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GRAVITATIONAL WAVES: SOURCES AND DETECTORS

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ABSTRACT

The world wide efforts for detecting gravitational waves, the detectors in vogue and the expected astrophysical sources of gravitational waves will be discussed. Ground based detectors especially, the resonant bar detectors and laser interferometers will be described with a brief mention of the space based detector (the LISA project). Astrophysical sources of gravitational waves such as coalescing binaries, supernovae, pulsars/ rotating neutron stars, stochastic background will be discussed in the context of detection.

I. INTRODUCTION

The 1993 Nobel prize for physics was awarded to Hulse and Taylor for the proof of existence of gravitational waves (GW). This was based on the observations of the binary pulsar PSR 1913+16 which showed a decay in its orbit. This decay is correctly predicted by the general theory of relativity and provides indirect evidence for the existence of gravitational waves. Direct evidence however is lacking and may not be provided until advanced ultra hig h sensitivity resonant bar detectors and large scale laser interferometric detectors (Abramovici et. al. 1992; Giazotto et. al. 1992) are completed. This network of detectors would not only detect GW but perform as directionally sensitive GW observatories.

Cosmic GW should be emitted by coherent bulk motions of matter while electromagnetic waves are usually emitted from regions of atomic size, atoms, molecules, charged particles, etc. GW are emitted from strong gravity and relativistic velocity regions whereas electromagnetic waves come almost entirely from weak gravity low velocity regions. Also matter is almost transparent to gravitational waves due to the weak coupling of gravity. Hence the GW pass easily through matter while the electromagnetic radiation is absorbed or scattered. These differences entail that, that GW will open a new window to the universe which will bring in information different from what is so far known. For astrophysics the observation of gravitational waves can bring us information on,

(i) dynamics of gravitational collapse, supernovae explosions,

(ii) rotation and asymmetry of progenitors,

(iii) direct detection of blackholes and their properties,

(iv) coalescing compact binary stars.

A new astronomy is in the offing - *Gravitational Wave Astronomy.*

Using a network of gravity wave detectors it would be possible to measure the velocity and polarisation properties of the gravitational wave and hence infer the mass and spin of the field. In the strong field regime gravitational wave observations are our best bet in proving the existence of blackholes and studying their properties, e.g., quasi-normal modes - the transient vibrations of the blackholes. Stochastic GW emitted by phase transitions occuring during the early universe era can tell us about the physics of the unification of interactions.

II. THE DESCRIPTION OF A GRAVITATIONAL WAVE

A weak GW on the background of flat spacetime can be described as a perturbation of the metric tensor over the average background field and is denoted by h_{ik}, A typical component of the perturbation, which we shall call h, is roughly given by,

$$h \sim \frac{1}{r}\frac{G}{c^4}\, E^{\text{kinetic}}_{\text{nonspherical}}, \qquad (1)$$

where r is the distance to the source, G is the gravitational constant, c the speed of light and $E^{\text{kinetic}}_{\text{nonspherical}}$ is the kinetic energy in the *nonspherical* motion of the source. Due to the tiny factor of $\frac{G}{c^4}$, h is a very small quantity. If we consider $E^{\text{kinetic}}_{\text{nonspherical}}/c^2$ of the order of a solar mass and the distance to the source ranging from galactic scale of tens of kpc to cosmological distances of Gpc, the h ranges from 10^{-17} to 10^{-22}. These numbers then set the scale for the sensitivities at which the detectors must operate.

GW have two polarisation states denoted by + and ×. A plane wave is easily visualised by its effect on a circular ring of test particles. Let a wave of circular frequency ω be incident normal to the plane of the ring. Then the circle deforms into an ellipse for each of the polarisation states + and × illustrated in (ii) and (iii) of figure (1) respectively, for $\omega t = \frac{\pi}{2}$ and $\omega t = \frac{3\pi}{2}$.

