Einstein's centennial gift: Gravitational waves discovered

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Abstract

A spectacular prediction of Einstein's general theory of relativity is gravitational waves. A century ago - in 1916 - Einstein predicted the existence of gravitational waves. Gravitational waves have now been detected by the LIGO detectors in the US. The physical existence of the waves was established long before by the observations of the Hulse-Taylor binary pulsar whose orbit decays exactly as predicted by Einstein's general theory of relativity. Weakness of the gravitational force implies that the waves are extremely difficult to detect - one must effectively measure distances much smaller than the size of a proton. During the past half century, technology has taken immense strides and the current advanced detectors are now capable of reaching the requisite sensitivity to detect the waves. Gravitational waves carry information about their dramatic origins and about the nature of gravity that cannot be otherwise obtained. A new astronomical window to the universe has been opened. This article will describe the physics of gravitational waves, the technological feats necessary for the detector to achieve unprecedented sensitivities, the current and future global efforts in this direction, the gravitational wave event that was detected, the Indian initiative and contribution to the global effort and the astrophysics that we can learn from this.

1 Introduction

History was created on 11th February 2016, when it was announced that gravitational waves (GW) had been directly detected [1]. The two LIGO detectors of the US detected gravitational waves emitted by the collision of two black holes of about 30 solar mass each on 14th of September, 2015 at 9:50:45 UTC which is at about 15:20 hrs Indian standard time. The data from both detectors, one in Louisiana and the other in Washington state, clearly shows almost identical waveforms in both detectors with time difference of about 7 milliseconds which is consistent with the geographical separation of 3000 km (10 ms GW travel time) between the detectors. This infact marks a three fold discovery: (i) direct detection of GW, (ii) direct detection of black holes and (iii) detection of a black hole binary system. The impact of the discovery is enormous on astronomy and generally on science. It has not only detected black holes but has confirmed general relativity in the strong field regime. It has given rise to the birth of a new astronomy - *Gravitational Wave Astronomy* by opening a new window to the universe. The GW window will complement other windows, namely, the optical one opened by Galileo four centuries ago, radio, infrared, ultraviolet, X-ray and γ-ray in electromagnetic astronomy and also the neutrino. Whenever a new window has been opened it has brought with it unexpected discoveries. Thus it is not unreasonable to expect the unexpected and all the more, because now even the physical interaction is a different one, namely, that of gravity.

The key to gravitational wave detection is the very precise measurement of small changes in distance. In the 1960s, Joseph Weber began his efforts to detect gravitational waves [2]. In a decade of pioneering experiments he investigated resonant bar detectors which were suspended, seismically isolated, aluminium cylinders. His work, though inconclusive encouraged others to build next generation detectors, namely, cryogenic resonant bars and laser interferometric detectors of arm lengths of tens of metres. However, it was soon realised that there were inherent limitations to the design of bar detectors in terms of scalability and narrow band response. A better design was a laser interferometric design which was naturally suited to the quadrupolar nature of GW waves. For laser interferometers, the precise measurement is the distance between pairs of mirrors hanging at either end of two long, mutually perpendicular vacuum chambers. A GW passing through the instrument will shorten one arm while lengthening the other. By using an interferometric design, the relative change in length of the two arms can be measured, thus signalling the passage of a GW. However, the distance measurements are phenomenally small - one-thousand'th the size of a proton! And performing such incredibly small measurement is in fact a feat in technology requiring long arm lengths, high laser power, and extremely well-controlled laser stability [3].

In this article we will first describe the physics of GW, laser interferometric detectors and noise sources, the recent detection of the GW event, the astrophysics we expect from

the new astronomy and the future global network of detectors which includes the detector in India - LIGO-India [4].

2   From Newton to Einstein

The theory of gravitation one usually learns at first is Newton's theory of gravity and the inverse square law. Newton's theory not only explained terrestrial gravity - the legendary falling of an apple - but also the motions of astronomical objects such as the planets and the moon, and in particular Kepler's laws. It came to be known as the universal theory of gravitation because it unified terrestrial gravity with gravity in space as applied to astronomical objects. Its range extended from macromolecules to galaxies and was a resounding success. So then why do we need another theory of gravity?

