

# The Laser Interferometer Gravitational-wave Observatory (LIGO)

**S**ample a large enough volume of the universe and exotic astrophysical events occur on a regular basis. Somewhere within a billion light-years of Earth: Several times per hour the core of a star reaches the end of its life, collapsing catastrophically to produce a neutron star and a spectacular supernova; about twice per month two ultra-dense neutron stars in close orbit touch and merge into one; less frequently, perhaps, black holes collide and merge. These phenomena release huge amounts of energy, but they are unobservable with conventional telescopes—either because, as in the case of the stellar core collapse, the light is obscured by matter that hides the collapse from direct view, or because the energy released is not in the form of light or any other electromagnetic radiation. There is another type of radiation associated with these sources—

**Snapshot: The Laser Interferometer Gravitational-wave Observatory (LIGO) project, scheduled for initial operation in 2000, aims to detect and study gravitational waves from astrophysical sources by precision interferometry between suspended test bodies over four-kilometer baselines. The required sensitivity, better than  $10^{-18}$ /m, places extreme demands on the performance of the optical systems, especially mirrors and lasers.**

gravitational waves—that travels at the same speed as light but is profoundly different from light in its nature and in the type of information that it carries.

Shortly after putting forth his theory of general relativity, Einstein realized that it gave rise to the exotic new phenomenon of gravitational waves. Static gravitational fields generate gravitational waves when the underlying sources (the masses that produce the gravitational fields) accelerate. This is analogous to the way electromagnetic waves are generated when the sources of electrostatic fields (charges) accelerate. A gravitational wave is a propagating distortion of space time, and its observable effect is to induce a mechanical strain in all matter in its path. When the wave impinges on two free masses, it changes their separation by an amount,  $Dx$ , that is proportional to the strength of the

wave, denoted  $h$ , and to the initial separation between the masses,  $L$ :  $Dx = hL$ .

Increasingly sensitive gravitational wave detectors have been built over the past 30 years. They have failed to detect anything because, although the waves can carry large amounts of energy, their effect on matter is extremely weak. The magnitude of  $h$  depends on the type of source and its distance, but in general the strongest astrophysical signals are expected to have a strength  $h \approx 10^{-21}$ . Such waves will affect masses separated by several kilometers (the largest practicable separation for Earth-based detectors) by a distressingly small amount:  $\Delta x$  of only  $3 \times 10^{-18}$  m or less. The effect lasts only a few milliseconds as the wave passes through the detector.

The Laser Interferometer Gravitational-Wave Observatory (LIGO)<sup>1</sup> aims to advance the science of gravitational wave detection by achieving a sensitivity at least 100 times better than the best current detectors.

LIGO will consist of L-shaped interferometers with 4-km long arms, one interferometer in South-Central Washington State near the city of Richland, the other in a forest near Baton Rouge, Louisiana. These two sites will operate in "coincidence mode" to help reject signals of terrestrial origin: Only gravitational waves are expected to register simultaneously in interferometers that are so far apart. The interferometer beams at each site are contained within 1.2-m diameter vacuum pipes running the full length of the arms, making one of the largest vacuum systems in the world. The total cost for construction of LIGO is about \$300 million.<sup>2</sup>

LIGO can trace its roots back to Rai Weiss's pioneering description of a laser interferometer gravitational wave detector at MIT in 1972.<sup>3</sup> A few years later, a second U.S. effort headed by Ron Drever was established at Caltech. In 1987 under the leadership of Robbie Vogt these two groups began to develop a conceptual design for LIGO, leading to funding of construction in 1992. Today, between the two institutions this effort involves over 65 scientists, students, engineers, and other professionals led by Principal Investigator Barry Barish. Construction began at the Washington site in 1994 and both facilities are expected to be completed by 1998. The first interferometer will then be installed and initial observations should begin by 2000.

