

THE SCIENCE AND DETECTION OF GRAVITATIONAL WAVES

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One of the most important consequences of the Theory of General Relativity is the concept of gravitational waves. As we enter the new millennium, a new generation of detectors sensitive enough to directly detect such waves will become operational. Detectable events could originate from a variety of catastrophic events in the distant universe, such as the gravitational collapse of stars or the coalescence of compact binary systems. In these two lectures, I discuss both the astrophysical sources of gravitational waves and the detection technique and challenges using suspended mass interferometry. Finally, I summarize the status and plans for the Laser Interferometer Gravitational-wave Observatory (LIGO) and the other large new detectors.

1 Introduction

Gravitational waves are a necessary consequence of Special Relativity with its finite speed for information transfer. Einstein in 1916 and 1918^{1,2,3} put forward the formulation of gravitational waves in General Relativity. He showed that time dependent gravitational fields come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light. This propagation is called gravitational waves.

The formulation of this concept in general relativity is described by the Minkowski metric, but where the information about space-time curvature is contained in the metric as an added term, $h_{\mathbf{m}\mathbf{m}}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}\right)h_{\mathbf{m}\mathbf{m}} = 0 \quad (1)$$

The strain $h_{\mathbf{m}\mathbf{m}}$ takes the form of a plane wave propagating with the speed of light (c). The speed is the same for electromagnetic and gravitational radiation in Einstein's theory. Since the underlying theory of gravity is spin 2, the waves have two components, like electromagnetic waves, but rotated by 45° instead of 90° from each other. It is an interesting fact observation that if gravitational waves are observed and the two components are decomposed, this classical experiment will be capable of observing the underlying quantum spin 2 structure of gravity. The solutions for the propagation of gravitational waves can be written as

$$h_{mm} = h_+(t - z/c) + h_x(t - z/c), \quad (2)$$

where z is the direction of the propagation and h_+ and h_x are the two polarizations.

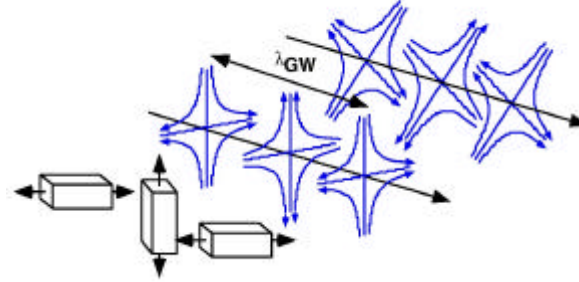


Figure 1. The propagation of gravitational waves illustrating the two polarizations rotated 45° from each other.

Evidence of these waves resulted from the beautiful observations of Russell Hulse and Joseph Taylor in their studies of a neutron star binary system PSR1913+16^{4,5,6}. They discovered this particular compact binary pulsar system in 1974. The pulsar frequency is about 17/sec. It was identified as being a binary system because they observed a variation of the frequency with just under an 8 hour period. Subsequent measurement accurately determined the characteristics of the overall binary system with remarkable precision. The most important parameters for our purpose are that the two neutron stars are separated by about 10^6 miles, have masses $m_1 = 1.4 m_\odot$ and $m_2 = 1.36m_\odot$, and the ellipticity of the orbit is $\epsilon = 0.617$. They demonstrated that the motion of the pulsar around its companion could not be understood unless the dissipative reaction force associated with gravitational wave production were included. The system radiates away energy, presumably in the form of gravitational waves, and the two neutron stars spiral in toward one another speeding up the orbit. In detail the inspiral is only 3 mm /orbit so it will be more than 10^6 years before they actually coalesce.

Hulse and Taylor monitored these pulsar signals with $50\mu\text{sec}$ accuracy over many years. They demonstrated the orbital speedup experimentally with an accuracy of a fraction of a percent. The speedup is in complete agreement with the predictions from general relativity as illustrated in Figure 2. Hulse and Taylor received the Nobel Prize in Physics for this work in 1993. This impressive indirect evidence for gravitational waves gives us good reason to believe in their existence. But, as of this date, no direct detection of gravitational waves has been made using resonant bar detectors. A new generation of detectors using suspended mass interferometry promising improved sensitivity will soon be operational.

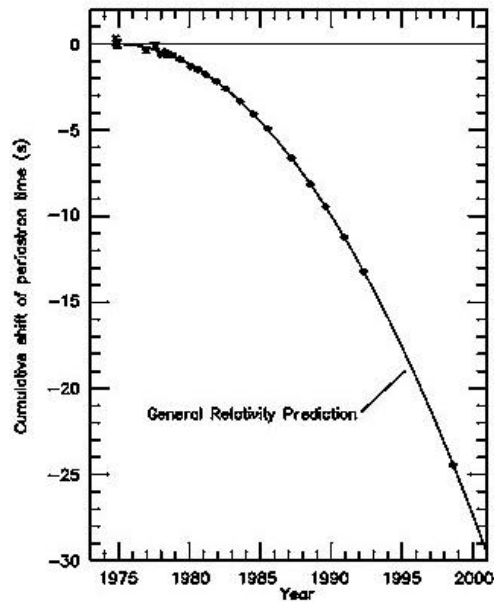


Figure 2. The compact binary system PSR1916+13, containing two neutron stars, exhibits a speedup of the orbital period by monitoring the shift over time of the time of the pulsar's closest approach (periastron) to the companion star. Over 25 years the total shift recorded is about 25 sec. The plot shows the data points as dots, as well as the prediction (not a fit to the data) from general relativity from the parameters of the system. The agreement is impressive and this experiment provides strong evidence for the existence of gravitational waves.

The theoretical motivation for gravitational waves, coupled with the experimental results of Hulse and Taylor, make a very strong case for the existence of such waves. This situation is somewhat analogous to one in the 1930's that concerned the existence of the neutrino. The neutrino was well motivated theoretically and its existence was inferred from the observed apparent non conservation of energy and angular momentum in nuclear beta decay. Although there was little doubt that the neutrino existed, it took another 20 years before Reines and Cowan made a direct observation of a neutrino by detecting its interaction in matter. Following that observation, a whole new branch of elementary particle physics opened up that involved studies of the neutrino and its properties (the mass of the neutrino this remains one of the most important subjects in particle physics) on one hand and the direct use of the neutrino as a probe of other physics (eg. the quark structure of the nucleon by studying neutrino scattering)

on the other hand. If we carry this analogy a step further, the next step for gravitational waves will likewise be direct observation. Following that important achievement, we can fully expect that we will open up a new way to study the basic structure of gravitation on one hand, and on the other hand we will be able to use gravitational waves themselves as a new probe of astrophysics and the Universe.