In 1905, Einstein presented to the world his special theory of relativity [5]. The special theory of relativity essentially deals with measurements of distance, time, mass etc. when the experimenter is moving with respect to the system of objects he is measuring. The principle of relativity says that the laws of physics must be the same for all observers moving uniformly with respect to each other. Special relativity does not concern itself with any specific physical law but requires all physical laws to conform to it. Thus classical mechanics, electromagnetism and quantum physics should obey special relativity. And gravity is no exception. New-

ton's theory of gravity is not consistent with the special theory of relativity; it is simply unacceptable to have physical theories inconsistent with each other. For example, special relativity requires that all signals must travel at finite speeds, in fact less than or equal to the speed of light in vacuum. But the gravitational force field as described by Newton's theory by the inverse square law is instantaneous, that is, there is no propagation of gravitational forces; the field equations of Newton's theory do not contain *time* - the inverse square law has no time in its description. Thus from this conceptual point of view a new theory of gravity was needed in which gravitational interaction propagates at finite speeds. Although at the beginning of the last century, it was observed that there was a discrepancy in Mercury's orbit - the advance of perihelion of Mercury - Einstein was more concerned with the conceptual problem. Einstein's theory of gravity, the general theory of relativity (GTR), incorporates the special theory of relativity. More importantly, it has come out in flying colours in all gravitation experiments conducted so far - the observations match the theory. Instead of just tinkering with Newton's theory, Einstein formulated conceptually a completely different theory - the general theory of relativity which is also a theory of gravitation [6].

We describe the theory in a prescriptive manner. Matter and energy (described by the energy momentum stress tensor) *curve* the spacetime in its vicinity. Gravitation is the manifestation of the curvature of spacetime. Note that it is a four dimensional curvature - the *spacetime* is curved - and that

space and time have already become a single entity in special relativity. So for instance, if we consider our solar system with the Sun as a central body producing the gravitational field and planets responding to this field and orbiting around it, in Einstein's theory, the Sun *curves* the spacetime around it and the planets move along the straightest possible paths they can in this curved geometry of spacetime. So the orbit of the planet appears curved because the spacetime is curved. The planet strives to follow a "straight" path, but since the spacetime itself is curved and so the "straight" path appears curved. Compare the situation with a sphere. A sphere is an example of the simplest curved space. On the sphere the great circles are the "straightest" possible paths - but they are remarkably different from the straight lines of Euclid's geometry. Such paths are called geodesics.

It remains to prescribe how the matter distribution curves spacetime [7]. This is accomplished by Einstein's field equations[1],

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \, , \qquad (1)$$

where on the left-hand side (LHS) we have terms describing the curvature in terms of the Riemann tensor and the metric and on the right-hand side (RHS) we have the stress tensor of the matter distribution. The constants G and c denote respectively the Newton's gravitation constant and the speed of light. On the LHS appear the Ricci tensor

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[1]Details on Einstein's equations are available in standard textbooks on GR. However, the readers do not need those details to understand this article.

$R_{\mu\nu}$ and the scalar curvature R, which are derived from the Riemann tensor $R_{\mu\nu\lambda\sigma}$. These equations are the analogue of Newton's equation:

$$\nabla^2\phi = 4\pi G\rho \, , \qquad (2)$$

where ϕ is the Newtonian gravitational potential and ρ is the mass density of matter. But Einstein's equations are much more complicated. They are 10 *coupled* non-linear second order partial differential equations for 10 components of the metric tensor $g_{\mu\nu}$ - the metric tensor is symmetric and so has 10 independent components in 4 dimensions (actually the number of independent equations reduces to six because we have four degrees of freedom in the choice of coordinates). The situation is far more complex than Newton's equation or even Maxwell's equations of electrodynamics and therefore the equations are extremely difficult to solve. Unless one assumes enough symmetries, which effectively reduces their complexity, solutions are hard to come by. For example, no exact analytic solution so far exists for the two body problem in GTR. It is only after years of clever hard work and only recently, that progress has been possible. Solutions can be obtained by a combination of methods involving post-Newtonian approximations [8, 9], numerical relativity [10] and black hole perturbation theory [11].

