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# ASTRONOMICAL GOALS OF LIGO

D. Ugolini[1]

RESUMEN

El experimento LIGO (Observatorio de interferometría laser de ondas gravitacionales) consiste en tres interferómetros Fabry-Perot diseñados para medir las perturbaciones infinitesimales de la curvatura del espacio tiempo debidas al movimiento de cuerpos astronómicos masivos. Los interferómetros son sensibles a esfuerzos de $h \sim 10^{-21}$ en un intervalo de frecuencias de 40 Hz a 1 kHz. Las fuentes de interés astronómico incluyen la caída en espiral de estrellas de neutrón u hoyos negros, fuentes "eruptivas" tales como supernovas, señales periódicas de pulsares y ondas estocásticas (equivalentes gravitacionales de la radiación de microondas cósmica). Aquí discutiré estas fuentes en detalle, incluyendo el estado actual de los interferómetros y los planes para la adquisicón de datos futuros.

ABSTRACT

The LIGO (Laser Interferometer Gravitational-Wave Observatory) experiment consists of three Fabry-Perot interferometers designed to measure the infinitesimal perturbations of the curvature of spacetime due to the motion of massive astronomical bodies. The interferometers are sensitive to strains of $h \sim 10^{-21}$ in a frequency range from 40 Hz to 1 kHz. Sources of astronomical interest include binary inspirals of neutron stars or black holes, "burst" sources such as supernovae, periodic signals from pulsars, and stochastic waves (the gravitational equivalent of the cosmic microwave background). In this talk I will discuss these sources in detail, as well as the current status of the interferometers and the plans for future full-time data collection.

*Key Words:* **GRAVITATIONAL WAVES — INSTRUMENTATION: INTERFEROMETERS**

## 1. INTRODUCTION

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is an experiment designed to measure the tiny distortions of space created by the movement of massive astronomical bodies (Abbott 2004a, Barish 1999). The immediate purpose of the experiment is the first direct detection of these waves, with a long-term goal of performing astronomical research by studying the waveforms. Commissioning and data analysis are conducted by the LIGO Scientific Collaboration (LSC), a collection of over 400 researchers from more than 40 universities and laboratories around the world. The LIGO experiment is also part of an international network of gravitational wave observatories, including experiments in Germany (GEO), Italy (VIRGO), Japan (TAMA), and Australia (AIGO). The network cooperates to improve confidence through coincidence detection, as well as to better measure the polarization of gravitational waves, their speed of propagation, and the direction of origin.

The experiment consists of three Michelson interferometers, two located in Hanford, Washington and one in Livingston, Louisiana. Figure 1 illustrates

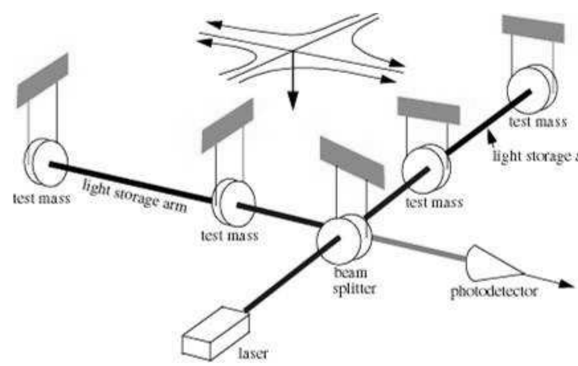


Fig. 1. Optical layout of the LIGO interferometer

the optical layout. Gravitational waves are a strain in spacetime with amplitude $h = \Delta L/L$, so sensitivity is optimized by measuring over as long a distance as possible. This is accomplished first by having a 4 km arm length (2 km for one of the Hanford interferometers). The arms are Fabry-Perot cavities with a finesse of several hundred, increasing the effective round-trip path length of the light by the same factor. Not pictured is a power recycling mirror at the laser input, which directs output light back into the interferometer, reducing the overall shot noise. The light at the output is measured to one part in $10^8$ of

[1]Trinity University, San Antonio, Texas, USA.

a fringe, resulting in a maximum strain sensitivity of better than $h \sim 10^{-21}$.

In this paper I will detail the four categories of gravitational wave sources to which LIGO is most sensitive – inspirals of binary neutron stars or black holes, "burst" sources such as supernovae, periodic sources such as pulsars, and stochastic gravitational wave backgrounds.