For fundamental physics, the direct observation of gravitational waves offers the possibility of studying gravitation in highly relativistic settings, offering tests of Relativistic Gravitation in the strong field limit, where the effects are not merely a correction to Newtonian Gravitation but produces fundamentally new physics through the strong curvature of the space-time geometry. Of course, the waves at Earth are not expected to be other than weak perturbations on the local flat space, however they provide information on the conditions at their strong field sources. The detection of the waves will also allow determination of the wave properties such as their propagation velocity and polarization states.

In terms of astrophysics, the observation of gravitational waves will provide a very different view of the Universe. These waves arise from motions of large aggregates of matter, rather than from particulate sources that are the source of electromagnetic waves. For example, the types of known sources from bulk motions that can lead to gravitational radiation include gravitational collapse of stars, radiation from binary systems, and periodic signals from rotating systems. The waves are not scattered in their propagation from the source and provide information of the dynamics in the innermost and densest regions of the astrophysical sources. So, gravitational waves will probe the Universe in a very different way, increasing the likelihood for exciting surprises and new astrophysics.

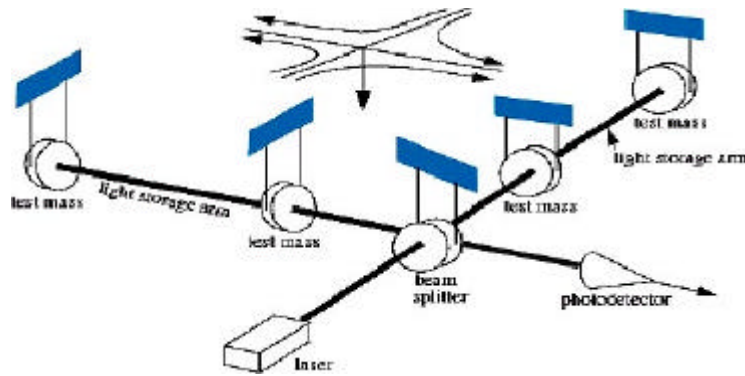


Figure 3. A schematic view of a suspended mass interferometer used for the detection of gravitational waves. A gravitational wave causes one arm to stretch and the other to squash slightly, alternately at the gravitational wave frequency. This difference in length of the two arms is measured through precise interferometry.

A new generation of detectors (LIGO and VIRGO) based on suspended mass interferometry promise to attain the sensitivity to observe gravitational waves. The implementation of sensitive long baseline interferometers to detect gravitational waves is the result of over twenty-five years of technology development, design and construction.

The Laser Interferometer Gravitational-wave Observatory (LIGO) a joint Caltech-MIT project supported by the NSF has completed its construction phase and is now entering the commissioning of this complex instrument. Following a two year commissioning program, we expect the first sensitive broadband searches for astrophysical gravitational waves at an amplitude (strain) of $h \sim 10^{-21}$ to begin during 2002. The initial search with LIGO will be the first attempt to detect gravitational waves with a detector having sensitivity that intersects plausible estimates for known astrophysical source strengths. The initial detector constitutes a 100 to 1000 fold improvement in both sensitivity and bandwidth over previous searches.

The LIGO observations will be carried out with long baseline interferometers at Hanford, Washington and Livingston, Louisiana. To unambiguously make detections of these rare events a time coincidence between detectors separated by 3030 km will be sought



Figure 4. The two LIGO Observatories at Hanford, Washington and Livingston, Louisiana

The facilities developed to support the initial interferometers will allow the evolution of the detectors to probe the field of gravitational wave astrophysics for the next two decades. Sensitivity improvements and special purpose detectors will be needed either to enable detection if strong enough sources are not found with the initial interferometer, or following detection, in order to increase the rate to enable the detections to become a new tool for astrophysical research. It is important to

note that LIGO is part of a world wide effort to develop such detectors^{7,8,9,10,11}, which includes the French/Italian VIRGO project, as well as the Japanese/TAMA and Scotch/German GEO projects. There are eventual plans to correlate signals from all operating detectors as they become operational.

2 Sources of Gravitational Waves

2.1 Character of Gravitational Waves and Signal Strength

The effect of the propagating gravitational wave is to deform space in a quadrupolar form. The characteristics of the deformation are indicated in Figure 5.

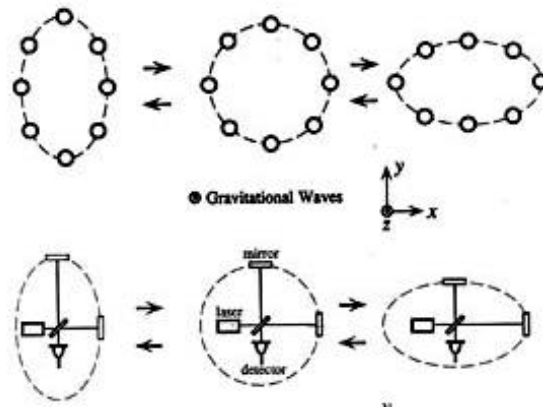


Figure 5. The effect of gravitational waves for one polarization is shown at the top on a ring of free particles. The circle alternately elongates vertically while squashing horizontally and vice versa with the frequency of the gravitational wave. The detection technique of interferometry being employed in the new generation of detectors is indicated in the lower figure. The interferometer measures the difference in distance in two perpendicular directions, which if sensitive enough could detect the passage of a gravitational wave.

One can also estimate the frequency of the emitted gravitational wave. An upper limit on the gravitational wave source frequency can be estimated from the Schwarzschild radius $2GM/c^2$. We do not expect strong emission for periods shorter than the light travel time $4\pi GM/c^3$ around its circumference. From this we can estimate the maximum frequency as about 10^4 Hz for a solar mass object. Of course, the frequency can be very low as illustrated by the 8 hour period of PSR1916+13, which is emitting gravitational radiation. Frequencies in the higher frequency range $1\text{Hz} < f < 10^4$ Hz are potentially reachable using detectors on the

earth's surface, while the lower frequencies require putting an instrument in space. In Figure 6, the sensitivity bands of the terrestrial LIGO interferometers and the proposed LISA space interferometers are shown. The physics goals of the two detectors are complementary, much like different frequency bands are used in observational astronomy for electromagnetic radiation.

