STATUS OF GRAVITATIONAL WAVES EXPERIMENTS

BARRY C. BARISH
LIGO 18-34, California Institute of Technology, Pasadena, CA USA
E-mail: barish@ligo.caltech.edu

ABSTRACT

The direct detection of gravitational waves is a very important experimental goal, both to test the predictions of general relativity and in the long run to open up a new field of gravitational wave astronomy. The effort to develop suspended mass interferometers for gravitational wave detection has lead to an ambitious new set of long baseline interferometers that will soon become operational. The goals and status of the various projects and planned early physics programs are reviewed. The anticipated sensitivities of these instruments are compared with expected source rates, and the prospects and challenges for science running as these instruments become operational is discussed. Finally, the planned evolution of these detectors in the future is outlined.

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, where the information about space-time curvature is contained in the metric as an added term, h. In the weak field limit, the propagation can be described with linear equations. If the choice of gauge is the transverse traceless gauge the formulation becomes a familiar wave equation.

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

The strain h_x takes the form of a plane wave propagating (Fig. 1) 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 observation that if gravitational waves are observed and the two components are decomposed and verified to be at 45°, this classical experiment will have demonstrated the underlying quantum spin 2 structure of gravity.

The solutions for the propagation of gravitational waves can be written as

$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

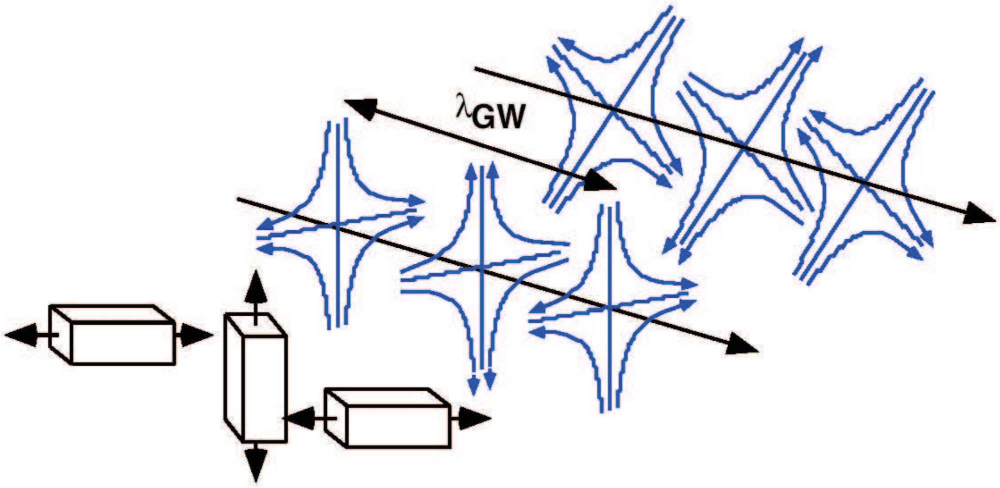

Figure 1: The propagation of gravitational waves illustrating the two polarizations rotated 45^o from each other.

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

Evidence for gravitational 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 $m_1 = 1.4m_\odot$ and $m_2 = 1.36m_\odot$, and the ellipticity of the orbit is x = 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 actuality the inspiral is only 3 mm /orbit so it will be more than 10^6 years before PSR 1913+16 actually coalesces.

Hulse and Taylor monitored the pulsar signals with 50μsec accuracy over many years. They demonstrated the predicted orbital speedup experimentally with an accuracy of a fraction of a percent. The observed speedup is in complete agreement with the predictions from general relativity as illustrated in Fig. 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, the technique employed until now.

