Detecting gravitational waves

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ABSTRACT

Gravitational waves carry information about regions of our universe which are otherwise obscured by interstellar matter or are 'invisible' due to the lack of emitting electro-magnetic radiation. Despite their prediction almost 90 years ago and 4 decades of experimental effort (summarized in this article) gravitational waves still await their direct detection. This article gives an introduction into the field of gravitational wave detection and points to more detailed papers within this proceedings issue.

Keywords: Gravitational Waves, Resonant Bars, Interferometer

1. INTRODUCTION

This article gives a brief overview of gravitational wave detection from the historical roots to today's km-scale interferometers and shortly introduces resonant bar/sphere detectors. For more detailed and comprehensive reviews and overview papers the reader may consider to have a look at[1] [2] [3] [4] [5] and references therein.

2. WHAT ARE GRAVITATIONAL WAVES?

Already more than 2 centuries ago in 1776 Laplace,[6] searching for an explanation of the timing of medieval solar eclipses, suggested that the gravitational interaction propagates at finite speed, which in consequence leads to the emission of some sort of gravitational radiation when mass distributions are changed. Relativity and with it General Relativity, where gravitation is described as a curvature of space-time, is built on this finite maximum speed of any signal as a basic assumption. The first approximate solutions of the field equations of General Relativity including the prediction of gravitational waves (GWs) were given by Einstein in 1916[9] and in a refined version in 1918.[10] In contrast to electro-magnetic waves (where due to the bipolar character of charges, dipole fields are the lowest order allowed) the lowest order of GWs are quadrupolar ones and are emitted whenever the quadrupole moment of a mass distribution changes in time. The observable effect of a GW is a change in the distance between free test masses. As a consequence of the quadrupolar nature of the GWs, during one half of a wave cycle space is elongated in one direction while in the direction perpendicular, lengths will be shortened and the opposite will occur during the next half of the GW cycle. Hence the measurement of these length changes provides a direct way to detect and measure the strength of GW. Despite large amounts of energy that are emitted by GWs in some astrophysical processes, space-time is so 'stiff' that the resulting strain is minuscule.

3. WHY DETECTING GRAVITATIONAL WAVES?

GWs are one of the last predictions of general relativity that still awaits direct proof. Indirect proof for the existence of GWs was achieved by Hulse and Taylor[23] who observed the changes of the orbital period of a binary system of two neutron stars and found perfect agreement with the predictions of General Relativity.

Our current understanding of the universe is almost exclusively based on the observation of electro-magnetic waves. Many interesting regions as the cores of galaxies or the center of super nova explosions are obscured by matter between us and the object of interest. Here the weakness of the interaction of gravitational waves with space-time turns into an advantage as GWs can travel long distances and arrive almost unchanged by interstellar matter.

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Some processes, e.g. the inspiralling of binary systems in distant galaxies (the event rate in our own galaxy is estimated to be too low for frequent enough observations) or seismic activity in neutron stars, cannot (yet) be resolved by electro-magnetic observations.

Investigations of the early universe are limited to times after it had cooled down enough to allow for the recombination of free charges (electrons and protons into hydrogen atoms), i.e. about 380,000 years after the big bang. In contrast gravitational waves propagate the universe freely from the time of their emission which may be as early as 10^{-43} s after the big bang.[34]

GWs could also shed new 'light' on questions concerning dark matter[57] which, although difficult to detect via electro magnetic waves, could be observed via the GWs it emits as it moves through space.

The detection of GWs and subsequently their astronomical use in GW observatories will yield new information about the most interesting regions of the universe and quite likely show new, unpredicted sources.

3.1. Sources

The following section describes the known sources of GWs that hopefully will be observed within the next decade.

3.1.1. Supernovae

Considering that the rapid movement of large amounts of mass is the main prerequisite for GW emission, core collapse supernovae (Type Ib, Ic, and II) are certainly good candidates for strong GW radiation[31 35] . The asymmetry of the collapse that is needed to create a big time-varying quadrupole moment is not necessarily fulfilled. Little is yet known about the symmetry of a supernova though the velocity of the supernova remnant suggest a certain asymmetry of the core collapse[8] . The centers of these violent processes are hidden for electro-magnetic observations by the surrounding outward-flowing matter. The GW emitted could send valuable information about the processes going on. Numerical simulations predict short, i.e. a few ms long, bursts of GW signals, where the exact wave-form will depend on the detailed processes going on. In a coincidence run between several detectors comparison of this signature should enable us to veto spurious signals that can arise from the noise of a single detector and differences in time-of-arrival will allow to determine the direction of the signal.