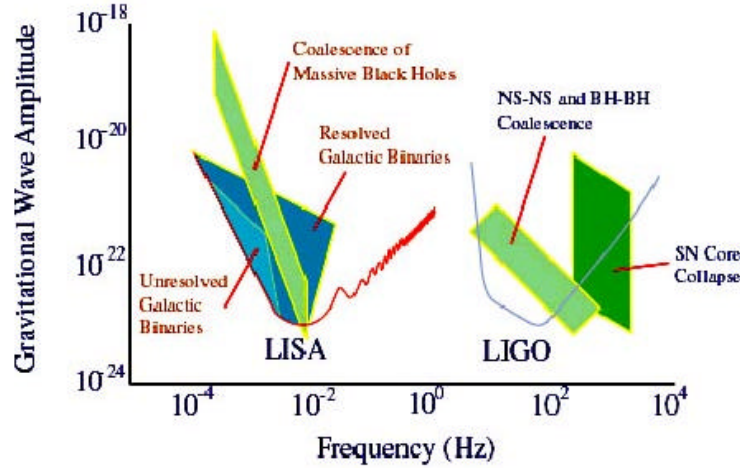


Figure 6. The detection of gravitational waves on earth are in the audio band from ~ 10 - 10^4 Hz. The accessible band in space of 10^{-4} - 10^{-1} Hz, which is the goal of the LISA instrument proposed to be a joint ESA/NASA project in space with a launch about 2010 complements the terrestrial experiments. Some of the sources of gravitational radiation in the LISA and LIGO frequency bands are indicated.

The strength of a gravitational wave signal depends crucially on the quadrupole moment. We can roughly estimate how large the effect could be from astrophysical sources. If we denote the quadrupole of the mass distribution of a source by Q , a dimensional argument, along with the assumption that gravitational radiation couples to the quadrupole moment yields:

$$h \sim \frac{G\ddot{Q}}{c^4 r} \sim \frac{G(E_{kin}^{non-symm.} / c^2)}{c^2 r} \quad (3)$$

where G is the gravitational constant and $E_{kin}^{non-symm.}$ is the non-symmetrical part of the kinetic energy.

For the purpose of estimation, let us consider the case where one solar mass is in the form of non-symmetric kinetic energy. Then, at a distance of the Virgo

cluster we estimate a strain of $h \sim 10^{-21}$. This is a good guide to the largest signals that might be observed. At larger distances or for sources with a smaller quadrupole component the signal will be weaker.

2.2 Astrophysical Sources of Gravitational Waves

There are a many known astrophysical processes in the Universe that produce gravitational waves¹². Terrestrial interferometers, like LIGO, will search for signals from such sources in the 10Hz - 10KHz frequency band. Characteristic signals from astrophysical sources will be sought over background noise from recorded time-frequency series of the strain. Examples of such characteristic signals include the following:

2.2.1 Chirp Signals

The inspiral of compact objects such as a pair of neutron stars or black holes will give radiation that will characteristically increase in both amplitude and frequency as they move toward the final coalescence of the system.

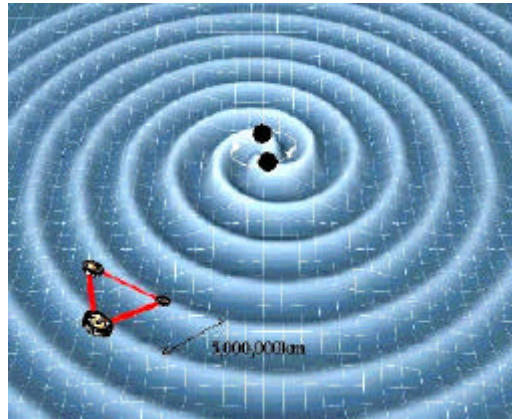


Figure7. An inspiral of compact binary objects (e.g. neutron star – neutron star; blackhole-blackhole and neutron star-blackhole) emits gravitational waves that increase with frequency as the inspiral evolves, first detectable in space (illustrated with the three satellite interferometer of LISA superposed) and in its final stages by terrestrial detectors at high frequencies.

This chirp signal can be characterized in detail, giving the dependence on the masses, separation, ellipticity of the orbits, etc. A variety of search techniques, including the direct comparison with an array of templates will be used for this type of search. The waveform for the inspiral phase is well understood and has been

calculated in sufficient detail for neutron star-neutron star inspiral. To Newtonian order, the inspiral gravitational waveform is given by

$$h_+(t) = \frac{2G^{\frac{5}{3}}}{c^4} (1 + \cos^2(i)) \frac{m}{r} (\mathbf{p}Mf)^{\frac{2}{3}} \cos(2\mathbf{p}ft) \quad (4)$$

$$h_-(t) = \pm \frac{4G^{\frac{5}{3}}}{c^4} \cos(i) \frac{m}{r} (\mathbf{p}Mf)^{\frac{2}{3}} \sin(2\mathbf{p}ft) \quad (5)$$

where the + and – polarization axes are oriented along the major and minor axes of the projection of the orbital plane on the sky, i is the angle of inclination of the orbital plane, $M = m_1 + m_2$ is the total mass, $m = m_1 m_2 / M$ is the reduced mass and the gravitational wave frequency f (twice the orbital frequency) evolves as

$$f(t) = \frac{1}{P} \left(\frac{c^3}{G} \right)^{\frac{5}{8}} \left(\frac{5}{256mM^{\frac{2}{3}}(t_0 - t)} \right)^{\frac{3}{8}} \quad (6)$$

where t_0 is the coalescence time. This formula gives the characteristic ‘chirp’ signal – a periodic sinusoidal wave that increases in both amplitude and frequency as the binary system inspirals.

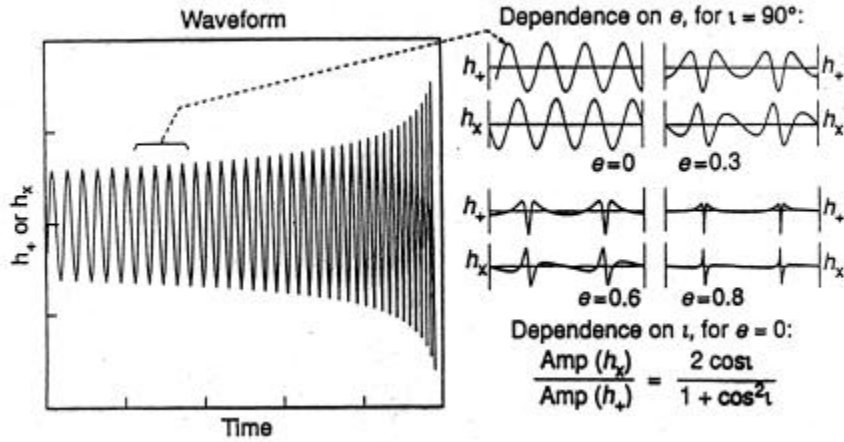


Figure 8. An example is shown of the final chirp waveforms. The amplitude and frequency increase as the system approaches coalescence. The detailed waveforms can be quite complicated as shown at the right, but enable determination of the parameters (eg. ellipticity) of the system

The Newtonian order waveforms do not provide the needed accuracy to track the phase evolution of the inspiral to a quarter of a cycle over the many thousands of cycles that a typical inspiral will experience while sweeping through the broad band LIGO interferometers. In order to better track the phase evolution of the inspiral, first and second order corrections to the Newtonian quadrupole radiation, known as the post-Newtonian formulation, must be applied and are used to generate templates of the evolution that are compared to the data in the actual search algorithms. If such a phase evolution is tracked, it is possible to extract parametric information about the binary system such as the masses, spins, distance, ellipticity and orbital inclination. An example of the chirp form and the detailed structure expected for different detailed parameters is shown in Figure 8.

