LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

— LIGO —

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Gravitational Waves and LIGO: Opening New "Eyes" on the Universe

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Throughout history, humans have relied on different forms of light to observe their universe and determine its history and mechanics. Today, we are on the edge of a new frontier in astronomy: gravitational wave astronomy. Gravitational waves carry information on changes in the positions of objects in the universe. Since gravity came into existence before light, gravitational waves will allow us to observe further back into the history of the universe than ever before. And since gravitational waves are not absorbed or reflected by the mass in the rest of the universe, we will be able to see them in the form in which they were created. Moreover, we will effectively be able to "see through" objects between Earth and the gravitational wave source. Most importantly, gravitational waves hold the potential of the unknown. Every time humans have opened new "eyes" on the universe, we have discovered something unexpected that revolutionized how we saw the universe and our place within it. Today, with the United States' gravitational wave detectors (LIGO) and its international partners, we are preparing to see the universe with eyes that do not depend on light.

GRAVITATIONAL WAVES

Many people are familiar with the story of "Newton's Apple" – while sitting under a tree one day, Newton observed an apple falling in the distance and realized the moon he saw in the sky orbits the Earth because of the same force that made the apple fall. This force is gravity, and Newton recognized that gravity acts over distances without physical contact—after all, nothing was touching that famous apple to make it fall. Masses feel gravitational force because every mass in the universe has its own gravitational field, which adds together with all of the other fields in the universe. According to Newton's theory of gravity, when a mass changes position, the entire gravitational field throughout the universe changes instantaneously, and the resultant gravitational forces are instantly changed accordingly.

But Einstein's Theory of General Relativity—the most commonly accepted description of gravity—asserts that no information can travel faster than the speed of light, including information on the positions of mass in the universe, which is communicated through the gravitational field. General Relativity predicts that a change in gravitational field will travel through the universe at the speed of light. It is exactly these changes in gravitational field that are gravitational waves.

Physicists sometimes call these gravitational waves "ripples on space-time," where space-time includes the 3 spatial dimensions we are used to and time. Relativity very accurately describes gravitation in this 4-dimensional universe. Since it is very difficult to visualize 4 dimensions, we can use a flexible surface such as a trampoline as a simplified model for space-time in 3 dimensions. Einstein stated that gravity is the result of the curvature of space-time (the surface of our trampoline in our visualization). If there is no mass on this surface to make depressions on it, then space-time is flat and a rolling ball on the surface will move in a straight line. But if there is a large mass that makes a depression on this surface, the rolling ball will be deflected toward the mass by the curvature of the surface, just as if there were a gravitational attraction between the two masses. Any change in position of the masses will make ripples on this surface representing our changing gravitational field—or gravitational waves.