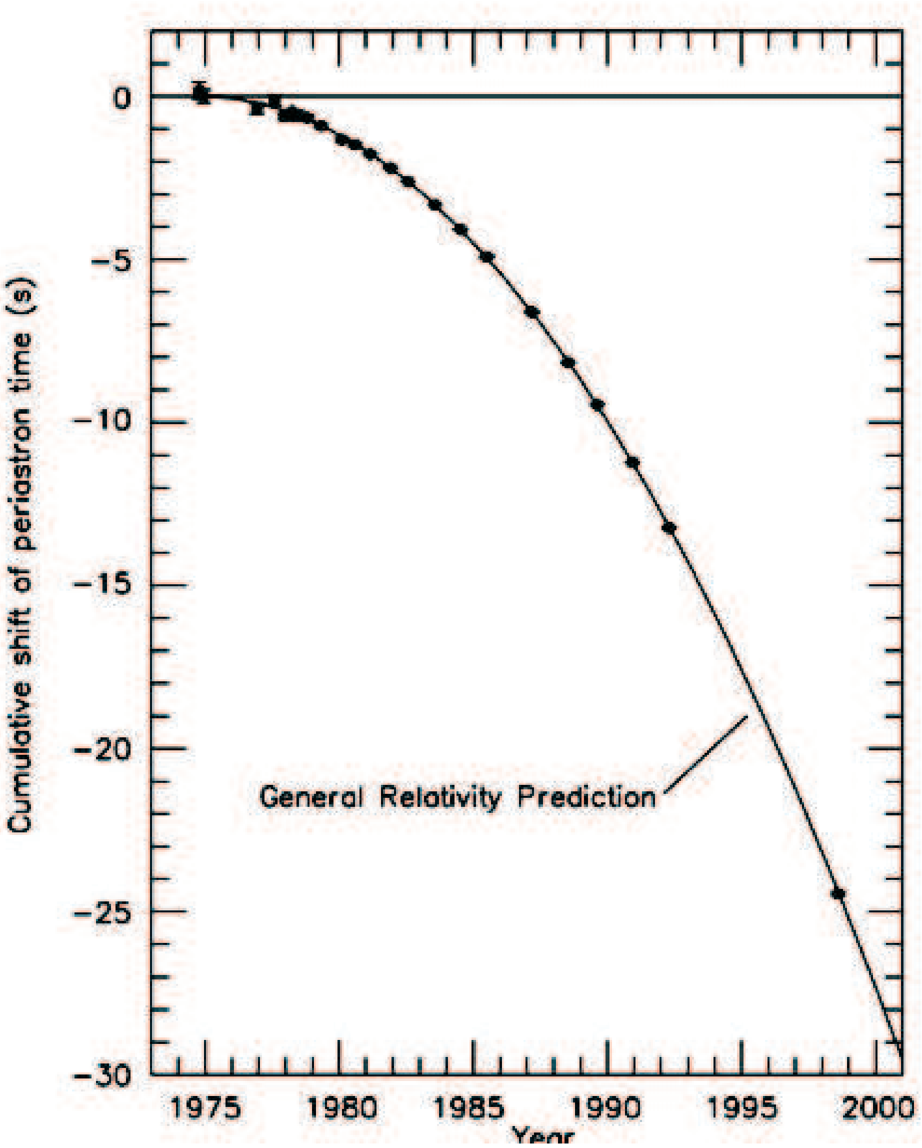

Figure 2: The compact binary system PSR1916+13, containing two neutron stars, exhibits a speedup of the orbital period. Hulse and Taylor monitored the shift of the time of the pulsar's closest approach (periastron) to the companion star. Over 25 years the total shift recorded is about 25 sec. The plot 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 experimentally 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 the analogy to gravitational waves a bit further, the next step for gravitational waves will likewise be direct observation. Following that important achievement, we can fully expect that we will also 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. Gravitational waves will probe the Universe in a very different way, increasing the likelihood for exciting surprises and new astrophysics.

2. Detection of Gravitational Waves

The effect of the propagating gravitational wave is to deform space in a quadrupolar form. The characteristics of the deformation are indicated in Fig. 3.