3.1.2. Compact binaries

Whenever an astrophysical object orbits another there will be a strong time-varying quadrupole moment and GW will be emitted. In order to fall into the frequency band that we will cover with the current or next generation of GW detectors these binaries have to have a reasonably short period, e.g. less than 10.000 secs (the lower frequency limit for the space borne detector LISA), and hence have to be close to each other. Ordinary stars would get disrupted by tidal forces before they reach this stadium, so good candidates are compact objects like white dwarfs, neutron stars, black holes, or super massive black holes in the centers of colliding galaxies. They span the whole observable frequency band from $10^{-4}Hz$ to $10^{4}Hz$. The final phase of coalescence will be the most interesting one as here the limits of known physics will be reached when the two companions orbit each other at relativistic speeds or the event horizons of two black holes merge into one.

The orbiting and final plunge of stellar sized objects into a super massive black hole can be used to map the curvature of space-time closer to the event horizon and gain insight into the dynamics of giant black holes.

3.1.3. Rotating neutron stars

A rotating object with deviations from symmetry with respect to its rotation axis has also got a quadrupolar moment and will hence emit GWs. The only objects that are compact enough to spin with a frequency to allow for a sufficient amount of GWs to be radiated are neutron stars and black holes. Centrifugal forces would tear ordinary stars apart before they can reach these speeds.

Irregularities can arise as a remnant from the formation process. If neutron stars or black holes are created in an asymmetric core collapse the newly created object will also be more or less asymmetric and mechanical eigen-modes will be excited and slowly ring down due to internal friction and radiation losses. Observing these processes can yield valuable information about inner processes of the stars.

There is a wide variety of modes (partly named after the restoring force) of neutron stars that could generate detectable amounts of GWs (g(gravity)-modes, p(pressure)-modes, f(fundamental)-modes, w(space-time)-modes,r-modes (Coriolis force))[36 37 58 59] which get excited either in the formation precess or by matter accreted from a close companion[30] .

3.1.4. Stochastic background radiation

If there are too many sources of GWs in a given frequency range such that single sources cannot be distinguished any more they will form a background of radiation. This is expected to be the case in the frequency band between 10^{-4} and 10^{-3} Hz from galactic white dwarf binaries[38] .

In contrast to the electro magnetic background radiation which decoupled about 380000 years after the big bang or neutrinos which may have been emitted when the universe was a few seconds old, relics of GWs [60 34] which originate from times as early as the Planck epoch, i.e. within the first 10^{-43} s, are expected to still propagate the universe at detectable levels. These GWs will have a very broadband spectrum ranging over the entire detection band of all detectors. For details see [33 32]and references therein.

The sources mentioned span a very wide frequency band from periods as long as the life of the universe (matter moving on cosmological time scales, e.g. super-cluster of galaxies, or quantum fluctuations in the early universe) to frequencies up to 10 kHz (neutron star eigen-modes).

4. HOW TO DETECT GRAVITATIONAL WAVES?

After the prediction by Einstein in 1916, GWs were almost ignored by physicists for about four decades as a seemingly artificial product of the equations of General Relativity. The effect onto space seemed anyway to be too small to be detectable. Even Einstein considered the effects of GWs to be too weak ever to be measured directly. After most of the predictions of General Relativity have been verified today (including the GW effect on the Hulse-Taylor pulsar PSR1913+16), and again and again physicists have rechecked the calculations and interpretations, no one really questions the existence of GWs any more.

Today two different principles are employed for the detection of GWs: Solid body resonances and electromagnetic length measurements.

- If a GW hits a solid body, say a metal cylinder, it will cause the body to get stretched and shortened and hence internal body resonances will be excited. These oscillations can then be monitored and serve as a measure of the strain of space.
- The best developed and most sensitive method using electromagnetic waves are Michelson type interferometric GW detectors, but long distance ranging to spacecrafts[20 21] , the moon[19] or pulsars[12 11] can set interesting limits in the nHz frequency range. Investigating the anisotropy of the cosmic micro-wave background can set upper limits in the extremely low frequency band (as low as attoHz)[13] .