### Gravitational wave sources

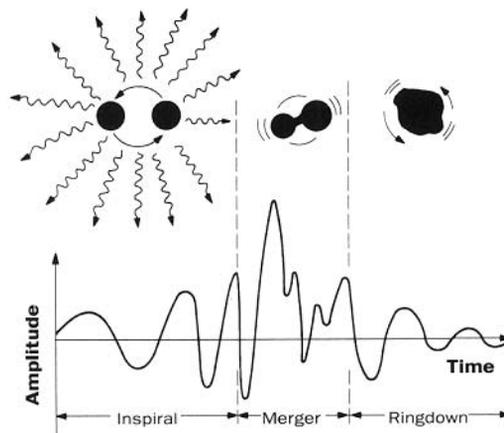
The challenge of detecting these waves would no doubt be enough to drive us to search for them, but there is a

more compelling reason: Gravitational waves carry distinctive information about their sources. If we can detect waves and measure their properties, then we open a new window in astrophysics. As a bonus, the predicted strong sources of gravitational waves include some of the most mysterious and difficult-to-study objects in the universe: Black holes, neutron stars, supernova cores, and possibly the Big Bang.<sup>4</sup>

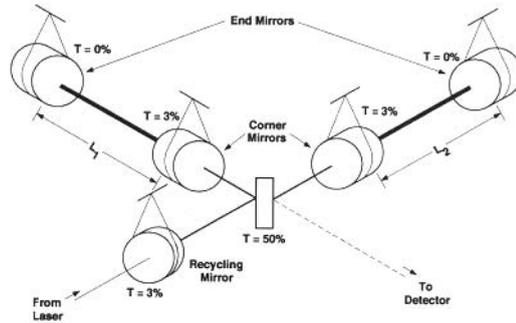
Neutron star binaries, systems that consist of two neutron stars orbiting each other, play an important role in LIGO for two reasons. The discovery of such a system ("the binary pulsar") by Hulse and Taylor started a 15-year quest for radio astronomy measurements that gave the first convincing evidence for the existence of gravitational waves. One of the two neutron stars in this system is a radio pulsar, which emits radio pulses every 59 milliseconds with a precision that rivals the best Earth-based clocks. By observing the variation of the pulse spacing as the stars orbit each other, Taylor and his collaborators<sup>5</sup> were able to detect a slight change in the orbital period, a change that agrees to better than 1% with what is calculated for the orbital energy carried away by the gravitational waves.

Neutron star binaries also serve as the primary benchmark for setting the sensitivity goals of LIGO. The gravitational waves emitted by Taylor's binary pulsar have a four-hour period—too long to be detected in the face of terrestrial disturbances. However, over the next 300 million years this system will slowly spiral together, until the two stars are only a hundred kilometers apart and the frequency of the waves—equal to twice the orbital frequency—increases to the 10-1000 Hz range. The final spiraling together will then be very rapid, 3 minutes or less, giving a very distinctive chirping gravitational wave signal (see Fig. 1). LIGO is designed to detect this final burst of gravitational waves from similar systems in other galaxies. Neutron star binaries are the only source for which physicists can calculate accurate wave strength and astronomers can make accurate predictions of the number of such systems in nearby galaxies. The best prediction is that there should be three coalescences per year within 600 million light years of Earth, with an  $h$  of about  $3 \times 10^{-22}$ .

Other sources for gravitational waves are very uncertain. Black hole binary systems (if they exist) would give even stronger signals than neutron star binary systems, and the collapse to form a black hole would give strong gravitational waves if the hole is not spherically symmetric, but our knowledge of the rate and the mecha-



**Figure 1:** Schematic depiction of the gravitational waves from the coalescence of two neutron stars. The in-spiral phase has a distinctive chirp signal, with increasing frequency and amplitude, up to the point where the two stars touch. The parameters of this chirp give important information about the masses and other properties of the stars. The merger waveform contains information about the properties of matter at nuclear densities. A binary black hole system would give a similar waveform, but with features that characterize the black holes.



