LIGO AND THE DETECTION OF GRAVITATIONAL WAVES

Large detectors on opposite sides of the country are about to start monitoring the cosmos for the gravitational waves that general relativity tells us should be emanating from catastrophic astrophysical events.

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The idea of gravitational waves was already implicit in the 1905 special theory of relativity, with its finite limiting speed for information transfer. The explicit formulation for gravitational waves in general relativity was put forward by Einstein[1,2] in 1916 and 1918. He showed that the acceleration of masses generates time-dependent gravitational fields that propagate away from their sources at the speed of light as warpages of spacetime. Such a propagating warpage is called a gravitational wave.

The best empirical evidence we have of the existence of gravitational radiation is indirect. It comes from the 1974 discovery and beautiful observations, by Russell Hulse and Joseph Taylor,[3] of the first binary pulsar ever found. (See PHYSICS TODAY, December 1993, page 17.) Exploiting the clockwork pulsar signal from the neutron star, they were able to monitor the orbital period of the binary star system with exquisite precision and confirm that it was indeed gradually speeding up at just the rate predicted for the general-relativistic emission of gravitational waves.

The *direct* detection of gravitational waves will mark the opening of a new window on the near and far reaches of the cosmos. For physics, its most important promise is the direct observation of gravitation in highly relativistic settings, so that one can test general relativity in the strong-field limit, where it is not merely a small correction to Newtonian gravity. (See the companion article in this issue by Clifford Will, on page 38.) In that limit, the strong curvature of the spacetime geometry should show us fundamentally new physics.

By the time they reach us, the gravitational waves are, of course, only very weak perturbations on our local flat space. But they will provide information about the strong-field regions where they began. The detection of the waves will also allow us to determine the wave properties of the gravitational radiation—for example, their propagation velocity and polarization states.

For the astrophysicist, the observation of gravitational waves will provide a new and very different view of the universe. These waves arise from motions of large aggregates of matter, rather than from the particulate sources that produce electromagnetic waves. Because gravitational waves are not scattered as they propagate between source and observer, they should provide information about what's happening in the innermost and densest regions of the astrophysical source. Probing the universe in this very different way, gravitational radiation is likely to bring us exciting surprises and unanticipated new astrophysics.

A new generation of detectors based on suspended mass interferometry promises to attain the requisite sensitivity for observing gravitational waves. (See figure 1.) These new detectors are the fruit of a quarter-century of worldwide technology development, design, and construction. The US effort, called LIGO (Laser Interferometer Gravitational-Wave Observatory), is a joint Caltech–MIT project, supported by the National Science Foundation. LIGO is a pair of L-shaped laser interferometers: one in Hanford, Washington, the other, some 3000 km away, in Livingston, Louisiana. (See figure 2.) Each evacuated interferometer arm is 4 km long.

The LIGO facilities at both sites have now been completed, and detector installation is under way. Following a two-year commissioning program, we expect the first sensitive searches for astrophysical gravitational waves to begin in 2002. This initial search, sensitive to changes (strains) as small as a part in 10^{21} in the lengths of the interferometer arms, will be the first attempt to detect gravitational waves at a sensitivity that reaches plausible estimates for astrophysical source strengths. It will mark a 100- to 1000-fold improvement over previous searches—both in sensitivity and bandwidth.

The two LIGO interferometers will operate in coincidence, so as to filter out local noise. In fact, to provide additional coincidence surety, a third independent interferometer, half as long as the other two, will share the vacuum system of the full-size interferometer at Hanford. Also, one determines the direction and polarization of a gravitational wave by measuring arrival-time differences between geographically dispersed detectors. At the Hanford and Livingston support facilities, efforts will continue on the development of improved and special-purpose detectors of increased search and follow-up sensitivity.

Gravitational radiation

The gravitational wave plays a role in gravitation similar to that of the electromagnetic wave in electricity and magnetism. But because mass, unlike charge, comes in only one sign and the momentum of a free system must be conserved, the lowest-order source of gravitational radiation is quadrupolar.