4.1. Resonant Bars

Resonant bars, as the name suggests, exploit the internal resonances of metal cylinders, typically with a weight of a few tons and resonance frequencies close to 1 kHz. For the ease of understanding let us imagine the bar cut into two pieces of equal length which are joined by a spring. If a GW passes, space will get stretched or shortened in the direction of the spring and hence the two masses will no longer be in their equilibrium positions (where we assume they have been before). Consequently the mass-spring system will start oscillating at its eigen-frequency. The same will be true for an elastic body. e.g. a metal bar. If the frequency of the GW coincides with the eigen-frequency of the bar, the oscillation will ring up and the displacement of the ends of the bar will be resonantly enhanced. If the displacement of the ends is monitored sensitively enough GWs can be detected. This technique was developed by Joseph Weber[26] , who, in the early 60' set up two aluminium resonant bar detectors separated by 1000 km. These detectors were aluminium cylinders with a weight of about 1 ton suspended inside a vacuum chamber by a wire slung around the circumference. He sensed the oscillations of the cylinders with piezoelectric transducers and in 1965 started reporting coincidences between the two detectors and for decades there were hot debates about whether or not the signals recorded by Weber were real gravitational wave events or just coincidences of detector noise. Experiments in other parts of the world including Munich/Frascati, Glasgow, Rochester, and Yorktown Heights failed to reproduce Weber's results. Over the years the transducers have been refined to improve the peak sensitivity and the bandwidth of similar detectors until the resonant bars reached the thermal noise limit, i.e. thermally excited off-resonant internal motion of the bar, where an improvement of the transducer and sensor could no longer improve the peak sensitivity. As the thermal excitation can be reduced by cooling the bar, the up to now most sensitive instruments are all operated at cryogenic temperatures in the range of a few K down to 100 mK and use sophisticated read-out transducers to achieve good sensitivity around the resonances (ALLEGRO Baton Rouge, LSU (USA),[14] EXPLORER Geneva, CERN, INFN (Switzerland),[16] NIOBE Perth, UWA (Australia)[17] ,NAUTILUS Frascati, INFN (Italy),[16] AURIGA Legnaro, INFN (Italy)[15]). I used the web-sites here for references as they should reflect the most up-to-date status of the projects. The major drawback of resonant bar detectors is the narrow bandwidth of sensitive operation which is a result of the resonant enhancement needed to overcome the noise of the read-out system. Lowering the read-out noise and splitting the main eigen-mode into multiple resonances by coupling to a slightly de-tuned resonant transducer leads to an improvement of the bandwidth from fractions of 1 Hz to 80 Hz at a sensitivity level of $4 \cdot 10^{-21}/\sqrt{Hz}$ which has recently been achieved in the AURIGA detector with a peak sensitivity of about $4 \cdot 10^{-22}/\sqrt{Hz}$.

Although cylindrical shapes have been used for most of the resonant detectors so far, other geometries (truncated icosahedrons, dodecahedron, spheres) have advantages over cylinders such as omni-directionality or larger cross sections for higher order modes. Spherical detectors will be discussed in more detail in another paper in this proceedings issue[63] .

A new proposal for increasing the bandwidth of resonant mass detectors suggests the use of two masses one nested into the other, where the resonance frequency of the bigger one is below the frequency band of interest and the resonance of the inner one above. Such the responses to a GW of the two masses will be 180 out of phase and are expected to yield a broadband response[39 44] .

4.2. Interferometer

The concept of mapping the curvature of space-time between free falling test masses with electro-magnetic radiation was brought up by Pirani in an 1956 paper[7] . Pulsar timing[12 11] , Doppler space-craft tracking[20] , planetary ranging[19] , and interferometers are measurement techniques based on this effect as they all measure the change in the time it takes an electro-magnetic wave to pass the space between two test masses. Using interferometers for the detection of gravitational waves now has a history of about 4 decades. For a review on interferometrical gravitational wave detectors see also[40] .