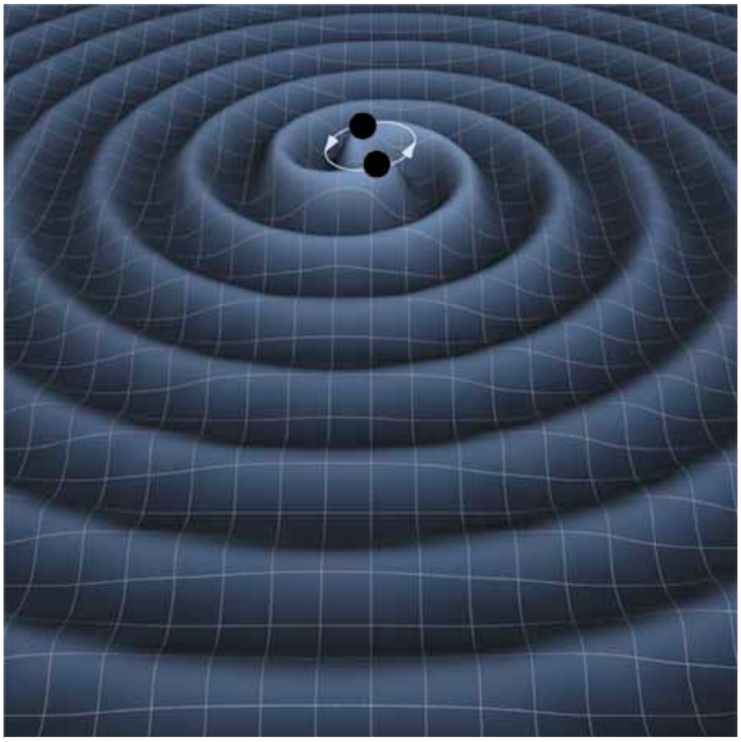

Figure 1: Waves on the surface of space-time from two orbiting black holes. [Image: K. Thorne (Caltech) and T. Carnahan (NASA GSFC)]

Consider the following thought experiment: It takes light from our Sun just over 8 minutes and 19 seconds to travel to the Earth. If the Sun were to disappear, it would take that long for us to see the Sun extinguished. The same would also be true for the information carried on the gravitational field that the Sun is no longer there. That means that the Earth would continue to orbit the point where the Sun used to be for a little more than 8 minutes until the gravitational wave arrived.

Gravitational waves are created by moving masses, much as electromagnetic waves are created by moving charges. But because gravity is the weakest of the four fundamental forces (the others being the electromagnetic, weak nuclear, and strong nuclear), gravitational waves are exceedingly small. For physicists, a *strong* gravitational wave will produce displacements on the order of 10^{-18} meters—this is *1000 times smaller* than the diameter of a proton. Waves of this strength will be produced by very massive systems undergoing large accelerations, like two orbiting black holes that are about to merge into one. Since systems like these are rare, these sources will be light-years away. Therefore, the search for gravitational waves is seeking the minute effects of some of the most energetic astrophysical systems from the depths of the universe.

SOURCES OF GRAVITATIONAL WAVES

In general, any acceleration that is not spherically or cylindrically symmetric will produce a gravitational wave. Consider a star that goes supernova. This explosion will produce gravitational waves if the mass is not ejected in a spherically symmetric way, although the center of mass may be in the same position before and after the explosion. Another example is a spinning star. A perfectly spherical star will not produce a gravitational wave, but a star with a bump or other deformity will. A few other examples include:

- Two objects orbiting each other the way a planet orbits the Sun **will** radiate. The Earth-Sun system produces gravitational waves as the Earth goes around the Sun.
- An isolated non-spinning solid object moving at a constant speed **will not** radiate.
- A symmetric spinning disk **will not** radiate.
- A spherically pulsating spherical star **will not** radiate.

An interesting feature of the gravitational waves that modern detectors are sensitive to is that they would be in the audible frequency range if they were sound waves. In that sense, these detectors can be thought of as 'gravitational wave radios.' Just like radio waves cannot be heard without a radio to detect the radio waves and decode the music signal to send to the speakers, gravitational waves cannot be heard without a detector to distinguish the gravitational wave and send that signal to speakers. All of the physics that went into the production of a gravitational wave is then encoded in this 'music' for physicists to decode. In the following descriptions of gravitational waves, the 'sound' they make will often be described to illustrate the properties of the expected signal.

There are four main sources of gravitational waves caused by different kinds of motion and changing distributions of mass - continuous, inspiral, burst, and stochastic:

Continuous gravitational waves are produced by systems that have a fairly constant and well-defined frequency. Examples of these are binary star or black hole systems orbiting each other (much like in figure 1) or a single star swiftly rotating about its axis with a large mountain or other deformity on it. These sources are expected to produce comparatively weak gravitational waves since they evolve over longer periods of time and are usually less catastrophic than sources producing inspiral or burst gravitational waves. The sound these gravitational waves would produce is a continuous tone since the frequency of the gravitational wave will be nearly constant.