## 2. CANDIDATE SOURCES OF GRAVITATIONAL WAVES

The expected sensitivity of the interferometer as a function of frequency is shown in Figure 2. The sensitivity is bounded at low frequencies by seismic noise, which drops sharply with frequency due to the passive filtering from pendulum optic suspensions and several layers of springs supporting the optical tables. At high frequencies, the sensitivity is limited by the shot noise of the laser and the "corner frequency" of the cavity – at these frequencies, the light is stored in the interferometer arms for longer than the period of the gravitational wave, causing the signal to partially cancel itself. In between, sensitivity is limited by the thermal excitation of the interferometer optics and their suspension wires. A strain sensitivity of better than $h \sim 10^{-21}$ is achieved between roughly 40 Hz and 1 kHz (Barish 1999).

This frequency band defines which sources LIGO can and cannot resolve. For example, binary stars that orbit their center of mass with a period of hours or days will generate gravitation waves at frequencies of 1 mHz or less. The waves generated by supermassive black holes ingesting surrounding material will also be several orders of magnitude too low. The sources that do fall within this relatively high-frequency band, and the strategies for detecting them, are listed below.

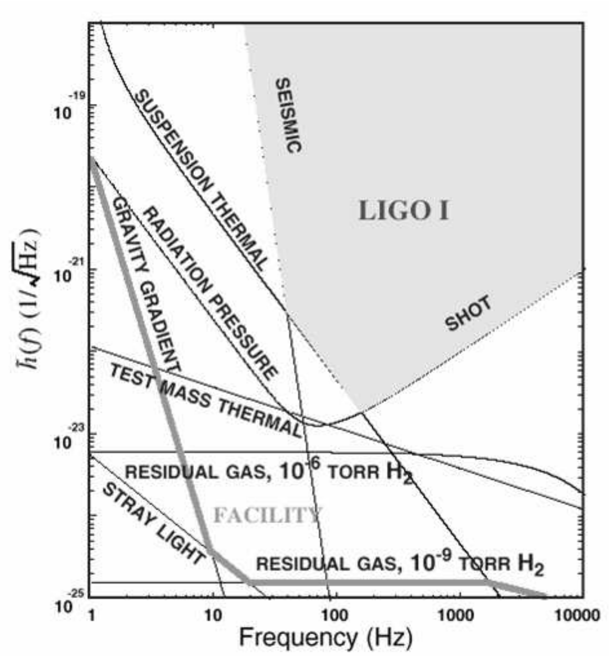


Fig. 2. Sources of noise in the LIGO interferometer

### 2.1. *Binary Inspirals*

As a binary system generates gravitational waves, it loses energy, causing the two bodies to fall closer together and rotate more quickly about their center of mass. The gravitational wave generated increases in both frequency and amplitude. By the time a star has spiraled into and collided with a neutron star or black hole partner, the gravitational wave will have reached audible frequencies; the waveform is often called a "chirp", due to how it sounds to the human ear when converted to audio. Two 1.4 solar mass objects would traverse the optimal LIGO frequency band (40 Hz to 1 kHz) during the last 30 seconds of inspiral before collision (Abbott 2004d).

The search for inspiral events in LIGO data is performed through a process called matched filtering. The initial chirp waveform can be well modeled based on the initial masses of the objects and the radius and eccentricity of their orbit. A filter bank of waveforms is generated from a variety of values for these orbital parameters, and correlations are computed between each filter and the three LIGO data streams. Note that the waveform for the collision itself can only be determined numerically, and models of such an event are strongly limited in precision by computing time. This is where LIGO as an instrument for studying astronomy comes into play; once a chirp is identified, the following waveform will allow us to study strong-field general relativity in a way previously inaccessible to us.

### 2.2. *Unmodeled Burst Sources*

Unlike binary inspiral waveforms, which are identified by matching the data to a specific waveform, other data analyses are conducted to search for short (< 1 second), unmodeled bursts of gravitational waves. A good example of such a source is a type II supernova, which will generate gravitational radiation as long as the star collapse is sufficiently asymmetric (Abbott 2004c). Searches for these burst sources are primarily conducted by looking for "clustering." In this method, the data are collected into bins in both time and frequency, and scanned for connected regions of excess energy over the usual background.

