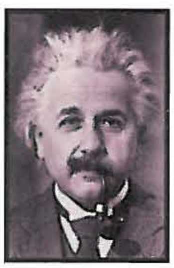
LIGO

Catching the Gravitational Wave

GRAVITATIONAL WAVES: RIPPLES IN THE FABRIC OF SPACE TIME

Albert Einstein predicted the existence of gravitational waves in 1916 as part of the theory of general relativity. Einstein described space and time as different aspects of reality, in which matter and energy are ultimately the same thing. Space-time can be thought of as a "fabric" defined by the measuring of distances by rulers and the measuring of time by clocks. The presence of large amounts of mass or energy distort space-time—in essence causing the fabric to become curved, or "warped"—and we observe this as gravity. Freely falling objects—whether a soccer ball, a satellite, or a beam of starlight—simply follow the most direct path in this curved space-time.

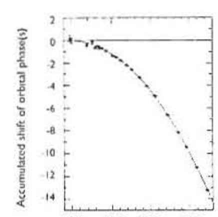


Albert Einstein, the father of general relativity theory

When large masses move suddenly, some of this space-time curvature ripples outward, spreading much the way ripples do on the surface of a pond after a stone has been thrown into the water. Imagine two neutron stars orbiting each other. A neutron star is the burned-out core that can be left behind after a star explodes. It is an incredibly dense object that can carry about as much mass as a star like our sun, in a ball only a few miles wide. When two such dense objects orbit each other, space-time is stirred by their motion, and gravitational energy ripples outward into the universe.

Two neutron stars in orbit around each other

In 1974 Joseph Taylor and Russell Hulse found such a pair of neutron stars in our own galaxy. One of the neutron stars is a pulsar, meaning that it beams regular pulses of radio waves toward Earth. Taylor and his colleagues were able to use these radio pulses, like the ticks of a very precise clock, to study the orbiting neutron stars. Over two decades, they watched for and found the telltale shift in timing of these pulses, which indicated the loss of energy from the stars—energy that had been carried away as gravitational waves. The result was just what Einstein's theory predicted it would be!



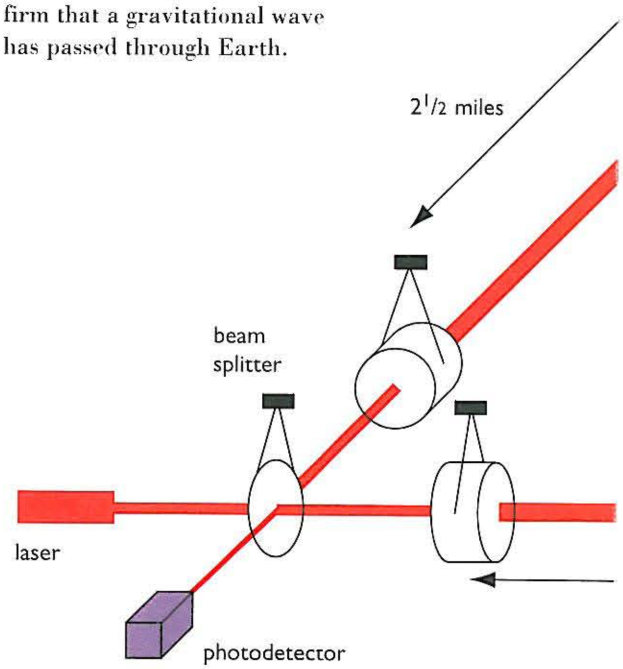
General relativity demands that two neutron stars, orbiting each other, produce gravitational waves. The waves carry away the stars' orbital energy, and in response the stars spiral toward each other a bit. This prediction (solid line) is brilliantly confirmed by observations of the stars' motions over the years (data points) made by Joseph Taylor of Princeton University and his colleagues.

HOW LIGO WORKS

Rendering of how LIGO will look when completed

LIGO will detect the ripples in space-time by using a device called a laser interferometer, in which the time it takes light to travel between suspended mirrors is measured with high precision using controlled laser light. Two mirrors hang very far apart, forming an "arm" of the interferometer, and two more mirrors make a second arm perpendicular to the first arm. When viewed from above, the two arms form an L shape. Laser light enters the arms through a beam splitter located at the corner of the L, dividing the light between the arms. The light is allowed to bounce back and forth between the mirrors many times before it returns to the beam splitter. If the two arms have identical lengths, then interference between the light beams returning to the beam splitter will direct all of the light back toward the laser. But if there is any difference between the lengths of the two arms, some light will travel to where it can be recorded by a photodetector.

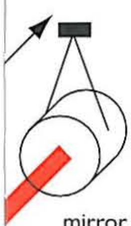
The space-time ripples cause the distance measured by a light beam to change as the gravitational wave passes by, causing the amount of light falling on the photodetector to vary. The photodetector then produces a signal telling how the light falling on it changes over time. The laser interferometer is like a microphone that converts gravitational waves into electrical signals. Two interferometers of this kind will be built for LIGO—one near Richland, Washington, and the other near Baton Rouge, Louisiana. LIGO must have two widely separated detectors, operated in unison, in order to rule out false signals and confirm that a gravitational wave has passed through Earth.