4.2.1. Historical review of interferometric gravitational-wave detectors

In 1962 two Russians physicists from Moscow (M. Gertsenshtein and V.I. Pustovoit) proposed to detect gravitational waves by observing the fringe shift at the output of a Michelson interferometer after recalculating the sensitivity of the Weber bar and coming to the conclusion, that the sensitivity was 10 orders of magnitude lower than Weber assumed. They estimated the sensitivity of such an interferometer to be $\delta l/l = 10^{-17}$ for frequencies of about 1 kHz assuming that white light would have to be used for a light source and already suggested to run multiple instruments in coincidence to extract information about polarization and direction of the source from the signals.[24] The strength of gravitational waves of astrophysical origin was not as well known as today so it did not appear an impossible undertaking to detect gravitational waves with such a poor sensitivity. Weber independently proposed the use of interferometers in a phone call to Forward two years later in 1964 [27] . Forward together with Moss and Miller at Hughes research labs in Malibu actually was the first one to build an interferometer for GW detection in 1970 [27] and reached a remarkable shot noise limited strain sensitivity of $6 \cdot 10^{-15}/\sqrt{Hz}$ which he could improve within the next two years to $1 \cdot 10^{-16}/\sqrt{Hz}$ using a more powerful laser and folding the optical path[28] . The setup used was a simple Michelson interferometer with an arm length of 2m which was slightly misaligned to get two separate output beams. The power of the two beams was measured with two photo detectors and electronically subtracted to yield the change in arm length difference. His interferometer was mounted onto an optical table with stacks of rubber/metal for seismic isolation. The differential arm length was controlled to give the same light levels on both photo detectors. To that date it was the interferometer with the best displacement sensitivity ever built although other shot noise limited interferometers have been reported earlier. Blum and Weiss submitted a paper in 1966 describing a shot noise limited interferometrical set-up with a sensitivity of about $10^{-14}m/\sqrt{Hz}$ with an interferometer arm length of 1 m[22] . After systematically considering all limiting noise sources Weiss's group at MIT in 1972 started to build an interferometer implementing many new techniques to reduce a variety of noise sources. Many of these techniques have become standard in today's detectors. An interferometer with two outputs has the disadvantage that at the operating point of maximum sensitivity half of the laser light power falls onto each photodiode, which can cause technical problems. One now commonly used way of reducing the amount of light on the photodiodes is the use of a modulation technique, e.g. modulating the frequency/phase of the incident laser beam called inline or Schnupp modulation (named after Lise Schnupp a former member of the Garching group who invented the method in 1978). Monitoring the interferometer output with a photodiode and demodulating with the modulation frequency gives a signal proportional to the arm length difference which, properly filtered, can be used to operate the interferometer at a 'null fringe', i.e. a 'dark output' and use only the signal of one output diode. This method reaches the same sensitivity as reading out the two outputs at 'mid fringe'.

In 1975 the group at the Max-Planck-Institut für Quantenoptik in Garching, Germany (Institut für Physik in Munich in those days) started to setup a 3m interferometer and later successfully operated a 30 m prototype throughout the 80's and 90's and should invent and develop a lot of novel techniques throughout the next two decades.

In 1977 the gravitational-wave research group in Glasgow started to build a 1 m prototype with optical white cells for motion detection and then continued to build a 10 m L shaped interferometer with Fabry-Perot cavities in the arms.

As the goal of a GW detector is to reach a high strain sensitivity it is useful to increase the length of the detector. With space being rather limited in most labs, schemes to increase the optical length were invented. Weiss already in 1972 proposed to fold the optical path of the light inside the interferometer arms to increase the effective length. In some experiments the light path was folded a few hundred times[47] . The optimum path length is half the wavelength of a GW. With even longer paths the phase shift that the laser light accumulated will be diminished by the reversed sign of the GW amplitude during the second half of a wave's period. It turned out in the Garching experiments though that scattered light in a delay line set-up causes up-conversion of the seismic motion and a strong coupling of laser frequency noise into the output signal which made delay-line unusable. Modulating the phase of the laser to give a beat frequency between main and scattered beam outside the detection window was independently proposed by Weiss (MIT) and Schilling from the Garching group and was demonstrated to work with several modulation functions. This method cannot be used together with Power Recycling though, which requires frequency-stable laser light, see below.

A mode cleaner (first proposed by the Garching group in 1979) to reduce lateral beam jitter and later more generally used[46] to suppress laser beam fluctuations (geometric, amplitude and frequency), is a cavity which is resonant to and hence transmits only the fundamental longitudinal and transversal laser mode but not higher order modes. Mode Cleaners are today used for all of the large scale GW detectors.

In 1979/1980 Drever, who moved from Glasgow to the California Institute of Technology in Pasadena, started building a 40 m prototype. This detector was similar to that in Glasgow using Fabry-Perot cavities in the interferometer arms. The optical energy stored in the Fabry Perot cavities determines the sensitivity of the interferometer.

One important step in improving the sensitivity was to reduce the coupling of seismic motion which moves the mirrors and thereby directly affects the arm length of the interferometer. By suspending the optical elements as pendulums the motion of the optics relative to ground rolls off like $1/f^2$ above the resonance frequency of the pendulum, which usually is around 1 Hz. The mirror suspensions have been refined along the years to reach ever better isolation[41] [62] [42] but still limit the performance of modern instruments at low frequencies.

