

Ripples from the Dark Side of the Universe – the Search for Gravitational Waves

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Abstract

Gravitational waves – a prediction of Einstein’s General Relativity – are among the most elusive signals incident on the Earth. These signals – ripples in the curvature of space-time - carry information about what is happening deep in the heart of some of the most violent events in the Universe. However their observation remains one of the most challenging problems in experimental astro-physics, as the measurement sensitivity required by the detectors is equivalent to measuring a change in the separation of the Earth and Sun by the diameter of an atom. A global network of such detectors - LIGO, Virgo and GEO - is now in operation, with enhanced versions being developed, and a space-borne detector, LISA, is planned as a joint ESA/NASA mission. In this talk I will discuss the nature of gravitational waves, how the detectors work, and the preliminary results which are already showing promise.

1. Introduction

Ever since their prediction by Einstein in 1917, gravitational waves have been the subject of some controversy as to whether they can be directly detected. Indeed several early relativists were sceptical about their existence, and little interest was shown in carrying out experiments in the field until the work of Joseph Weber in the 1960s. While Weber's experiments did not demonstrate the existence of gravitational wave signals, they did encourage many other research groups around the world to start working in the area. Further the field was recognized by the 1993 Nobel Prize in Physics being awarded to Hulse and Taylor for their experimental observations of the *binary pulsar* (PSR 1913+16) and subsequent interpretation that the evolution of the binary orbit is consistent with angular momentum and energy being carried away from this system by gravitational waves. With the commissioning, operation and potential upgrading of the long baseline detectors LIGO (USA), GEO 600 (Germany/UK), Virgo (Italy, France) and TAMA 300 (Japan) we are heading into an era where verification of Einstein's predictions should be made and a new field of astronomy born.

2. Gravitational Waves

Gravitational waves (GW), predicted in General Relativity to be produced by the acceleration of mass, are propagating strains in space. They are the gravitational analogue of electromagnetic or radio waves. Just as electromagnetic waves are produced by the acceleration of charge, GW are produced by the acceleration of mass. Due to the fact that mass has only one sign, unlike charge, the accelerations required involve a change of shape or *quadrupole moment* of the source. Gravitational waves lead to tiny deformations or distortions of any mechanical systems with which they interact. The deformations are of the type where a circle is changed into an ellipse and vice-versa and are known as *quadrupole* deformations. The strain ($\Delta l/l$), between objects a distance l apart, is represented by the gravitational wave amplitude (h) where $h = 2\Delta l/l$. For quadrupole radiation there are two orthogonal polarizations of the wave at 45 degrees to each other, as shown in Figure 1.

In order to sense the quadrupole deformations expected to be induced by gravitational waves a good way forward is to set up two optical paths at right angles to each other and measure the relative changing lengths of the two paths using laser interferometry.

Such an arrangement is provided by a *Michelson interferometer* formed between freely hanging mirrors as illustrated in Figure 1 also.

Because of the very weak nature of gravity and the fact that there is only one sign of mass, the efficiency of converting mechanical energy in a system into gravitational radiation is very low and thus signals produced by accelerating systems tend to be very weak. Indeed the only sources of

gravitational waves that are likely to be detected are astrophysical, where there are potentially huge masses accelerating very strongly.

Thus gravitational wave detectors will uncover dark secrets of the Universe by helping us to study sources in extreme physical conditions: strong non-linear gravity and relativistic motion, extremely high density, temperature and magnetic fields, to list a few.

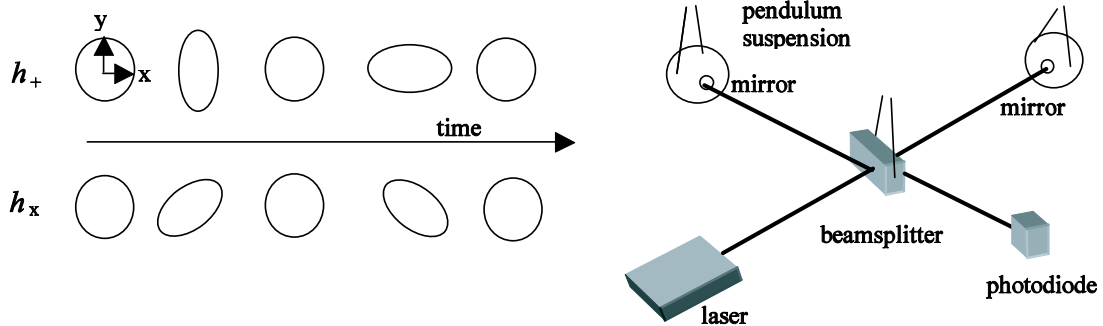


Figure 1. Schematic diagram of how gravitational waves interact with a ring of matter. The ‘quadrupole’ nature of the interaction can be clearly seen, and if the mirrors of the Michelson Interferometer on the right lie on the ring with the beamsplitter in the middle, the relative lengths of the two arms will change and thus there will be a changing interference pattern at the output.