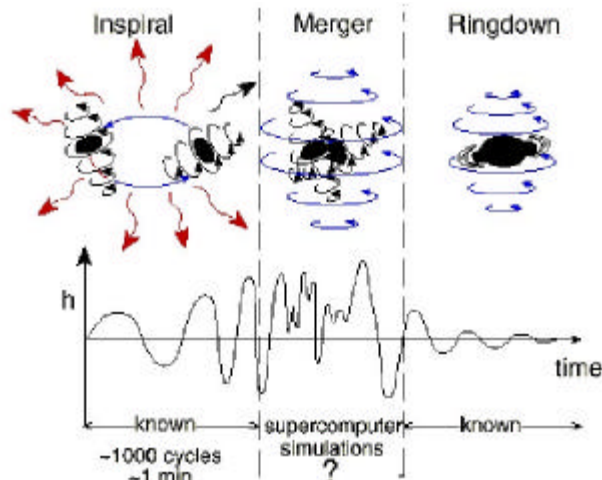


Figure 9. The different stages of merger of compact binary systems are shown. First there is the characteristic chirp signal from the inspiral until they get to the final strong field case and coalescence; finally there is a ring down stage for the merged system

This inspiral phase is well matched to the LIGO sensitivity band for neutron star binary systems. For heavier systems, like a system of two black holes, the final coalescence and even the ring down phases are in the LIGO frequency band (see Figure 9). On one hand, the expected waveforms for such heavy sources in these regions are not so straightforward to parameterize, making the searches for such systems a larger challenge. Research is ongoing to better characterize such systems. On the other hand, these systems are more difficult to characterize because they probe the crucial strong field limit of general relativity, making such observations of great potential interest.

The expected rate of coalescing binary neutron star systems (with large uncertainties) is expected to be a few per year within about 200 Mpc. Coalescence of neutron star/black hole or black hole/black hole pairs may provide stronger signals but their rate of occurrence (as well as the required detection algorithms) are more uncertain. Recently, enhanced mechanisms for $\sim 10M_{\odot}$ blackhole-blackhole mergers have been proposed, making these systems of particular interest.

2.2.2 Periodic Signals

Radiation from rotating non-axisymmetric neutron stars will produce periodic signals in the detectors. The emitted gravitational wave frequency is twice the rotation frequency. For many known pulsars, the frequency falls within the LIGO sensitivity band. Searches for signals from spinning neutron stars will involve tracking the system for many cycles, taking into account the doppler shift for the motion of the Earth around the Sun, and including the effects of spin-down of the pulsar. Both targeted searches for known pulsars and general sky searches are anticipated.

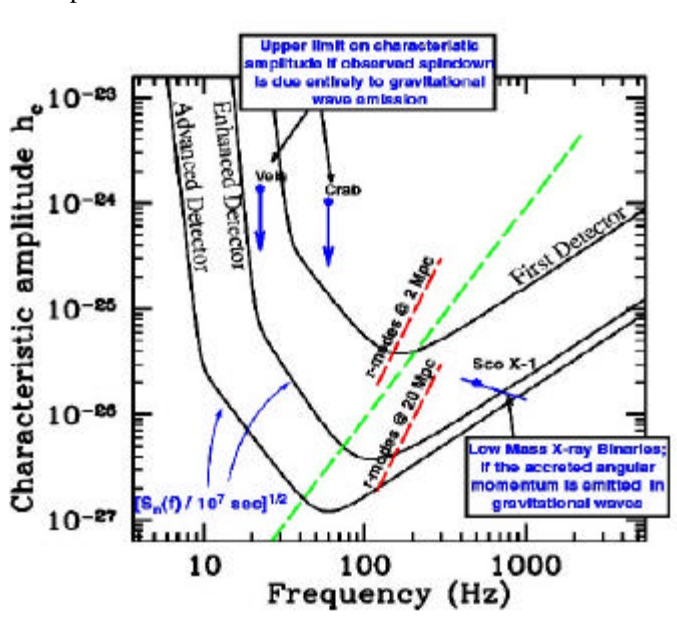


Figure 10. Sensitivity of gravitational wave detectors to periodic sources is shown. The curves indicate the sensitivity in strain sensitivity of the initial LIGO detector and possible enhanced and advanced versions. The known Vela and Crab pulsars are shown at the appropriate frequencies and with the strain signal indicated if the spindown was dominantly into gravitational radiation. The signal from r-modes is also indicated.

2.2.3 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} sec, can be detected through correlation of the background signals from two or more detectors. Gravitational waves can probe earlier in the history of the Universe than any other radiation due to the very weak interaction.

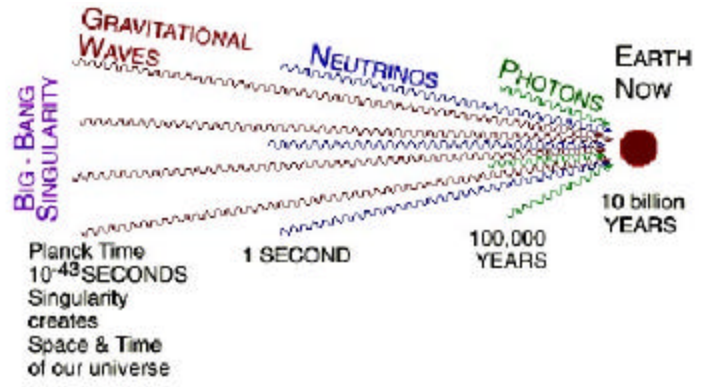


Figure 11. Signals from the early universe are shown. The COBE studies of electromagnetic radiation have been extremely important in understanding the evolution of the early universe. That technique probes the early universe back to $\sim 100,000$ years after the big bang singularity. Neutrino background radiation, if that could be detected, would probe back to within one second of the big bang, while gravitational radiation would actually allow probing the early universe to $\sim 10^{-43}$ sec.

Some models of the early Universe can result in detectable signals. Observations of this early Universe gravitational radiation would provide an exciting new cosmological probe.

