Gravitational Waves: Sources and Detection

Abstract

This report gives a brief summary of what gravitational waves are and why they could be important. It describes several sources of gravitational waves and puts them into three distinct types: burst, periodic, and stochastic sources. It discusses various ways of detecting these waves, and problems associated with such methods, with a focus on two types of ground based detectors: resonant bar, and laser interferometer detectors. There is a look at space based detection systems with an overview of the LISA mission for a space based laser interferometer.

Introduction

As the many major laser interferometer gravitational wave (GW) detector projects near completion, in terms of construction and noise analysis/reduction, and will soon be operational I am going to look into the possible astrophysical importance of these detectors with regards to our understanding of the workings of the universe, as well as a bit of the history behind them.

The revolution in our understanding of the universe, which could take place as a product of the study of gravitational waves, has been compared to the difference in understanding caused by the introduction of radio astronomy to the purely visual astronomy that had taken place previously. Radio astronomy showed a far more violent universe than was seen before when compared to visual observations. Still, radio waves and light waves are part of the same spectrum, although at wildly different wavelengths, whereas GWs are a completely different phenomenon. This means that study of GWs could prove many times more revolutionary, with it providing information on some of the most violent events in the universe, structure of galaxies and even the formation of the universe.

I am going to try and describe what we understand about the theory of gravitational waves and their production from different sources, although without a thorough mathematical description, as this is beyond the need of this report. I am also going to provide an overview of different types of gravitational wave detector that have been constructed or postulated, along with their theoretical sensitivities and noise sources, with a more detailed look at the laser interferometer type of detector.

What are Gravitational Waves?

When the theory of gravity was first published by Newton in his *Philosophiae Naturalis Principia Mathematica* in 1686, it was very successful in describing the mechanics of the observed world and especially planetary motions. Within Newton's equation for gravitational potential, there was no time derivative, meaning that the potential would be felt instantaneously at any distance from its source. Newton's theory remained as the only description of gravity until Einstein published his Theory of General Relativity in 1915, from which he postulated the existence of gravitational waves. Einstein showed that gravity is actually a product of the curvature/geometry of space-time, which is induced by the distribution of mass and energy. Einstein's theory included a time derivative in his equations that showed that a gravitational field would propagate at a specific speed, and therefore not act instantly over any distance. If the gravity source were time-varying , it would produce a time varying gravitational field (analogous to an electromagnetic field) which would be a wave in the structure of space-time, propagating away from the source i.e. a Gravitational Wave. The existence of GWs and their emission from various sources has since been studied by many people, using different approximate mathematical treatments, to determine their possible amplitudes, energies and waveforms.

In describing GWs physically and mathematically it is easiest to make some approximations. One of the main things that has to be accounted for is the fact that gravity is non-linear with many contributions to background curvature of space-time. Generally, the lengthscales over which you get variation in the curvature of space-time are much greater than those over which the GWs vary, and therefore the two contributions to the curvature can be split up. Also from the equations it can be shown that, like light, there are two polarisation states of GWs, called + and x polarisations because of the orientation of their force fields. Unlike light, GWs are generally unaffected by their passage through matter and are quadrupolar in manner, which means that they have motion simultaneously in two directions, i.e. stretch or shrink space. GWs can only be emitted by objects or systems which are not spherically symmetric. There are several other approximations and formalisms that are used when describing the emission and propagation of the waves, both of which require different mathematical analyses, but these are too complex to go into here.

In this report I will omit giving any value for the dimensionless amplitude of a GW from a particular source, as these values are liable to vary from source to source and over different distances, and any values given here could well be greatly underestimated or overestimated due to the limited knowledge we have. The one thing that should be known is that the dimensionless amplitude is extremely small for any GW, and they will therefore be very difficult to detect. The energy carried by a GW also varies from source to source.

Sources of Gravitational Waves

Different types of astrophysical event produce different types of gravitational wave; there are burst sources, which produce a pulse of radiation; periodic sources, which produce a continuous, monochromatic GW; and stochastic sources, which are the sources of background GWs. Theoretical models of many different sources have been calculated, although not all these sources are known to actually exist in the universe, but could exist theoretically. Different sources are covered in more detailed below.