The radiation field causes a strain in space itself, transverse to the propagation direction. The strain pattern contracts space along one transverse dimension while expanding it along the orthogonal direction in the transverse plane. One way of imagining this distortion of space

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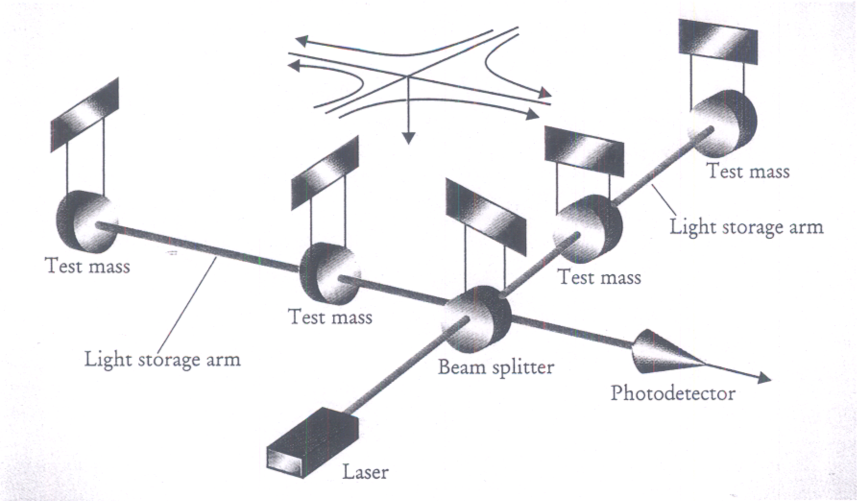

FIGURE 1. THE LIGO GRAVITATIONAL-WAVE DETECTORS are equal-arm Michelson laser interferometers whose hanging mirrors serve as the gravitational test masses. An incident gravitational wave, indicated in red by the stress pattern coming down from above, stretches one interferometer arm and compresses the other, causing a difference between light travel times in the two orthogonal arms. This time difference is manifested in the interference pattern when the two laser beams recombine on the way to the photodetector, which can measure phase shifts to a few ten-billionths of an interference fringe.

is to look at the weave in a piece of cloth when it's pulled along one dimension. The little squares of the weave distort in just this way. Furthermore the strain is quite uniform, so that the relative motion of points in the cloth depends linearly on their separation.

It is this linear increase in the relative motion that provides the motivation for LIGO's 4 km interferometer arms. Such ambitious length is intended to provide adequate sensitivity to passing gravitational waves in the face of inevitable local perturbations. The tensor character of gravity (the putative graviton is a spin-2 particle) means that the push/pull pattern of the strain field for a plane gravitational wave has two orthogonal polarizations. If a candidate signal really is a gravitational wave, and not just noise, the half-length auxiliary interferometer at the Hanford site should see a coincident displacement half as large as that experienced by its full-length neighbor.

One can also think of the gravitational wave as producing a tidal force field such that the relative force between masses grows as their separation. The field will pull masses together along one transverse direction while pushing them apart along the orthogonal direction. How one chooses to view the wave–matter interaction is really a matter of taste. But one must be careful to maintain consistency in one's view and not mix the geometric and tidal representations.

The strength of the gravitational field is expressed by the dimensionless strain

$$h \approx \left(\frac{GM}{Rc^2}\right)\left(\frac{v^2}{c^2}\right)$$

where the factor in the first pair of brackets is the Newtonian potential due to a source mass M at a distance R, divided by the square of the speed of light. On the surface of the Earth, that comes to 10^{-8}, a very weak field. But, at the surface of a neutron star, it can be as large as 10^{-1}. And at the horizon of a black hole, it is close to unity—the ultrarelativistic limit of a strong gravitational field. The factor in the second bracket pair—an estimate of the system's kinetic energy in asymmetric motion relative to its rest energy—is a measure of the strength of the relativistic dynamics.

This expression gives us an immediate estimate of the scale of the strains we might encounter. Consider, for example, a solar-mass source at a Galactic distance, moving at about 10% of the speed of light. In such a case, the strain we would observe halfway across the Galaxy would not exceed a part in 10^{18}. This simple estimate explains why we have to take such heroic measures to detect the strains. Even over the 4 km span of a LIGO arm, the relative displacement of two objects would be only a few times 10^{-13} cm, just about the size of an atomic nucleus! It's even worse than that. As discussed below, plausible sources typically lead to strains of only 10^{-21}, corresponding to LIGO displacements a thousand times smaller than the width of a nucleus.

Candidate sources

There is a large range of processes in the universe that should produce detectible gravitational waves.[4] Terrestrial interferometers like LIGO will search in the frequency range from 10 Hz to 10 kHz for characteristic signals from a variety of astrophysical sources for which one might hope to discern the signatures of gravitational radiation over the background noise. (See figure 3.)

▷ **Chirp signals.** The terminal spiraling of a star into a "compact" binary partner (a neutron star or a black hole) will produce radiation that increases in amplitude and frequency as the two move toward final coalescence. This chirp signal can be well characterized, depending on parameters such as the mass, separation, and orbital eccentricity. That makes it possible to formulate efficient detection templates.