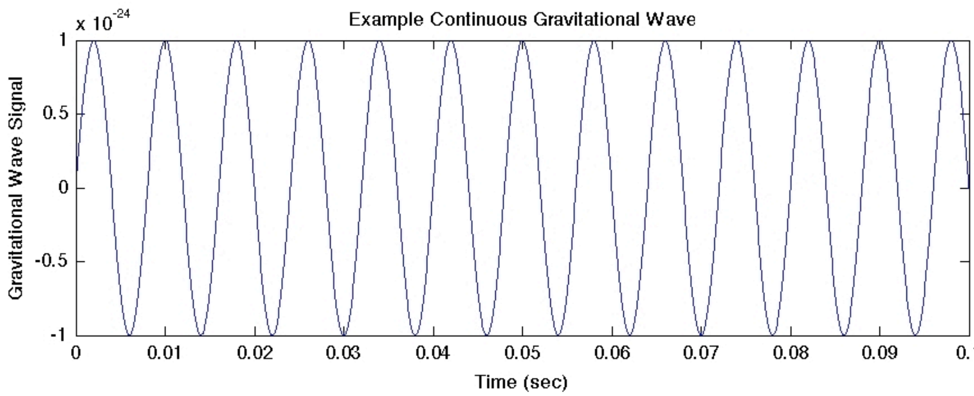

Figure 2: An example signal from a continuous gravitational wave source. [Image: A. Stuver]

Inspiral gravitational waves are generated during the end-of-life stage of binary systems where the two objects merge into one. These systems are usually two neutron stars, two black holes, or

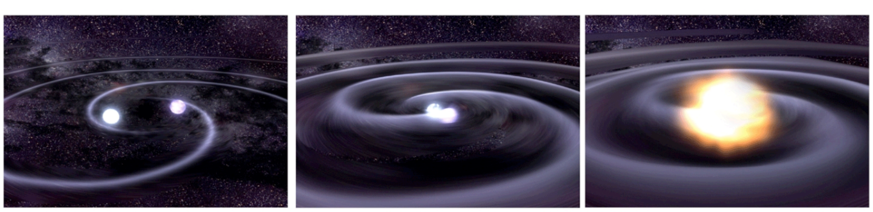

Figure 3: An artist's impression of two stars orbiting each other and progressing (from left to right) to merger with resulting gravitational waves. [Image: NASA]

a neutron star and a black hole whose orbits have degrad-ed to the point that the two masses are about to coalesce. As the two masses rotate around each other, their orbital distances decrease and their speeds increase, much like a spinning figure skater who draws his or her arms in close to their body. This causes the frequency of the gravitational waves to increase until the moment of coalescence. The sound these gravitational waves would produce is a chirp sound (much like when increasing the pitch rapidly on a slide whistle) since the binary system's orbital frequency is increasing (any increase in frequency corresponds to an increase in pitch).

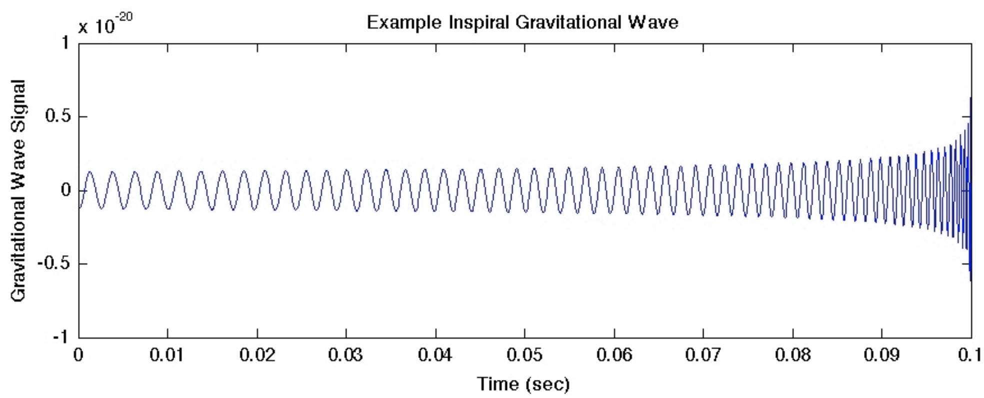

Figure 4: An example signal from an inspiral gravitational wave source. [Image: A. Stuver]

Burst gravitational waves come from short-duration unknown or unanticipated sources—they are the gravitational waves that go bump in the night. Every time humans have looked at the universe with a new set of 'eyes' (for instance, using telescopes to look at visible light or radio waves, or gamma ray detectors to view gamma rays) they have found things that were unexpected and revolutionized our understanding of the universe. Therefore, in burst gravitational waves we are expecting the unexpected. There are hypotheses that some systems such as supernovae or gamma ray bursts may produce burst gravitational waves, but too little is known about the details of these systems to anticipate the form these waves will have. The sounds these gravitational waves are expected to produce are 'pops' and 'crackles' (it is difficult to say since very little can be assumed of their origin).