2.2.4 Burst Signals

The gravitational collapse of stars (e.g. supernovae) will lead to emission of gravitational radiation. Type I supernovae involve white dwarf stars and are not expected to yield substantial emission. However, Type II collapses can lead to strong radiation if the core collapse is sufficiently non-axisymmetric. The rate of Type II supernovae is roughly once every 30 years in our own Galaxy. This is actually a lower bound on the rate of stellar core collapses, since that rate estimate is determined from electromagnetic observations and some stellar core collapses could give only a small electromagnetic signal. The ejected mantle dominates the electromagnetic signal, while the gravitational wave signal is dominated by the dynamics of the collapsing core itself.

Numerical modeling of the dynamics of core collapse and bounce has been used to make estimates of the strength and characteristics. This is very complicated and model dependent, depending on both detailed hydrodynamic processes and the initial rotation rate of the degenerate stellar core before collapse. Estimating the event detection rate is consequently difficult and the rate may be as large as many per year with initial LIGO interferometers, or less than one per year with advanced LIGO interferometers. Probably a reasonable guess is that the initial detectors will not see far beyond our own galaxy, while an advanced detector should see out to the Virgo cluster.

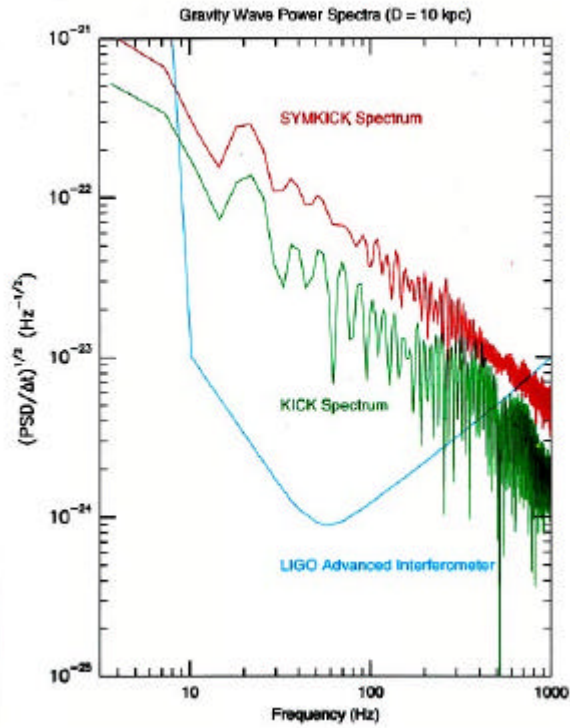


Figure 12. Gravitational wave power spectra from Burrows et al compared to the LIGO advanced detector sensitivity. The LIGO detectors are expected to have sensitivity out to the Virgo cluster.

The detection will require identifying burst like signals in coincidence from multiple interferometers. The detailed nature of the signal is not well known, except that it is burst like and is emitted for a short time period (milliseconds) during the actual core collapse. Various mechanisms of hangup of this collapse have been considered and could give enhanced signatures of collapse. Burrows *et*

al have calculated the gravitational wave signal, taking into account the detailed hydrodynamics of the collapse itself, the typical measured recoil neutron star velocities and the radiation into neutrinos. Figure 12 shows a model calculation of the emission power spectrum into gravitational waves compared with advanced LIGO sensitivities.

3 The Interferometry Technique

A Michelson interferometer operating between *freely suspended* masses is ideally suited to detect the antisymmetric (compression along one dimension and expansion along an orthogonal one) distortions of space induced by the gravitational waves (Figure 13).

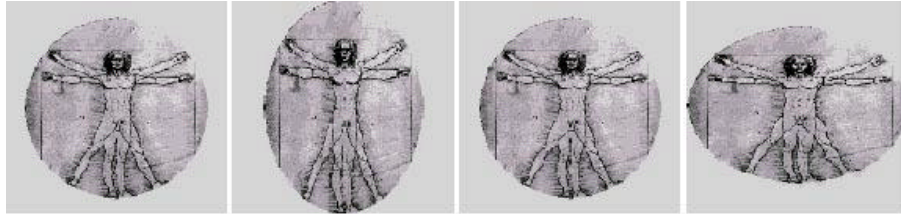


Figure 13. The cartoon illustrates the effect of the passage of a gravitational wave through Leonardo da Vinci's "Vitruvian Man". The effect of the gravitational wave is to alternately stretch and squash space in two orthogonal directions at the frequency of the wave. The effect in this picture is greatly exaggerated, as the actual size of the effect is about 1000 times smaller than the nuclear size.

The simplest configuration, a white light (equal arm) Michelson interferometer is instructive in visualizing many of the concepts. In such a system the two interferometer arms are identical in length and in the light storage time. Light brought to the beam splitter is divided evenly between the two arms of the interferometer. The light is transmitted through the splitter to reach one arm and reflected by the splitter to reach the other arm. The light traverses the arms and is returned to the splitter by the distant arm mirrors. The roles of reflection and transmission are interchanged on this return and, furthermore, due to the Fresnel laws of E & M the return reflection is accompanied by a sign reversal of the optical electric field. When the optical electric fields that have come from the two arms are recombined at the beam splitter, the beams that were treated to a reflection (transmission) followed by a transmission (reflection) emerge at the antisymmetric port of the beam splitter while those that have been treated to successive reflections (transmissions) will emerge at the symmetric port.

In a simple Michelson configuration the detector is placed at the antisymmetric port and the light source at the symmetric port. If the beam geometry is such as to have 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, providing the arms are equal in length (or their difference in length is a multiple of $1/2$ the light wavelength), the entire field at the antisymmetric port will be dark. The destructive interference over the entire beam wavefront is complete and all the light will constructively recombine at the symmetric port. The interferometer acts like a light valve sending light to the antisymmetric or symmetric port depending on the path length difference in the arms.

If the system is balanced so that no light appears at the antisymmetric port, the gravitational wave passing through the interferometer will disturb the balance and cause light to fall on the photodetector at the dark port. This is the basis of the detection of gravitational waves in a suspended mass interferometer. In order to obtain the required sensitivity, we have made the arms very long (4km) and included two additional refinements.