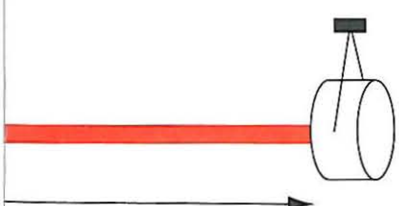


PUSHING THE LIMITS OF TECHNOLOGY

LIGO must measure the movements of its mirrors (which are separated by two and a half miles) with phenomenal precision. To achieve its goal, LIGO must detect movements as small as one thousandth the diameter of a proton, which is the nucleus of a hydrogen atom. Achieving this sensitivity requires a remarkable combination of technological innovations in vacuum technology, precision lasers, and advanced optical and mechanical systems.

LIGO's interferometers are the world's largest precision optical instruments. As such, they will be housed in one of the world's largest vacuum systems, with a volume of nearly 300,000 cubic feet. The beam tubes and associated chambers must be evacuated to a pressure of only one-trillionth of an atmosphere, so that the laser beams can travel in a clear path, with a minimum of scattering due to stray gases. To do this, LIGO scientists and engineers have worked with industry to produce steel with a very low dissolved hydrogen content.





The LIGO laser light will come from high-power, solid-state lasers that must be so well regulated that, over one-hundredth of a second, the frequency will vary by less than a few millionths of a cycle. This severe requirement will make the LIGO detectors among the most precise test beds available for laser stabilization and will attract significant laser development activity worldwide.

The suspended mirrors must be so well shielded from vibration that the random motion of the atoms within the mirrors and suspension fibers can be detected. The high-precision, vibration-isolation systems needed to achieve this are very closely related to equipment used for the masking and etching of circuitry on silicon in semiconductor manufacturing.

More than 30 different control systems are required to hold all the lasers and mirrors in proper alignment and position, to within a tiny fraction of a wavelength over the four-kilometer lengths of both arms of the interferometers. These control systems must be monitored continuously and able to function without human intervention. Sophisticated simulation software and state-of-the-art electronics designs are being developed to perform these tasks.

Imagine watching a concert on television with the volume turned down. The rousing musical score can only be imagined. Could we, in fact, even imagine the music if we had never heard music before? Throughout human history, we have viewed the heavens in a similar way. First with our unaided eyes, then with telescopes, we viewed the visible light from heavenly objects to learn their secrets. Eventually, we learned to view a broader variety of radiation, such as infrared light, x rays, gamma rays, and radio waves, which are invisible to our eyes but are detectable by electronic devices. But all these different kinds of radiation, including light, are made up purely of electricity and magnetism.

Today we know that only about 10 percent of all the matter in the universe can be observed in this way. How else might we gain insight into the majority of matter in the universe? We now have the technology to use a very different force, the force of gravity, to explore the heavens. LIGO (for Laser Interferometer Gravitational-wave Observatory) is an instrument for sensing the presence of matter, whether shining or dark, in the distant reaches of the cosmos. LIGO does this by detecting the gravitational waves—ripples in the force of gravity—created by violent events such as the collisions of stars and the vibrations of black holes.

Imagine now turning up the volume on that televised concert performance and hearing the stirring sounds of a symphony. What a difference it makes to experience music with this new sense! What new experiences await us when we begin exploring the heavens with LIGO?

40-meter laser interferometer at Caltech campus, used to test technologies for LIGO detectors

LIGO: AN OBSERVATORY FOR THE 21ST CENTURY

LIGO should start the new millennium by directly detecting gravitational waves for the first time, perhaps recording the final death spiral of two orbiting neutron stars just before they collide and merge into one. Physicists have predicted that such an event will produce a burst of gravitational waves with a characteristic pattern, its own fingerprint, that LIGO should be able to detect and measure, initially out to distances of 70 million light-years. As has happened so often, when we enter a new domain of measurement, totally unexpected discoveries could surprise us. Improved detectors will look deeper into the universe and detect more exotic events.

Science like this is the epitome of basic research. As always with basic work, no one knows where it will lead or what its consequences and ramifications will be. For example, 19th-century scientists classified the spectral lines found in sunlight because it was interesting, having no idea that a century later their work would lead to the understanding of atomic structure and the development of quantum mechanics. In turn, the inventors of the laser built upon the foundation of quantum mechanics, never imagining that their invention would be used for delicate eye-saving surgery, in supermarket checkout counters, for printing daily newspapers, or as a light source for LIGO.

Will the discoveries made by LIGO have such an impact? We hope so, but we need to do the experiments first!

PARTICIPATION IN LIGO

LIGO is a scientific collaboration of the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). Funded by the National Science Foundation, LIGO will function as a national resource for both physics and astrophysics. There will be significant involvement with other universities and institutions besides Caltech and MIT, both within the United States and abroad.

Recently the LIGO Research Community (LRC) has been organized to foster such participation. It offers a mechanism for two-way communication about design decisions today and about science program decisions in the future.

LIGO will strongly support science education and other educational activities in the states and communities where the observatories are located. The resident staff at the Washington State and Louisiana observatories, as well as the steady stream of top scientists visiting from all over the globe, will contribute to the intellectual and cultural life of the local communities.

LIGO Home Page on the Web:
http://www.ligo.caltech.edu/

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