Gravitational Wave Detection

- forefront or backwater of astronomy?

A dissertation for the UCL evening certificate in astronomy (2nd year)

A J Rumsey, May 2009

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1. Introduction and preamble

The race is on to be the first to detect a gravitational wave.

Considerable resources around the globe have been channelled into cutting-edge gravitational wave detection research and associated technological development in the last two decades. Scientists clearly believe that they are on the verge of making some exciting historical discoveries and the prizes will be substantial if they are right. Not only is personal kudos there for the winners, but also the immense scientific satisfaction of substantiating, yet again, the substance of the theories of one of the world's foremost genii – Albert Einstein. His general theory of relativity, which has towered over all of science through the 20th century and into the 21st conceivably stands or falls depending on the outcome.

The very existence of gravitational waves remained theoretical until quite recently, but finding the astronomical basis of the indirect evidence for their existence was enough to earn two astronomers a Nobel Prize. Interestingly, it seems as if the Nobel Prize panel were not quite convinced enough of those conclusions and cleverly hedged their bets by awarding the prize for finding a new type of Pulsar - *not* for proving the existence of gravitational waves and speed of propagation (although those very conclusions were drawn by the recipients). But perhaps history repeats itself; Einstein himself of course received his Nobel Prize not for his special or general theories of relativity, but for developing a law that proved the photo-electric effect.

So what are gravitational waves? How are they produced and how can they be directly detected? This dissertation is an attempt to draw together some information on the subject.

But what if they cannot be detected because they simply do not exist?

If they do not exist, a lot of scientists will find themselves instead of being on a surfboard at the forefront of a new wave of discovery, will suddenly discover that they have been frantically paddling pointlessly up a backwater of astronomy; a scientific cul-de-sac.

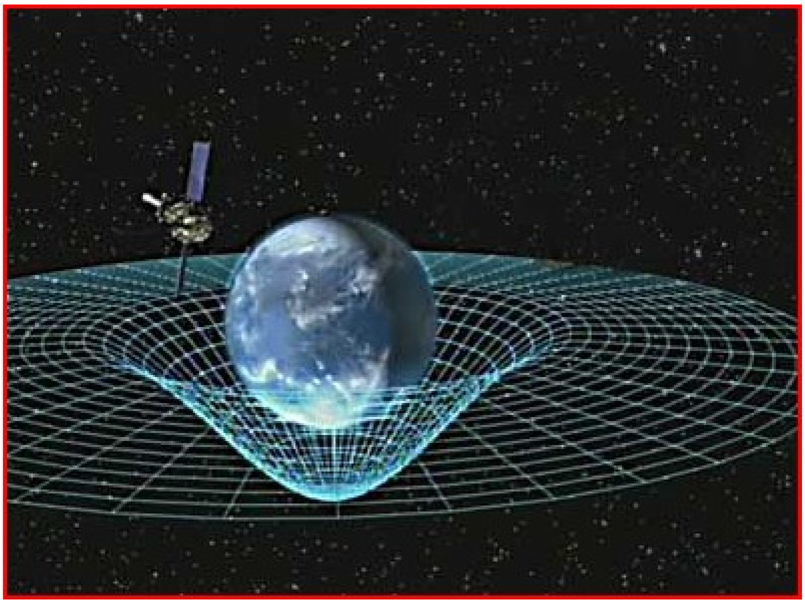
But how will we ever know we are wrong? Perhaps will we keep designing and building ever more complex and sensitive instruments and listening out for sounds from the distant universe that will never be heard.

What then? ... back to the drawing board. Perhaps when the large hadron collider at Cern is fixed, one of the missing pieces of the quantum theory jigsaw will be found and somehow a plausible connection between relativity and quantum theory can be forged; or perchance a 21st century Einstein will provide us with a grand new unified theory of everything.

2. Development of the idea

The idea that waves of gravitational disturbance can occur within the medium of space (or space-time) stems from Einstein's conception of how gravity works. His relativity theories conceive of the effects of gravity being caused by the existence of mass creating a so-called curvature within the very stuff of space-time - and the effect of the curvature is an area of gravitational potential around the object, relative in strength to that object's mass-density. For instance, a relatively lightly dense object such as a star would have a relatively low gravitational potential around it, and a highly mass-dense object such as a collapsed neutron star would have a much stronger gravitational 'well' around it.