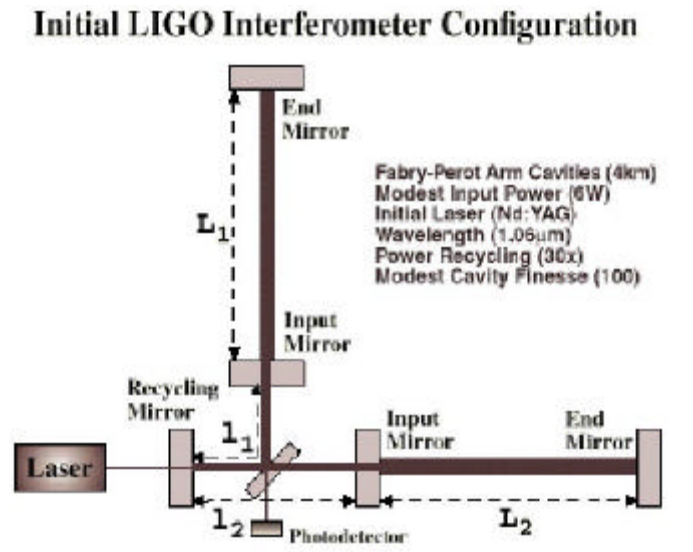


Figure 14. The Optical layout of LIGO suspended mass Michelson interferometer with Fabry-Perot arm cavities.

The amount of motion of the arms to produce an intensity change at the photodetector depends on the optical length of the arm; the longer the arm the greater is the change in length up to a length that is equal to $1/2$ the gravitational

wave wave-length. Equivalently the longer the interaction of the light with the gravitational wave, up to $1/2$ the period of the gravitational wave, the larger is the optical phase shift due to the gravitational wave and thereby the larger is the intensity change at the photodetector. The initial long baseline interferometers, besides having long arms also will fold the optical beams in the arms in optical cavities to gain further increase in the path length or equivalently in the interaction time of the light with the gravitational wave. The initial LIGO interferometers will store the light about 50 times longer than the beam transit time in an arm. (A light storage time of about 1 millisecond.)

A second refinement is to increase the change in intensity due to a phase change at the antisymmetric port by making the entire interferometer into a resonant optical storage cavity. The fact that the interferometer is operated with no light emerging at the antisymmetric port and all the light that is not lost in the mirrors or scattered out of the beam returns toward the light source via the symmetric port, makes it possible to gain a significant factor by placing another mirror between the laser and the symmetric port and 'reuse the light'. By choosing this mirror's position properly and by making the transmission of this mirror equal to the optical losses inside the interferometer, one can "match" the losses in the interferometer to the laser so that no light is reflected back to the laser. As a consequence, the light circulating in the interferometer is increased by the reciprocal of the losses in the interferometer. This is equivalent to increasing the laser power and does not effect the frequency response of the interferometer to a gravitational wave. The power gain achieved in the initial LIGO interferometer is designed to be about 30.

The system just described is called a power recycled Fabry-Perot Michelson interferometer and it is this type of configuration that will be used in the initial interferometers (Figure 14). There are many other possible types of interferometer configurations, such as narrow band interferometers with the advantage of increased sensitivity in a narrow frequency range. Such interferometers may be used in subsequent detector upgrades.

The LIGO interferometer parameters have been chosen such that our initial sensitivity will be consistent both with the dimensional arguments given above and with estimates needed for possible detection of these known sources. Although the rate for these sources have large uncertainty, we should point out that improvements in sensitivity linearly improve the distance searched for detectable sources, which increases the rate by the cube of this improvement in sensitivity (Figure 15). So, improvements will greatly enhance the physics reach and for that reason a vigorous program for implementing improved sensitivities is integral to the design and plan for LIGO.

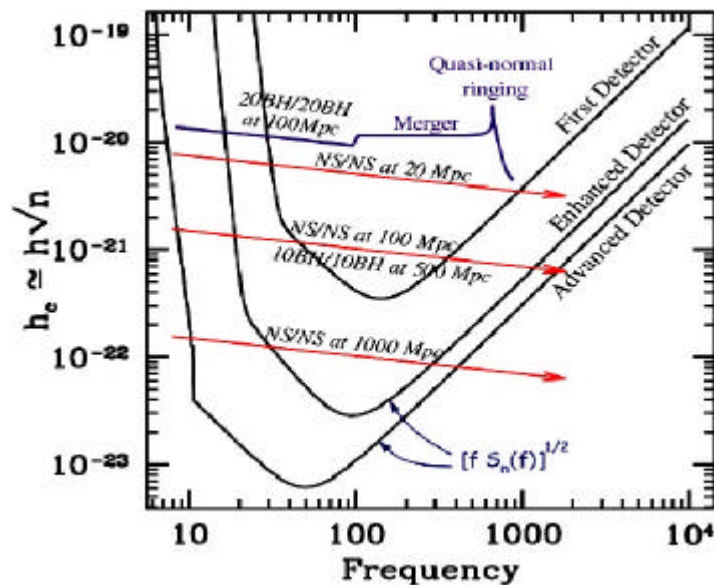


Figure 15. The sensitivity curves of the initial and potential improved LIGO interferometers are shown and compared with the expected signal from the neutron star – neutron star binary inspiral benchmark events. Note that the sensitivity of the initial detector has been chosen as a balance of the arguments above making detection plausible and the use of demonstrated technologies. A program of improvements is envisioned, as indicated in the figure.

4 The Noise or Background: Limits to the Sensitivity

The success of the detector ultimately will depend on how well we are able to control the noise in the measurement of these small strains. Noise is broadly but also usefully categorized in terms of those phenomena which limit the ability to sense and register the small motions (sensing noise limits) and those that perturb the masses by causing small motions (random force noise). Eventually one reaches the ultimate limiting noise, the quantum limit, which combines the sensing noise with a random force limit. This orderly and intellectually satisfying categorization presumes that one is careful enough as experimenters in the execution of the experiment that one has not produced less fundamental, albeit, real noise sources that are caused by faulty design or poor implementation. We have dubbed these as technical noise sources and in real life these have often been the impediments to

progress. The primary noise sources for the initial LIGO detector are shown in Figure 16.

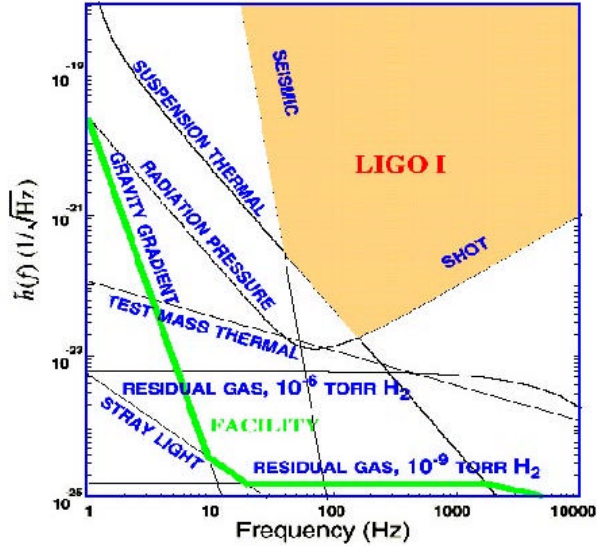


Figure 16. Limiting noise sources for the initial LIGO detectors. Note that the interferometer is limited by different sources at low frequency (eg. seismic), middle frequencies by suspension thermal noise, and at high frequencies by shot noise (or photo statistics). Lurking below are many other potential noise sources.

