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THE SEARCH FOR GRAVITATIONAL WAVES WITH LIGO: STATUS AND PLANS

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The Laser Interferometer Gravitational-Wave Observatory (LIGO) project has been designed to detect gravitational waves directly using large interferometers at two widely separated sites. Construction of the observatory facilities is now complete, and commissioning of the interferometers is well underway. Following a series of engineering runs, science running is scheduled to begin in 2002. A parallel effort is underway to develop improved detector designs to achieve dramatically greater sensitivity in the future.

Einstein's theory of general relativity predicts that a massive system with a rapidly time-varying quadrupole moment emits gravitational radiation which, far from the source, appears as quadrupolar transverse waves. There is strong evidence for the existence of gravitational waves (GWs) from radio observations of the binary pulsar PSR 1913+16, whose gradual orbital decay since its discovery in 1974 perfectly matches the prediction.[1] However, GWs have not yet been directly detected.

The LIGO project is the largest component in a worldwide effort to detect GWs using large interferometric detectors, which have become practical thanks to advances in lasers and optics technology over the last decade or so.[2] LIGO has constructed two facilities: the LIGO Hanford Observatory, in Washington state, with 2-km and 4-km interferometers; and the LIGO Livingston Observatory, in Louisiana, with a 4-km interferometer.

Figure 1 shows the conceptual optical layout of the LIGO interferometers. The Pre-Stabilized Laser system is based on a Nd:YAG laser with an output power of about 10 W, along with electro-optic components to stabilize the frequency and intensity of the beam. The Mode Cleaner is a triangular cavity of suspended mirrors which conditions the beam before it enters the interferometer. The large mirrors in the interferometer are made of fused silica with very low bulk absorption and high mechanical Q, polished to a flatness of ~1 nm (rms) and coated to reflect with < 50 ppm scattering loss. Each is suspended by a single loop of wire and is actively aligned and positioned using electrical coils which exert force on magnets glued to the back of the mirror. All of the in-vacuum optical components are mounted on tables with passive vibration-isolation systems to filter out ground motion.

Operation of the interferometer depends critically on active control of many degrees of freedom, including the laser frequency, alignment of the large mirrors, and

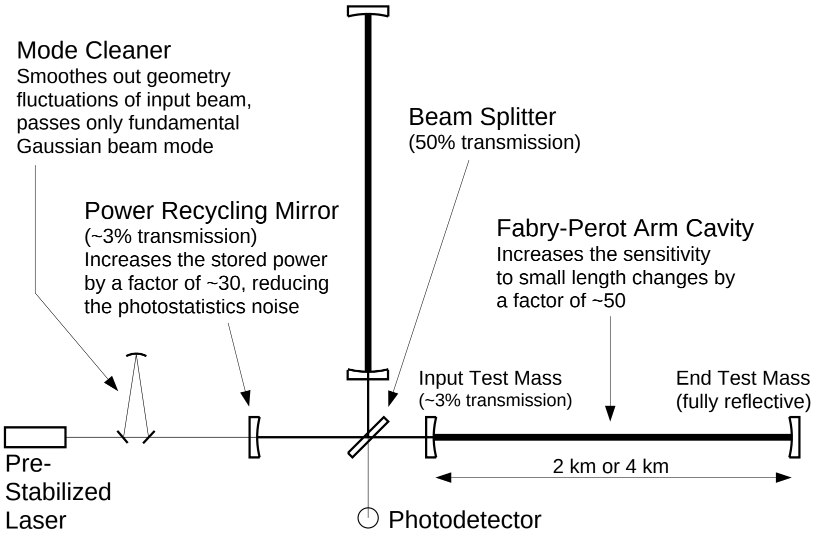

Fig. 1. Simplified optical layout of the LIGO interferometers, showing the major components.

lengths of the various optical cavities in the system. This is accomplished using several interconnected servo systems, which keep the interferometer "locked" on a dark fringe (destructive interference) at the output photodiode. A GW signal is manifested as servo effort required to correct the length difference between the two arms. LIGO will be most sensitive to signals in the frequency range 40–1500 Hz, with a peak displacement sensitivity of $\sim 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ near 150 Hz. The primary servo inputs and outputs are continuously sampled at 16384 Hz, along with several hundred auxiliary channels to monitor other servo loops, the pre-stabilized laser, mirror suspension controllers, and environmental conditions (seismic, acoustic, electromagnetic, etc.). The total data rate from each interferometer is $\sim$3 MB/s.

The first basic science goal of LIGO is to directly establish the existence of GWs, with consistent signals seen at both observatories. The observed waveforms may be used to check the fundamental properties of GWs, such as their propagation speed and quadrupole nature, against the expectations from general relativity.[3] The longer-term goal is to carry out a program of astrophysical observations. One primary target is binary systems of massive objects (neutron stars or black holes) in tight orbits, for which gravitational radiation leads to orbital decay and ultimately to the coalescence of the objects; the GW signal emitted in the process has a distinctive frequency evolution ("chirp") which is relatively easy to detect in the noisy data. LIGO is expected to be able to detect neutron-star binary coalescences out to a distance of $\sim$65 million light-years, and binaries with one or two black holes out to even farther distances. Unfortunately, the best estimates of the rates of such events suggest that the first generation of LIGO interferometers may expect to see less than 0.1 event per year.[4] Other potentially observable sources of GWs include "ringdown" modes of newly-formed black holes; supernovae; "r-mode" oscillations of young neutron stars; asymmetric, rapidly-rotating neutron stars; and a stochastic GW remnant from the evolution of the early universe. Detailed knowledge of these processes is lacking, so it is not known what sources might be detected first.

Construction of the LIGO observatory facilities, including the long beam tubes, began in early 1996 and was completed in early 2000. Installation of the 2-km interferometer at Hanford was completed in August 2000, and its commissioning is well underway; it is expected to be operating reliably (though at limited sensitivity) by the end of 2000. The Livingston 4-km interferometer has now been completely installed and should become operational in Spring 2001; it will then operate simultaneously with the Hanford 2-km during a series of engineering runs, which should lead to the first LIGO science results. During 2001 there will also be much effort to improve the performance of the interferometers and to study the effects of environmental and instrumental disturbances. The Hanford 4-km interferometer should be operational by August 2001, and long-term science running with both sites should begin in 2002. The initial science run is expected to last for about three years.

The LIGO observatory facilities allow much greater sensitivity than the initial interferometers can achieve, and so a substantial effort is underway to develop improved detector technologies for a future detector upgrade. A baseline design has been formulated, which includes increasing the laser power to 180 W, using 30-kg sapphire mirrors as test masses, adding new active and passive stages to the vibration isolation systems, redesigning the mirror suspensions, and adding a "signal recycling mirror" at the output of the interferometer to enhance signal extraction and provide frequency tunability. The net result of these changes, which could be installed as early as 2005–2006, should be a factor of $\sim$10 improvement in sensitivity to GWs, leading to a factor of $\sim$1000 in event rates. There are also ideas for even more advanced interferometer designs. From a combination of extended running periods and occasional detector upgrades, gravitational-wave astronomy promises to tell us much about the universe in the years to come.

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