**Figure 2:** The main optical components of a typical interferometric gravitational wave detector. The corner mirrors have energy transmission of 3%, and the end mirrors are coated for maximum reflectivity (close to zero transmission). In LIGO, the average length of the arms  $L_1$  and  $L_2$  is 4 km; a medium-strength gravitational wave may change  $L_1 - L_2$  by  $3 \times 10^{-18}$  m. The reflectivities of the mirrors are selected, and their positions controlled, to maximize the sensitivity. The  $T = 50\%$  beamsplitter divides the light equally between the arms, where it builds up in a resonant cavity. A weak beam escapes from the beamsplitter toward the detector, where the beam intensity is measured to determine  $L_1 - L_2$ . Light that would ordinarily return in the direction of the laser is intercepted by the recycling mirror and sent back into the interferometer, causing a power buildup at the beamsplitter of a factor of approximately 30.

nisms for making black holes is almost nonexistent. The collapse of a stellar core that results in a supernova explosion and the formation of a neutron star could give strong gravitational waves or almost none at all, depending on the amount of asymmetry. Small bumps on the surface of a rapidly rotating neutron star could give continuous sinusoidal gravitational waves, but no one knows whether such bumps occur or not. The mechanisms for generating gravitational waves in the very early universe invoke exotic phenomena such as cosmic strings, whose only proof of existence may rest with detecting the relic gravitational waves from their decay. This is both the most vexing and exciting aspect of LIGO—vexing because we can't predict how sensitive our detectors must be to see the waves and exciting because of the potential for great surprises.

### LIGO interferometers

LIGO is designed to detect the tiny force of gravitational waves by measuring the relative positions of free masses, using the venerable technique of optical interferometry (see Fig. 2). The masses are the mirrors of an interferometer, shown in the figure as a modified Michelson interferometer. Hanging by wires like the bob of a 1-second pendulum, each cylindrical mass is free to respond to the fast push exerted by the waves. The wave has two transverse

axes; when these axes are aligned with the arms of the interferometer, one arm shrinks and the other expands. This is just the kind of change to which the interferometer is sensitive. The catch is that typical interferometers do not detect motions much smaller than about 1/10th of the wavelength of light; to detect gravitational waves

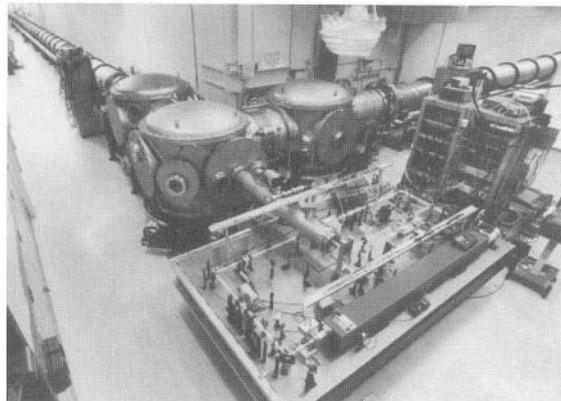
probably requires 11 orders of magnitude better sensitivity.

LIGO relies on two modifications to the simple Michelson interferometer to bridge the sensitivity gap: High-power, extremely high-quality laser beams are used to "split the fringe," effectively using almost all the photons emitted by the laser. Further improvement is achieved by exploiting the highest-quality available mirrors in more sophisticated interferometer configurations.

The interferometer shown in Figure 2 is different from an ordinary Michelson interferometer in that each arm is a resonant cavity.<sup>6</sup> The two mirrors at the corner of the L have transmission of 3%; during operation, the 4-km distance to the mirrors at the ends (which have reflectivity very close to 100%) is controlled to keep the arms in resonance, resulting in a power

buildup of  $B = 30$ . The resonance results in a sensitivity increase of a factor of  $B$ , the same as if the beams were to traverse the arms by  $B$  discrete bounces. The mirror between the laser and the 50%-transmitting beamsplitter, also of approximately 3% transmission, increases the effective power incident on the beamsplitter. The use of this "recycling" mirror is equivalent to increasing the laser power from a nominal 2 W incident on the beamsplitter to approximately 60 W. With these enhancements, the displacement

sensitivity is approximately  $x = \lambda / (2\pi B N^{1/2})$  where  $\lambda$  is the laser wavelength ( $0.5 \mu\text{m}$ ) and  $N$  is the number of photons used during the measurement of the gravitational wave signal. For signals lasting a few milliseconds,  $N$  is large enough (greater than  $10^{18}$ ) for a measurement precision approaching  $x = 10^{-18}\text{m}$ .