In 1981 Drever and Schilling independently came up with the idea of inserting another mirror in the input of the interferometer. If the interferometer is locked to a dark output port all the laser power is reflected back to the laser itself and thus wasted. If a mirror is placed in the input the light transmitted can be overlapped with the light reflected from the inside. Doing this with the proper phase relation the light power inside the interferometer can be considerably enhanced and hence the influence of the photon shot noise decreased. Power

Recycling can also be used if Delay lines or Fabry Perot cavities are in the interferometer arms. To optimize the sensitivity the optical power in the interferometer arms has to be as high as possible. Then the GW can convert more power from the carrier into signal sidebands. In the case of a detector with arm cavities Power Recycling allows to reach a high power inside the arm cavities without getting a very narrow line width of the arm cavities.

In 1982 the Garching group started to build their 30m prototype using delay lines increasing the effective arm length to about 3 km.

Throughout the next years improvements in the suspensions, modulation methods, laser stabilization etc. led to further enhancement of the sensitivity of the prototypes[47 45] .

1986 the Japanese started to build a 100m delay-line prototype called TENKO100 which reached a sensitivity of about $7 \cdot 10^{-20}/\sqrt{Hz}$.

The first Power Recycling experiments were started in Garching and Orsay/France in 1987 but only moderate recycling factors were achieved due to high losses inside the interferometer. Meers at the University of Glasgow realized that a similar recycling technique can also be used for the signal sidebands by placing a mirror in the interferometer output[43] . If the interferometer is held at a dark port, the carrier frequency exits through the input port where it is recycled by the Power Recycling mirror. The signal sidebands created by the GW are produced with a phase difference of 180 degrees in both arms and thus exit through the dark port. Placing a mirror there, the sidebands can be re-injected into the interferometer and can also be resonantly enhanced giving a stronger GW signal. This idea was demonstrated in a bench-top experiment by Strain and Meers in the Glasgow labs.

In the case where both, Power and Signal Recycling are used it is commonly called Dual Recycling. De-tuned Dual Recycling was first demonstrated in a fully suspended interferometer in the Garching 30m prototype in 2000[44] .

If the Finesse of the Fabry-Perot cavities in the interferometers arms is high and the arms long then the bandwidth of the cavities can become that small (e.g Finesse $\sim$ 1000 and L=4 km $\succ$ bandwidth $\sim 40Hz$) that the sidebands created by the GWs (say at 400Hz) are too far from the resonance (which is tuned for the carrier) as to be enhanced. Therefore the sidebands will be attenuated by the transmittance of the coupling mirror and no net gain will be achieved. To overcome this effect a mirror with high reflectivity for the carrier wavelength and a low reflectivity for the signal sidebands would be required. Jun Mizuno in 1993 published a paper[29] describing how this can be done with an arrangement very similar to Signal Recycling. Here also a mirror is placed at the output port of the interferometer. For the signal sidebands which exit through the output port this mirror together with the first Fabry Perot mirror acts like a composite mirror which can be tuned such that it gives a rather low reflectivity. Hence the signal sidebands can exit the arm cavities without experiencing high losses. The carrier light which exits from the interferometer back through the input port will not 'see' the extraction mirror and will hence only 'see' the high reflectivity of the first Fabry Perot mirror. As the signal sidebands are resonantly extracted out of the Fabry-Perot cavity the scheme is called Resonant Sideband Extraction. This technique has first experimentally been proven in the Garching group[48] and will be used in the next generation of large scale GW detectors. Currently more advanced techniques, e.g. squeezed light, quantum non-demolition read-outs or quantum correlations, are being investigated to further improve the sensitivity of future interferometric GW detectors. Lasers, which delivered just 80μW for Forward's first interferometer are now able of producing more than 100 W of high quality laser light and for the next generation of GW detectors the light power inside the interferometers will be increased close to 1 MW.