### 2.3. *Periodic Sources*

The rotation of an elliptical pulsar, or the motion of the material on the surface of a neutron star, can generate periodic gravitational waves. This is a unique category of sources for several reasons. First, there are over 100 known pulsars in our galaxy with expected gravitational wave emission frequencies (equal to twice the spin frequency) within the LIGO frequency band. Several of these sources are less than 1 kpc away. Second, the expected frequency of gravitational radiation from these sources and the rate of their spindown can be measured to excellent precision, allowing data analyses to focus on a tight frequency band. Third, the signal can be studied over many periods, during which time the movement of the Earth will induce Doppler shifts on the signal that experimenters can look for (Abbott 2004b).

Along with known sources, another goal for the detection of continuous signals is a blind search. Great care has been invested in developing coherent and incoherent search techniques, which optimize sensitivity for given computational resources and parameter space. One such coherent detection pipeline is also being deployed in a distributed computing environment through the Einstein@home software package, which uses the idle computing cycles of private machines that have signed up to contribute to the search.

In the future, searches for periodic sources will benefit from a revision to the optical layout called signal recycling. In this scheme a partially-transmissive optic called the signal recycling mirror is added to the output port of the interferometer. This creates a compound cavity with the signal recycling mirror at one end, and the combination of the arm optics at the other. The position of the signal recycling mirror is tuned to make this compound cavity resonant at the beats between the laser carrier frequency and an expected signal frequency. Signals at the expected frequency will be preferentially transmitted at the output port, while power at other frequencies will be reflected back into the interferometer. The net result is a dip in sensitivity at the chosen signal frequency, with the depth and width of the dip determined by the transmission of the signal recycling mirror. Such a cavity could be tuned to put maximum sensitivity at the frequency of a known pulsar for targeted searches. A control system for signal recycling is currently being prototyped at the Caltech LIGO 40-meter prototype for inclusion in a future generation of the LIGO interferometers (Weinstein 2002, Miyakawa 2004).

### 2.4. *Stochastic Sources*

A stochastic source is a seemingly random waveform generated by a large number of weak, independent sources of gravitational radiation. One possible source of such a signal could be emissions from the early universe – the gravitational equivalent of the cosmic microwave background. Indirect limits on the magnitude of such a background can be placed based on other observations, such as the microwave background or the timing of radio pulsars, but most such limits apply at frequencies far below the LIGO sensitivity band (Abbott 2004e). Searches for stochastic backgrounds are conducted by cross-correlating the outputs of two or more interferometers.

## 3. STATUS OF LIGO EXPERIMENT

Figure 3 shows measured sensitivities from the 4 km Hanford interferometer for the first three LIGO science runs. The upper curve is from the first science run, which ran from August 23 through September 9 of 2002; upper limits on candidate sources from these data have been published (Abbott 2004b,c,d,e). The lowest measured curve is from August 2004. This corresponds to a range of 8 Mpc, where "range" is defined as the maximum distance, averaging over possible sky positions and orientations relative to line of sight, at which the interferometer would be sensitive to the inspiral of two 1.4 solar mass neutron stars. The solid curve below this is the LIGO target sensitivity, which corresponds to an inspiral range of 20 Mpc. This last factor of two is important for a number of reasons. First, since the LIGO interferometer is an antenna performing a volume search of the sky rather than pointing in a specific direction, an improvement in sensitivity can result in an even greater increase in event rate, depending on the distribution of mass within the interferometer's range. Second, 20 Mpc extends LIGOs reach to the Virgo cluster, which greatly increases the number of candidate objects.

A fourth science run was conducted in March 2005, with all three interferometers achieving sensitivities within a factor of two of the Hanford 4 km August 2004 noise curve shown in Figure 3. In addition, the triple coincidence live time – the percentage of time that all three interferometers are locked in resonance and taking data – improved to 55%. Data analysis for this science run is currently underway. The interferometers are now going through a final commissioning phase, with full-time data taking tentatively scheduled to begin in late autumn 2005.