Gravitational wave signals propagate essentially unattenuated and are expected over a wide range of frequencies, from 10^{-17} Hz in the case of ripples in the cosmological background, through 10^3 Hz when neutron stars are born in supernova explosions, up to possible signals at GHz from processes in the early Universe, with many sources of great astrophysical interest spanning this range in between, including

- supermassive binary black hole formation, interactions and coalescences,
- neutron star binary coalescences,
- low-mass X-ray binaries such as Sco-X1,
- rotating asymmetric neutron stars such as pulsars
- cusps and kinks in cosmic strings and
- a general noise background from a superposition of many sources

By observing the rich variety of signals from these sources the goal of the GW community is to answer key scientific questions in:

Fundamental physics and general relativity

- *What are the properties of gravitational waves?*
- *Is general relativity the correct theory of gravity?*
- *Is general relativity still valid under strong-gravity conditions?*
- *Are Nature's black holes the black holes of general relativity?*
- *How does matter behave under extremes of density and pressure?*

Cosmology

- *What is the history of the accelerating expansion of the Universe?*
- *Were there phase transitions in the early Universe?*

Astronomy and astrophysics

- *How abundant are stellar-mass black holes?*
- *What is the central engine behind gamma-ray bursts?*
- *Do intermediate mass black holes exist?*
- *Where and when do massive black holes form and how are they connected to the formation of galaxies?*
- *What happens when a massive star collapses?*
- *Do spinning neutron stars emit gravitational waves?*
- *What is the distribution of white dwarf and neutron star binaries in the galaxy?*
- *How massive can a neutron star be?*
- *What makes a pulsar glitch?*
- *What causes intense flashes of X- and gamma-ray radiation in magnetars?*
- *What is the history of star formation rate in the Universe?*

The lowest frequency gravitational waves are being sought in the structure of the microwave background by experiments such as Planck (launched in May 2009) and its successors. Further up the frequency spectrum at a billionth of a Hz or so, measurements of the fluctuations in the arrival time of the radio signals from pulsars are a very promising way ahead. Further up again in frequency, at a ten thousandth of a Hz and above, and as discussed earlier, laser interferometry is a particularly suitable detection technique.

However it is important to note that predicted strains in space at the earth are typically of the order of one part in a thousand billion billion, i.e. 10^{-21} , or smaller, equivalent to a change in the separation of the Earth and Sun by less than the diameter of an atom.

Such low levels of strain fluctuation are very challenging indeed to measure, as there are many other sources of noise fluctuations in any apparatus. In the case of the laser interferometer detectors on earth the mirrors of the interferometer described above

may be isolated from seismic motion by the use of one or more pendulums but still are affected by changing gravitational gradients, as well as Brownian and thermo-elastic motion due to their being at room temperature. Further quantum effects predicted from the Heisenberg Uncertainty Principle and related to the quantum nature of the laser light used in the interferometer also impose limitations on displacement measurement. Thus in order to achieve high strain sensitivity, given the noise fluctuations in the positions of the mirror/masses, long arm-lengths in the interferometer are required. In practice on earth, arm lengths are restricted to a few km. However, as will be discussed later, much longer arm-lengths are achievable in space.

It is worth remembering that to remove any scintillation effects on the optical beams and gas damping effects on the mirrors, the systems must be evacuated to ultra-high vacuum levels; such levels are intrinsic in space but require vacuum enclosures on the ground.

3. Long baseline interferometric detectors on earth

This idea of using laser interferometry between freely suspended test masses was proposed in 1962 in the USSR by Gertsenshtein and Pustovoit but implementation of the ideas had been awaiting the availability of relevant laser and optical technology. Robert Forward built the first laser interferometric prototype in the early 1970s at the Hughes Aircraft Laboratories in Malibu, although the sensitivity was limited by the short distance between the masses and the low power of the helium neon laser used. As mentioned above a Michelson interferometer is particularly suited to the detection of gravitational waves as they have a quadrupole nature (Figure 1). Waves propagating perpendicular to the plane of the interferometer will result in one arm of the interferometer being increased in length while the other arm is decreased and vice versa. The induced change in the length of the interferometer arms results in a small change in the intensity of the light observed at the interferometer output. The concept is very attractive in that it offers the possibility of very high sensitivities over a wide range of frequency.