4.2.2. Large Scale Detectors

In 1989 the proposals for all of the large scale detectors were submitted: LIGO[49 50] (USA), VIRGO[51 52 53] (France/Italy) and GEO (Germany/UK)(at that time still proposed to be a 3km detector). The construction of the 3km GEO detector failed due to financial problems after the reunification of Germany, so in a new proposal in 1994 GEO was down-scaled to GEO600[54 55] , a 600m detector. The Japanese started their work on TAMA300 in 1995. LIGO, VIRGO and TAMA300 are Power Recycled Michelson interferometers with arm cavities, whereas GEO600 is a dual recycled Michelson interferometer with folded arms, increasing the effective arm length to 1200 m[55] . GEO600 uses advanced techniques as triple pendulum suspensions with a quasi-monolithic fused-silica last stage, thermally adaptive optics correction, a novel vacuum tube design with corrugated tubes, and electro-static actuators to compensate for the shorter arm length in comparison to LIGO and VIRGO. All of the large scale detectors are now in the commissioning phase, i.e. all major systems are installed and the teams are working on improving the noise performance towards the design sensitivity. The current (end of may 2004) best sensitivities for the various detectors are given in table 1 . Once the detectors have approached their design sensitivity their will be prolonged (many months) data taking periods where as many as possible detectors will run in coincidence, as has already been practised for shorter stretches (up to two months) in the past. After the extended data runs the existing detectors will be upgraded to further increase their sensitivity. These upgrades will be based on experiences with the current detectors and prototypes, e.g. the 40 m prototype at the Caltech [67] . In order to decrease environmental disturbances efforts to install detectors underground are made, especially by the Japanese[65] . Thermal noise issues will be treated by cooling the relevant optics to cryogenic temperatures and using different optics materials[66] .

Collaboration	Location	Arm length [m]	Best strain sens. $[/\sqrt{Hz}]$	Best displ. sens. $[m/\sqrt{Hz}]$
GEO600	Hannover/Germany	600	$3 \cdot 10^{-21}$	$2 \cdot 10^{-18}$
TAMA300	Tokyo/Japan	300	$3 \cdot 10^{-21}$	$6 \cdot 10^{-19}$
LIGO	Hanford/USA	4000	$6 \cdot 10^{-23}$	$1 \cdot 10^{-19}$
LIGO	Hanford/USA	2000	$4 \cdot 10^{-22}$	$8 \cdot 10^{-19}$
LIGO	Baton Rouge/USA	4000	$5 \cdot 10^{-22}$	$2 \cdot 10^{-18}$
VIRGO	Pisa/Italy	3000		

Table 1. Sensitivities of the large scale interferometric detectors. The values for the VIRGO detector were left out, because especially for VIRGO being at the beginning of the commissioning process the sensitivity can be expected to change rapidly. At the time of print this information would be completely out-of-date, which of course is what the other teams aim for too.

5. LISA

Due to environmental influences it is currently judged to be impossible to construct interferometric GW detectors on earth that work below frequencies of 1 Hz. It would be extremely difficult to reduce the coupling of local gravity gradients, earth modes and earth tides to the required level. In this regard the ultimate step is to leave earth's limitations and go into interplanetary space for detectors like LISA[69] [68] . LISA is an ESA/NASA mission planned to be launched in the next decade. The interferometric GW detector will consist of an equilateral triangle of three spacecrafts in a heliocentric orbit following the earth at a distance of about 50 million km. The separation of the spacecrafts will be 5 million km. LISA will be most sensitive in the frequency range between 100 μHz and 0.1 Hz and reach an optimum sensitivity of about $1 \cdot 10^{-20}/\sqrt{Hz}$. LISA will be capable of seeing a big number of GW sources and even the best predictable sources, i.e. orbiting compact binaries (white dwarfs, neutron stars, black holes) can be detected with very good signal to noise ratios. For a more detailed overview and status report within this issue see the article of O. Jennrich[69] .

REFERENCES

1. M. Bartusiak, 'Einstein's unfinished symhony', Berkeley publishing group, New York, (2000)
2. P.R. Saulson, 'Fundamentals of interferometric gravitational wave detectors, Singapore: Wolrd Scientific, (1994)
3. S.A. Hughes, 'Listening to the universae with gravitational-wave astronomy', Annals Phys. **303**, 142, (2003), http://arxiv.org/abs/astro-ph/0210481
4. F. Ricci, A. Brillet, 'A review of gravitational wave detectors', Annu. Rev. Nucl. Part. Sci., **47**, 111-156, (1997)
5. S. Rowan et al., 'Gravitational wave detection by interferometry (ground and space)',Living Rev. Relativity, **3**, (2000), http://www.livingreviews.org/Articles/Volume3/2000-3hough/