**Figure 3:** Photograph of a prototype interferometer with 40-m long arms at Caltech. This device is used to develop and demonstrate the techniques needed for the full-size LIGO interferometers.

Achieving this sensitivity in practice is not easy. Disturbances that might cause noise in the interferometry, or that directly perturb the positions of the masses, must be strongly attenuated. We start by enclosing the interferometer in a vacuum system, effectively eliminating noise from air molecules crossing the laser beams or bumping against the masses. The effect of ground vibrations is reduced by a seismic isolation structure consisting of layers of metal separated by springs, and finally by the pendulum suspension of the mirrors. The random fluctuations in the positions of the atoms making up the masses can produce a significant noise background. This "internal thermal noise" is reduced by concentrating almost all of the vibrational energy in a bell-like resonance that has a frequency higher than the expected signals (about 10 kHz). By using special materials (such as the highest-quality fused silica) and construction methods, this resonance is kept so pure that if it were struck, the mirror would "ring" at its resonant frequency for about one hour!

These techniques have been developed on relatively small-scale gravity wave detectors, such as the LIGO 40-m interferometer<sup>7</sup> (see Fig. 3). It uses radio-frequency phase modulation and electro-mechanical servo systems to control the frequency of the laser light and the positions of the mirrors, about a dozen auxiliary lasers to monitor their angular orientation, and specialized sensors and actuators to damp their swinging and rocking in the wire slings. All of these systems must work to control the absolute positions of the masses with a precision of better than  $10^{-11}$  m for the interferometer to operate. The sensitivity performance of the 40-m detector ( $h \approx 2 \times 10^{-19}$ ) is close to the expected limits imposed by the interferometry, seismic noise, and thermal noise. This achievement of theoretically predicted performance gives us confidence that the sensitivity will scale up with the size when the LIGO detectors become operational.

### Challenging the limits of optical technology

LIGO has benefitted from numerous optical developments, but perhaps none are more important than the development of low-loss polishing and coating techniques, originally developed for ring laser gyroscopes, but soon recognized to be critical to LIGO. During the two decades elapsed since laser interferometer gravitational wave detectors were first suggested, scattering and absorption losses in the best laser optical components have dropped from near 1% to an amazing few parts per million.<sup>8</sup> With such low losses, it is possible to contemplate an interferometer in which the light is

reflected  $10^4$  or even  $10^5$  times from a single mirror. Combined with LIGO's long arms, this translates into storage times for the light on the order of 1 second!

To take advantage of this phenomenal advance in technology, LIGO must combine it with other state-of-the-art optical fabrication techniques. Ultra-low-loss coating and polishing technologies have been developed for small-scale components, typically 2.5 cm or less in diameter. The LIGO mirrors will be 25 cm in diameter, sized to reduce diffraction from the 4-8 cm diameter laser beams (see Fig. 4). Maintaining low-loss performance on this size mirror requires combining 100  $\mu\text{m}$ -scale uniformity on the order of 1  $\text{\AA}$  with accurate optical figure on scales up to a few centimeters. The optical figure required for the initial interferometers depends on spatial scale: Over the central region the requirement is an rms value of 8  $\text{\AA}$ , and anticipated improvements to these detectors will need a factor of three better than this value. Polishing, coating, and even metrology of this precision are at the limits of current capabilities.

The laser wavelength is the yardstick with which LIGO makes its precision measurements, so it is no surprise that LIGO also makes strenuous demands on the laser that illuminates the interferometer. Although a goal in the design of the interferometer optics is to make the optics insensitive to changes in the laser frequency and intensity, laser frequency and intensity noise can still enter through small asymmetries. Servo systems are required to reduce the natural noise to a level that does not compromise the sensitivity of the interferometer. For frequency noise this

requires a reduction of more than  $10^8$ , for intensity noise a more modest factor of  $10^3$ .