This conception is often visualised in two-dimensions as follows:



Using this 2-dimensional conception of a gravity field, it can be visualised that a movement of the mass (an acceleration, or oscillation other than spin) could somehow cause a wave to develop within the stuff of space and propagate through the continuum of space-time, in the same way as observed when dropping a pebble in water, or the expanding wake of a ship after the ship has passed. But these two-dimensional concepts then have to be conceived in three dimensions to get the picture. Waves in water occur on the surface between the two mediums of air and water: here we are trying to picture something akin to pressure waves in air such as allow sound to propagate). In particular, oscillations of compact massive bodies that create very strong gravitational effects, such as white dwarfs, neutron stars/pulsars, and black holes - and especially, binary combinations of these, in slowly decaying orbits about their common centre of mass - should create waves with particular frequencies that can travel great distances through space-time and be detected with suitable receivers on, or even better, above the earth. Such waves, it is posited, propagate as electro-magnetic waves do, at the speed of light.

If these waves do exist, then it must be possible to detect them.   And once detected, they could provide additional insights for astronomers into some of the most fascinating objects and systems in the universe.

So far however, direct detection has eluded scientists. Gravitational waves would be extremely difficult to detect: primarily because they are expected to interact very weakly with matter, and secondly, having only been a small fraction of the power of electro-magnetic waves at the outset they will dissipate greatly over time and distance. Therefore the amount of the expected ‘strain’ – the effect the gravitational wave will have on any detecting apparatus, will be fantastically small, and the detecting instruments will need to be correspondingly fantastically sensitive. E.g. it is estimated that a binary neutron star system 100 Mega parsecs distant, oscillating at 100 Hertz, would create a strain (the fractional change in distance) of about $h = 10^{-21}$ [source: presentation by John S Jacob, Australian International Gravitational

Research Centre]. This fraction represents an infinitesimal amount of movement: in a 100 kilometre long detector, this translates to 1 x 10 trillionth of a millimetre – about 20 times smaller than a proton or neutron!

So how might gravitational waves be detected? Unlike electro-magnetic radiation, gravitational waves cannot be trapped and focussed and so cannot be used to form an image of the emitting body/system. Electro-magnetism is generated by individual particles, whereas detectable gravitational waves are generated by whole bodies or systems. One analogy used is that where telescopes are our eyes on the universe, so gravity wave detectors will become our ears.

The possibility that astronomy could have another medium with which to investigate the far reaches of the universe is a bit of a holy grail to some. It is only in relatively recent years that astronomers have been able to expand the usefulness of wavebands of the electromagnetic spectrum outside of the visible; first, the development of radio astronomy in the middle of last century and then, through being able to launch telescopes into space infra-red, x-ray and some gamma ray astronomy has been possible.

Because gravitational waves move through the substance of space their passage should not be impeded by the existence of material such as gas and dust (and perhaps even dark matter) that can otherwise prevent us seeing through it, thus allowing astronomers to glean information on otherwise invisible objects. Particularly exciting is the prospect that black holes, and black hole binaries which cannot be directly seen because their gravity is so powerful that it prevents the escape of light, could reveal information on their activity to us via gravitational waves.

It is also conjectured that because gravitational waves can pass through space-time unhindered there may be information to be gleaned that could provide insights to events in the very early universe (similar to the way that the cosmic microwave background, which is radiation released from shortly (380,000 years) after the big bang, is available to us today and helps us piece together theories of cosmic evolution).

3. Evidence for the existence of gravitational waves

There is clearly an international race on at the moment to see who will be the first to provide conclusive direct evidential proof of the existence of gravitational waves. In that event, it will be of course, ‘business as usual’: international kudos for the winners; oblivion for the also-rans.

Currently there is **no** direct i.e. experimental/observational evidence for the existence of gravitational waves; no GW detectors have published any conclusive findings – or indeed *any* findings of significance.