Further GTR reduces to Newton's theory of gravitation in the limit of weak fields and slow motion as it must, because a new theory must certainly explain phenomena explained by the old theory in its regime of validity; but the new theory may extend be-

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yond the old theory's regime of validity. This happens with GTR. When velocities are not small compared to the speed of light and when the fields are strong, Newton's theory can no longer describe gravitational phenomena accurately and reliably - the spacetime can no longer be considered as a small deviation from the flat (non-curved) spacetime of special relativity - GTR must be used.

The successes and predictions of GTR are spectacular. GTR predicts the expanding universe, black holes and gravitational waves among many other phenomena. In this article we will concern ourselves mainly with GW.

3 The physics of gravitational waves

Einstein's equations admit wave solutions - this is readily seen if we make a weak field approximation [12]. A weak GW is described by a metric perturbation $h_{\mu\nu}$ in general relativity. Typically, for the astrophysical GW sources which are amenable to detection, $h_{\mu\nu} \sim 10^{-22}$. Consider a spacetime which differs slightly from the Minkowski spacetime of special relativity. So the Minkowski metric will be slightly modified. Writing,

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \,, \qquad (3)$$

where $\eta_{\mu\nu} = \mathrm{diag}\{1, -1, -1, -1\}$ is the Minkowski metric tensor and where $h_{\mu\nu}$ is a perturbation on this 'Minkowski background'. To the linear order in $h_{\mu\nu}$, it can be easily shown (after a fair amount of algebra)

in a certain gauge - transverse and traceless (TT) [13] - that Einstein's field equations reduce to the wave equations:

$$\Box h_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu} \,, \qquad (4)$$

where the $\Box$ is the D'Alembertian operator. It is apparent from this equation that firstly, GTR predicts GW and secondly, GW travel with the speed of light because the velocity c occuring in the $\Box$ operator is the speed of light as seen below:

$$\Box \equiv \frac{\partial^2}{c^2 \partial t^2} - \nabla^2 \,. \qquad (5)$$

Thus GW are waves in the metric field $g_{\mu\nu}$. Now the curvature or the Riemann tensor is essentially formed by taking the second derivatives of the metric - a very complicated formula; details of which need not concern us here. Thus GW can be described also as waves in the curvature of spacetime. And it is the curvature which can be measured with the help of test masses and thus is a physical field. Thus, one may use either the metric or the curvature to describe gravitational waves.

We can deduce the properties of GW from GTR. We list them below:

- GWs travel with the speed $c \sim 3 \times 10^5$ km/sec.

- GWs are transverse.

- GWs have two polarisations.

It is easy to visualise the two polarisations in the TT gauge; the $h_{\mu\nu}$ can be expressed in terms of just two amplitudes, h_+

and $h_\times$, called the 'plus' and 'cross' polarisations. The two polarisation states are easily understood, if we examine the effect of the waves on test particles. The test particles are just free test masses. A single free mass particle cannot detect a wave (or any gravity) because of the equivalence principle of GTR - one can just transform to the freely falling frame of the test particle and the particle then will remain at rest in this frame and thus will not detect any GW. We need at least two spatially separated particles to observe the effect of GW; one tracks the variation in the separation between the particles as a function of time. Since in GTR the metric is a second rank tensor, it is customary to take a ring of test particles and take the reference particle at the centre. If a weak monochromatic gravitational wave of + polarisation is incident on a ring of test-particles, the ring is deformed into an ellipse as shown at the top of Figure 1. Phases, half a cycle apart, of the GW are shown in the figure. For the $\times$ polarisation the ellipses are rotated by an angle of 45°. A general wave is a linear combination of the two polarisations.
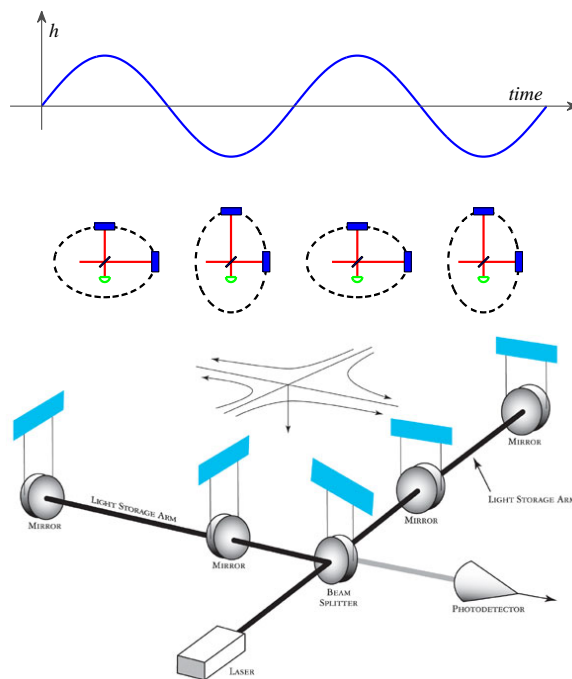