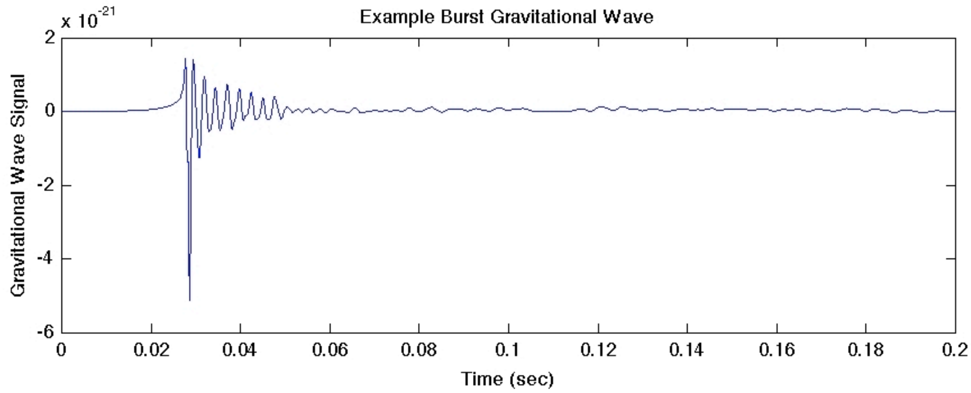

Figure 5: An example signal from a burst gravitational wave source. [Image: A. Stuver using data from C. Ott, D. Burrows, et al.]

Stochastic gravitational waves are the relic gravitational waves from the early evolution of the universe. Much like the Cosmic Micro-wave Background (CMB), which is likely to be the leftover light from the Big Bang, these gravitational waves arise from a large number of random, independent events combining to create a cosmic gravitational wave background. The Big Bang is expected to be a prime candidate for the production of the many random processes needed to generate stochastic gravitational waves (and the CMB), and therefore may carry information about the origin and history of the universe. If these gravitational waves truly originated in the Big Bang, they can tell us about the very beginning of the universe—they

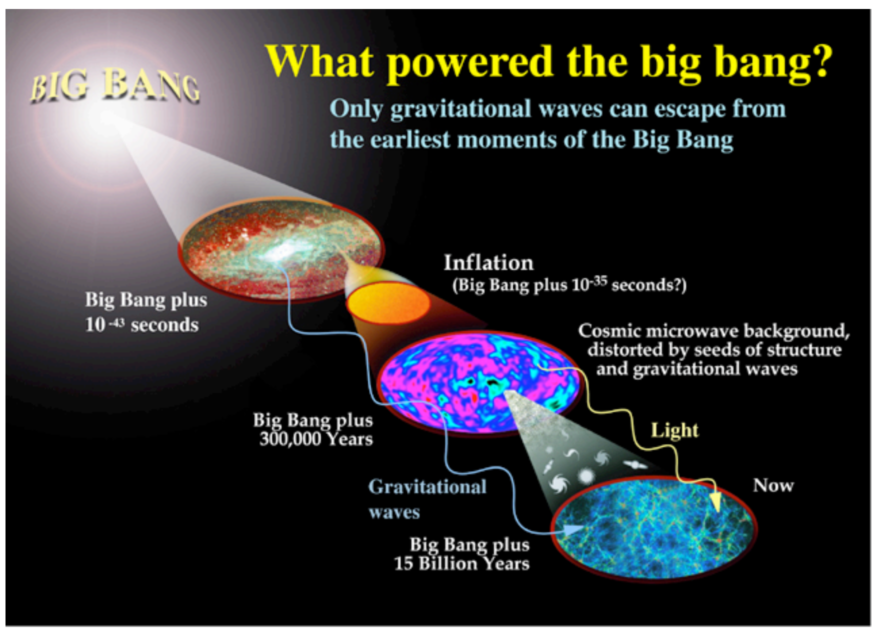

Figure 6: Diagram showing different stages in the evolution of the universe since the Big Bang and when gravitational waves and the CMB came into existence. [Image: NASA]