In order to observe a full range of sources and initiate gravitational wave astronomy using detectors on earth, theoretical predictions suggest that a sensitivity or noise performance in strain of better than 10^{-21} has to be achieved over most of the proposed operating range from 10 Hz to a few kHz. (The low frequency end of this range is set by the effect of gravitational gradients on the earth and the upper end by technical limitations.) For such an Earth-based detector the distance between the test masses is limited to a few km by geographical and cost factors. If we assume an arm length of 3 to 4 km, detecting a strain in space of the above level implies measuring a residual motion of each of the test masses of less than a thousandth of the diameter of an atomic nucleus. This sets a formidable but achievable goal for both the fine mechanics and the optical detection systems of the interferometers.

There are currently in operation, or undergoing upgrading, a network of gravitational wave detectors each of which is based on using large-scale variants of Michelson-type interferometers, where the arms are formed between freely-hung mirrors. Lasers used for illumination are single frequency Neodymium YAG devices of ~ 10 - 30W output power.

The American LIGO project comprises two detector systems with arms of 4 km

length, one in Hanford, Washington State, and one in Livingston, Louisiana. One half length, 2 km, interferometer has also been built inside the same evacuated enclosure at Hanford. The French/Italian Virgo detector of 3 km arm length is built and operating at Cascina near Pisa, and the Japanese TAMA 300 detector, which has arms of length 300 m, is operating at the Tokyo Astronomical Observatory. These systems utilise resonant optical cavities in the arms of the interferometers to enhance sensitivity and use simple wire loops to hang the main mirrors of the interferometer. The German/British detector, GEO 600 has arm lengths of 600 m and uses a somewhat different interferometric scheme, known as *Signal Recycling* which allows selective tuning of the interferometer. GEO also uses silica fibres to hang the interferometer mirrors which – because of the very pure mechanical resonance properties of silica – reduces Brownian fluctuations. GEO is operating at Ruthe near Hannover.

Bird's eye views of LIGO, VIRGO and GEO are shown in Figure. 2.



Figure 2. Bird's eye view a) of the LIGO detector site at Hanford (courtesy of the LIGO project), b) of the Virgo detector site at Cascina in Italy (courtesy of the Virgo project) and of the GEO site at Ruthe (courtesy of the GEO project).

4. What we have achieved to date.

Five science runs have so far been completed with these new interferometric detectors. 'Upper limits' have been set on the strength of gravitational waves from a range of

sources: coalescing compact binaries, pulsars, burst sources and a stochastic background of gravitational waves. For example for a range of rotating neutron stars (of radius 10 km) it has been shown that any ‘bumps’ on the surface must be smaller than 1mm in height! As yet no detections have been reported but this is not surprising at the sensitivity level of the initial instruments. Some *enhancement* of performance by increasing laser power and improving the optical and suspension systems is currently underway.

During the next few years, following these intermediate upgrades or enhancements to the LIGO and Virgo detectors, we can expect to see searches for gravitational wave signals at a sensitivity level where a detection could be made. Recent discoveries of additional compact binary systems have improved the statistics for the expected rate of binary coalescences detectable by the LIGO system by a significant factor, giving some possibility of a first detection over the next few years. An upper limit on the rate of BH-BH coalescences could be around 2 events per year although the most probable rate is likely to be $\sim 1/12$ years.

5. What do we need for the near future?

In the first instance we should like to be able to detect the signals from compact binary coalescences at a useful rate of 30 to 40 per year.

This requires an improvement of a factor of ~ 10 to 15 in sensitivity (or range) of the initial interferometric detectors (or ~ 5 to 7.5 for the *enhanced* detectors) as the number of expected detections is expected to increase approximately as range to the power three (Figure.3).

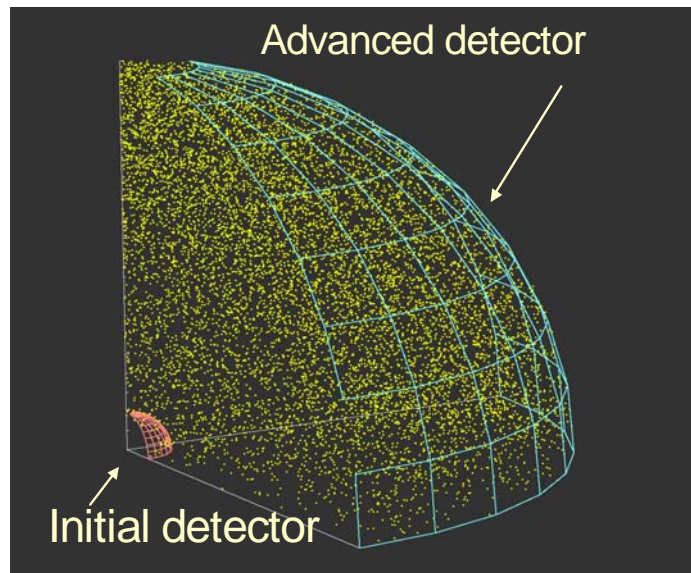


Figure 3. Schematic of the relative range and hence volume of space accessible to initial and advanced detectors (courtesy the LIGO project)