▷ **Burst signals.** The collapse of a supernova may produce gravitational radiation. Type II supernova collapses can generate strong gravitational radiation, *if* the core collapse departs sufficiently from axial symmetry. Estimates suggest that detection might be possible for such collapses as far out as the Virgo Cluster of galaxies, some 50 million

Initial parameters for the LIGO detectors

Arm length	4000 m
Arm cavity storage time	880 μs
Laser type and wavelength	Nd:YAG, $\lambda = 1064$ nm
Input power at recycling cavity	6 W
Power recycling gain	30
Mirror mass	10.7 kg
Mirror diameter	25 cm
Mirror loss	$< 1\times10^{-4}$
Mirror internal Q	1×10^{6}
Cavity input mirror transmission	3×10^{-2}
Pendulum Q (structure damping)	1×10^{5}
Pendulum period (single)	1 s
Seismic isolation system	–110 dB at 100 Hz

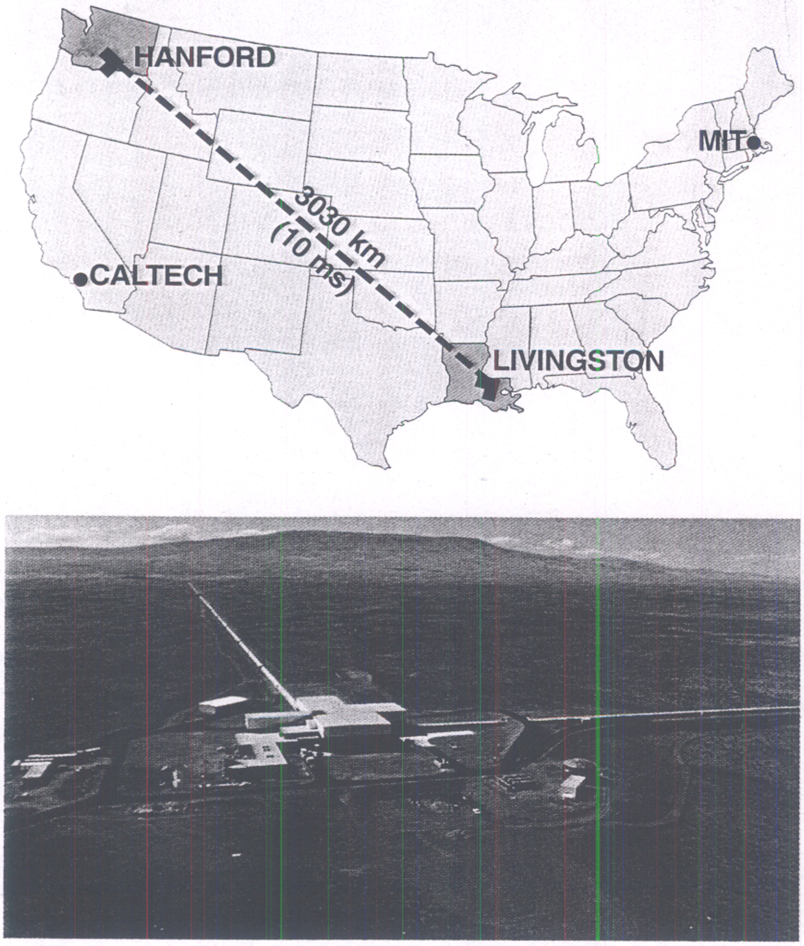

FIGURE 2. THE TWO LIGO SITES, 3030 km apart, in Hanford, Washington and Livingston, Louisiana, will work in coincidence. The recent photo of the Hanford site shows the two orthogonal 4 km vacuum pipes going off into the distance. The vacuum system also houses a smaller auxiliary interferometer, with 2 km arms to help distinguish true gravitational wave signals from noise.

light-years away. That would yield type II supernova observation rates of one or more per year. Another possible burst source accessible to LIGO is the brief, burplike oscillation of a black hole's event horizon just after it swallows a star. The detection of supernova or postprandial black hole events will require coincident observation of burst signals in several geographically dispersed interferometers.

▷ **Periodic signals.** Radiation from the nonaxisymmetric motion of a neutron star, or of the nuclear fluid on its surface might produce periodic signals in the detectors. Happily, for many known pulsars the frequency of such periodic signals lies within LIGO's sensitivity band. The searches for periodic gravitational signals from identified neutron stars will be facilitated by the fact that one can track the system continually over very many cycles, taking account of the gradual slowing of the pulsar's spin and the Doppler shifts and amplitude variation due to the Earth's diurnal and annual motions. We expect to perform general sky searches as well as targeted searches of known pulsars.

▷ **Stochastic signals.** Signals from gravitational waves emitted in the first instants of the early universe—as far back as the Planck epoch at 10^{-43} seconds—can be detected by way of correlations of background signals from two or more detectors. Some models of the early universe predict detectable signals. Such relic gravitational radiation would provide us with an exciting new cosmological probe.