would have been produced between approximately 10^{-36} to 10^{-32} seconds after the Big Bang, whereas the CMB was produced approximately 300,000 years after the Big Bang. The sound these gravitational waves would produce is a continuous noise (much like static) and will be same from every part of the sky (just like the CMB).

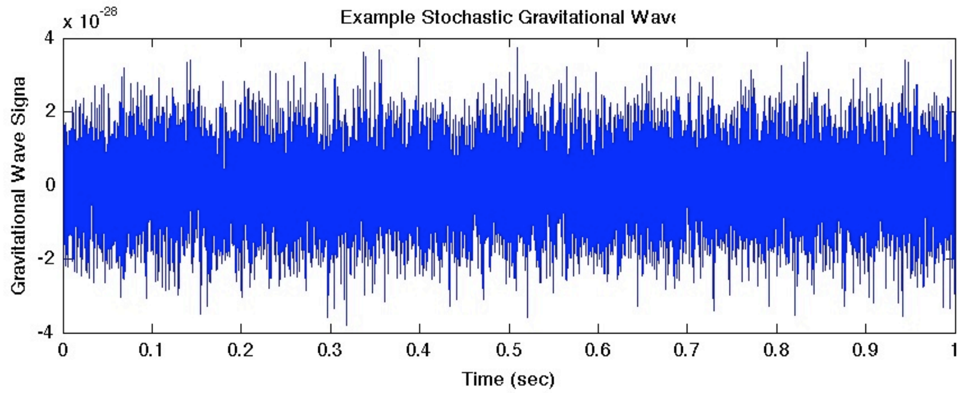

Figure 7: An example signal from a stochastic gravitational wave source. [Image: A. Stuver]

DETECTING GRAVITATIONAL WAVES

Gravitational waves interact with matter by compressing objects in one direction while stretching them in the perpendicular direction. Therefore, the current state-of-the-art gravitational wave detectors are L-shaped and measure the lengths of each of the arms relative to each other using interferometry, which looks at the interference patterns produced by the combination of two light sources. There are two such interferometers in the United States—one in Hanford, Washington and the other in Livingston, Louisiana—and they are collectively called LIGO (Laser Interferometer Gravitational-wave Observatory). LIGO is the largest of the gravitational wave

Figure 8: Aerial view of the LIGO detector in Hanford, WA. [Image: LIGO]

detectors with arms 4 km (a little less than 2.5 miles) in length interferometers (the international detectors include VIRGO in Italy, GEO in Germany and TAMA in Japan).

Multiple interferometers are needed to detect gravitational waves, since directional observations cannot be made with a single detector like LIGO, which is sensitive to large portions of the sky at once. However, gravitational waves have a finite speed and are expected to travel at the speed of light. This will induce a detection delay (up to about 10 milliseconds) between the two LIGO detectors. Using this delay and the delay between the international detectors will help pinpoint the sky location of the gravitational wave source. Multiple detectors also help sort out candidate gravitational wave events that are caused by local sources, like trees falling in the woods or even a technician dropping a hammer on site. These events are clearly not gravitational waves but they might look like a gravitational wave in the collected data. If a candidate gravitational wave is observed at one detector but not the other within the light travel time between detectors, the candidate event is discarded.

Figure 9: Aerial view of the LIGO detector in Livingston, LA. [Image: Aero Data, Baton Rouge, LA]

THE INTERFEROMETER

To measure the relative lengths of the arms, a single laser source is split at the intersection of the two arms. Half of the laser light is transmitted into one arm while the other half is reflected into the second arm. Mirrors are suspended as pendula at the end of each arm reflect the light back to intersection. If the lengths of both arms have remained unchanged, then the two combining light waves should completely subtract each other (destructively interfere) and there will be no light observed at the output of the detector. However, if a gravitational wave were to slightly (about 1/1000 the diameter of a proton) stretch one arm and compress the other, the two light beams would no longer completely subtract each other, yielding light patterns at the detector output. Encoded in these light patterns is the information about the relative length change between the two arms, which in turn tells us about what produced the gravitational waves.

