Astronomy of the 21st century: Gravitational Wave Astronomy

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Abstract

An important prediction of Einstein's theory of relativity is gravitational waves. A change in the gravitational field propagates at a finite speed, although extremely large compared to speeds we encounter in normal everyday life. These are gravitational waves (GW). They travel at the universal speed $c \sim 3 \times 10^5$ km/sec which is also the speed of light. This article begins with the physics of GW, their detection and generation. It then moves on to the detectors being constructed around the world, namely, the laser interferometric detectors, their current status and future plans. Then the GW sources are described and what information we can glean from them about the universe. The observation of GW will be the beginning of a new astronomy - gravitational wave astronomy - the astronomy of the 21st century. India is poised to be an important participant in this worldwide effort.

1 Introduction

This article is dedicated to Profs. Vaidya and Raychaudhuri and based on the Vaidya-Raychaudhuri lecture, delivered at St. Xavier's College, Kolkata.

Gravitational waves (GW) can be described as a space-time warpage which travels with the speed of light. Astrophysical GW will bring us information complementary to that obtained from electromagnetic observations, because the GW have very different properties. GW are produced in compact, dense, high velocity regions of matter in the universe and are not easily scattered, unlike electromagnetic waves. Therefore, it seems reasonable to expect a revolution in understanding of our universe akin to the one brought on by radio astronomy in the last half a century. For example, radio astronomy brought to us the discovery of the cosmic microwave background, pulsars etc. We expect even more startling discoveries here because we are changing the interaction from electromagnetic to gravitational. Exciting times lie ahead for GW astronomy.

Currently, the large scale detectors, LIGO of the US, Virgo of Italy and France, the Japanese TAMA detector and the UK-German GEO detector [1] have achieved impressive sensitivities. Some of them have infact surpassed their proposed design sensitivities. Now efforts are on to construct advanced detectors which will have the requisite sensitivity for detecting astrophysical sources of gravitational waves with a reasonable event rate. A large scale detector LCGT in Japan [2] has been recently funded and the LIGO would like to build a detector far away from the existing detectors in US, in the Asia-Pacific region, in order to obtain a long baseline; a long baseline has several advantages such as more accurately determining the location of a GW source in the sky. On the Indian front, during the past two years, an initiative in gravitational wave astronomy has begun on the experimental front - there has already been expert effort on data analysis and waveform computations over the past two decades in India - and an Indian consortium involving researchers from several Indian leading institutions has been formed - the IndIGO consortium.

Several types of GW sources have been envisaged which could be directly observed by Earth-based detectors, such as the burst sources, examples are binary systems of neutron stars and/or black holes and supernovae explosions; stochastic backgrounds of radiation, either of primordial or astrophysical origin and continuous wave sources – e.g. rapidly rotating asymmetrical neutron stars, where a weak deterministic signal is continuously present in the data stream. We will here describe in some detail the compact inspiraling/coalescing binary - the various advances that were made in the course of last two decades in the analytics as well as in numerical relativity.

2 What are gravitational waves?

2.1 Well-known wave phenomena in physics

Let us begin with something we know. Sound waves for example. Let us consider sound waves in air. Sound waves are fluctuations in the pressure p and density ρ of air and which travel at a certain speed, 330 metres/sec in air under normal conditions. There are alternating rarifactions and compressions of the air molecules along the direction of propagation. A snapshot of such a wave is shown in Fig. 1. What are their properties? First of all, sound waves require a medium to propagate. Secondly, they are longitudinal. The motion of the particles is along the direction of propagation. They are generated by objects rhythmically pushing the medium about - like the diaphragm of a loud speaker or the vocal cords of a human being.

We are also familiar with electromagnetic waves. These are waves in the electric and magnetic fields. These waves do not require a medium - they can propagate in vacuum. They are transverse meaning that the electric and magnetic fields are orthogonal to the direction of propagation. A snapshot of such a wave is shown in Fig.2. They are generated by accelerated electric charges - for example charges harmonically moving along a linear antenna.

Figure 1: A snapshot of a sound wave: waves in the pressure field.