The initial parameters for the LIGO interferometers have been chosen to provide a sensitivity with a reasonable chance for detecting gravitational waves. (See the table on page 45.) The anticipated rates for the various sources, however, are burdened with large uncertainties. As future advances in detector sensitivity increase the distance over which one can find sources, the rate at which events are observed will grow *as the cube* of LIGO's reach. That lends particularly high priority to a vigorous effort to improve the system's sensitivity.

Basic idea of the interferometer

A Michelson interferometer operating between freely suspended masses is ideally suited to detect the antisymmetric compression and distension of space induced by gravitational waves.[5] Figure 1 is a schematic drawing of the LIGO equal-arm Michelson interferometer. The two interferometer arms, each 4 km long in the full-length detectors, have identical light-storage times. Light sent from the laser light source to the beam splitter is divided evenly between the two arms.

Having traversed the arms, the light is reflected back to the splitter by mirrors at their far ends. On the return journeys to the photodetector, the roles of reflection and transmission in the splitter are interchanged for the two beams and, furthermore, the phase of the reflected beam is inverted by 180°. Therefore the recombined beams heading toward the photodetector interfere destructively, while the beams heading back to the laser source interfere constructively. If the interferometer arms are of precisely equal length, the photodetector ideally sees no light, all of it having been diverted, by perfect interference, back to its source.

One would get this kind of perfect interference if the beam geometry provides a single phase over the propagating wavefront. An idealized uniphase plane wave has this property, as does the Gaussian wavefront in the lowest-order spatial mode of a laser. Then, provided the arms are equal in length (or their length difference is a multiple of half the wavelength of the monochromatic beam), the photodetector sees no light at all. The destructive interference over the entire beam wavefront is complete.

If, in the absence of any disturbance, the interferometer is carefully balanced so that no light appears at the photodetector, a sufficiently strong gravitational wave passing though the interferometer can disturb this balance and cause light to fall on the detector. That, in essence, is how LIGO will sense gravitational waves. To obtain the required sensitivity, we have made the arms 4 km long, and we have included two refinements:

▷ First, the intensity change at the photodetector due to a gravitational wave depends on the interaction time of the wave with the light in the arms. The longer this interaction time—up to half the period of the gravitational wave—the larger is the resulting optical phase shift and the consequent change of the light intensity at the photodetector. To gain further interaction time, beyond what one gets simply from the 4 km arm length, the initial

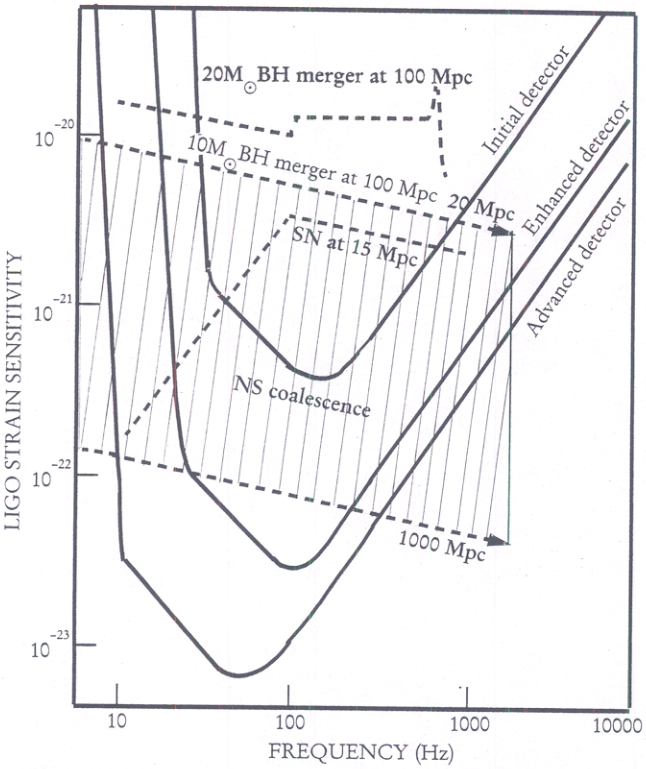

FIGURE 3. RMS STRAIN SENSITIVITY LIMITS as a function of signal frequency, for three LIGO generations indicated by the U-shaped black curves, are compared with signal estimates for various astrophysical sources. The "enhanced" detector is anticipated for 2006, and the "advanced" detector four years later. The shaded red region indicates the strain signal expected from the coalescence of two neutron stars at distances from 20 to 1000 megaparsecs (1 Mpc = 3×10^6 light-years), and from the merger of two 10 $M_\odot$ black holes at least 100 Mpc away. The larger and more structured signal expected from the merger of two 20 $M_\odot$ black holes at 100 Mpc is indicated by the purple dashed curve. The green dashed curve indicates the signal expected from an asymmetric supernova 15 Mpc away. One expects a few events per year within the red parallelogram.