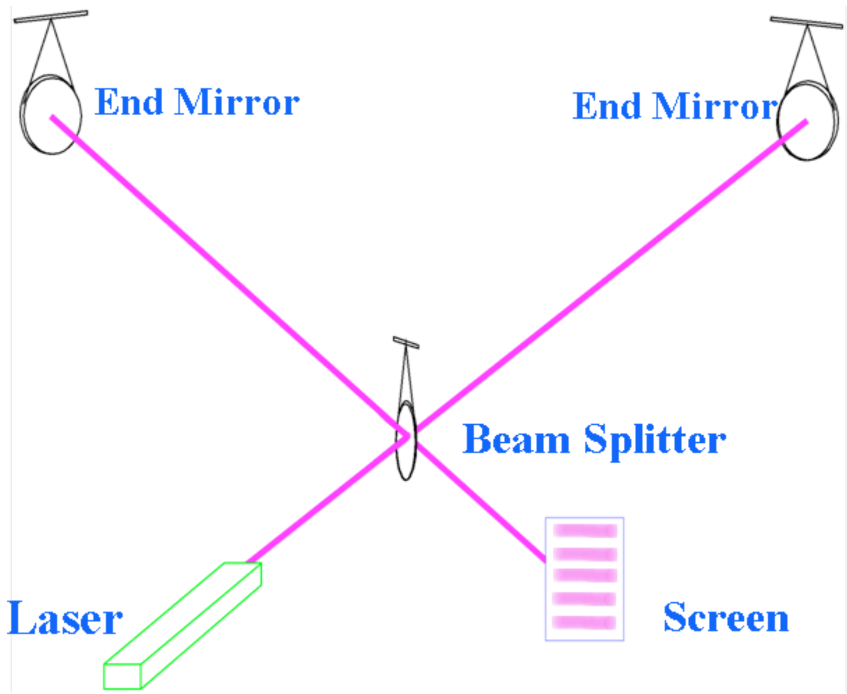

Figure 10: Diagram of a basic interferometer design. [Image: Einstein@Home]

There are many entities and elements on Earth that all add together to cause a constant and very small relative length change in the arms of LIGO. Because of this, there is a constant signal that LIGO is detecting and these signals are regarded as noise (and would sound very much like static when the signal is sent through a speaker). In science, noise is defined to be anything that is measured that is not what was intended to be measured. Here, LIGO is trying to measure the change in length of its arms due to a gravitational wave and not the incessant little motions of LIGO's components caused by the environment. To help minimize local effects on the detector, LIGO has made many enhancements to the basic interferometer design (besides requiring both detectors to detect the same signal within the light travel time between detectors).

One measure is to place LIGO's optical components inside a vacuum. On the superficial level this keeps air currents from disturbing the mirrors (even in a well-isolated and contained system, temperature differences along the arms of the detector could induce

Figure 11: LIGO technicians work on internal optical components. Clean room protocols are used any time these components are exposed to atmosphere to prevent future vacuum contamination. [Image: D. Hoak]

convection currents) but mainly this is to insure that the laser light can travel a straight path in the arms. Slight temperature differences across the arm will cause the light to bend due to temperature dependent index of refraction (a measure of how much light bends as it passes through a medium). Even slight bending of the light in the arms will cause the laser to hit the inside of the approximately 1.2 meter diameter beam tube over its 4,000 meter length. Ultimately, LIGO is the largest sustained ultra-high vacuum in the world (8x the vacuum of space) keeping 300,000 cubic feet (about 8,500 cubic meters) at *one-trillionth* the pressure of Earth's atmosphere.