It is then natural to ask the question whether gravitational waves are generated by moving or accelerating *masses*. In gravity the mass is the analogue of the electric charge of electromagnetic theory, because mass generates gravity just as a charge generates electromagnetic fields. The answer is a resounding yes in Einstein's theory of gravity or what is also known as the general theory of relativity.

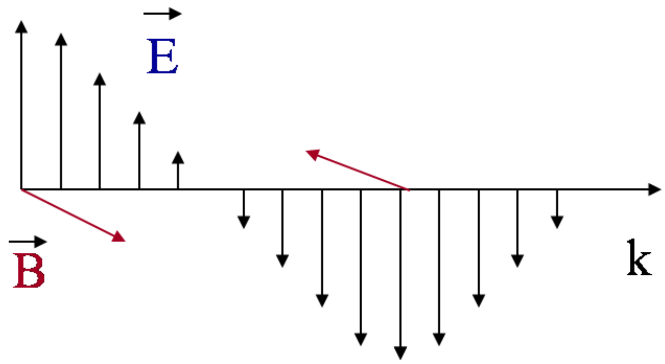

Figure 2: A snapshot of a linearly polarised electromagnetic wave. **k** is the direction of propagation of the wave and the electric and magnetic fields $\vec{E}$ and $\vec{B}$ are orthogonal to it.

2.2 Einstein's theory of gravity

The theory of gravitation one usually learns at first is the Newton's theory of gravity and the inverse square law. Newton's theory not only explained terrestrial gravity - the legendary falling apple - but also the motions of astronomical objects such as the planets and the moon, and in particular the Kepler's laws. It came to be known as the universal theory of gravitation because it unified terrestrial gravity with gravity in space. Its range extended from macromolecules to galaxies and thus was a resounding success. But when Einstein put forward his special theory of relativity it was apparent that there was a flaw in Newton's theory of gravity. According to Einstein's theory 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 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. Infact there are no gravitational waves in Newton's theory of gravity. Thus from this conceptual point of view a new theory of gravity was needed in which gravitational interaction propagates at finite speeds. Einstein's theory fulfils this criterion and infact does much more. Most importantly, it has come out in flying colours in all the 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 (GTR) which is also a theory of gravitation.

I will not go into the reasons of how Einstein arrived at his theory of gravity. I will only describe the theory in a prescriptive format. 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 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. These paths are called *geodesics*. So the orbit of the planet appears curved because although the planet strives to follow a "straight" path, the spacetime itself is curved and so the straightest path appears curved. Compare the situation with a sphere. A sphere is an example of the simplest curved space (a manifold). On the sphere the geodesics are great circles - these are the "straightest" possible paths on the sphere - but they are far from straight lines of Euclid's geometry. See figure 3 below for a planet orbiting the Sun.

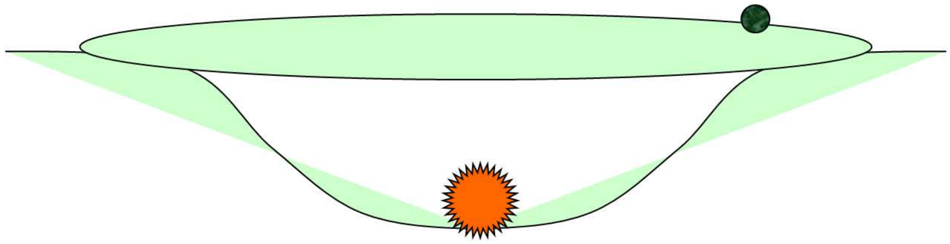

Figure 3: The Sun curves the spacetime around it and the planet moves in the straightest possible path in this curved geometry.