Figure 1: Upper: A circular ring of test particles is deformed into an ellipse by an incident GW (image taken from [14]). Phases, half a cycle apart are shown for the + polarisation. The length change in the interferometric arms is also shown schematically. Lower: a schematic diagram of an interferometer is drawn (Image: Caltech/MIT/LIGO Lab.).

4 Detection of gravitational waves

We will confine ourselves to interferometric detection [3]. The figure 1 shows a schematic diagram of an interferometer. If we select two masses on this ring of test masses at right angles and monitor their distance with respect to the centre of the ring, which we take to be the reference point, we will find that during one half cycle of the wave one arm shortens while the other arm elongates. In the next half cycle of the wave the opposite happens. By using a laser interferometric arrangement a passing GW will produce a time-varying path difference which can be detected on a photodiode.

However, there is a catch! The changes in distances are exceedingly small in astrophysical situations. For example, a neutron star binary at distance of 100 Mpc [2] - a typical distance to a GW source - will produce a differential length change of $\sim 10^{-16}$ cm. for test masses kept few kilometres apart, which is the typical length of the arm of a large scale ground-based interferometric detector! For a GW source, h (a typical component of $h_{\mu\nu}$) can be estimated from the well-known Landau-Lifschitz quadrupole formula. This formula can be obtained by integrating the inhomogeneous wave equation (4) under certain assumptions. The formula relates the GW amplitude h to the second time derivative of the quadrupole moment (which has dimensions of energy) of the source. For obtaining order of magnitude estimates, we can strip the tensor indices of the formula and then it reads:

$$h \sim \frac{4}{r}\, \frac{G}{c^4}\, E^{\text{kinetic}}_{\text{nonspherical}},\qquad (6)$$

where r is the distance to the source and $E^{\text{kinetic}}_{\text{nonspherical}}$ is the kinetic energy in the *nonspherical* motion of the source. 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, then h ranges from 10^{-17} to 10^{-22}. These numbers then set the scale for the sensitivities at which the detectors must operate.

How does the quantity h relate to the change in distance between the test particles?

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[2]These are units which astronomers use; 1 Mpc or mega parsec is $\sim 10^{19}$ km.

The following formula answers this question. Let L be the distance separating the test masses, then the change in distance δL due to a GW with metric perturbation h is given by,

$$\delta L \sim hL\,.\qquad (7)$$

This result is easily obtained by integrating the geodesic deviation equation. The geodesic deviation equation is justified for ground based detectors because typically the wavelength of the GW - few hundred km or more - is much greater than the distance between the test masses, namely few km, so that the worldlines of the test masses could be thought of as "neighbouring".

However, since detection involves impossibly small measurements, the noise in the detector needs to be suppressed by several orders of magnitude in order that there is a chance of extracting the signal from the noise by statistical signal detection methods. There is a host of noise sources in interferometric detectors which contaminate the data. At low frequencies there is the seismic noise. The seismic isolation is a sequence of stages consisting of springs and pendulums and heavy masses. Each stage has a low resonant frequency about a fraction of a Hz. The seismic isolation acts as a low pass filter, strongly attenuating frequencies much higher than the resonance frequency of the isolation system. This results in a 'noise wall' at low frequencies at around 10 Hz. Also below 10 Hz is the gravity gradient noise which is difficult (if not impossible) to shield. At mid-frequencies upto few hundred Hz, the thermal noise is important and

is due to the thermal excitations both in the test masses - the mirrors - as well as the seismic isolation suspensions. At high frequencies the shot noise from the laser dominates. This noise is due to the quantum nature of light. From photon counting statistics and the uncertainty principle, the phase fluctuations are inversely proportional to the square root of the mean number of photons arriving during a period of the wave. Thus, long arm lengths, high laser power, and extremely well-controlled laser stability are essential to reach the requisite sensitivity.