Burst Source

- **Supernovae, i.e. core collapse to a neutron star**. Supernovae could be very strong sources of GWs although they are difficult to model for the collapse to a neutron star, due to rebounds and modes of vibration in the star. To produce a source of GWs the core collapse must be non-spherical, with the strength of the wave depending on the degree of non-sphericity. Type II Supernovae are thought to definitely produce neutron stars from their collapse although probably in a fairly spherical manner leading to only weak GWs. Type I Supernovae although thought less likely to produce a neutron star as a product, if they did it could have a highly non-spherical collapse from centrifugal forces due to rapid rotation of the original white dwarf, leading to strong GWs. Both types of supernova event are thought to occur about 1 time per forty years in our galaxy, which would mean that out to about 10 Mpc, i.e. to the centre of the Virgo cluster, the event rate could be a few per year for each type. The characteristic frequencies, f_c, of waves produced by collapse to a neutron star is around 1000 Hz, although models have been produced for a range of frequencies from $200\ \text{Hz} < f_c < 10000\ \text{Hz}$. The timescales for these bursts and the oscillations are over a few milliseconds.
- **Core collapse to a black hole**. These events, like those for collapse to a neutron star, are also highly dependent on the non-sphericity of the collapse. As a black hole is a simpler object than a neutron star the waves it emits from vibrations are better understood and are easily triggered. These events are unlikely to exceed a rate of over ~ 1/3 that of neutron stars, meaning approximately 1 per year out to 10 Mpc. The frequency range over which these occur is likely to be similar to that for neutron stars. This type of event due to direct collapse of a star will only lead to black holes at the lower end of

their mass range. Collapse of star clusters that could occur at galactic centres could lead to much higher mass black holes, although this would be at a much lower event rate.
- **Coalescing binaries (neutron stars and black holes)**. Many stars are in binary systems, meaning there could be many systems where the stellar remnants within them are neutron stars or black holes. If the two compact objects in the system are close enough they will gradually radiate weak gravitational radiation, causing them to eventually spiral into each other in a period that is short enough for the events to have occurred in the universe. For such close binaries this process should occur over a period of about 10^9 years. The GWs will appear as a burst source during the final inspiral and coalescence when the frequency of the binaries becomes high and the source of GWs becomes intense. For a neutron star binary the burst will be seen approximately when the frequency reaches 100 Hz, which will quickly sweep up to about 800 Hz in about 3 seconds, within this period the wave will still be uncomplicated by close range effects such as tidal distortions and accretion. There should also be a violent burst of radiation at the act of coalescence. As for supernovae, the waveform models for black holes are less complicated than for neutron stars. The typical event rate for coalescing binaries of either type could be of a few per year to distances of 100 Mpc.
- **Fall of stars and black hole into supermassive black holes**. Supermassive black holes are thought to inhabit the cores of most galaxies. These could grow through accretion of stars onto them with the release of a burst of GWs. The radiation would be at low frequencies of $\sim 10^{-4}$ Hz. Out too a distance of 10 Mpc a reasonable event rate could be expected.
- **Others**. There could be other sources burst radiation that are not known, and also as our electromagnetic knowledge of the above sources is very uncertain it seems that GW observations could well be very different from current knowledge. Gravitational bursts could be much more common or stronger than thought at the moment due to very uncertain knowledge about the existence of the sources and their abundances.

Periodic Sources

- **Rotating neutron stars**. Rotating neutron stars, e.g. a pulsar, will emit gravitational radiation if its rotation deviates off its axis, with the greater the deviation the greater the strength of the emitted GW. This could be caused in a number of ways, like deformations in the stars crust (maybe caused by star quakes or other events), distortion of the star by very strong internal magnetic fields, or ripples in the stars surface of rapidly rotating stars (rotation periods of ~ 0.7 - 1.7 ms). The degree of deviation of stars off axis is not well understood,

as it is hard to tell what state a neutron star might be in from electromagnetic radiation, therefore estimates of wave strengths are hard to make, although it is thought that the strength is small. The frequency of the waves depends on the speed of rotation of the star, meaning waves caused by ripples in the surface should have frequencies in the kHz range.
- **Binary stars**. All binary systems will emit GWs, and they are also the most well understood of sources, and with knowledge of the system (masses and rotation periods) the GWs can be computed with fair accuracy. The waves emitted by these will be very weak, with the strongest sources being the neutron star of black hole binaries. Nearly all binaries have rotation periods that are relatively long (i.e. greater than an hour) and will emit waves with low frequency ($<10^{-3}$), with the more highly evolved stars being at the upper end of this scale.