For an astrophysical source, one can estimate the frequency of the emitted grav-

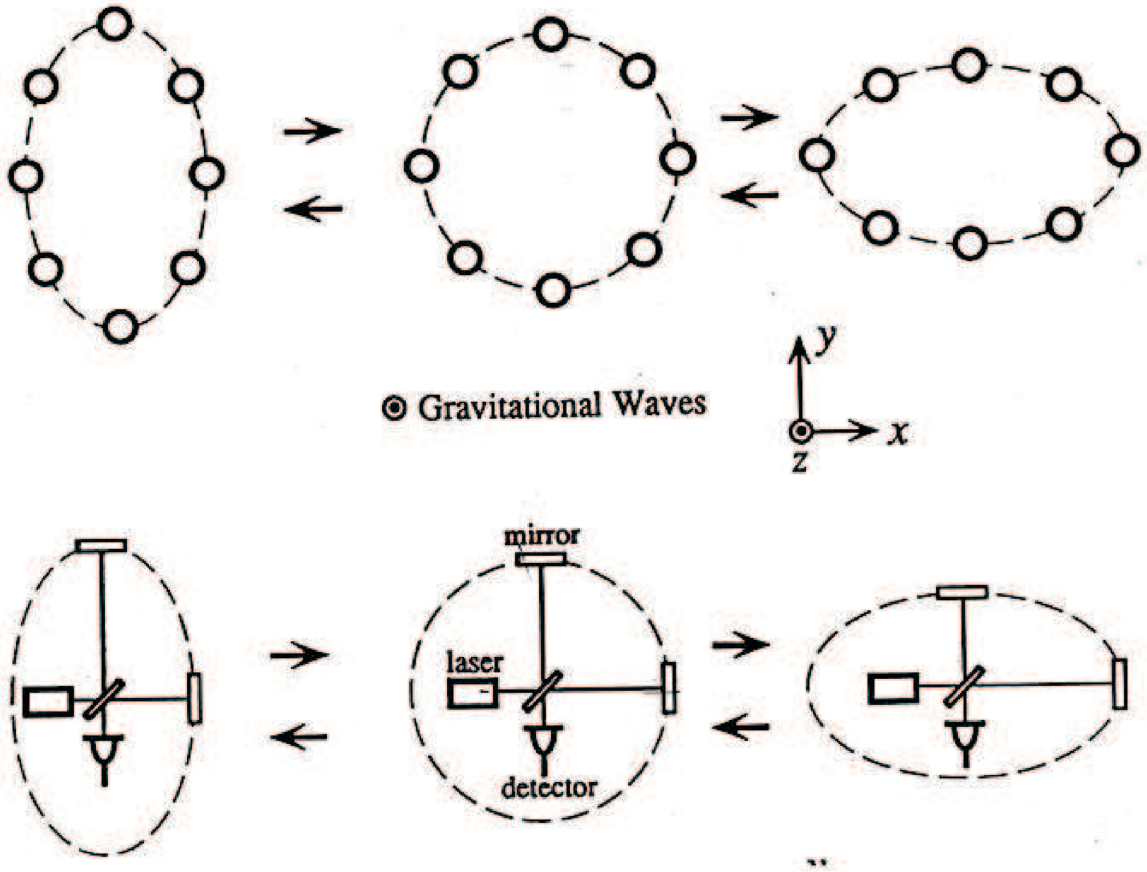

Figure 3: The effect of gravitational waves for one polarization is shown at the top on a ring of free particles. The circle alternately elongates vertically while squashing horizontally and vice versa with the frequency of the gravitational wave. The detection technique of interferometry being employed 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.

itational wave. An upper limit on the gravitational wave source frequency can be estimated from the Schwarzshild radius $2GM/c^2$ of the radiated object We do not expect strong emission for periods shorter than the light travel time $4xGM/c^3$ 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 much lower as illustrated by the 8 hour period of PSR1916+13, which is emitting gravitational radiation. Frequencies in the higher frequency range $1Hz < f < 10^4$ Hz are potentially reachable using detectors on the earth's surface, while the lower frequencies require putting an instrument into space. The physics goals of the terrestrial detectors and the LISA space mission are complementary, much like different frequency bands are used in observational astronomy for electromagnetic radiation.

The strength of a gravitational wave signal depends crucially on the quadrupole moment of the source. We can roughly estimate how large the effect could be from astrophysical sources. If we denote the quadrupole moment 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:

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

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

3. Long Baseline Suspended Mass Interferometry

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 as was illustrated in figure 3. Other optical configurations or interferometer schemes, like a Sagnac, might also be used and could have advantages, but the present generation of interferometers discussed here are of the Michelson type.

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 though 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, the arms of the interferometer must be long.

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 wavelength. 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 or delay lines 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.)

Another feature employed in these interferometers 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'. This technique is general referred to as power recycling. 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 by this scheme can be a factor of 10 or even 100.

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. 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. This can be accomplished by adding yet another mirror in the output port and is generally called signal recycling. Such interferometers are planned for future versions of the various interferometers facilities and the GEO600 interferometer has already incorporated this capability.