5 Gravitational waves discovered

The two LIGO detectors of the US in Louisiana and Washington state detected gravitational waves on 14th of September, 2015 at 9:50:45 UTC [1]. The data from both detectors clearly shows almost identical waveforms in both detectors with time difference of about 7 milliseconds which is consistent with the geographical separation of 3000 km (10 ms GW travel time) between the detectors. The waveforms are shown in units of the strain of $h = 10^{-21}$.

The signal was emitted by two black holes of individual masses 28 amd 36 $M_\odot$ which coalesced to form a remnant black hole of mass 62 $M_\odot$ and angular momentum $J = 0.67 GM^2/c$, where M is the mass of the final black hole. These masses are given in the
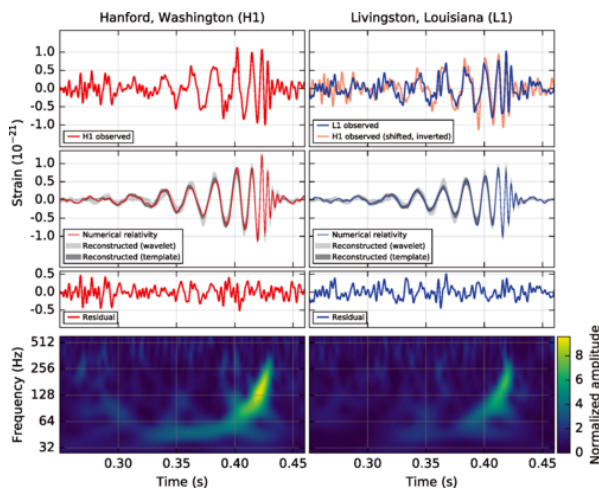

Figure 2: The upper two rows show the GW strains for the two detectors at Louisiana (L1) and Washington State (H1) (image taken from [1]). For visual comparison in the upper right panel H1 data are shown time shifted and inverted to take into account their geographical separation and different orientations. The third row shows residuals and the bottom row shows time-frequency representation of strain data. It is apparent from this plot that the frequency of the signal increases with time.

source frame. The energy emitted in GW was 3 $M_\odot c^2$ which amounts to $\sim 5\%$ of the total mass. The waveform sweeps through a frequency range from 30 Hz to about 250 Hz in 10 cycles lasting for ~ 0.2 sec. The combined signal-to-noise from two detectors is ~ 24. The estimated distance to the binary black hole is about 410 Mpc. The false alarm probability for the event is less than 2×10^{-7}. The characterstics of the waveform show that this cannot be a neutron star binary nor a neutron

star - black hole binary. Exhaustive investigations were carried out to rule out environmental and instrumental noise. The signal is consistent with GTR.
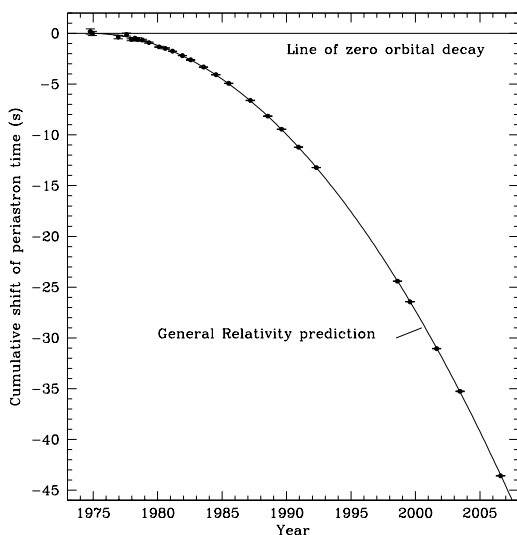

Figure 3: The cumulative advance of periastron is shown as a function of time in years from 1975 to 2005, taken from [15]. The black dots are the observation points while the continuous curve is the prediction of GTR.