We further need to prescribe how mass curves the spacetime. This is accomplished by Einstein's field equations,

$$R_{ik} - \frac{1}{2} R g_{ik} = \frac{8\pi G}{c^4} T_{ik} \,, \tag{1}$$

where on the LHS we have terms describing the curvature in terms of the Riemann tensor and the metric and on the 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 R_{ik} and the scalar curvature R which are derived from the Riemann tensor R_{ijkl}. These equations are the analogue (infact more than that) of Newton's equation:

$$\nabla^2 \phi = 4\pi G \rho \,, \tag{2}$$

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* equations for 10 independent components of the metric tensor g_{ik} - the metric tensor is symmetric and so has 10 independent components in 4 dimensions. Further, they are nonlinear and of second order. The situation is far more complex than Newton's equation or even Maxwell's equations in electrodynamics. So 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 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. The problem has been solved not analytically but post-Newtonian approximations and numerical relativity were required to obtain the solution. More about this later because the compact binary system is an important source of GW especially during its end stages when it coalesces. This was in fact the motivation for solving this problem. It has happened for the first time in the field of gravitation that experiment has driven theory, a situation which routinely happens in other areas of physics and in general science. This is because in general, gravitation experiments are difficult; gravitation being the weakest of the forces of nature.

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 must extend beyond the old theory's regime of validity. When velocities are not small compared to the speed of light and when the fields are strong, Newton's theory can no more describe gravitational phenomena accurately or even reliably - the spacetime can no more be considered as a small deviation from the spacetime of special relativity - GTR must be used.

2.3 GW: Waves in the curvature of spacetime

Now GTR predicts many new phenomena. One is black holes, from which no matter or even light can escape; the other relevant to this lecture is *gravitational waves*. Einstein's equations admit wave solutions - this is readily seen if we make a weak field approximation. Consider a spacetime which differs slightly from the Minkowski spacetime of special relativity. So the Minkowski metric will be slightly modified. Writing $g_{ik} = \eta_{ik} + h_{ik}$, where $\eta_{ik} = \mathrm{diag}\{1, -1, -1, -1\}$, the Minkowski metric tensor and where h_{ik} is a perturbation on this 'Minkowski background' it can be easily shown (after a fair amount of algebra) in a certain gauge (called transverse and traceless) that Einstein's field equations reduce to the wave equations:

$$\Box h_{ik} = \frac{16\pi G}{c^4} T_{ik} \,, \tag{3}$$

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 constant c occuring in the $\Box$ operator is the speed of light as seen below:

$$\Box \equiv \frac{\partial^2}{c^2 \partial t^2} - \nabla^2 \,. \tag{4}$$

Thus GW are waves in the metric field g_{ik}. 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 measured with the help of test masses and thus is a physical field. Thus we may describe GW either in terms of the metric or in terms of curvature. The metric and curvature are the dynamical variables of Einstein's theory. This is analogous to Maxwell's electrodynamics theory in which one can either consider the electric and magnetic fields $\vec{E}, \vec{B}$ or alternatively the potentials $\vec{A}$ and ϕ to describe the electromagnetic field. Here the fields are first derivatives of the potentials. One can therefore in analogy consider the metric as the "potential" and the "curvature" as the field in Einstein's theory. Either of them can be used to describe the gravitational field. So GW are waves in the curvature of spacetime. To understand this better, one needs to understand the notions of metric and curvature.

3 Metric and curvature

These concepts can be readily understood by considering a surface such as a sphere. Consider a sphere of radius R and with the usual spherical coordinates (θ, ϕ). This is a two dimensional space or manifold as it is normally called because one needs just two coordinates θ, ϕ to describe any point on it (this is not correct in the strict mathematical sense, but in any case 'most' points (except for a set of measure zero) on the sphere are covered by this coordinate system). The metric is the distance between two adjacent points with coordinates $P(\theta, \phi)$ and

$Q(\theta + d\theta, \phi + d\phi)$, where the differentials are small and in the limit tend to zero. Then the distance ds between P and Q is given by the equation:

$$ds^2 = R^2(d\theta^2 + \sin^2\theta d\phi^2)\,. \tag{5}$$

This equation can be readily generalised to any surface parametrised by the coordinates (u, v). The distance between two adjacent points $P(u, v)$ and $Q(u+du, v+dv)$ on the surface is given by the quadratic form:

$$ds^2 = E(u,v)du^2 + 2F(u,v)dudv + G(u,v)dv^2\,, \tag{6}$$

where E, F, G are the components of the metric and in general are functions of u and v. This is also called the Ist fundamental form of the surface in literature.

