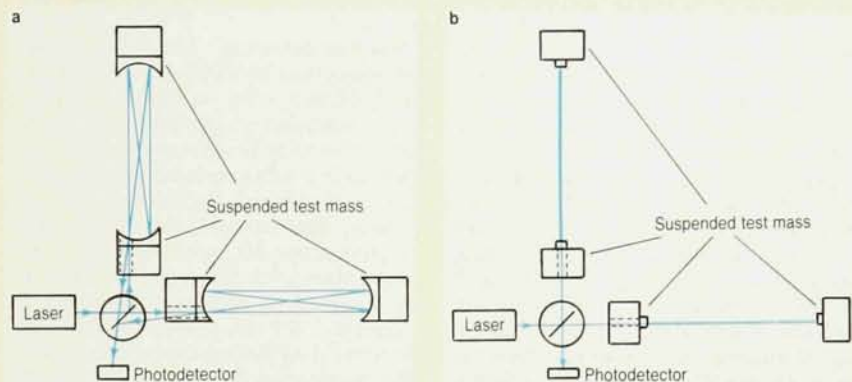


Searching for gravity waves with interferometers

A collaboration of physicists from Caltech and MIT has recently produced detailed plans for a pair of large detectors, based on laser interferometry, that they believe should be sensitive enough to detect gravity waves from several types of astrophysical sources. The detectors, which will each consist of an L-shaped vacuum chamber 4 kilometers long through which laser-interferometer beams will travel, are tentatively to be located in Columbia, Maine, and at Edwards Air Force Base, California. The projected cost is between \$50 and \$60 million. If this sum is forthcoming from NSF the detectors could be on the air as early as 1991. According to Ronald Drever (Caltech), who, along with Rainer Weiss (MIT), heads the collaboration, the leap in sensitivity from existing detectors to their planned interferometer is like "going from the human eye to the Mount Palomar telescope." Successful detection would not only help sort out competing theories of gravity, but open up a new window on violent processes throughout the universe.

Gravity waves. In 1918 Einstein predicted that moving masses produce gravitational waves, ripples in the geometry of space-time propagating at the speed of light. All subsequent relativistic theories of gravitation also predict gravitational radiation. Unfortunately, the amplitude of gravitational radiation from any currently practical laboratory source is far too small ever to be detected. Astrophysical phenomena that involve the coherent motion of large masses at relativistic speeds, however, could produce enough gravitational radiation to be detected.

Promising sources of gravitational radiation include binary systems consisting of pairs of neutron stars or black holes. The orbiting, massive stars lose energy via gravitational radiation and spiral inward at increasingly greater speeds until they coalesce, emitting a final, large burst of gravitational radiation. In fact, the only observational evidence for the existence of gravitational radiation comes from observations of PSR 1513-16, a system con-



The Caltech and MIT interferometers use slightly different methods to store light in the interferometer arms. The MIT approach (a) is to use curved mirrors that "walk" the light back and forth; the Caltech group prefers (b) making each arm a giant, tuned Fabry-Perot cavity.

sisting of a pulsar orbiting a neutron star. The precise regularity of the pulsar provides investigators with a clock to determine that the orbital period is decaying at the rate predicted by general relativity. Three similar binary systems are known in our galaxy, which suggests that they occur commonly throughout the universe. Gravitational radiation produced when such sources coalesce could eventually be detected by the interferometric detectors.

Supernovas also should be sources of gravitational radiation, but just how much of their explosive energy is converted to gravity waves is hard to estimate. Pulsars and black holes, as well as esoteric processes that occurred right after the big bang, are also gravity-wave sources, but the magnitudes of these sources and their frequency of occurrence throughout the universe are unknown. In fact, one of the most important uses of gravity-wave detectors will be as telescopes through which to view the gravitational—as opposed to the electromagnetic—universe.

Detection. When a gravity wave passes, freely falling masses—that is, those traveling along geodesics of the four-dimensional space-time geometry—bob up and down like boats on the ocean. Detecting a gravity wave is simply a matter of measuring this

bobbing motion. One way to do this, the way chosen by the Caltech-MIT collaboration, is to measure the time it takes light to travel between two mirrors anchored to heavy pendulums, which are essentially freely falling masses. More particularly, the experimenters compare the transit times of two beams of light traveling at right angles along the legs of a Michelson-type interferometer. Because of the transverse, quadrupole nature of gravity waves, one arm of the interferometer is compressed exactly as much as the other is stretched.

The principal investigators of the Caltech and MIT groups began experimenting with interferometric gravity-wave detectors in the early 1970s, proceeding along different but parallel lines. Both started with the realization that the phase delay a beam of light incurs from the passage of a gravity wave is almost unbelievably small: The strain of a typical astrophysical gravity wave is about 10^{-21} , so that a 4-km interferometer arm will gain or lose 4×10^{-16} cm—about one-thousandth the width of a nucleus! But the phase change accumulates with each passage of the beam of light through the interferometer. The trick to increasing sensitivity, therefore, is to let the light bounce between the mirrors many times. The MIT group does this with what is known as a delay-line interfer-

ometer. Curved mirrors are arranged in such a way that the light "walks" across the mirror surface as it bounces back and forth along the interferometer arm around 50 times. The arms of the Caltech interferometer are gigantic Fabry-Perot cavities—the laser light bounces off the same spot on the mirror on each of its transits. The Fabry-Perot scheme requires lasers with excellent frequency stability but has the advantage of using smaller mirrors. In a 4-km detector the Fabry-Perot interferometer needs 7-inch-diameter mirrors; the delay-line system needs mirrors 20 or 30 inches in diameter. Reduction in mirror size could be important, because the mirrors themselves must be of extremely high quality. They are of a type developed originally for laser gyroscopes and lose only about 1 part in 10^4 of the incident light.