The first attempt at physical detection, by Joseph Weber at Maryland University, used a wire suspended detector with a resonant cylinder of aluminium. He announced first in 1969 that he had detected signals that could only be passing gravitational waves, and secondly in 1970 that these peaked in line with the direction of the galactic centre [ref: Physical Review Archive 25, 180-184 1970]. Unfortunately no-one else could duplicate his results in spite of building similar apparatus, and his results were subsequently discredited as not being sufficiently scientifically robust. Nevertheless his pathfinding methods showed that the techniques could be viable using mass resonant devices.

Even indirect evidence for the existence of gravitational waves was elusive until the 1970's. Then in 1974 the giant 305 metre diameter Arecibo radio telescope was being used by Joseph Taylor and Russell Hulse to find new pulsars.

A pulsar is a spinning neutron star. It emits electro magnetism in the form of gamma rays, x-rays, radio waves and some light in a regular way (the first one was discovered famously by the Cambridge astronomers Jocelyn Bell and Antony Hewish in 1967).

One of the many new pulsars found by Taylor & Hulse turned out to be a binary pulsar pair – i.e. two pulsars orbiting round a common centre of gravity. Analysis of four years of observational data showed that the two pulsars were slowly closing in on each other, their orbits were decaying. Taylor and Hulse showed that this decay was consistent with the energy loss due to the production of gravitational waves as predicted by Einstein's theory of relativity.

Following is a graph of the shift (decay) of the orbital phase of the binary pulsar over time and the general relativity prediction of energy losses from gravitational radiation (brought up to the date of their Nobel Prize lectures):

Joseph H. Taylor, Jr. 87

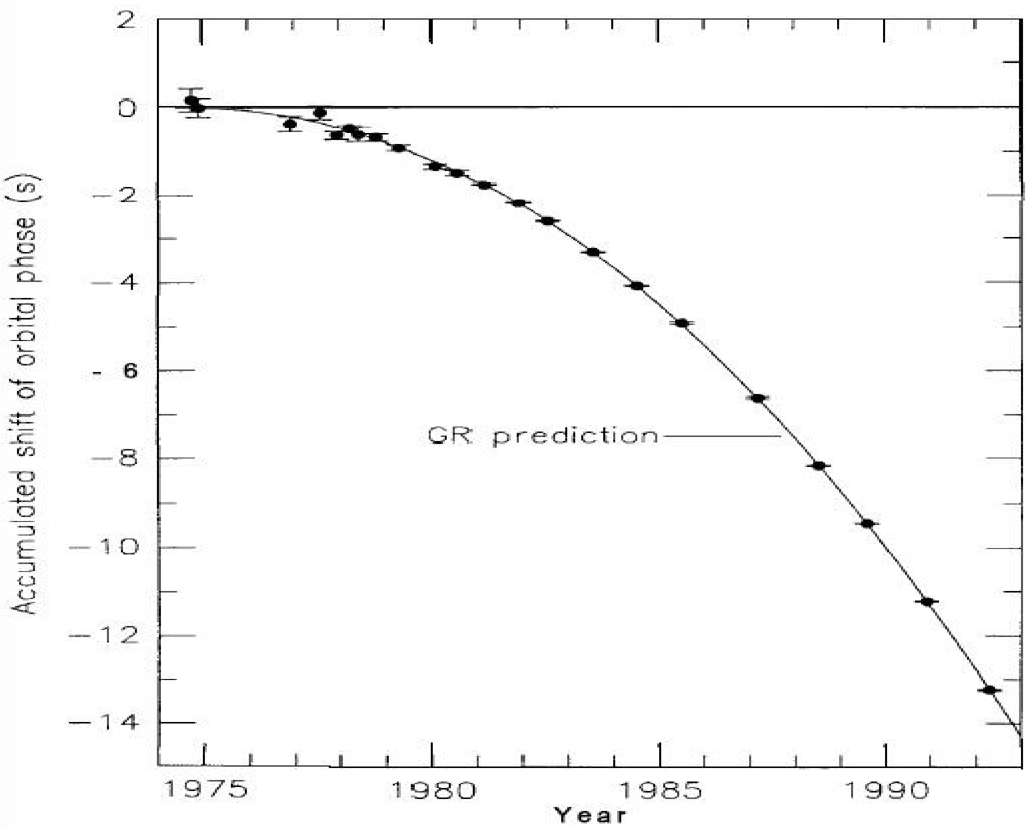


Fig. 10: Accumulated shift of the times of periastron in the PSR 1913+16 system, relative to an assumed orbit with constant period. The parabolic curve represents the general relativistic prediction for energy losses from gravitational radiation.