Stochastic Sources
The stochastic background will consist of components from all the above sources, with it in general being random and incoherent. With binary sources there should be a higher background radiation in the plane of the galaxy, with a random distribution everywhere else. Other sources of stochastic waves could be:

- **Primordial gravitational waves**. These are waves produced during the Big Bang. There last interaction with other material is thought to be of the scale of Planck time (10^{-43} s). These waves could have been amplified by interaction with the background curvature of space-time, leading to more graviton creation, meaning that small fluctuations could be seen as significant background now.
- **Cosmic strings**. The vibrations of closed loop cosmic strings could produce a strong background at the time of galaxy formation.

Detection of Gravitational Waves

There are several methods by which we expect to be able to observe GWs which all must somehow detect a strain in space caused by the GW. These various methods have different frequency ranges and sensitivities at which they are able to detect. With the various types of detectors a fairly large spectrum of frequencies can be observed. The two main methods at the moment being extensively researched are both ground based and are the resonant bar detectors and the laser interferometer detectors. Both types of detectors are sensitive in the frequency range of a few Hz to a few kHz. In general a detector will consist of two test masses, of which a displacement can be measured between them.

Detection of waves, initially at least will rely on computed waveforms from possible sources, for without these we wouldn’t know what to look for in the results. A physicist called Wai-mo Suen has managed to write a program which is able to solve General Relativity equations for GW emitting systems, which is no mean feat as the equations are very messy and can have thousands of terms in them along with a varying co-ordinate system. With this program and the best supercomputers these waveforms are being calculated by various groups to eventually build up a library of different sources, which can be used as starting points for searches and identifications. Even with the program and supercomputers only the simplest events, such as head on collisions of neutron star (head on collisions are very unlikely, with them generally being glancing), have been accurately calculated so far.

Resonant bar detectors

Resonant bar detectors were the first type of detector used to try and detect GWs, with many initial experiments being carried out by Joseph Weber in the 1960’s (Weber originally thought he had detected GWs due to coincidences in readings from several detectors, but later repeats of the test by other groups found no evidence to support this). Weber’s general form of a bar detector is a heavy cylinder of aluminium, suspended around its circumference, with transducers fixed around the centre of the bar, and all placed inside a vacuum chamber. The bar can be thought of as two masses with a spring between them. A GW incident on the bar will set up mechanical oscillations in the bar, which can be measured as a displacement by the transducers and then be amplified. The type of metal needs to be chosen for a high quality factor, meaning that when excited, the bar will continue to oscillate for a relatively long period, thereby increasing the sensitivity. The main limit on the sensitivity of such a detector is thermal motion of the bar, which will produce a background noise. To try and reduce this effect the bar can be cooled. With liquid helium bar temperatures of 4 K have been achieved. Another way to increase the sensitivity of the bar is to increase its mass which reduces the effect of thermal noise, but there are practical limitations to how heavy a bar can be. Better suspension, to further isolate the bar from external vibrations, has also been developed. There will be other spurious random noise events which would have to be reduced by having two or more detectors working in coincidence. To detect GWs of different polarisation and orientation several differently oriented bars are needed.

There are several groups around the world working with bar detectors and improving the sensitivity of their devices all the time. There were experiments in 1991 to cool the detectors to even lower temperatures. As the sensitivities of the bar become better, the transducers have to become less noisy to achieve the maximum sensitivity. Also being looked into are spherical bars, because these can be more massive and they are resonant in 5 different modes, effectively giving 5 different detectors in one, both factors which will increase sensitivity. There has been work on a form of spherical detector with a truncated icosahedral shape. The current best detectors should be sensitive enough to be able to detect a gravitational collapse within our galaxy with an energy of a few percent of a solar mass, although to get a reasonable event rate for this distances would have to be further, requiring an improvement in energy resolution of the system. This could be achievable with spherical detectors.

A main drawback of resonant bar detectors is that they have only a small frequency range around there fundamental natural frequency, which is a property of the speed of sound in the bar material and their size.