The interferometer parameters of the new set of detectors just being brought online have been chosen such that the initial sensitivity will be consistent both with the dimensional arguments given above and with estimates needed for possible detection of known sources. Although the rate for these sources are very uncertain, large improvements in sensitivity are anticipated as the detectors are improved. This is because the planned incremental improvements in sensitivity correspond to the cube of that improvement in the event rate, which scales as the volume searched.

4. The Noise Floor for Interferometer Detectors

The success of the detector ultimately will depend on how well we one can 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. These might be referred to as technical noise sources and in real life these have often been the impediments to progress and mask the limiting noise sources of the interferometer. The primary noise sources for the initial detectors is illustrated in Fig. 4, where the estimated levels of the various noise sources are shown for LIGO. The other interferometers have similar curves with some difference in detail due to the different trade-offs that have been made.

In order to control the 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

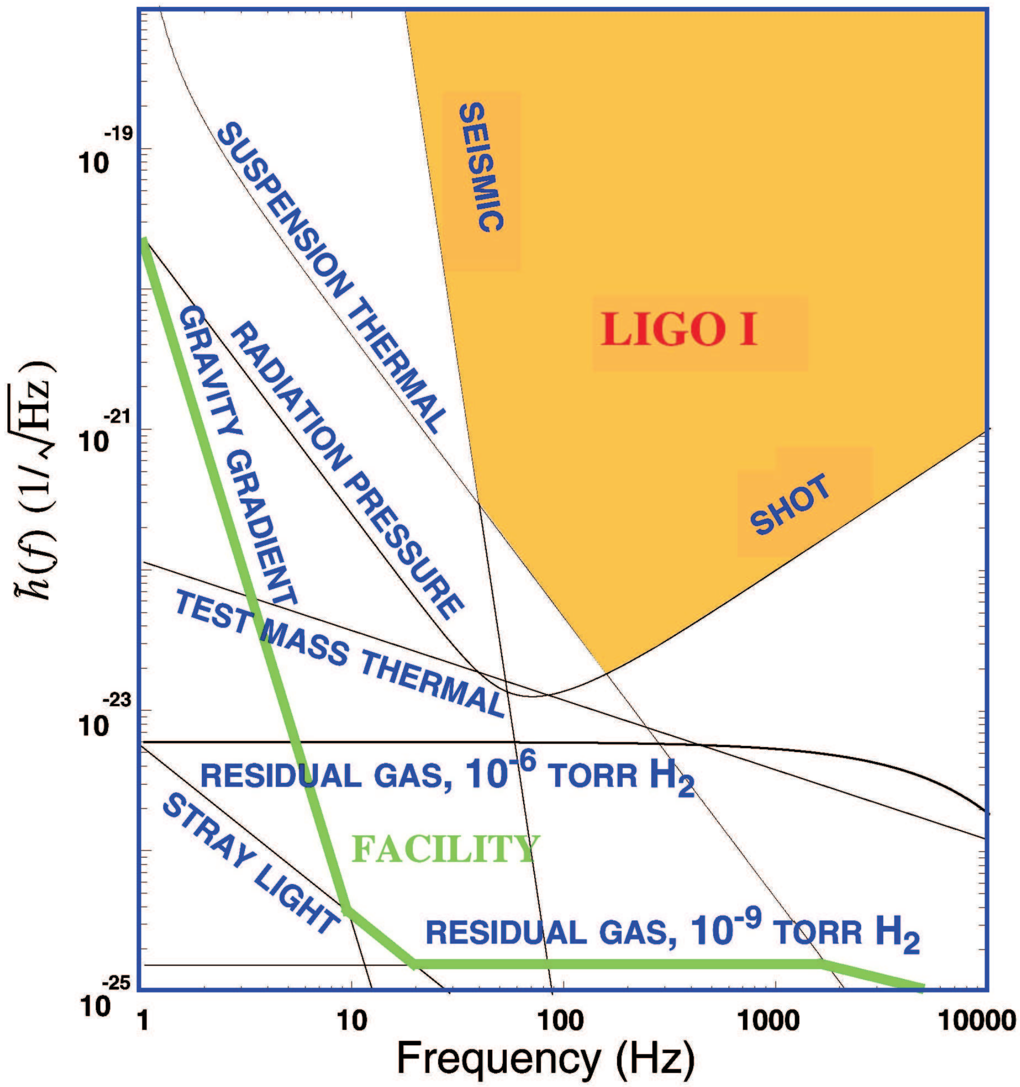

Figure 4: Limiting noise sources for the initial LIGO detectors. Note that the interferometer is limited by different sources at low frequency (eg. seismic), middle frequencies by suspension thermal noise, and at high frequencies by shot noise (or photo statistics). Lurking below are many other potential noise sources.

signal required to hold the mirror.