III. DETECTORS

Two designs of ground based detectors have emerged after long and expert experimentation namely, resonant bars and laser interferometers. Laser interferometers can also be put into space. The LISA project (Bender et al. 1994) planned by the European Space Agency

(ESA) envisages a laser interferometer in space whose arm length is five million kilometres. The detector can operate in the low frequency range (below 10 Hz) and will especially be useful for observing stochastic gravitational radiation. Another idea that is being implemented is the 'spherical bar' detector or an elastic solid sphere which has five different quadrupole modes and can effectively couple to various polarisations and directions (Bassan 1994). It will be useful in the high frequency range $\sim$ few thousand Hertz, where the laser interferometers are likely to be noisy.

(a) Bar Detectors

A resonant bar detector consists of a large, solid bar usually made of aluminium in which mechanical oscillations are produced by GW. A transducer converts the mechanical signal into an electrical signal which is amplified and then recorded. From astrophysics, 1kHz is a reasonable frequency to expect from gravitational wave sources and hence the typical lengths of resonant bars are around 2 metres and masses are few tonnes. This length gives the required frequency for the fundamental mode of the bar. The bar can be modelled as two masses coupled by a spring so that classically it behaves as a forced simple harmonic oscillator.

The cryogenic bars of today operate with a sensitivity of $h \sim 10^{-18}, 10^{-19}$ and it may be pushed down to about $\sim 10^{-20}, 10^{-21}$. Cooling the bar (cryogenic bars) to temperatures close to absolute zero reduces the thermal noise. This improvement in sensitivity of few orders over the bars of the early days is remarkable and encouraging.

(b) Laser Interferometers

An alternative approach is to use freely suspended test masses placed a long distance apart. The larger separation tends to increase the signal. The arrangement is inherently wideband. Here it is possible to avoid absolute length measurements by suspending the test masses along two perpendicular baselines. Such a system is highly suitable to the quadrupolar nature of the wave. The incidence of a gravitational wave on the test masses produces differential strain in the two arms of the interferometer (the ellipse of the previous section). One arm reduces in length while the other arm increases in length in the first half period of the wave, and viceversa for the next half period. The relative length of the two arms can be monitored by laser interferometry (see figure 2).

Developments in laser and mirror technology and clever inventions of optical configuration of detectors (Drever 1983; Vinet 1989) have greatly enhanced the potential sensitivities of laser interferometers. Current designs are based on armlengths of 3 - 4 km. with sensitivities of $h \sim 10^{-22}$. Such detectors are expected to achieve good isolation down to 10 Hz. This wideband operation has made it possible to think of a wider range of sources. An exciting such source is the coalescing binary.

The present laser interferometers are basically prototypes whose armlengths range from 10 metres to 100 metres. These interferometers have approached sensitivities of few times 10^{-20}. However, to achieve higher sensitivities in the range of 10^{-22} it is necessary to increase the arm length to 3 or 4 km. Among the large scale detectors the LIGO project of the U. S. and the French-Italian VIRGO project have begun construction. The LIGO project consists of two detectors of armlength 4 km being constructed at Hanford and Louisiana. The VIRGO project involves a 3 km armlength detector near Pisa in Italy. Among the medium scale detectors are the German-British GEO project, 600 metre armlength and the Japanese TAMA detector 300 metres armlength whose construction has also begun. The Australian AIGO project has been proposed.

IV. SOURCES OF GRAVITATIONAL WAVES

The likely sources involve the supernovae, coalescing binaries, pulsars and stochastic.

(a) Supernovae

The supernova being the most violent event that we know of became the most likely candidate for the detection of gravitational waves. Astrophysically, the detection of electromagnetically quiet supernovae would be extremely important. The strength of the waves emitted by a supernova depends on the amount of non-sphericity of the gravitational collapse. We can characterise the wave bursts by the amount of energy that it emits in gravitational waves. Strong bursts would contain, say 0.1 $M_\odot c^2$ energy which would give $h \sim 6 \times 10^{-18}$ if the burst occured in our galaxy. This could be detected by the present bars, such bursts if they occured in the Virgo cluster could produce $h \sim 4 \times 10^{-21}$ which could be detected by a medium sized laser interferometer of arm length $\sim$ 100 metres.