" The clock-comparison experiment for PSR 1913 + 16 thus provides direct experimental proof that
changes in gravity propagate at the speed of light, thereby creating a dissipative mechanism in an orbiting system. It necessarily follows that gravitational radiation exists and has a quadrupolar nature."

Graph and quote taken from Joseph Taylor's Nobel lecture of Dec 8 1993.

It can be seen that the plots of the orbital phase shift are almost perfectly correlated to the line with the general relativity prediction.

For their discovery of the new type of pulsar, Taylor and Hulse won the 1993 Nobel prize for physics.

So if gravitational waves are eventually directly detected this will provide another long sought substantiation of Einstein’s general theory of relativity as the simplest and most effective current description of gravity in modern physics.

If not, then until it is *proven* that they do not exist, significant amounts of money, time and effort will surely go into building more and more sophisticated detecting apparatus, while the received wisdom of Einstein’s general theory will increasingly be questioned.

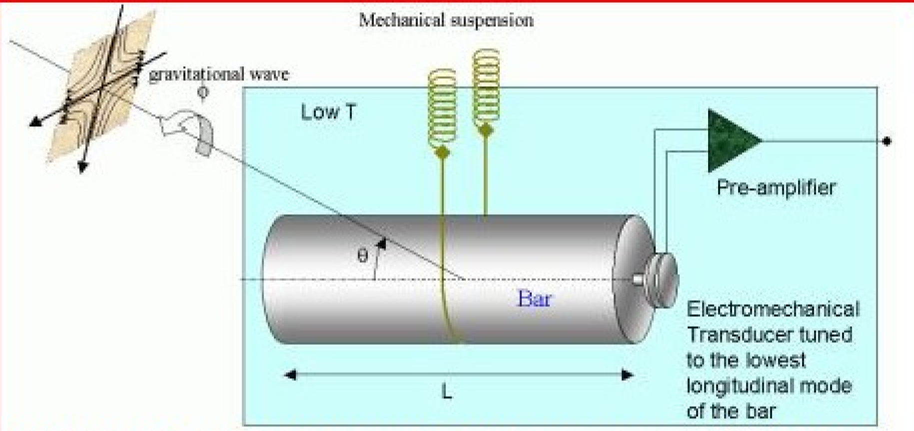
4. Gravitational Wave Detectors

There are two types of detector being developed and refined at the moment: those based on resonant mass detectors (using either a bar or a sphere) and those based on laser interferometers. Both types of detector are based on the assumption that gravitational waves are quadrupolar in nature and will distort matter alternately in two perpendicularly opposing dimensions as they pass. A resonant mass detector is designed to effectively resonate and the resulting vibrations are measured. In the case of laser interferometers, the changing length of two long perpendicular arms can be measured.

Comparing results between two detectors is key to verifying attributable detections or ‘coincidences’.

a)Resonant mass detectors

These essentially represent refinements of the design used by Joseph Weber where a mass, usually a cylinder (e.g. ‘Nautilus’ & ‘Explorer’ : Italy) or sphere (e.g. ‘miniGrail’: Netherlands), is suspended within an area damped to try and exclude non-gravitational wave influences. One or more transducers are connected onto the mass. The transducers are tuned to detect resonances within the bar and so convert the mechanical ‘strain’ in the bar to an electrical signal. It seems there are no longer any spherical detectors currently operating and some bar detectors such as ‘Allegro’ have finished their science runs.



Schematics of a gravitational wave bar detector: Image courtesy of AURIGA Detector.

For Allegro, the sensitivity range of the bar antenna was around 900 Hz, where, it transpires, there are forecasted to be very few specific astronomical sources available. In addition a number of problems occurred with continuity of data: routine maintenance (top up of helium for the cryogenics); global seismic interruptions effectively saturating any likely resonances from GWs; local weather conditions interfering with reception for their radio clock. In addition there were limited computer resources available for data analysis.