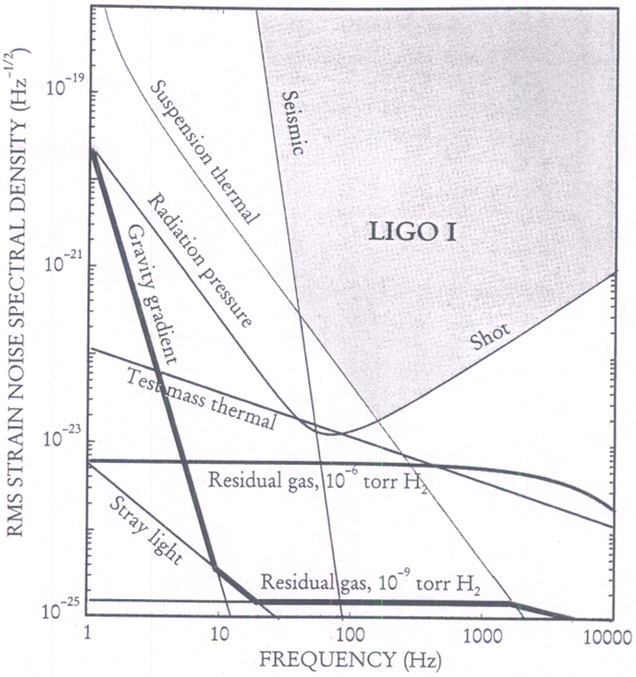

FIGURE 4. LIMITING NOISE SOURCES for the initial LIGO interferometers are shown on a plot of frequency against spectral noise density. The vertical axis denotes the RMS strain noise in 1 Hz of bandwidth. The noise increases as the square root of bandwidth, so that the noise in a typical 100 Hz window would be 10 times that shown on the axis. At the lowest frequencies, sensitivity is limited by geophysical and man-made seismic noise; at intermediate frequencies by thermal noise; and at the highest frequencies by the shot noise of photon statistics. The green line represents the minimum noise at the present LIGO facilities, irrespective of eventual detector upgrades.

LIGO interferometers will also fold the optical beams within the arms by means of optical cavities. This trick results in a light-storage time of about 1 millisecond. That's about 50 times longer than a simple straight transit through a 4 km arm.

▷ A second refinement increases the interfering light intensity by making the entire interferometer a resonant optical storage cavity. Most of the light interferometrically diverted from the photodetector direction—when the arms are unstrained—returns toward the light source. That makes it possible to achieve a significant gain by placing another mirror between the laser and the beam splitter. By properly choosing this extra mirror's position and making its transmission equal to the optical losses inside the interferometer, one can match the losses so that no light at all is reflected back to the laser. This is equivalent to increasing the laser power by about a factor of 30, without adversely affecting the frequency response of the interferometer to a gravitational wave.

Sensitivity limits

The success of the detector will ultimately depend on how well we can control the noise in the measurement of the exceedingly small strains we have been discussing. That has been the prime technological challenge in this field for the past several decades, and it is the central focus of our development of the technology for LIGO. The noise we have to contend with is broadly divided into sensing noise, random force noise and, ultimately, quantum noise. Sensing noise involves the various phenomena that limit our ability to sense and register the small motions in question. Random force noise, on the other hand, results from disturbances that cause small motions of the suspended masses. Eventually one confronts the ultimate quantum noise limit. This orderly classification presumes that one is careful enough in the design and execution of the experiment to reach the fundamental limits. The quantum limit will not be an issue for the first or second generation of LIGO detectors. So we do not address it in this article. There is, however, important ongoing work that seeks to understand the quantum noise limit and develop techniques to circumvent it in measuring the strain.

In order to approach the fundamental limits, we have made extensive use of two concepts in experimental physics promoted by Robert Dicke (1916–97) of Princeton University. The first is the technique of modulating the signal to be detected at frequencies far above the 1/*f* noise due to the drift and gain experienced by all instruments. For example, we measure the optical phase to determine the motion of an interference fringe at radio frequency rather than near DC.