(b) Coalescing Binaries

This is the most promising source for detection by the LIGO/VIRGO type of detectors. The coalescing binary consists of two compact objects, neutron stars or blackholes, which revolve around each other and emit gravitational waves thereby lose energy and spiral into each other and finally coalesce. A simple model consists of a Newtonian orbit of two mass points which decays by the quadrupole radiation reaction (Peters and Mathews 1963). In the last stages of coalescence a gravitational wave with regular waveform, growing amplitude and frequency is emitted in a burst. Because of the high predictability of the waveform, matched filtering techniques can be applied to decode the signal from the noise allowing such systems to be detected to great

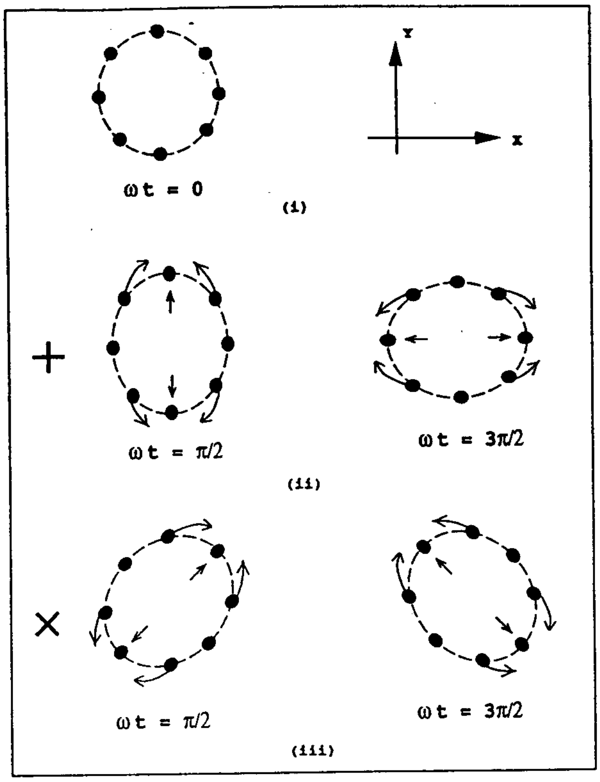

Fig. 1.— The effect of a plane gravitational wave is shown on a ring of test particles for various phases of the wave and for the two polarisations + and ×.

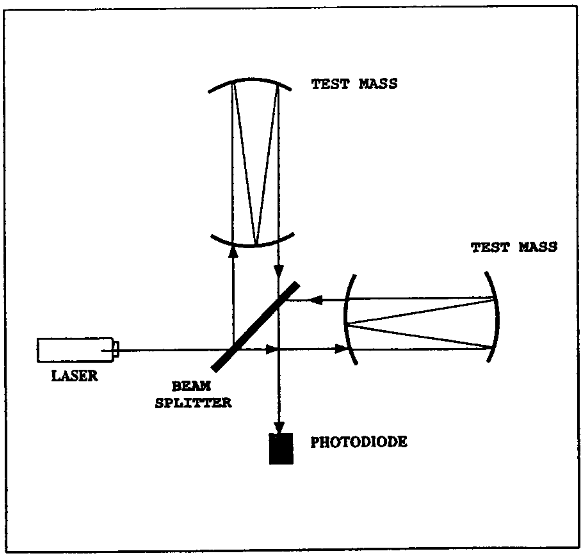

Fig. 2.— A schematic diagram of the laser interferometric detector is shown in the figure. The gravitational wave induces a path difference in the laser light which is detected as a phase difference by the photodiode.

distances. The GW amplitude for the source is,

$$h \sim 3.6 \times 10^{-23}\left(\frac{M}{2.8M_\odot}\right)^{2/3}\left(\frac{\mu}{0.7M_\odot}\right)$$

$$\left(\frac{f}{100Hz}\right)^{2/3}\left(\frac{100Mpc}{r}\right), \qquad (2)$$

where, $M = M_1 + M_2$, $\mu = M_1M_2/M$, M_1, M_2 are the masses of the component stars, r the distance to binary system and f is the GW frequency.