[A relevant aside to this last point is the development of distributed processing of gravitational wave detector data via the internet. 'Einstein@Home' is very similar to 'Seti at home' – the well-known Search for Extra-Terrestrial Intelligence where data from the giant radio telescope at Arecibo is distributed to home PC users via the internet for analysis. Similarly the Einstein@Home scheme distributes data from LIGO, an interferometer gravitational wave detector in the USA. Huge amounts of numerical data can be produced from these detectors. The data is pre-processed and analysed by PC users at home (for free) while their PCs are otherwise idle and the results then returned. It is a most ingenious system for circumventing both the lack of and cost of data processing. Amateurs can thereby feel they are making a useful contribution to the advance of science.]

Of course initial runs operate as test beds for future more sensitive detectors. The authors of the paper on the Allegro results comment "we have essentially made a demonstration of the capabilities of resonant detectors for this type of search" and go on to say: "however, it is important to note that even with these restrictions, the analysis has reached a level of sensitivity which is astrophysically interesting. If a source were to become known with the correct frequency, and, as our sensitivity was limited by hardware which has been substantially improved, it seems likely that such a signal could be detected and new astrophysics learned”.

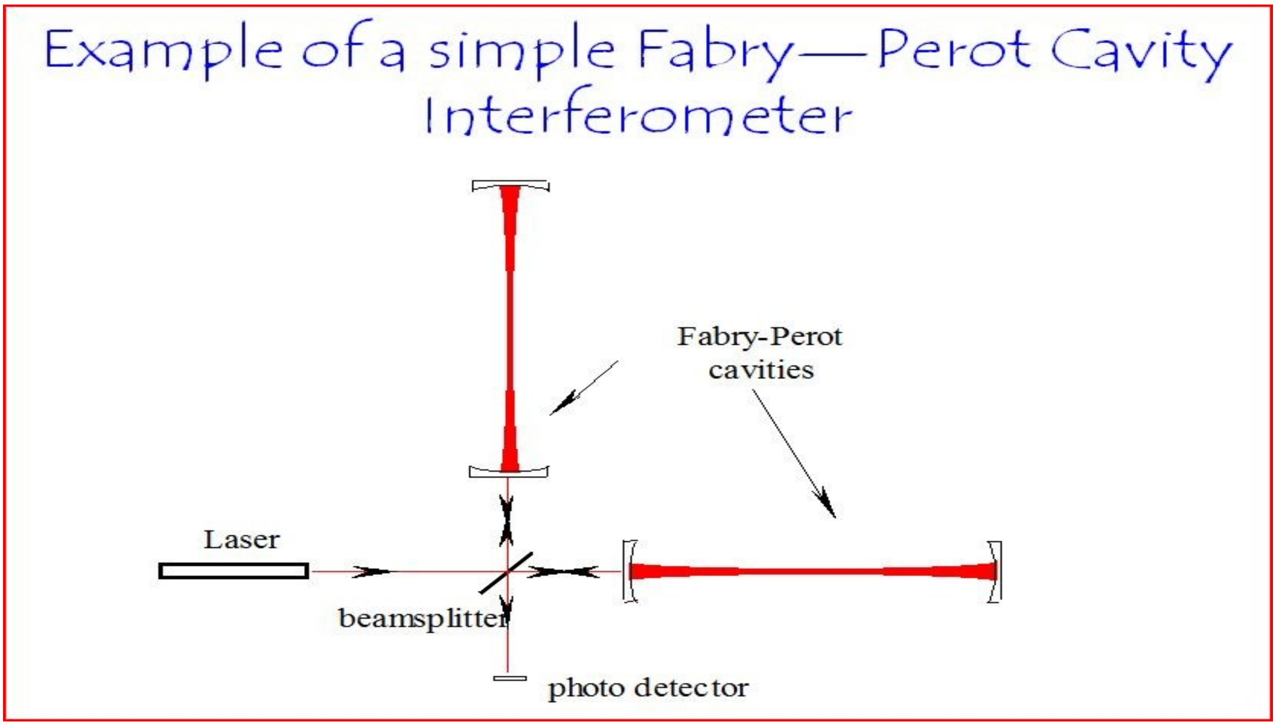
Resonant mass detectors are very much the first attempt at detection. Because of the physical limits of length, the frequency range is high.

b) Laser Interferometers

Interferometers have been around for a long time (the speed of light was verified and various refinements to its magnitude were made using interferometer technology over 100 years ago). Because of the tiny fluctuations that need to measured, it became apparent that interferometry could provide a solution. Instead of measuring the whole length of a detecting arm, using interferometry enables the change in length to be detected down to an astonishingly minute level – less than the wavelength of the light being used.