Much before this, few decades ago, the existence of GW had been established for which the radio astronomers Hulse and Taylor were awarded the Nobel prize. Hulse and Taylor [16] discovered the binary pulsar PSR 1913 + 16 and subsequent observations showed energy loss and decrease in orbital period

of the system [17]. This decay in the orbit is exactly as predicted by GTR. The binary system loses energy through GW, thus shrinking in its orbit and steadily decreasing its period P. The $\dot{P}$ can deduced from the quadrupole formula and also the rate of energy loss through GW. The rate of decrease in the period $\dot{P} \sim -2.4 \times 10^{-12}$ which amounts to about 75 microseconds per year. But because of this the periastron (the epoch at which the stars are closest to each other) advances. The figure above shows the cumulative advance in periastron of the orbit plotted versus the year [15]. The observations exactly agree with the predictions of GTR.

Although this observation establishes the existence of GW it is not a direct detection, because we do not observe the waves themselves; we infer their existence from their effect on the orbit of the binary pulsar.

The direct detection of GW however, has opened a new window to the universe and given rise to the birth of a new astronomy - *Gravitational Wave Astronomy.*

6 Gravitational wave astronomy

6.1 Global network of interferometric detectors

A global network of geographically widely separated detectors is essential for GW astronomy [18] as they are required to (i) localise GW sources in the sky, (ii) increase detection confidence, (iii) increase duty cycle

and (iv) determine polarisation which would give us information on the orientation of the GW source.

The era of advanced detectors has arrived with the state of the art technology which will be capable of observing GW sources and doing GW astronomy. With these future goals in mind, a radical decision has been taken by the LIGO of the US - to build one of the detectors in India in collaboration with India [4]. The reason for this decision is clear - it is to increase the baseline and have a detector far removed from other detectors on Earth, which has several advantages, such as improving the localisation of the GW source, which can then make it feasible to follow up a GW event with electro-magnetic telescopes. There are two LIGO detectors of armlength 4 km in the US, one at Hanford, Washington and one at Livingston, Louisiana geographically separated by 3000 km. The first observation run called O1 of the two LIGO detectors has just taken place which lasted for 4 months. The detectors operated at a sensitivity few times better than the initial detectors. The goal in the next few years will be to improve the sensitivity few times, thereby increasing the volume of the universe the detectors are sensitive to by about an order of magnitude.

In Europe the VIRGO project of Italy and France has constructed a 3 km armlength detector. After commissioning of the project in 2007, it also had science runs. The GEO600 is a German-British project, whose detector has an armlength of 600 metres and is constructed near Hannover. One of the goals of GEO600 is to develop advanced technolo-

gies required for the next generation detectors with the goal of achieving better sensitivity.

Japan was the first (around the year 2000) to have a large scale detector of 300 m armlength - the TAMA300 detector under the TAMA project - operating continuously at high sensitivity. Now Japan is constructing a cryogenic interferometric detector called the KAGRA. The purpose of the cryogenics is to reduce the thermal noise in the mirrors and the suspensions and thus increase sensitivity at midrange frequencies.

6.2 The IndIGO consortium and the LIGO-India project

GW research in India had a 25 year legacy and wide recognition in the international GW community. Two groups at IUCAA, Pune and Raman Research Institute (RRI), Bangalore contributed significantly to the global effort, mainly in data analysis of GW signals buried in the noisy detector data and computation of the inspiraling compact binary waveform employing post-Newtonian methods. A lot of trained manpower was created from the students and postdoctoral fellows from these two groups and currently they are occupying key faculty positions both in India and abroad. Given this background, a consortium called *Indian Initiative in GW observations* (IndIGO) was formed in 2009. The aim of this consortium is to foster and promote GW research in India, interact actively with the international community and build up a community of Indian scientists compe-

tent in GW research in theory and experiment. The consortium has proposed a GW detector - LIGO-India - in collaboration with the US, on Indian soil.

The LIGO-India project has been recently approved in principle. The goal of the project is constructing and then operating an advanced interferometric gravitational wave detector in India. A timely opportunity to leap-start gravitational wave research and astronomy in India has arisen through the possibility of the LIGO Laboratory offering and National Science Federation (NSF), US agreeing to transfer one set of components prepared for the advanced LIGO-interferometer, as part of the collaborative effort. Indian scientists will install and operate the detector as well as build the entire infrastructure including the ultra-high vacuum vessels and tubes required to house the interferometer at a suitable, gravitationally and seismically quiet site in India and operate it as part of the global network of detectors for gravitational wave astronomy during the next two decades. The proposal to build and operate the Indian detector is timed to be in this exciting decade of the first detection and observations of GW. To be a key partner in this global endeavour with an interferometer detector built and operated in India is the goal of this project.