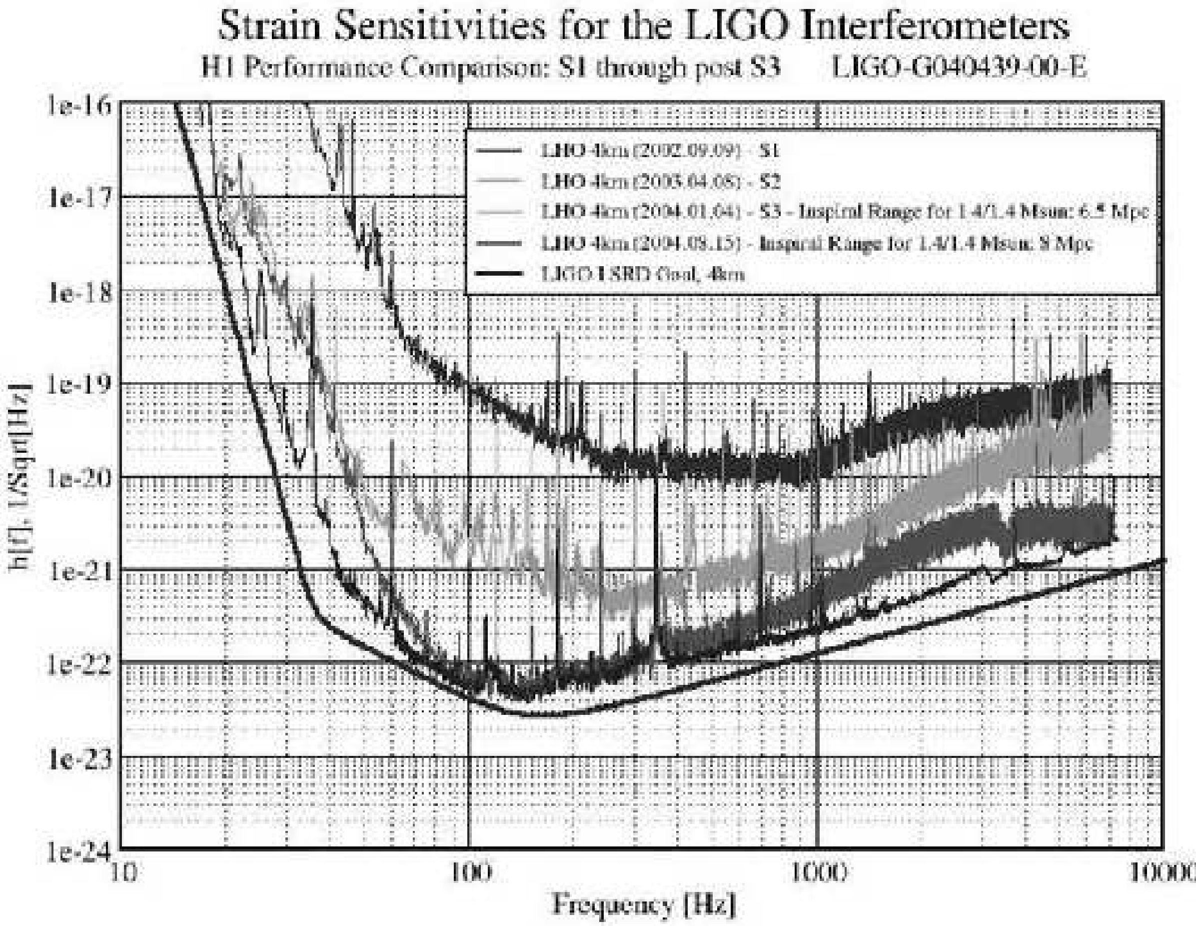


Fig. 3. Measured sensitivity at Hanford 4km interferometer for the first three LIGO science runs

## 4. SUMMARY

The Laser Interferometer Gravitational-Wave Observatory, consisting of three Fabry-Perot Michelson interferometers up to 4 km in length, has an expected strain sensitivity of better than $h \sim 10^{-21}$ between 40 Hz and 1 kHz. Expected sources in this frequency band include inspiral collisions of neutron star or black hole binary systems, type II supernovae, pulsars or other rotational periodic sources, and stochastic gravitational wave backgrounds. A science run ending in September 2002 has resulted in upper limits on the frequency of these events, and five analyses from a second science run in April 2003 have either been published (Abbott 2005) or submitted for publication. Meanwhile, the interferometers have been improved to within a factor of two of design sensitivity. A fourth science run has recently ended, and LIGO may begin full time data collection as early as autumn 2005.

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Dennis Ugolini: Department of Physics and Astronomy, Trinity University, One Trinity Place, San Antonio, Texas 78212, USA (dugolini@trinity.edu).