But since spacetime is 4 dimensional, we need to go to higher dimensions. For this better book-keeping is required. Instead of using different letters u, v for coordinates we just use one letter but with a superscript - $x^i, i = 1, 2, ...n$ in n dimensions. The metric components E, F, G now generalise to a $n \times n$ matrix g_{ik} and the above equation generalises to,

$$ds^2 = g_{ik}dx^i dx^k\,, \tag{7}$$

where summation over the repeated indices is implied (Einstein's summation convention). It is therefore written in a compact form. The RHS actually contains n^2 terms which because of symmetry reduce to $n(n+1)/2$. It is the metric on the manifold which determines the geometrical properties of the manifold including curvature.

We may understand curvature, again, by drawing a triangle on a sphere. Join any three points (not collinear) by the shorter of the arcs of great circles and we get a triangle on a sphere as shown on the left of Fig. 4.

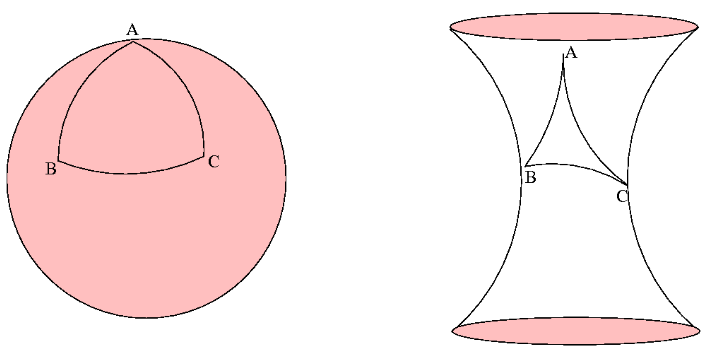

Figure 4: A sphere (left) has positive curvature, while a hyperboloid of one sheet (right) has negative curvature.

The arcs of the great circles are in general called geodesics and they are the straightest possible paths that can be drawn on a sphere. Now if we measure the angles of the triangle and add them up, they add up to greater than 2π radians. This immediately shows that the geometry on a sphere is non-Euclidean because in Euclidian geometry the angles of a triangle always add up to 2π. Secondly, the bigger the triangle the larger the discrepancy from the

Euclidean value of 2π. In fact if we denote the discrepancy by δ, then δ is given by the formula (Gauss-Bonnet):

$$\delta = \int_{\triangle} K dS \,, \tag{8}$$

where K is the Gaussian curvature of the sphere, which for the sphere is a constant and equal to $1/R^2$, where R is the radius of the sphere. dS is an element of area and the integral is taken over the interior of the triangle. This formula is quite general and applies to any triangle drawn on a surface. It is clear from this equation that δ must be positive because the integrand $K > 0$. For a symmetric surface such as a sphere the K is constant, but for a general surface, K is a function of the position on the surface and in general varies from point to point. We say that a surface is curved if $K \neq 0$ at some point on it and flat if $K \equiv 0$ everywhere on the surface. So for a plane $K \equiv 0$ and we say that the plane is flat, while since $K \neq 0$ for a sphere, the sphere is curved. Note that K is the *intrinsic* curvature - the curvature can be computed by making measurements confined to the surface only - it does not depend on its embedding in higher dimensions such as the 3 dimensional Euclidean space. K can be negative also as is the case for a hyperboloid of one sheet shown to the right of Fig. 4. Here $\delta < 0$. That the curvature can be negative is important for GW - in particular, the curvature varies sinusoidally for a monochromatic plane wave.

One must again investigate what happens in dimensions greater than 2. In 2 dimensions, one function K suffices to describe the curvature. However, in dimensions more than 2 we need several functions to completely describe curvature. This is achieved by the Riemann tensor R_{ijkl}. In 4 dimensions this tensor has 20 independent components. For a surface, it has only one independent component R_{1212} and it is essentially the Gaussian curvature K, in fact it is the same as K except for a factor of square root of the determinant of the metric (Note they cannot be exactly equal because K is a scalar, while R_{1212} is a component of a tensor). So one may think of the Riemann tensor as a generalisation of the Gaussian curvature to higher dimensions. So a manifold is flat if the Riemann tensor vanishes identically and curved if it does not.