Another measure is to add seismic isolation systems internally and externally to LIGO. Internally, there are tiny magnets attached to the back of each mirror and the positions of these magnets are sensed by the shadows they cast from LED light sources. If the mirrors are moving too much, an electromagnet creates a countering magnetic field to push or pull the magnets and mirror back into position. This method is not only good for countering the motion of the mirrors due to local vibrations, but it is also used to counter the tidal force of the Sun and the Moon as they pull the mirrors towards them just like they pull on the water in the ocean. Externally, there are hydraulic systems that counter the Earth's surface vibrations (as detected by nearby seismometers) before they can cause vibrations in the internal components of LIGO.

THE POTENTIAL OF GRAVITATIONAL WAVES

Gravitational waves will usher in a new era in astronomy. All of astronomy to date has relied on different forms of electromagnetic radiation (visible light, radio waves, X-rays, etc.), but electromagnetic waves are easily reflected and absorbed by any matter that may be between their source and us. Even when light from the universe is observed, it is often transformed during its journey through the universe. For example, when light passes by large gravitational fields, its trajectory is bent and it can be split into separate beams, resulting in the observation of multiple distinct images of the same object – this effect is called gravitational lensing.

Gravitational waves will change astronomy because the universe is nearly transparent to them: intervening matter and gravitational fields neither absorb nor reflect the gravitational waves to any significant degree. Humans will be able to observe astrophysical objects that would have otherwise been obscured, as well as the inner mechanisms of phenomena that do not produce light. For example, if stochastic gravitational waves are truly from the first moments after the Big Bang, then not only will we observe farther back into the history of the universe than we ever have before, but we will also be seeing these signals as they were when they were originally produced.

All of the physics that went into the creation of a gravitational wave is encoded in the wave itself. To extract this information, gravitational wave detectors will act very much like radios—just as radios extract the music that is encoded on the radio waves they receive, LIGO will receive gravitational waves that will then be decoded to extract information on their physical origin. It is in this sense that LIGO truly is an observatory, even though it houses no traditional telescopes. However, the data analysis that is required to search for gravitational waves is much greater than that associated with traditional optical telescopes, so real-time detection of gravitational waves will usually not be possible. Therefore, LIGO creates a recorded history of the detector data. This provides an advantage when cooperating with traditional observatories, because LIGO has a 'rewind' feature that telescopes do not. Consider a supernova that is only observed after the initial onset of the explosion. LIGO researchers can go back through the data to search for gravitational waves around the start time of the supernova.

Gravitational wave astronomy will help explore some of the great questions in physics: What are the sources of gamma ray bursts (these are some of the most energetic and most distant events observed)? What do gravitational waves from extremely large gravitational fields look like (the equations that describe these situations are very complicated)? What is the proportion of matter in the universe (relative to dark matter and dark energy)? Is there physical evidence of the cosmic strings that are predicted by string theory? These are just a few of the questions that could be answered by the observations of LIGO and its international counterparts.

For Further Information:

READING:

- ✓ *Einstein's Unfinished Symphony* gives a great background to the non-expert on the Theory of General Relativity, gravitational waves and the history of gravitational wave experimentation:

  Einstein's Unfinished Symphony: Listening to the Sounds of Space-time
  By Marcia Bartusiak
  Published by Joseph Henry Press, 2000
  ISBN 0309069874, 9780309069878
  249 pages

  (This book can also be previewed on Google Books by going to:
  http://books.google.com/books
  and searching for "Einstein's Unfinished Symphony")

- ✓ More information can also be found at the Einstein@Home website at http://einsteinathome.org as well as the LIGO web pages at http://www.ligo.org.

VIEWING:

- ✓ The National Science Foundation has produced a documentary (~20 min) on gravitational waves and LIGO called "Einstein's Messengers." To view this documentary and to read more go to:

  http://www.einsteinsmessengers.org.

- ✓ The American Museum of Natural History has also put together a short documentary (~7.5 min) on LIGO called "Gravity: Making Waves." To view this documentary and read more (including working your own virtual interferometer) go to:

  http://www.amnh.org/sciencebulletins/astro/f/gravity.20041101/index.php.

CONTACT:

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