Neutron star binaries could be detectable by advanced detectors to a distance of 500 Mpc while black-hole binaries could be detected out to 1 Gpc. Even though the statistics are uncertain these enormous distances should entail a reasonable event rate. The event rate from several considerations appears to be about 50 to 100 events per year.

The need for on line gravitational data analysis is spurring researchers to look for faster and more efficient algorithms which produce results quickly with high accuracy. In this endeavour the GW group at IUCAA, Pune is actively involved.In 1991 B. S. Sathyaprakash and S. V. Dhurandhar had presented a procedure for detecting coalescing binaries with matched filtering techniques. Online detection of the signal is well within the capabilities of present day computers (Sathyaprakash & Dhurandhar 1991, Owen 1996). Typically the online speed needed is of the order of tens of Gflops for initial detectors and hundreds of Gflops for advanced detectors. This method uses a finely spaced bank of filters. However, this method is computationally labour consuming and recently a hierarchical search was recently proposed (Mohanty & Dhurandhar 1996) where the data is searched in two stages. Optimisation has been performed with respect to thresholds etc. and a cost saving of a factor of eight is obtained for the Newtonian waveform. Work is in progress for the post-Newtonian waveforms and larger cost saving factor is expected.

(c) Pulsars

Asymmetry about their axis of rotation results in their generating GW waves which are emitted at a discrete set of frequencies. The asymmetry δ may be in the form of ellipticity which is defined as 1 minus the ratio of semi-minor-axis to semi-major-axis.

$$h \sim 10^{-21}\delta\left(\frac{f}{100Hz}\right)^2\left(\frac{10kpc}{r}\right). \qquad (3)$$

For $\delta \sim 10^{-6}, h \sim 10^{-27}$, which is certainly far below the raw sensitivity level of the LIGO whose sensitivity would be 10^{-24}. But integrating the signal for a few months can result in an acceptable signal-to noise ratio. Millisecond pulsars can be ideal sources for resonant bars, since they are narrow band and the bars can be tuned (Dhurandhar et al.1996). It has been shown that even axis symmetric objects can emit gravitational waves since they precess (Zimmerman & Szedenits 1979). But the question is whether the ellipticity is high enough so that sufficiently strong GW are emitted to be detectable. Recent calculations (Bonazzola & Gourgoulhon 1996) show that considering a fluid model for the neutron star within the general relativistic framework can result in acceptable ellipticities.

(d) Stochastic Sources

Among the several stochastic sources, the strongest source among them is the cosmic string scenario which makes definite predictions. During the early universe era, at the so called GUT (Grand Unified Theories) epoch, cosmic strings are supposed to have been formed from phase transitions. The motion of the strings gives rise to stochastic gravitational waves which carry the signature of the early universe. From the galaxy formation scenario the estimated amplitude of the Fourier component $\tilde{h}$ of the stochastic gravitational wave background at 1 kHz is about 10^{-24} or 10^{-25} which is already being constrained by the pulsar timing observations. Detectors in space are the answer since they are less noisy at low frequencies.

There could be primordial gravitational waves produced during the bigbang itself. In the inflationary scenario, the graviton field is parametrically amplified by inflationary expansion to produce a measurable stochastic background.

V. CONCLUDING REMARKS

In the past two decades or so, one is struck by the enormous advance in our theoretical understanding of gravitational waves. The more understanding we have about likely sources, the easier will it be for us to identify the signal from the noise. One is even more impressed by the progress made by the experimentalists to invent, design and strive for detectors with greater sensitivities. There is no doubt that the quest will succeed, the only question is when.

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