Laser interferometer detectors (beam detectors)

The basic principle of a beam detector is that of a Michelson interferometer, with the mirror being attached to the suspended test masses. Laser light is split by a beam splitter into two perpendicular beams, which each travel a certain distance to the respective mirrors, are reflected and then recombined at the beam splitter. The interference pattern of the resulting recombined beam depends on the difference in path length of two arms. A GW incident on the device will induce a difference in the arm lengths, which will show as a certain interference pattern. Due to the nature of GWs, if they are polarised in the direction of the interferometer arms, they will produce an increase in one arm and a corresponding decrease in the other arm, thereby doubling the difference. There are variations on this simple design to create more sensitive detectors, like simply increasing the arm lengths and the use of Fabry-Perot cavities. There are many potential noise sources in these systems, which will be looked at later, and much time has been spent on analysing them in attempts to reduce their effect. The frequency range from these detectors is wideband.

In the late 1970’s and 1980’s prototypes of beam detectors ranging in size from 1-40 m were made to test and improve the design. Some detectors were able to achieve about five times greater sensitivity than the best bar detectors at the time. There are several teams currently working on beam detectors with arm lengths in the km scale. The most advanced and biggest project is LIGO (Laser Interferometer Gravitational-Wave Observatory) which is jointly run by Caltech and MIT and shall be talked about more extensively later. Others include VIRGO (Italian and French) with a 3km detector, GEO-600 (German and British) with a 600m detector, and TAMA-300 (Japanese) with a 300m detector. The set-up of these detectors can be changed when trying to detect waves from different sources, i.e. at different wavelengths, due to noise sources being different under different regimes. When all these detectors come on-line they will be able to co-operate in coincidence searches, and also provide positional information of sources with a precision of up to 0.5°.

Noise in laser interferometers

The noise sources in any GW detector are one of the most important things to be considered for analysis, as these can be large given the weakness of GWs, and if the noise was not taken into account no coherent signal could ever be seen. Here I shall go over some of the noise sources for beam detectors and what can be done to reduce them.

- **Photon shot noise**. This noise is the fluctuation of the number of photons received at the output of the device and comes from the quantum nature of light. For the case where the time the light spends in the interferometer arms is less than the timescale of the GWs the noise can be reduced by either physically increasing the arm length or including a Fabry-Perot cavity. Another possible case is that when the time the light spends in the arms is equal to that of the GW being looked for. This can be achieved with the use of ultra-high reflectivity mirrors, where the number of times the light bounces in the arms can be chosen to be the same as the timescale of the GW. When this method is used the photon shot noise is inversely proportional to the power of the laser used. To get the noise down to the level of sensitivity required needs a much higher power laser than could actually be used, so a method called power recycling has to be used. An extra mirror is added in front of the laser which reflects light that was directed back towards the laser back into the interferometer in a way that it adds coherently to the original laser light. This method can be used to obtain the same photon noise in different size interferometers by adjusting the number of bounces in the arms, but then other noise sources come into effect.
- **Seismic noise**. Seismic noise is obviously due to seismic motions, which even away from man-made sources is much higher than GW strengths. The seismic motions can effect each of the masses separately making maters worse. Again here the longer the arm length the less the noise, but increasing arm length is nowhere near enough even for the 4km LIGO. What is needed is for the masses to be isolated from these motions. This isolation is achieved via the suspension of the masses as a pendulum, where the more suspensions cascaded together the greater the isolation, and via stacks of rubber and metal between the ground and point of suspension. Seismic noise is hardest to isolate against at low frequencies, meaning that without major advances in the isolation techniques earth based detectors are unlikely to be able to see GWs of low frequency.
- **Thermal noise**. This noise is present in the modes of suspension wires and the masses. It can be reduced by choosing materials with certain properties with which to make the various components. Silica is a good material that is currently being used for the test masses.
- **Others**. Others sources of noise are the mechanisms required to

stabilise the many components of the interferometer and the fluctuations in the laser.

LIGO

LIGO is an American based laser interferometer project, which will eventually consist of two 4km arm length interferometers at different locations in the US. The facilities started construction in 1992 and were supposed to come on-line for observing before the turn of the century, unfortunately this didn't happen and LIGO still has yet to make any observations. The LIGO facilities, which have a large L shape, have been designed so that they can accommodate a number of different interferometers of 2 and 4km arm length, and so that different experiments can be fitted for observing various sources. The test masses and optical paths are all housed in vacuum chambers to prevent the air molecules causing unnecessary noise. There is also the opportunity of fitting more advanced detector systems. In its first stage of operation LIGO will not work at full sensitivity using the full arm lengths, with initial testing being made with the 2km arm lengths, making it comparable to the other projects such as GEO-600. The most recent development is the "first lock" of a 2km detector at the Hanford, Washington site in October 2000. This involved the first time laser light had been resonated throughout the entire system, with the mirrors also being locked into position to great precision. Now this has been done, work can be begun on tuning the detector to its maximum sensitivity. There will have to be a great deal of testing but it is hoped that the detector will eventually be able to start proper scientific observing in 2002. The next step will be to bring on line the 4km detector in Louisiana, and then the 4km in Washington. When these are up and running they will combine to make the most sensitive GW detector we have. One of the main sources that such detectors will be looking for, due to their probable relatively high event rate and strong emission, are the coalescence of neutron star and black hole binaries.