A second concept is to apply feedback to physical vari-

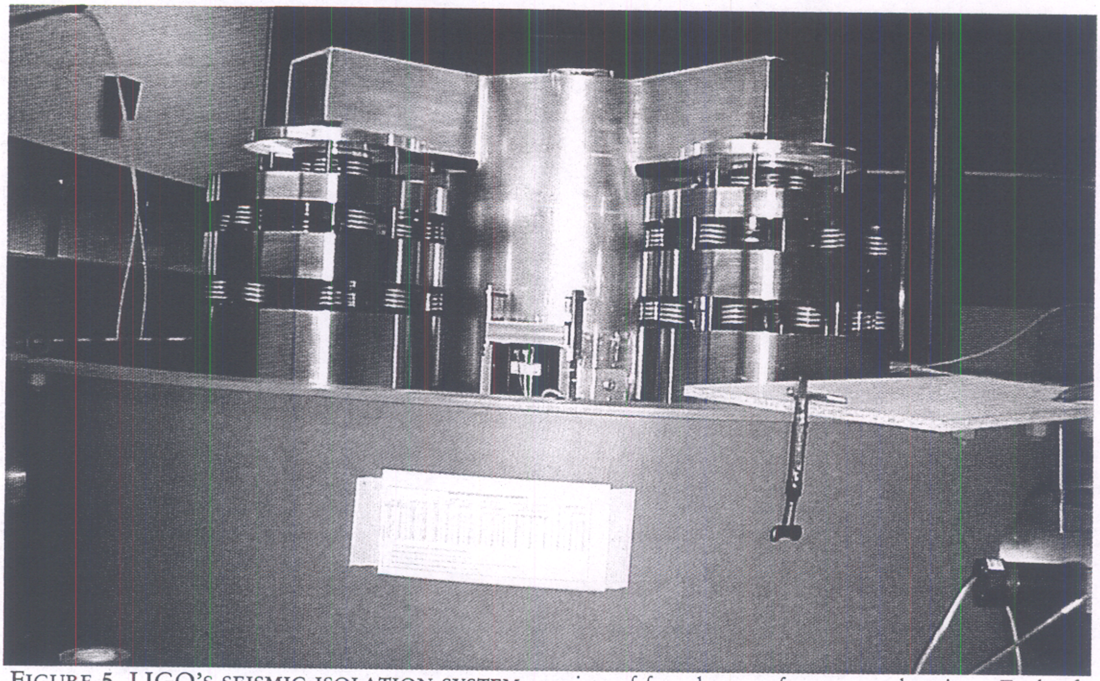

FIGURE 5. **LIGO'S SEISMIC ISOLATION SYSTEM** consists of four layers of masses and springs. Each of the coil springs seen here is made by lining the inside of a straight metal tube with rubbery damping material and then filling the lined tube with a line of metal slugs strung on a rubber core. The tube is then coiled and sealed.

ables in the experiment in order to control and damp large excursions at low frequencies. The variable is measured by way of the control signal required to hold it stationary. A good example is the position of the interferometer mirrors. At low frequencies, we maintain the interferometer fringe at a fixed phase by holding the mirrors at fixed positions with coil/magnet actuators.

Sensing noise

Our ability to determine the relative motions of the mirrors at the ends of the arms interferometrically is limited by the smallest change in optical phase that we can measure. The light emitted by a conventional laser is in a coherent state in which the photon occupation number n obeys a Poisson distribution with variance

$$\Delta n = \sqrt{n} = \sqrt{\dot{n}\tau}$$

where $\dot{n}$ is the rate at which photons encounter the beam splitter and τ is the integration or observation time. Because the phase and photon occupation number are conjugate variables obeying an uncertainty relation, one gets

$$\Delta\phi = 1/\sqrt{\dot{n}\tau}$$

for the variance in the interferometric measurement of the relative phase of the recombining beams at the photodetector. We expect the optical-phase variance in the initial LIGO detector to be about 3×10^{-10} radians, corresponding to a strain variance in a 10-millisecond measurement of about 2×10^{-22}. That would be the fundamental Poisson limit. It is sometimes called the shot-noise limit, because it can also be derived from the statistics of photon counting in the photodetection. This shot noise determines LIGO's sensitivity limit for frequencies above 300 Hz. (See figure 4.)

Before one reaches this limit, however, one has to deal with a host of practical problems, such as laser frequency fluctuations, laser amplitude noise, and stabilization of the beam geometry. We must also reduce additional sensing noise terms that can occur in the beam propagation—for example, scattering by residual gas molecules and scattering off the vacuum tube walls driven by seismic and acoustical noise. We limit these effects by using baffling and low-scatter optics in the evacuated beam tubes. But even if one controls these noise terms and achieves the fundamental Poisson noise limit, one cannot easily reduce the noise any further by simply increasing the laser power to get more photons. That remedy raises problems of optical heating in the mirrors and coatings and, finally, radiation pressure fluctuations.