Great care must be taken to control these technical noise sources. In order to test and understand the sensitivity and limiting noise, extensive tests have been perfomed 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 understand noise and performance before the full-scale LIGO interferometers are in operation. The 40 m prototype device has achieved a displacement sensitivity of $h \sim 10^{-19} m/Hz^{1/2}$, which is close to the displacement sensitivity that is required in the 4 km LIGO interferometers. The modeled noise sources are shown and for the most part are a good representation of the observed performance, including the most of the line structures that are due to wire resonances and other such sources. The same model has been used to determine the expected sensitivity curve for LIGO.

5. Status of the New Long Baseline Interferometers

5.1. TAMA300

The first of the new generation of interferometers (TAMA300) has begun initial operation over the past year. TAMA300 is a Fabry-Perot Michelson interferometer with arm lengths of 300m. The site is at the National Astronomical Observatory of Japan (Tokyo, Mitaka). The interferometer uses a 10W injection-locked LD-pumped Nd:YAG laser and employs a 10m-length ring-type cavity mode cleaner to condition the input beam. The interferometer is designed for power recycling with gain of x10 which has not yet been employed. The design sensitivity is $h_{RMS} = 3x10^{-21}$. The best sensitivity achieved to date is a displacement noise of about $4x10^{-18} m/Hz^{1/2}$, corresponding to a strain sensitivity of approximately $h \sim 1x10^{-20}/Hz^{1/2}$.

5.2. GEO600

The GEO600 interferometer facility, a U.K.- German collaboration is located in Hanover, Germany. It has 600m long arms and incorporates signal recycling and an advanced suspension system. The triple suspension system consists of an upper mass/cantilever spring and intermediate mass and a test mass / reaction mass combination. The controls are applied to the upper masses to reduce noise. 4 x 180mm silica wires are welded to the silica test mass. GEO construction is complete and commissioning is underway. The vacuum system is operational, central optics are installed and a long arm test of the interferometer is in progress.

5.3. LIGO

LIGO at Hanford has both a half-length (2km) and a full-length (4km) interferometer installed in the same vacuum chamber. The extra constraint of requiring a half-size signal in the shorter interferometer will be used to eliminate common noise and lower the singles rate in the coincidence between the sites. Recently, the long 2 km arm cavities have been locked one at a time for typical few hour times, at which point lock is lost due to tidal effects. The electronics to compensate for tidal effects have not yet been installed. This first success at locking a long cavity is an important accomplishment and gives confidence that the entire LIGO interferometer will be locked soon. The next and final step for the first interferometer is to lock both arms at the same time, at which point an operational LIGO suspended mass Michelson Interferometer with Fabry-Perot arms will have been achieved.

Following the locking of the long arms earlier this year, attention this summer has shifted the power-recycled Michelson part of the interferometer, formed by the input mirrors, as well as the beam splitter and the recycling mirror. To make LIGO as sensitive as possible, one wants as much light as possible returning to the beam splitter. This occurs when the recycling mirror is placed at the correct distance from the beam splitter, 'trapping' the reflected light in the Michelson interferometer. This causes the laser light in the interferometer to build up to a high level. For the full system, recycling will cause the light to build up by about a factor of thirty. When this build up occurs, the power-recycled Michelson interferometer is resonating. Such a resonant state was achieved within the last few weeks for the short arm system.

The next step will be to add one of the 2-km-long arms resonating, which will be the final step in preparation for turning on the full interferometer and achieving 'first lock,' which is anticipated this fall.

5.4. Virgo

The Virgo Experiment is a French-Italian collaboration and is located at Cacina, Italy not far from Pisa. The infrastructure housing the central interferometer is complete and the sophisticated seismic-suspension system is being implemented. All four long suspensions for the entire central interferometer are scheduled for completion by October 2000.