Using two arms that are perpendicular should enable the gravitational wave to elongate one arm and compress the other as a result of the quadrupolar nature of the wave-form. The change in lengths in the arms is detected by careful observation of the interference patterns created on re-combining the laser light beams that had earlier been split and directed into the different arms.

[One thing I do find puzzling and cannot find an explanation for, is why the light beam itself would not be affected by the gravity wave to the same degree as the distance between the mirrors in the interferometry detector arm. i.e. If you tried measuring the longitudinal expansion of say a railway sleeper using a metal rule made of the same material with the same coefficient of expansion, you would likely get a null result. We know that light can be bent by gravity; and we know that [the wavelength of] light can be stretched [red-shifted] by the expansion of space, so why would the laser light not be affected to the same degree as the tube it is in, by a gravitational wave? Does it have a different coefficient of 'effectedness'?]



Nevertheless it seems the experts are confident that interferometers are a viable way of detecting gravitational waves, and there are number of these currently being refined:

LIGO – USA joint venture between Caltech and MIT
GEO600 – Joint German-British
AIGO – Australia
VIRGO – France – Italy

TAMA300 – Japan
CLIO – Prototype cryogenic 100m arm interferometer

LCGT – 3Km dual arm cryogenic mirror interferometer


The two 600 metre arms of GEO600 (picture from GEO 600 website).

LIGO has the current set up with two detectors of 4kilometer arm length at different sites, and one 2k arm-length.

Advanced LIGO is a proposal to significantly upgrade the sensitivity of the detecting instrument (other countries including UK also pledged to join funding consortium).

[There has been what looks like a bit of attempted scene-stealing, viz. Caltech's announcement of February 2008 that because the 3 combined interferometers of LIGO found no evidence of gravitational waves from the Crab pulsar, therefore no more than 4% of its energy dissipation can be attributed to gravitational radiation; which seems to me to be rather over-confident of LIGO’s detection ability.]

c) LISA (Laser Interferometer Space Antenna)

LISA is a planned space based laser interferometer, a joint project of both NASA and ESA. It is expected to be launched in 2018-20 with an expected life of from 2 to perhaps 5 years.

The idea is that three spacecraft, each with two optics systems angled at 60 degrees apart, will be positioned in an equilateral triangle with sides of 5 million kilometres length. Two dual-arm Michelson type interferometers will be formed, thereby allowing some redundancy in the system. In each case the connecting third arm of the triangle provides independent positioning and gravitational wave polarisation information. The whole system will follow the earth in orbit about 20 degrees behind.

Artist's conception of LISA spacecraft

[Image from Wikipedia]

LISA will be designed to detect gravitational waves of a lower frequency than similar systems on earth. Theory suggests that the most predictable sources (binary systems in our galaxy) and the most powerful (supermassive black holes in distant galaxies) will emit gravitational waves at frequencies below 10 milliherz (i.e. less than 10,000 per second, with corresponding wavelengths of 30 kilometers and above, although these may be lengthened further by ‘red-‘ or long-shifting by the expansion of space over the intervening distances). But the fluctuations in the length of the interferometer arms will be a small fraction of the wavelength, as the expected ‘strain’ (the lengthening and compressing of space) is caused by the quadrapolar nature of the waves.

Being space-based will avoid the interferences and distortions caused by earth bound activities both manmade (vehicle/aircraft noise, nearby logging & mining activity) and natural (seismic, plate tectonics, kangaroos!); but will introduce significant additional technical challenges including maintaining precise positioning of the spacecraft relative to each other.