Random force noise

At lower frequencies, the sensitivity limit is set by how well the motions of our test masses—the hanging mirrors—are controlled. At the lowest frequencies (about 10–100 Hz), the largest disturbances come from "seismic noise"—the motion of the Earth's surface driven by wind, water flow, and human activities, as well as by low-level earthquakes. At intermediate frequencies (100 Hz), the principal culprit is thermal noise—that is, Brownian motion driven by thermal excitations. Less important for the initial LIGO interferometers, but increasingly significant as the detectors are upgraded, will be fluctuations in the Newtonian gravitational forces on the mirrors resulting from density fluctuations in the ground and the atmosphere and, ultimately, the radiation pressure fluctuations.

In general, these random forces are not correlated at the different mirrors, and they are independent of the length of the interferometer arms. By contrast, displacements due to gravitational waves grow linearly with the arm length. That's our principal motivation for going to the expense and trouble of having 4 km arms.

The LIGO suspended mirrors, which serve as the test masses, are isolated from motions of the Earth by cascaded stages of vibration isolation. The first level of isolation, consisting of four stages of springs and masses, reduces the seismic motion a millionfold at frequencies around 100

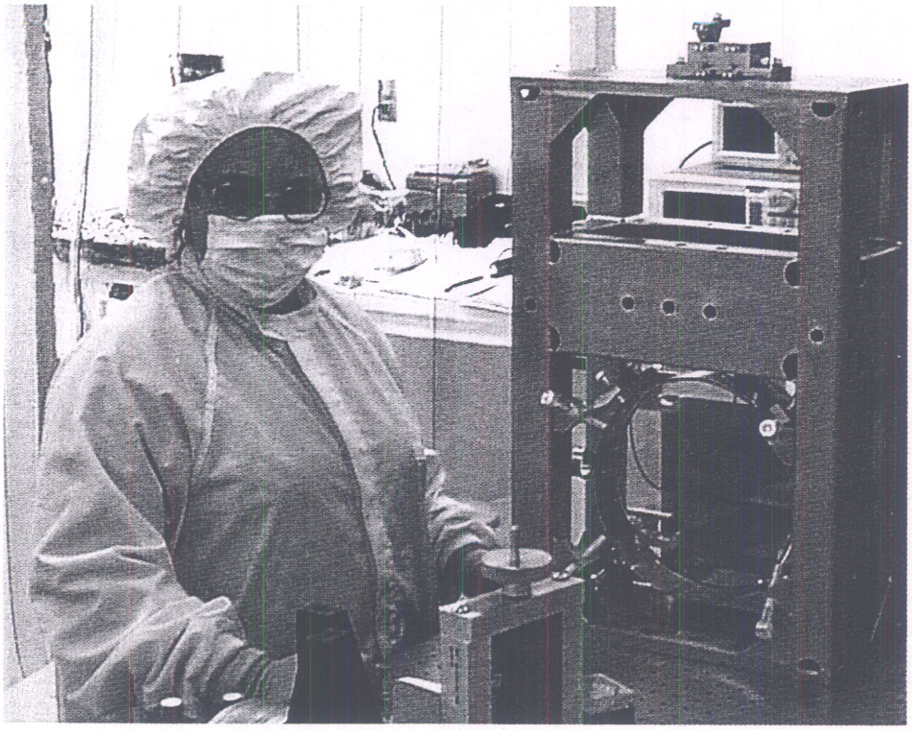

FIGURE 6. A LIGO MIRROR, 25 cm in diameter and 10 cm thick, is made of ultrapure fused silica. Its purple coating is a highly reflective multilayer stack of dielectric materials. Absorption and scattering losses must not exceed a few parts per million.

Hz, and progressively more at higher frequencies. (See figure 5.) This isolation works much like the suspension in a car. The final stage of the isolation system is the hanging mirror itself. Each test mass is, in effect, a pendulum suspended by flexures. The pendulum provides another stage of vibration isolation. But, more important, it also serves to reduce the influence of thermal noise.

Mechanical thermal noise enters the system by exciting the pendulum, causing the test mass to move, and by exciting acoustic waves that disturb the mirror surface. The acoustic noise can be represented as a superposition of the motions induced in the normal modes of the mass. The strength of the perturbation is estimated by taking the overlap of the acoustic-mode shape with the optical wavefront. The equilibrium thermal excitation of each normal mode at temperature T is $kT/2$, yielding significant motion at the principal resonant frequencies. Therefore we choose these frequencies to be outside LIGO's detection band for gravitational waves.

The thermal noise is a more fundamental and difficult problem than the seismic noise. Our primary techniques for reducing the thermal noise are to cool specific modes and to design systems with low dissipation. The seismic noise, by contrast, is motion relative to the inertial frame. So one can use the inertial frame as a reference to reduce the driving accelerations.