Prototypes of the two detectors are currently operating at MIT and Caltech. Interferometers of both types have been built by groups at the Max Planck Institute, Garching, FRG, and at the University of Glasgow. The Caltech Fabry-Perot interferometer has 40-m arms, making it effectively a $1/100$ -scale model of the proposed detector. Light can be stored for as long as milliseconds in the interferometer, making 10 000 trips between the mirrors; the full-scale detector should store light for an astonishing half second. The MIT prototype delay-line interferometer has 1.5-m arms. The mirrors are arranged so that the light traverses the arm 56 times before leaving.

The signal-to-noise ratio of either interferometer increases as a function of the arm length. There are several reasons for this; an important one is simply that whereas the phase delay due to a gravity wave grows with the length of the interferometer arm, seismic noise, which enters only at the mirrors, is independent of arm length. On the other hand, although sophisticated measures such as active damping—which involves canceling sensed vibrations with active controllers—can be taken to isolate the mirrors, seismic vibrations are still an important source of noise at low frequencies.

Another important source of noise is the lasers themselves. Gravity waves will only produce a tiny fraction of a fringe shift in the interferometer. The apparatus is, in a sense, an alternative physical realization of that well-known

gedanken experiment, the Heisenberg microscope. If the laser light is too faint, the tiny fringe shifts caused by a passing gravity wave will be impossible to resolve because of a type of quantum fluctuation known as shot noise. Increasing the laser power solves this problem but potentially causes another: The hail of photons may jostle the mirrors sufficiently to wipe out the fringe pattern. These two extremes define the quantum limit of detectability. Currently the experimenters are safely below the quantum limit, but they believe a later generation of detectors might be limited by quantum effects.

Practical detectors. The interferometer, regardless of which design is eventually chosen, is by far the least expensive component of the proposed detector. Both interferometers must operate in a vacuum to eliminate noise due to statistical fluctuations in air density. The current design calls for vacuum pipes 48 inches in diameter, which allows for different interferometer designs and choices of laser wavelength and the simultaneous operation of several different interferometers. The motivation for this design is to allow the development of future generations of gravity-wave detectors without interruption of the ongoing search.

The wide diameter of the vacuum tube will also allow the experimenters to play other tricks aimed at increasing the sensitivity of the detectors. One plan is to include a second interferometer half as long as the first in the vacuum tube. The response of this second detector to gravity waves will be exactly half as large as that of the first, but they will respond differently to seismic shocks. This should help the experimenters to discriminate the waves from the noise.

The only sure way to discriminate between the two is to look for coincidences between two or more widely separated detectors. In addition, by measuring the difference between the arrival times of gravity-wave signals at the detectors in California and Maine the experimenters will be able to approximate the general direction of the gravity-wave source. But to really pin a source down, which is necessary if gravity-wave detectors are to become astronomical tools, four widely separated detectors will be needed. With luck, these will be built by the groups now

active in Europe.

Second-generation improvements. Although the experimenters believe there is a fair chance that the initial detector system will detect gravity waves, they have thought of improvements that should increase the sensitivity by several orders of magnitude, possibly opening up new, fainter astrophysical sources to their scrutiny.

One such improvement is known as light recycling. The sensitivity of an interferometer depends on the amount of light bouncing between the mirrors: The more photons, the better a fringe can be resolved. One can increase the amount of stored light by using more and more powerful lasers, but the energy costs of running these lasers eventually get prohibitive. Another approach stems from the fact that most of the light that goes into an interferometer is wasted. The light that travels down the arms recombines at a beam splitter, where it exits in two directions. The experiment is adjusted so that the observed pattern is at a dark fringe to avoid overloading the photodiode. This means that most of the light escapes through the other side of the beam splitter. The idea behind light recycling is simply to feed this light back into the interferometer. The difficulty is that the light must be fed back in precisely the right phase. The idea does not give a useful advantage in small systems and awaits testing in the large interferometers.

Another clever idea is applicable only to the detection of periodic sources. When a gravity wave passes through the interferometer for one half-cycle, one arm is shortened while the other is lengthened. During this time the light in the arms begins to accumulate their phase shift. If, after a half-cycle of the gravity wave, the light in the arms is interchanged, the phase shift will continue to grow. By adjusting the frequency of interchange to that of the gravity wave a significant sensitivity improvement due to resonance should be possible.

The National Science Foundation has provided around \$2.5 million this year toward the continuing development of the prototypes at Caltech and MIT. If nature and NSF are kind, sometime in the 1990s astrophysicists and relativists will have a new tool for viewing the universe.

—BRUCE SCHECHTER

Superconducting-cavity progress spurs new CEBAF design

What is the best way to provide nuclear physicists with continuous beams of 4-GeV electrons? Three years ago the pulse-stretcher-ring concept embodied in the winning SURF design for the

Continuous Electron Beam Accelerator Facility appeared to be the optimal solution (PHYSICS TODAY, July 1983, page 57). But while construction of CEBAF has not yet begun, accelerator

technology has not stood still. In the light of recent progress in the development of superconducting rf cavities, a review of CEBAF technology initiated last summer by Hermann Grunler, the