The Japanese TAMA300 detector was the first of this new generation of interferometers to achieve full lock, which was in May 1999, and has already carried out a short search. Improvement on this instrument are continuing. The recording of data from all the interferometers has been standardised to a format developed by the VIRGO team, to aid comparisons between detectors.

Space-based detectors

There are several ways to try and detect GWs using space based or natural systems, which would be able to observe the low frequency waves that Earth based detectors can't.

- **Laser Interferometer Space Antenna (LISA)**. This is a proposed ESA scheme in which three spacecraft would form an equilateral triangle, with sides of length 5 x 10^6km, orbiting 20° behind the earth at an angle of 60° to the plane of Earth’s orbit. The triangle would be rotating. This means that as it orbits, its view will change to help show the direction of a source. The three spacecraft would be launched together then independently position themselves. The spacecraft would send out lasers from which phase differences could be measured and therefore arm lengths deduced, with the test masses floating weightless at the centre of each craft. The frequency range of such a system would be between 10^{-1} - 10^{-4}Hz. This frequency range can be achieved due to there being no seismic noise or gravity gradient of the earth to worry about, although there will be other perturbations to consider. Each craft will have to be able to measure external forces on it, such as that from radiation pressure, and correct itself for this. The project is now a joint ESA/ NASA venture which if it gets approved could be operational by 2010, by which time ground based detectors should hopefully have been successful. The scheme would be technically difficult to do, but its viability has been confirmed. LISA would be able to detect such events as the formations of supermassive black holes and binary systems up to about a year from coalescence.

- **Doppler tracking of spacecraft**. Spacecraft, such as probes sent to other solar system planets, can be tracked using radio signals. These signals can be sent to the spacecraft at a time recorded by a highly stable master clock, and when received by the spacecraft the signal is sent back. The comparison of the sent and received signal gives the Doppler shift of the craft. A GW will change the earth-spacecraft separation, and should be detectable as a change in Doppler shift. This has been tried with previous spacecraft, but sensitivities have been low.
- **Pulsar timing**. This is similar to the Doppler tracking technique, except that you are looking at the Doppler shift in the radio signals from the pulsar. Due to the large distances involved the frequency ranges for this are 10^{-7} - 10^{-9}Hz.
- **Cosmic microwave background radiation (CMBR) anisotropies**. Large scale anisotropies in the CMBR could be produced by GWs near the Earth today, with small scale anisotropies being produced at the time when the CMBR was formed. These waves would be of extremely low frequency $< 10^{-16}$Hz.

Although as of yet gravitational waves have not been detected experimentally, they have been inferred to exist with close observance to general relativity’s predictions. This happened when two astronomer, Hulse and Taylor, discovered a binary system with one object being a pulsar and the other being another massive compact object, most likely a neutron star. After years of observation of this system, and study of its rotation, it has been shown to be losing energy as if it were radiating it away via GWs. This system has now been studied for over 25 years, providing very accurate data that fits very well with general relativity, and could be said to prove the theory.

A couple of things that could be established fairly quickly by observing GW from a extragalatic sources, if accompanied by electromagnetic radiation, are whether GWs travel at the speed of light and a more accurate value for Hubble's constant.

Conclusion

There is still lots of effort to be put in and progress to be made in the search for GWs, but this needs to continue with current projects and new projects such as LISA. This new way of looking at the universe will open up the world of physics and astronomy with many new possibilities. It will provide a way of probing the origins of the universe, and events that could show how structure formed within the universe. It could also show objects that have yet to even be predicted, but will mainly offer new insight and understanding of objects from which little knowledge can be gleaned by electromagnetic radiation. Along with all of this GW studies could be a way to prove, improve or overthrow one of the biggest scientific breakthroughs of the twentieth century: general relativity. These goals are within sight and with enough interest and investment could provide a scientific revolution.

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