In order to control these technical noise sources, extensive use is made of two concepts. 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 instabilities experienced in all instruments. For example, the optical phase measurement to determine the motion of the fringe is carried out at radio frequency rather than near DC. Thereby, the low frequency amplitude noise in the laser light will not directly perturb the measurement of the fringe position. (The low frequency noise still will cause radiation pressure fluctuations on the mirrors through the asymmetries in the interferometer arms.) A second concept is to apply feedback to physical variables in the experiment to control the large excursions at low frequencies and to provide damping. The variable is measured through the control signal required to hold it stationary. Here a good example is the position of the interferometer mirrors at low frequency. The interferometer fringe is maintained at a fixed phase by holding the mirrors at fixed positions at low frequencies. Feedback forces to the mirrors effectively hold the mirrors “rigidly”. In the initial LIGO interferometers the forces

are provided by permanent magnet/coil combinations. The mirror motion that would have occurred is then read in the control signal required to hold the mirror.

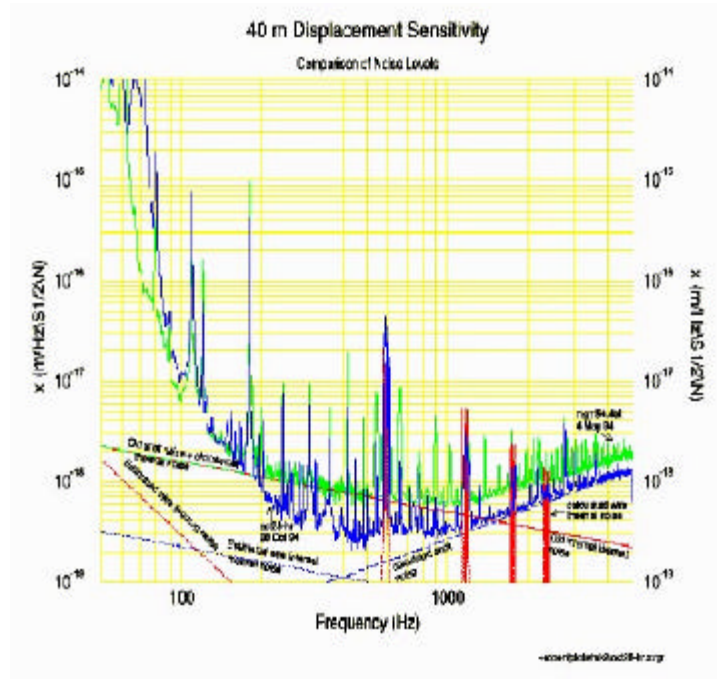


Figure 17. The displacement noise measured in the 40m suspended mass interferometer LIGO prototype on the Caltech campus. The general shape and level are well simulated by our understanding of the limiting noise sources - seismic noise at the lowest frequencies, suspension thermal noise at the intermediate frequencies, and shot noise at the highest frequencies. Also, the primary line features are understood as various resonances in the suspension system.

We have taken great care in LIGO to control these technical noise sources. In order to test and understand our sensitivity and the noise limitations, we have performed extensive tests with a 40 meter LIGO prototype interferometer on the Caltech campus. This interferometer essentially has all the pieces and the optical configuration used in LIGO, so represents a good place to demonstrate our understanding before using in LIGO. The device has achieved a displacement sensitivity of $h \sim 10^{-19} m$, which is essentially the displacement sensitivity required in the 4 km LIGO interferometers. Figure 17 shows the measured noise curve in this instrument and our understanding of the contributions from various noise sources.

In order to test our ability to split a fringe (or demonstrate we can reach the required shot noise limit) to 1 part in 10^{10} , we built a special phase noise interferometer. We have demonstrated that we can achieve the necessary level as shown in Figure 18.

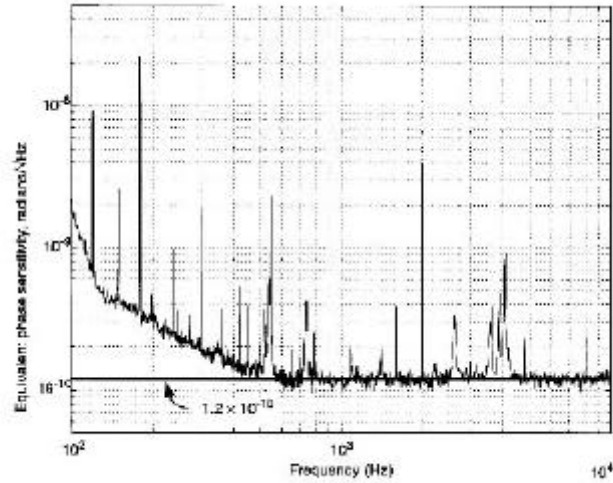


Figure 18. The spectral sensitivity of the phase noise interferometer as measured at MIT. A demonstration interferometer has reached the required shot noise limit of LIGO above 500 Hz. The additional features are from 60 Hz powerline harmonics, wire resonances (600 Hz), mount resonances, etc

5 LIGO - Status and Prospects

Construction of LIGO infrastructure in both Hanford, Washington and in Livingston, Louisiana began in 1996 and was completed on schedule at the end of last year. The infrastructure consists of preparing both sites, civil construction of both laboratory buildings and enclosures for the vacuum pipes, as well as developing the large volume high vacuum system to house the interferometers..

The large vacuum system was the most challenging part of the project, involving 16 km or 1.2 m diameter high vacuum pipe. That system is in place and achieved 10^{-6} torr vacuum pumping only from the ends with vacuum and turbo pumps. The pipes were then 'baked' to accelerate the outgassing by insulating the pipes and running 2000 amps down the pipes raising the temperature to $\sim 160^{\circ}$ for about one week. Following cooldown, the pipes achieved a vacuum of better than 10^{-9} torr. All 16 km of beam pipe is now under high vacuum and the level of vacuum is such that noise from scattering off residual molecules should not be a problem for either initial LIGO or envisioned upgrades.

The long beam pipes are kept under high vacuum at all times and can be isolated from the large chambers containing the mirror-test masses and associated optics and detectors by the means of large gate valves that allow opening the chambers without disturbing the vacuum in the pipes. Figure 19 shows a photograph of several of the large chambers in the central area containing the lasers, beam splitters, input test masses, etc.