6. P. Laplace, "Sur le Principe de la Gravitation Universelle", 1776; reprinted in "Ouevres completes de Laplace VIII", p. 201, Gauthier-Villars et fils, Paris, 1891.
7. F.A.E. Pirani, 'On the physical significance of teh Riemann Tensor', Acta Physica Polonica, **XV**, pp. 389-405, (1956)
8. C.L. Fryer et al., 'Gravitational wvaes from stellar collapse: Correlations to explosion asymmetries', accepted by Astrophys. J., http://arxiv.org/abs/astro-ph/0403188 and references therein, (2004)
9. A. Einstein, Königlich Preussische Akademie der Wissenschaften Berlin, Sitzungsberichte, Erster Halbband, 688 (1916).
10. A. Einstein, 'Approximative integration of the field equations of gravitation', in The Collected Papers of Albert Einstein, pp. 201210, Princeton University Press, 1987.
11. A.N. Lommen et al., 'Using pulsars to detect massive black hole binaries via gravitational radiation: Sagittarius A* and nearby galaxies',Astrophys. J., **562**, 297-302, (2001),http://xxx.lanl.gov/abs/astro-ph/0107470
12. D.C. Backer et al, 'Massive black holes, gravitational waves and pulsars', Carnegie Obs. Astrophys. Series. **1**, Pasadena, (2003), http://nedwww.ipac.caltech.edu/level5/March03/Symp1/backer/Backer.html
13. M. Kesden et al, 'Separation of gravitational-wave and cosmic-shear contributions to cosmic microwave background polarisation', Phys. Rev. Lett. **89**, 011304 (2002), http://xxx.lanl.gov/abs/astro-ph/0202434
14. http://gravity.phys.lsu.edu
15. http://www.auriga.lnl.infn.it
16. http://www.roma1.infn.it/rog/
17. http://gravity.pd.uwa.edu.au
18. http://www.minigrail.nl
19. K. NordtvedtClass.,'30 years of lunar laser ranging and the gravitational interaction', Quantum Grav., **16**,A101A112,(1999)
20. J. Armstrong,'Low-Frequency Gravitational Wave Searches Using Spacecraft Doppler Tracking',http://www.cco.caltech.edu/ cajagwr/pdf/Armstrong.pdf, (2000)
21. S.F. Abbate,'The Cassini gravitational wave experiment', Proceedings of the SPIE, **4856** in Gravitational-Wave Detection, edited by M. Cruise et al., 90-97, (2003)
22. R. Weiss, G.D. Blum, 'Experimental Test of the Freundlich red-shift Hypothesis', Physical Review, **155**, 5, pp. 1412ff (1967)
23. Joseph H. Taylor Jr. Nobel Lecture,(December 1993), Binary Pulsars and Relativistic Gravity from *Nobel Lectures, Physics 1991-1995*, Editor Gsta Ekspong, World Scientific Publishing Co., Singapore, 1997
24. Gertsenshteîn M E, Pustovoît V I Zh. Eksp. Teor. Fiz. 43 536 (1962) [Sov. Phys. JETP **16**, 433 (1962)]
25. Weisberg, 'A new test of general relativity: gravitational radiation and the binary pulsar PSR 1913+16', The Astrophysical Journal, vol. 253, pp. 908920, 1982.
26. J. Weber, 'Detection and generation of gravitational waves', Physical Review, vol. 117, pp. 306313, 1960.
27. R.L. Forward et al.,'Photon-noise-limited Laser transducer for gravitational antenna',Applied Optics, **10**, 11, 2495-2498, (1971)
28. R.L. Forward, 'Wideband laser-interferometer gravitational-radiation experiment', Physical Review D, **17**, 2, 379-390, (1978)
29. J. Mizuno,'Resonant sideband extraction: a new configuration for interferometric gravitational wave detectors', Physics Letters A, **175**, 5, 273-276, (1993)
30. R.V. Wagoner, 'Conditions for steady gravitational Radiation from accreting neutron stars', http://arxiv.org/abs/astro-ph/0207589, (2002)
31. C.B. Kimberly, 'Gravitational waves from gravitational collapse', Living Rev. Rel. 6, (2003), http://arxiv.org/abs/gr-qc/0206041
32. L.P. Grishchuk, 'Update on gravitational-wave research', http://arxiv.org/abs/gr-qc/0305051
33. L.P. Grishchuk, 'The early universe odyssey with gravitational waves', http://arxiv.org/abs/gr-qc/0202072, (2002), submitted to World Scientific (March 2004)
34. R.A. Battye et al., 'Primordial gravitational waves: a probe of the early universe',http://arxiv.org/abs/astro-ph/9604059, (1996)