Thus plans for an upgraded LIGO, '*Advanced LIGO*', were devised and are already well formed and the project is fully funded. Advanced LIGO will incorporate 40 kg fused silica test mass mirrors, suspended by fused silica fibres to help reduce Brownian noise, along with an improved seismic isolation system, and increased laser power, close to 200 W. The upgrade is planned to commence in 2011, with full installation and initial operation of the upgraded system by 2014. On approximately the same timescale we can expect to see a similar upgrade to VIRGO, and the rebuilding of GEO as a detector aiming at high sensitivity in the kHz frequency region. On a slightly longer timescale we are anticipating the building of a long-baseline detector of 3 km arm length, LCGT, in Japan and a detector of similar scale in Australia. The Japanese detector is particularly interesting as it is proposed to be built underground in the Kamioka mine - see Figure 4 - (to reduce seismic and gravitational gradient fluctuations) and to be cooled to cryogenic temperatures to reduce thermal noise.



Figure 4. Artist's impression of the LCGT detector in the Kamioka mine, Japan (Courtesy of the LCGT project)

To go beyond this point, however, a number of challenges involving reducing Brownian and thermoelastic fluctuations in suspensions and mirror coatings, and the use of non-classical light to ameliorate the quantum limitations resulting from the use of standard laser light, will have to be met.

Thus research groups in the field are already looking towards the next generation of ground-based detectors and a European design study for such a system funded under the EC Framework 7 programme is now underway. Meanwhile there is a high level of activity in research towards the space-borne detector LISA, the Laser Interferometer Space Antenna , illustrated in Figure 5.

6. Long Baseline Detectors in Space

A very interesting class of gravitational wave signals (those resulting from the formation and coalescence of black holes in the range one thousand to one million solar masses) lies in the region of 10^{-4} Hz to 10^{-1} Hz, and a detector whose strain sensitivity is approximately 10^{-23} over relevant timescales is required to search for these. The most promising way of looking for such signals is to fly a laser interferometer in space. LISA is being proposed by an American/European team; it consists of an array of three drag-free spacecraft at the vertices of an equilateral triangle of length of side 5×10^6 km. This cluster is placed in an Earth-like orbit at a distance of 1 AU from the Sun, and 20 degrees behind the Earth. Proof masses inside the spacecraft (two in each spacecraft) form the end points of three separate but not independent interferometers.

LISA is a project in NASA's Beyond Einstein Program and the advisory committee reviewing the program (BEPAC) has recently recommended that LISA be the Flagship mission for the program. LISA is expected to be launched as a joint NASA/ESA mission around 2020 and to be producing data for up to ten years. A demonstrator mission, LISA Pathfinder, is in phase C/D of development and hardware is being built for a launch in late 2011.

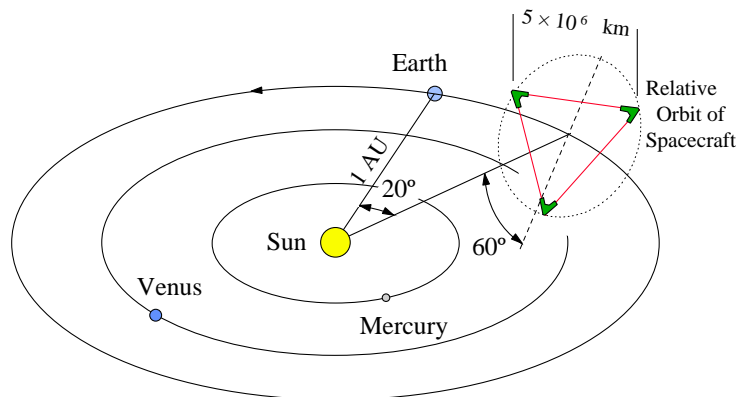


Figure 5. Schematic diagram of LISA and its orbit around the sun

7. Conclusions

The next stages forward in interferometric gravitational wave detectors on the ground and in space are well defined with the upgrades in the US and Europe, proposals for new detectors in Japan and Australia, and the ongoing developments towards LISA and the Einstein Telescope.

We are looking at a really exciting future as fundamentally new information about many violent astrophysical events is uncovered.

8. Acknowledgments

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