This is quite a bit weaker than the lasers used in the LIGO and VIRGO and thus the accuracy of LISA's measurements are only in the range of about one picometer. However, over the total distance of $5x10^9$ meters, LISA will be able to detect a strain[27] on the order of 10^{-23}. It is estimated that LISA will be operational as early as 2008.

Table 1: Comparative table of 3 gravitational wave detectors.



	LIGO	VIRGO	LISA
No. of detectors	Two	One	One
Location	Livingston, LA; Hanford, WA	Cascina, Italy	Solar orbit
Arm length	4 km	3 km	5 million km
Detection frequency	10 Hz – 10 kHz	10 Hz – 6 kHz	10^{-4} Hz – 10^{-1} Hz
Laser type	Nd:YAG (λ=1064 nm)	Nd:YAG	Nd:YAG
Mirror loss	$1x10^{-4}$	$1x10^{-5}$	Not Applicable
Completion Date	2002	2001	2008

CONCLUSION

The factors that will determine when gravitational waves are detected are: how often these waves pass through our region of spacetime, the capability of the experimental equipment, and when these experiments are operational. Even though there is a bit of uncertainty with regards to how often waves pass through the earth, we are confident that within the period of one year a number of detectable waves win pass through our region of space. With all three programs operating, LIGO, VIRGO and LISA, we will be prepared to detect waves over a large range of frequencies. We believe that the first detection of gravitational waves win occur within one year of the LIGO's first data run, sometime in the year 2003. We also feel confident that not. VIRGO and LISA will be capable of detecting waves once they are operational.

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