6.3 GW astrophysical sources

Several types of GW sources have been envisaged [19, 20] which could be directly observed by Earth-based detectors: (i) burst sources – such as binary systems consisting of compact objects such as neutron stars and/or black holes in their inspiral, merger and ring down phase; burst sources such as supernovae – whose signals last for a time much shorter, between a few milli-seconds and a few minutes, than the typical observation time; (ii) stochastic backgrounds of radiation, either of primordial or astrophysical origin, and (iii) continuous wave sources – e.g. rapidly rotating non-axisymmetric neutron stars – where a weak sinusoidal signal is continuously emitted.

We will discuss here only the compact coalescing binary sources because this is the type of source which has been detected - a black hole binary. Compact coalescing binaries emit enormous amount of GW energy, and also they are clean systems to model; the inspiral waveform can be computed accurately to several post-Newtonian orders [8, 9] adequate for optimal signal extraction techniques such as matched filtering to be used. In the past decade IUCAA has focussed on the design, validation and implementation of search algorithms for inspiraling binaries [21, 22]. Numerical relativity has been able to make a breakthrough by continuing the inspiral waveform to the merger phase and eventually connect it with the ringdown of the final black hole [10]. The full waveforms are obtained by stitching together the inspiral, merger and ring down waveforms. The full waveform consisting of inspiral, merger and ring down can also be obtained directly from numerical relativity alone, but this is computationally very expensive at the moment.

The astrophysical inferences from the currently detected event are as follows [1]. Stellar mass black holes of more than $25 M_\odot$ ex-

ist and also form binaries within a Hubble time. From the data and the current event, one may estimate the median rate of such events, which turns out to be about 16 events per Gpc^3 per year for a false alarm rate of one per century. One can also deduce how much stochastic background can be produced from the above event rate. An upper limit of 1.2×10^{-22} eV/c^2 can be put on the mass of the graviton from dispersion arguments.

7 The road ahead

Given the situation that the detectors sensitivity will improve in the next few years, one expects to detect many more sources such as the black hole binary event already detected. From these detections we may be able to learn many new aspects in astrophysics, such as the population of black holes of various masses, their distrbution, the GW stochastic background they may produce etc. Also we should be able to observe neutron star - neutron star and neutron star - black hole binaries. We could also have detections of continuous wave sources such as isolated spinning neutron stars, accreting neutron stars etc.

A new window to the universe has been opened and this may bring to us new type of astrophysical sources never imagined. Whenever a new window has been opened, it has brought with it surprises. To cite an example, let us consider radio astronomy. It brought to us pulsars, the cosmic microwave background, radio jets etc. These were completely new discoveries not seen by optical telescopes. Astronomies in other frequency bands have also brought to us new information not available through other windows. This wealth of information from different channels has seen the rise of multi-messenger astronomy where one studies a given astrophysical source pooling together information from the different windows available.

There are also plans to build GW detectors in space. The advantage here is that one can go to very low frequencies of a fraction of a Hz or even mHz. For groundbased detectors a natural limit occurs on decreasing the lower frequency cut-off below $\sim$10 Hz, because of the gravity gradient noise which is difficult to eliminate below 10 Hz. Thus, the ground based interferometers will not be sensitive below the limiting frequency of $\sim$10 Hz. But on the other hand, there exist in the cosmos, interesting astrophysical GW sources which should be emitting GW below this frequency such as the galactic binaries, massive and super-massive black hole binaries. If we wish to observe these sources, we need to go to lower frequencies. The solution is to build an interferometer in space, where such noises will be absent and will allow the detection of GW in the low frequency regime. There are plans to build such detectors, such as the eLISA [23] and DECIGO [24] in future. But this may take 20 years or more.

The ground-based detectors and the space-based detectors complement each other in the observation of GW in an essential way, analogous to the way optical, radio, X-ray, γ-ray observations do for electromagnetic waves. As both these types of detectors begin to operate, a new era of GW astronomy is on the horizon and a radically different view of the

Universe is expected to emerge.

Acknowledgments

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