Detection strategies and confidence

In developing LIGO's search techniques, statistical tests, and detection criteria, we seek to minimize false observations. Within the statistics associated with the instrument noise, a viable gravitational wave signal from a distant astrophysical source must appear in the data streams of all three LIGO interferometers in the US, and of any other detectors in a worldwide network of comparably sensitive instruments.

For specific astrophysical searches, we will require signals consistent with calculated expectations of how the frequency varies with time. For the terminal in-spiraling of a binary system with a neutron star, for example, one can calculate the waveform as a function of the system parameters. So we can compare a candidate chirp signal over thousands of cycles, as it crosses LIGO's sensitivity band, with detailed templates of calculated waveforms.

Futhermore, the geographically dispersed detectors will have to exhibit consistent waveforms in proper coincidence. There will also be anticoincidence vetoes to weed out environmental effects. The hardest problem in a burst search is the elimination of false signals associated with non-Gaussian noise in the individual interferometers. By requiring multiple-detector coincidence, we can reduce the rate of such spurious events to less than one per decade.

Periodic sources will have to satisfy a very special set of criteria. The observed signal must exhibit amplitude modulation and Doppler frequency modulation consistent with the effects of the Earth's rotation and revolution around the Sun.

A stochastic background of gravitational waves can be detected by searching for a common "noise" in a set of interferometers. The detection requires the cross-correlation of two or more interferometers. In the LIGO geographic configuration, the cross correlation will be made between the Washington and Louisiana interferometers, with some penalty in bandwidth due to the large separation. We will also be able to correlate the two interferometers at the Washington site, assuming that their independence is not overly compromised by correlated perturbations at the same location.

Plans for the future

At first, LIGO will carry out a broadband search, because we do not know what kinds of astrophysical or cosmological sources we are most likely to see first. The LIGO facilities have been designed for a lifetime of 30 years, during which time, we expect, there will be a continuing and active program of detector development. The facilities can accommodate detectors operating at the quantum limit of a 1 ton mass and at the Newtonian limits imposed by the terrestrial environment. The vacuum and optical systems have been designed so as not to compromise eventual operation at these ultimate limits. It should be possible eventually to operate improved LIGO detectors that are several hundred times more sensitive than what we will start with next year.

Our initial detector design is a compromise between performance and technical risk. It incorporates some educated guesses as to what directions we should take to arrive at a reasonable probability for finding gravitational waves. It is a broadband system with modest optical power in the interferometer arms and a low-risk vibration isolation system. The mirror suspensions have been well tested in prototype interferometers.

We expect to make improvements in the LIGO interferometers following the first scientific data run, which is scheduled to end in 2004. These improvements will include a new suspension system, provided by the collaborating GEO project, to further reduce the thermal noise. We may also, at that point, change to sapphire test masses. We also expect that significant improvement in the seismic isolation of the test masses will extend LIGO's sensitive observation band down to 10Hz.

We plan to reduce the sensing noise by going to a new interferometer configuration and by applying higher-power lasers in conjunction with improved optical materials and techniques to handle the higher power.

We expect that LIGO's sensitivity at 100 Hz will be improved by about a factor of 15, and that the overall high-sensitivity band will be expanded significantly to both lower and higher frequencies. That should expand the cosmic volume LIGO can search at a given sensitivity—and hence the discovery rate—by a factor close to 3000.

In the longer run, greater changes in the detector might use still newer interferometer configurations to drive the system to the ultimate limits dictated by quantum fluctuations and fluctuations in terrestrial gravity. It will be particularly interesting to improve LIGO's sensitivity for detecting periodic sources and possibly even a stochastic background of primordial gravitational waves. Searching for this speculative primordial background at high frequencies, where stochastic noise is tolerable, can be accomplished by using interferometers that greatly reduce the phase noise of the interference fringes at the cost of reduced bandwidth.

The scientific collaboration

As we enter LIGO's commissioning phase, we have expanded the scientific community's involvement by creating the LIGO Scientific Collaboration. It presently consists of about 30 research groups comprising more than 200 physicists and astrophysicists. We expect the collaboration to continue to grow and become the scientific center of LIGO as it develops over the next decade.

It is, of course, difficult to predict how LIGO will really evolve. But we believe we have set out on a course that has bright prospects for the early detection of gravitational waves. We plan a flexible approach toward improvements that will either let us follow up sources that have been detected or, if we find nothing at first, undertake more sensitive searches.

There are plenty of opportunities for new technical ideas and search methods. We look forward to developing an international collaboration with other gravitational-wave detectors to form a world-wide network. After LIGO's first data run, we plan to interleave subsequent searches with a series of detector upgrades that promise to lead to ever-enhanced sensitivity, making the direct detection of gravitational waves a reality within the next decade.

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