The heart of each of the interferometers optical systems consists of a free-flying (shielded within the spacecraft) 40mm block of platinum-gold, highly polished to act as a reflector and optical reference. In effect, once the blocks (the 'rest-masses') are positioned in their orbits, they will be released within the spacecraft, and the spacecraft will follow the rest masses without interfering (by 3-dimensional sensing of the rest mass relative to the spacecraft). The changes in the optical path length between these blocks will be detected and compared as a passing gravitational wave should increase the length of one optical arm and compress the length of the adjacent one. Although the spacecraft body will shield the free-flying masses from non-gravitational influences, they would be exposed to being electrically charged by cosmic rays and solar flares, so a discharge system has been designed utilising a UV light source.

The level of positional precision of the spacecraft that is required is quite astonishing to bounce laser light between two 40mm surfaces, 5 million kilometres apart; detection of the relative movements of the blocks is targeted to be down to 1 picometer (one millionth of one millionth of one meter).

In order to test some of the technologies needed for the full mission (gravitational sensing, laser ranging, electric propulsion) a LISA Pathfinder mission consisting of a single satellite that will orbit for six months to a year around the Lagrange 1 point (1.5m kilometres towards the sun), is due to be launched at the end of this year (2009).

DECIGO (Deci-Herz Interferometer Gravitational wave Observatory)

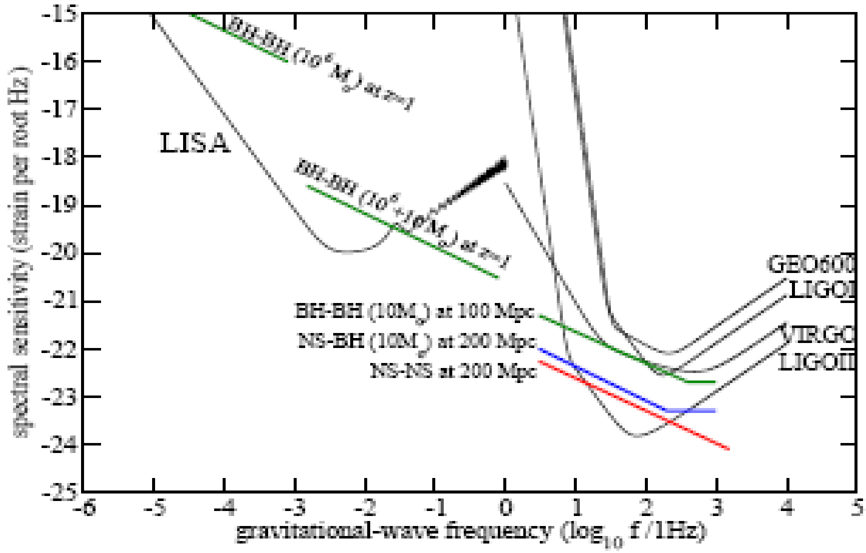
A very similar design of space based interferometer is also being planned by the National Astronomy Observatory of Japan. Three space vehicles will operate at distances of 1,000 Km giving planned sensitivity of 0.1~10 Hz. No details of timescale to launch were given on the website.

5. Detectable sources and events

A lot of analysis has been done to forecast the types of objects or systems and events that will produce detectable gravitational waves, the frequency and magnitude of those waves and the probabilities of detection (number of occurrencies).

It seems obvious that it will be the movements of highly gravitationally-bound objects that are likely to have the most easily detectable signatures, but clearly the wave-lengths of the detection band of the receiver must be set to the right frequency. Not surprisingly, inspirals and subsequent merger of a pair of binary black holes or Neutron stars feature as a strong candidates.

This next graph shows the sensitivity of several of the detectors against some inspiralling binaries.