35. C.Y. Cardall,'Core-collapse supernovae and gravitational waves', http://arxiv.org/abs/aqstro-ph/0401060, (2004)
36. N. Anderson et al., 'On the dynamics of superfluid neutron star cores', Monthly notes of the royal astronimical Society, **328**, 4, p. 1129 (2001), http://www.blackwell-synergy.com/links/doi/10.1046/j.1365-8711.2001.04923.x/full/
37. B.S. Sathyaprakash et al., 'Neutron star normal modes', talk at the LSC meeting 2004 in Baton Rouge, www.ligo.caltech.edu/docs/G/G040141-00/G04141,00.ppt,(2004)
38. N.J. Cornish, 'Detecting a stochastic gravitational wave background with the Laser Interferometer Space Antenna', Phys. Rev. D, **65**, 022004, (2002)
39. T. Briant et al., 'Thermal and back-action noises in dual-sphere gravitational-wave detectors', http://arxiv.org/abs/gr-qc/0301048, Phys. Rev. D, **67**, 102005, (2003)
40. N.A. Robertson, 'Laser interferometric gravitational wave detectors', Class. Quant. Grav., **17**, R19.R40, (2000)
41. N.A. Robertson et al., 'Quadruple suspension design for advanced LIGO', Class. Quant. Grav. **19**, 4043-4058, (2002)
42. The VIRGO Collaboration, 'The inertial damping of the VIRGO superattenuator and the residual motion of the mirror', Class. Quantum Grav. **19**, 1631-1637, (2002), stacks.iop.org/CQG/19/1631 and references therein.
43. B. Meers, Phys. Rev. D, **38**, p. 2317, (1988)
44. A. freise et al., 'Demonstration of detuned dual recycling at the GArching 30m laser interferometer', Phys. Lett. A, **277**, p. 135-142, (2000)
45. H. Ward,'Workshop contribution to GR12', reviewed by J. Hough, in *General Relativity and Gravitation*, Porceedings of the Twelfth International Conference on General Relativity and Gravitation, Boulder, Colorado, 1989, ed. by N. Ashby et al., Cambridge press, Cambridge, England, (1990)
46. A. Rüdiger et al., Optica Acta, **28**, p.641ff, (1981)
47. D. Shoemaker, 'Noise behaviour of the Garching 30-meter prototype gravitational-wave detector', Pys. Rev. D, **38**, 2, 423-432, (1988)
48. G. Heinzel et al., 'An experimental demonstration of resonant sideband extraction for laser-interferometric gravitational wave detectors',Phys. Lett. A, **217**, 305, (1996)
49. A. Abramovici et al., Science, **256**, 325, (1992)
50. F.J. Raab, 'Overview of LIGO instrumentation', this issue
51. C. Bradaschia et al., Nucl. Instr., Methods Phys. Res. A, **289**, 518, (1990)
52. F. Acernese et al., Class. Quantum Grav.,**19**, 1421, (2002)
53. http://www.virgo.infn.it
54. K. Danzmann, in *First E. Amaldi Conf. on gravitational wave experiments*, edited by E. Coccia et al., (World Scientific, Singapore), 100-111, (1994)
55. K.A. Strain, 'The status of GEO600', this issue
56. M. Ando et al., 'Stable operation of a 300-m laser interferometer with sufficient sensitivity to detect gravitational-wave events within our galaxy', Phys.Rev. Lett., **86**, 3950, (2001)
57. T.J. Sumner, 'Dark matter', this issue
58. G. Woan, 'Graviastronomy with neutron stars', this issue
59. A. Vecchio et al., 'Searching for accreting neutron stars with GEO and LIGO', this issue
60. C. Ungarelli et al., 'Early universe cosmology with gravitational wave laser interferometers', this issue
61. B.S. Sathyaprakash, 'Searching for black holes in gravitational wave data', this issue
62. N.A. Robertson et al., 'Seismic isolation and suspension systems for advanced LIGO', this issue
63. E. Coccia, 'Spherical detectors', this issue
64. M. Bignotto et al., 'Dual detectors of GW', this issue
65. S. Sato et al., 'Ultra-stable performance of an underground-based laser interferometer observatory for gravitational waves', http://arxiv.org/abs/gr-qc/0403080

66. T. Uchiyama et al.,'Present status of large-scale cryogenic gravitational wave telescope', Class. Quantum Grav., **21**, 1161-1172, (2004)
67. O. Miyakawa, 'Sensing and control of the advanced LIGO optical configuration', this issue
68. http://lisa.jpl.nasa.gov
69. O.Jennrich, 'LISA: a mission to detect and observe gravitational waves', this issue