Figure 19. A photograph of the large vacuum chambers containing the various LIGO detector components is shown. These chambers are isolated from the long vacuum pipes by gate valves to access the equipment.

The installation and commissioning of the detector subsystems has begun in earnest this year. The laser for LIGO is a 10W Nd:YAG laser at 1.064 μm in the TEM00 mode. The laser has been developed for production through Lightwave Electronics, using their 700 mwatt NPRO laser as the input to a diode pumped power amplifier. This commercialized laser is now sold by Lightwave as a catalog item. We have been running one laser continuously for about one year with good reliability. We are optimistic that this laser will make a reliable input light source for the LIGO interferometers.

For the LIGO application, the laser must be further stabilized in frequency, power and pointing. We have developed a laser prestabilization subsystem, which is performing near our design requirements. We require for $40 \text{ Hz} < f < 10 \text{ KHz}$,

$$\text{Frequency noise: } dn(f) < 10^{-2} \text{ Hz/Hz}^{1/2}$$

Intensity noise: $dI(f)/I < 10^{-6} / \text{Hz}^{1/2}$ This low noise highly stabilized laser system has been tested and is performing near specifications. Figure 20 shows some performance measurements of the prestabilized laser system. Detailed characterization and improvement of noise sources continues.

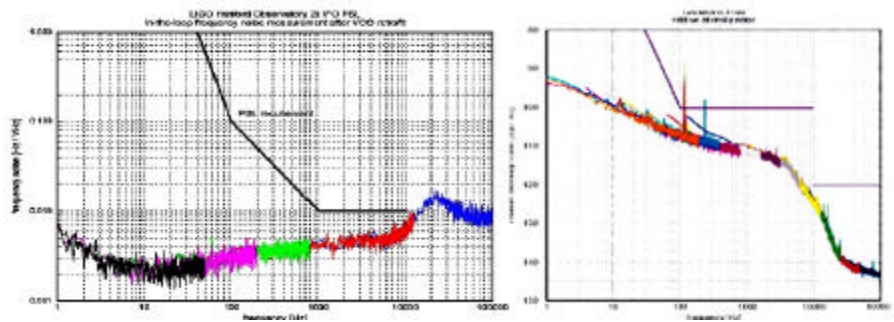


Figure 20. Performance of the LIGO prestabilized laser in frequency (left) and power (right). The lines indicate the noise requirements for the interferometers.

The pre-stabilized laser beam is further conditioned by a 12 m mode cleaner, which is also operational. The beam has been transported through that system and then sent down the first 2 km arm. There is a half length and full length interferometer installed in the same vacuum chamber. The extra constraint of requiring a $\frac{1}{2}$ size signal in the shorter interferometer will be used to eliminate common noise and lower the singles rate in the coincidence between the sites. The first long 2 km cavity has been locked for typical few hour times, at which point tidal effects need to be compensated for and those systems are not yet installed. Various monitoring signals for a 15 minute locked period are shown in Figure 21. Overall, the full vertex system consisting of a power recycled Michelson Interferometer has been made to operate, as well being done as in conjunction with each long arm of the Hanford 2km interferometer, individually. The next and final step for the first interferometer, which we are using as a pathfinder, is to lock both arms at the same time, in order to create the full LIGO suspended mass Michelson Interferometer with Fabry-Perot arms.

We are now optimistic that we will achieve that major milestone this year and will then be able to concentrate on the noise issues, which we expect to interleave with some engineering test runs for data taking. Our long-term plan is to begin a science data taking mode during 2002 with an eventual goal to collect at least 1 year of integrated coincidence data between the two sites with sensitivity near 10^{-21} . Depending on how well we do making LIGO robust and how quickly we solve the noise problems we estimate that goal should be reached by sometime in 2005, at which point we want to be prepared to undertake improvements that will give a significant improvement in sensitivity.

As described above, the initial LIGO detector is a compromise between performance and technical risk. The design incorporates some educated guesses

concerning the directions to take to achieve a reasonable probability for detection. It is a broadband system with modest optical power in the interferometer arms and a low risk vibration isolation system. The suspensions and other systems have a direct heritage to the demonstration interferometer prototypes we have tested over the last decade. As ambitious as the initial LIGO detectors seem, there are clear technical improvements we expect to make, following the initial search. The initial detector performance and results will guide the specific directions and priorities to implement from early data runs.

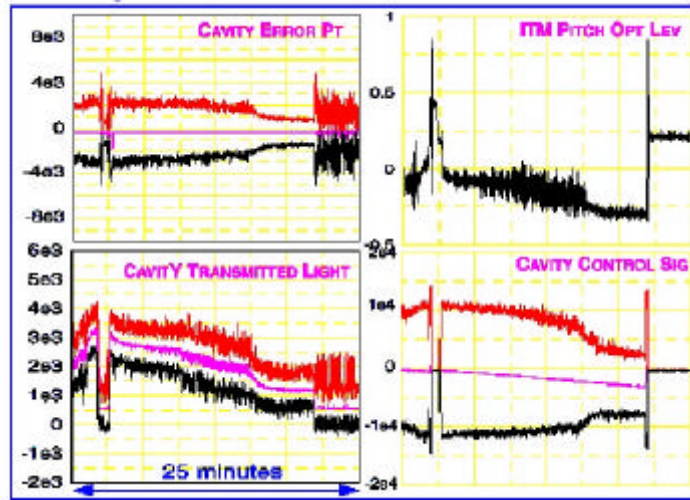


Figure 21. A locked stretch of a 2km arm of LIGO showing the transmitted light and various control and error signals. This marks an important milestone in making LIGO operational.

We expect to be prepared to implement a series of incremental improvements to the LIGO interferometers following the first data run (2002 - 2005). We anticipate both reduction of noise from stochastic sources and in the sensing noise. These improvements will include improvements in the suspension system to improve the thermal noise, the seismic isolation and improvements to the sensing noise through the use of higher power lasers in conjunction with improved optical materials for the test masses/mirrors to handle this higher power. We believe it is quite realistic to improve the sensitivity at 100 Hz by at least a factor of 10, and to broaden the sensitive bandwidth by about a factor without any radically new technologies or very large changes. This will improve the rate (or volume of the universe searched) at a fixed sensitivity by a factor of 1000. If the physics arguments favor an even greater sensitivity in a narrower bandwidth, it will be

possible to change the optical configuration and make a narrow band device. Longer term and move major changes in the detector might use new interferometer configurations and drive the system to its ultimate limits determined by the terrestrial gravity gradient fluctuations and the quantum limit.

We believe that prospects are good that gravitational wave detection will become a reality within the next decade and hopefully sooner.

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