Initially, LIGO is planning to use high power argon ion lasers operating at 514 nm with single frequency output power of approximately 5 W. Most of our development work has been carried out with these lasers, and the current laboratory versions have the required performance, though the final demonstration can only be made once they are installed in the full-scale interferometers. Looking beyond the first interferometers, the future belongs to solid-state lasers. Higher output powers, 100 W or more, will be needed to improve the sensitivity of LIGO for gravitational waves with frequencies greater than 200 Hz. Several groups around the world (most notably those at Stanford, at Laser Zentrum Hannover, at Australian National University, and at the University of Electro-Communications, Tokyo) are developing diode pumped, solid-state lasers suitable for improved gravitational wave detectors. Recent devices have demonstrated up to 40 W from cw



**Figure 4:** A comparison of a full scale LIGO mirror (right) with one of the 40-m interferometer mirrors (left). A program is underway with industry to develop and test the technology for polishing and coating to the demanding LIGO requirements.

Nd:YAG lasers,<sup>9,10</sup> though there is still much to be done to integrate these lasers with the required servo control systems.

One of the exciting directions for LIGO evolution is to use lasers and interferometers that alter the nature of light itself. All light, including that from lasers, has noise in both intensity and phase. These two types of noise obey an inequality similar to the Heisenberg uncertainty relationship. Most sources of light have equal amounts of these two types of noise (expressed in the appropriate units), but it is possible to prepare light with a reduced amount of one type and an increased amount of the other, so-called "squeezed light." If your interferometer is designed to respond to the type of variation that is reduced and to be insensitive to the type of noise that is increased, it is possible to achieve a significant improvement in sensitivity.<sup>11</sup> Considerable ingenuity to generate squeezed light must be combined with extreme care in the way it is used before it can give practical benefits, but a substantial number of researchers are pushing new ideas forward, driven in part by the potential application to future gravitational wave detectors.

### Toward an international network

The excitement of detecting gravitational waves has spawned similar projects around the world. The VIRGO project,<sup>12</sup> an Italian-French collaboration, is beginning to build a 3-km detector near Pisa which should be operational about the same time as LIGO. The GEO600<sup>13</sup> project, a German-British effort, has started on a 600-m detector near Hannover. In Japan, scientists are building a 300-m detector in the outskirts of Tokyo, while dreaming of a future 3-km detector. A consortium of universities and companies in Australia was recently funded to develop technology that would permit that country to build a large detector in a few years.

Working together, these far-flung detectors can function as a powerful international observatory for gravitational waves, and this recognition has fostered a growing sense of collaboration. Correlation and sharing of data is essential. The need to confirm the tiny effects of gravitational waves by observations at widely separated locations to eliminate spurious local disturbances is obvious. Further, the same penetrating ability of gravitational waves that makes them good probes of dense matter allows them to pass through the earth with essentially no attenuation, making an individual detector sensitive to waves from nearly all directions. Determining the location of a source of gravitational waves relies on timing the arrival of the wave at different detectors. The time differences are small, up to 50 msec for detectors on opposite sides of the earth, but readily measurable. A world-wide network would have an angular resolution on the order of 1°, clearly no match for what is obtained in modern astronomy, but reminiscent of the resolution of early radio telescopes.

What we will see when LIGO and the other projects go into operation is anyone's guess. LIGO's initial sensi-

tivity will open for study a million times larger volume of the universe than is accessible with current gravitational wave detectors and may lead to the first detection. This step builds on improvements in laser and optical technology that were unforeseen 20 years ago. The long-term success of LIGO requires that the pace continues well into the next century.

### Acknowledgment

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### Glossary

**Gravitational waves:** A perturbation in the fabric of spacetime that travels at the speed of light, predicted by the general theory of relativity, but as yet unobserved; generated by accelerating astrophysical objects such as neutron stars, gravitational waves are expected to be detectable by the small forces they exert on test bodies on earth.

**Neutron star:** The ultra-dense remnant of a star that has burned out in a supernova explosion, made entirely of neutrons packed together by gravity so closely that the star has the same density as an atomic nucleus: the entire mass of a star like the sun is shrunk to a sphere only a few kilometers in diameter.

**Neutron star binary coalescence:** The final stage of evolution of a system of two co-orbiting neutron stars, in which they collide and merge into a single object.