The laser, input optics and mode cleaner have been installed and testing of this system, which will lead to a commissioned short arm version of Virgo are planned while the long arms are under construction. The first long arm is scheduled to be completed by 2002, as well as the large optics. The full long baseline interferometer is scheduled to begin operations by the end of 2002.

5.5. AIGO

Initial steps toward a long baseline interferometer facility have been initiated near Perth, Australia. A collaboration of Australian Universities (ACIGA) is developing the facility, as well as actively collaborating with the other interferometer groups. The consortium is doing research on high power lasers, new optical configurations, suspensions, test masses, etc. The central facility for AIGO has been constructed and work is underway to build the central optics and a short arm interferometer as the first step toward the hope of eventually extending the arms to a long baseline interferometer to be used in conjuntion with those being developed in the northern hemisphere. In addition, an R & D program to test optics at the high powers envisioned for second generation inteferometers is being planned.

6. Astrophysical Sources of Gravitational Waves

There are a many known astrophysical processes in the Universe that produce gravitational waves[12]. Terrestrial interferometers 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:

6.1. 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.

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 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 can be represented by the equations

$$h_+(t) = \tfrac{2G^{\frac{5}{3}}}{c^4}(1 + \cos^2(i))\tfrac{\mu}{r}(\pi M f)^{\frac{2}{3}} \cos(2\pi f t)$$

$$h_+(t) = \pm\tfrac{4G^{\frac{5}{3}}}{c^4}(1 + \cos(i))\tfrac{\mu}{r}(\pi M f)^{\frac{2}{3}} \cos(2\pi f t)$$

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, $\mu = m_1 m_2/M$ is the reduced mass and the gravitational wave frequency f (twice the orbital frequency) evolves as

$$f(t) = \frac{1}{\pi}[\frac{c^3}{G}]^{\frac{5}{8}}[\frac{5}{256\mu M^{\frac{2}{3}}(t_0 - t)}]^{\frac{3}{8}}$$

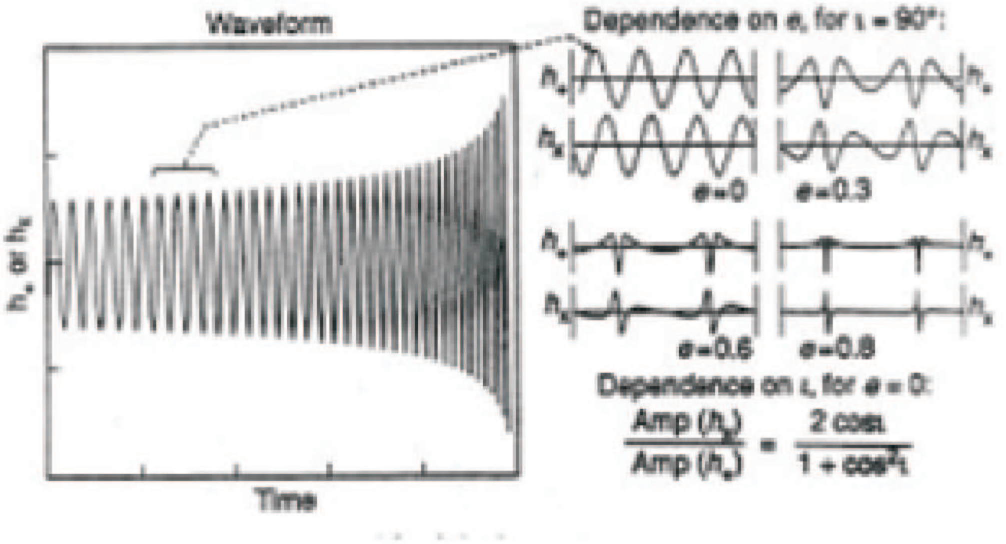

Figure 5: An example is shown of the final chirp waveforms. The amplitude and frequency increase as the system approaches coalescence. The detailed waveforms can be quite complicated as shown at the right, but enable determination of the parameters (eg. ellipticity) of the system.

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.

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 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 Fig. 5.

This inspiral phase is within the terrestrial interferometer 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 interferometer frequency band. 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 airs may provide stronger signals but their rate of occurrence (as well as the required detection algorithms) are more uncertain. Recently, enhanced mechanisms for $\sim 10M >$ blackhole-blackhole mergers have been proposed, making these systems of particular interest.

6.2. Periodic Signal

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 interferometer sensitivity bands. 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.