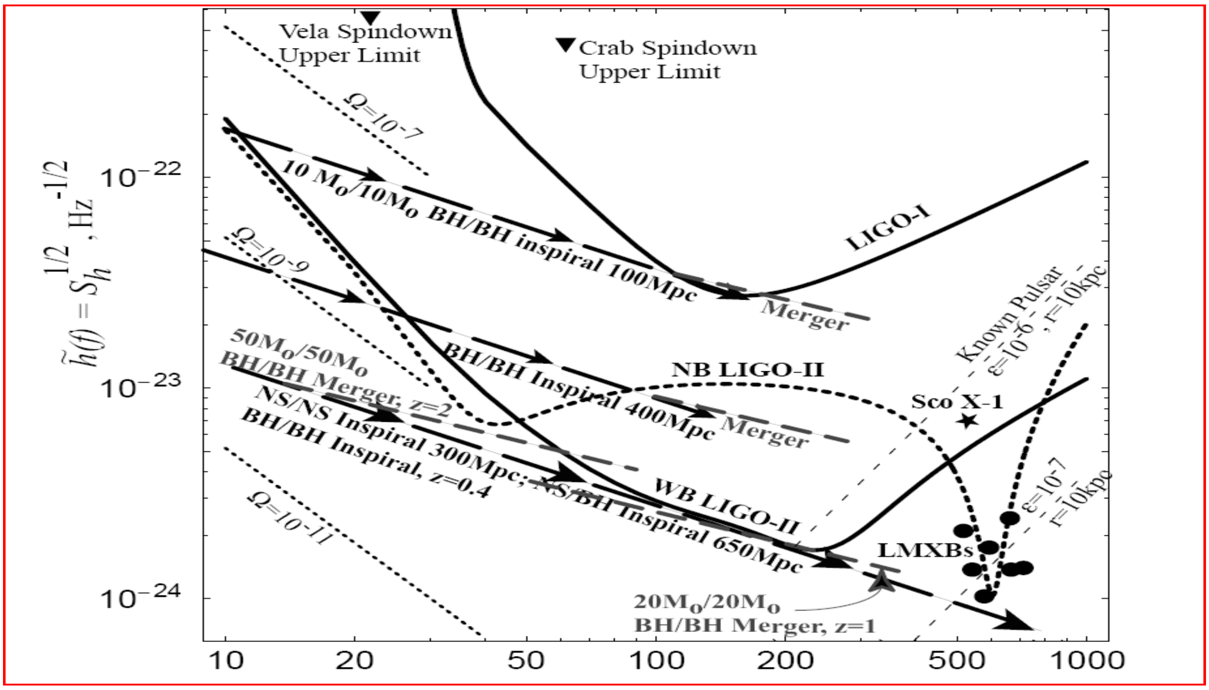


Source: Kostas D Kokkotas: Gravitational Wave Astronomy

The following graph shows the sensitivity of the initial (LIGO-1) and upgraded (LIGO-II narrow and wide band) detectors together with the expected signal strengths from some objects and events.

The signal strength is defined such that if an object or event signal is plotted above the noise curve of LIGO then that signal should be detectable with a false alarm probability of less than 1%.

The big dots represent low-mass x-ray binaries.



Frequency Hz

Figure 1. The noise $\tilde{h}(f)$ in several planned LIGO interferometers plotted as a function of gravity-wave frequency f, and compared with the estimated signal strengths $\tilde{h}_s(f)$ from various sources. The signal strength $\tilde{h}_s(f)$ is defined in such a way that, *wherever a signal point or curve lies above the interferometer's noise curve, the signal, coming from a random direction on the sky and with a random orientation, is detectable with a false alarm probability of less than one per cent;* see the text for greater detail and discussion.

Source: Curt Cutler/Kip Thorne: An overview of Gravitational-Wave sources

6. Conclusions:

No gravitational waves have been directly detected as yet.

What is clear to me from this research is that it is not yet know what gravity actually is, why it works as it does and what causes it. The most we can do at the moment is to describe its effects as best we can in mathematical terms. There are those who argue that Einstein's theories are not the 'best fit' and several alternative or complimentary theories are available with various claims as to their ability to resolve or nullify some of the outstanding problems such as dark matter and/or dark energy and to unify with quantum theory.

Whether or not gravitational waves do exist, we are on the cusp of finding out. Strong, more than circumstantial, evidence exists from analysis of Taylor & Hulse's binary pulsar observations for them to state that the only source of the orbital wind-down can be radiation in the form of gravitational waves.

The next wave of sensitivities in detectors (ground and space) will very likely resolve the issue: if we can convince ourselves that the detectors definitely have the required sensitivities and still we find nothing, then a lot of head scratching (and a new Einstein) will doubtless be required.

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