6.3. 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.

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.

6.4. 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.

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.

6.5. First Astrophysics Search with TAMA

TAMA has presented a first search for astrophysical signals at this conference. The sensitivity is not yet such that they can improve over previous searches or approach detection levels expected by theoretical estimates, nevertheless this analysis provides a good guide toward the ability to do an actual search with interferometer data, especially with its noisy lines, non stationary noise, non gaussian noise and other instrumental effects. More sensitive searches can be expected in the near future.

The TAMA group has perfomed a search for binary inspirals in our galaxy, using a 2-step hierarchical method for Matched templates. The search was performed over a wide range of chirp masses (0.3 $\sim$ 10 M solar), MACHO pair $\sim$ BH-BH. They had a precise calibration of strain & its evaluation in analysis dh/h$\sim$ 1%.

The observed signal / noise distribution is consistent with no signal. For example, for a SNR of 7.2, the expected rate from background noise with no signal is 2.5 events, while the observed rate is 2.0 events. This result can be translated to a limit on binary inspiral events: $Rate < 0.59$ ev/hr 90% C.L. For a $1.4 M_x$ NS-NS inspiral this limit corresponds to a max distance = 6.2 kpc.

It should be noted that this rate limit is orders of magnitude away from the expected rate of binary inspirals from our galaxy ($\sim 10^{-6}/yr$). A previous search[16] was performed with the Caltech 40m suspended mass interferometer prototype, which used 45 hours of data taken in 1994 at a sensitivity of $h \sim 3.510^{-19} mHz^{-1/2}$ and used 687 "matched filters." The limit set in that experiment was $R < 0.5/hour$ with 90% CL. These searches from real data demonstrate the ability to do a physics analysis with real data having various noise features in the data, including non stationary and non gaussian noise.

6.6. Conclusions

The first generation interferometers having sensitivities that should allow searches with $h \sim 10^{-21}$ are becoming operational. These will be the first experimental searches that approach the sensitivity where detection of gravitational waves is plausible. In addition to the anticipated 'stand-alone' searches using each of these detectors, discussions and preparations are underway to bring the data together from the different detectors to do coincidence work to both improve overall sensitivity and confidence in detection. Significant improvements to these detectors are anticipated to be initiated in about 5 years that should improve the sensitivity to $h \sim 10^{-22}$.

7. References

1) Einstein, A. Ndherungsweise Integration der Feldgleichungen der Gravitation. In Sitzungsberichte der Kvniglich Preussischen Akademie der Wissenschaften, Sitzung der physikalich-mathematischen Klasse (1916) p688
2) Einstein, A. Gravitations-wellen. In Sitzungsberichte der Kvniglich Preussischen Akademie der Wissenschaften, Sitzung der physikalich-mathematischen Klasse (1918) p154
3) Pais A. Subtle is the Lord:The Science and the Life of Albert Einstein, Oxford University Press, New York 1982
4) Hulse, R.A. and J.H. Taylor Discovery of a pulsar in a binary system. Astrophysical Journal 195 (1975) L51-L53
5) Taylor, J.H. and. Weisberg, J.M A new test of general relativity: gravitational radiation and the binary pulsar PSR 1913+16. Astrophysical Journal 253 (1982) 908-920
6) Taylor, J.H. and J.M. Weisberg Further experimental tests of relativistic gravity using the binary pulsar PSR 1913+16. Astrophysical Journal 345 (1989) 434-450
7) LIGO http://www.ligo.caltech.edu/
8) VIRGO http://www.pi.infn.it/virgo/virgoHome.html
9) TAMA http://tamago.mtk.nao.ac.jp/ /
10) GEO http://www.geo600.uni-hannover.de
11) ACIGA http// www.anu.edu.au/Physics/ACIGA
12) Thorne K.S. Gravitational Radiation. In 300 Years of Gravitation Edt S.W. Hawking and W. Israel Cambridge University Press, Cambridge, England (1987) Chapter 9
13) Andersson N. A new class of unstable modes of rotating relativistic stars Astrophys. J, (1997) in press.
14) Lindblom L., Mendell G., Astrophys. J., 444 (1995) p804
15) Wagoner R.V. Astrophys. J. 278 (1984) p345
16) Allen, B. et al Physical Review Letters 83 (1999) p1498