Thus in Einstein's theory, Riemann tensor being identically zero, implies the absence of any gravitational field and then we have the flat spacetime of special relativity. While on the other hand the non-vanishing of the Riemann tensor implies the presence of a gravitational field. Thus the phenomenon of gravitation is a manifestation of the curvature of spacetime. Since the weak field slow motion limit of the metric is the Newtonian potential, the Riemann tensor being the second derivatives of the metric represents the tidal force between test particles. Thus the presence of a gravitational field can be ascertained by observing the trajectories of "free" (free of all other forces except gravitation - gravitation is not a force in Einstein's theory) test particles. If the particles move away or towards one another it implies a non-zero Riemann tensor component and signaling the presence of a gravitational field. This behaviour is governed by the so called geodesic deviation equation which we will describe in more detail in the next section. The ground-based GW detector precisely makes use of this property for detecting a GW.

4 The detection of gravitational waves

The early attempts started by Weber in 1960s involved resonant mass detectors which were later cooled to cryogenic tempratures in order to reduce thermal noise. But later it became clear that a laser interferometric arrangement would serve the purpose better because (i) of its scalability (ii) wide bandwidth. Here I will confine myself only to laser interferometric detectors. But first let us understand the underlying principle of detection of GW.

4.1 The principle of detection of GW

As we remarked before, a mass is the gravitational 'charge', so just as electric charges respond to an electromagnetic wave and test charges can be used to detect electromagnetic waves, so can test masses be used to detect gravitational waves. We must therefore examine the effect a gravitational wave has on test masses. This we proceed to do now. We analyse the effect of a GW on two nearby test particles. Before doing this we must examine the effect of a gravitational field, or which is curvature in Einstein's theory, on the trajectories of nearby test particles. This, as we have remarked before, is the phenomenon of geodesic deviation. We again take recourse to two dimensional examples.

First consider two test particles in the absence of gravity. We take two particles at rest in the flat spacetime of special relativity. If we take the two particles initially at rest at say $x = x_1$ and $x = x_2$ and other space coordinates zero, then if they are free (no forces) they will continue to remain at the same space points while their time coordinate will change as time progresses. The particles will have worldlines (trajectories in spacetime) which are straight lines (geodesics in flat spacetime) parallel to the t axis and more importantly parallel to each other. If we think of a connecting vector joining the worldlines, then the length of this connecting vector remains constant. This in fact shows that curvature is identically zero - a direct consequence of the geodesic deviation equation - and so gravity is absent.

Now consider a similar situation on a curved manifold. Let us take a sphere. Consider two geodesics starting out parallel. It is easiest to see this by taking the curves as nearby longitudes starting from the equator towards the North pole. Firstly, they are geodesics - great circles - and secondly, they start out parallel, the derivative of the connecting vector along the longitude at the starting point vanishes. But now we ask: does the connecting vector remain constant as one progresses towards the North pole? It does not. In fact the longitudes meet at the North pole where the length of the connecting vector becomes zero. This we assert implies the presence of curvature - the sphere is curved. Further we notice that the length of the vector *reduces* which implies that the curvature is *positive*, that is $K > 0$. We have already seen this from the triangle drawn on a sphere. We can do the same excercise for a hyperboloid of one sheet. If we start with geodesics at the waist and parallel to each other they move away. This shows that the hyperboloid is not only curved but has $K < 0$. See Figure 5 for the above discussion. All this is encoded in the geodesic deviation equation.

Now consider the situation for a monochromatic GW. Now the curvature oscillates taking alternately positive and negative values along the worldlines of the two test particles. A two dimensional analogue is shown in Fig. 6.

As the curvature oscillates so does the connecting vector joining the worldlines of the particles. So if we can monitor the distance between the particles, we could detect a GW. This is in fact the principle behind detecting a GW. Of course, since the GW in Einstein's

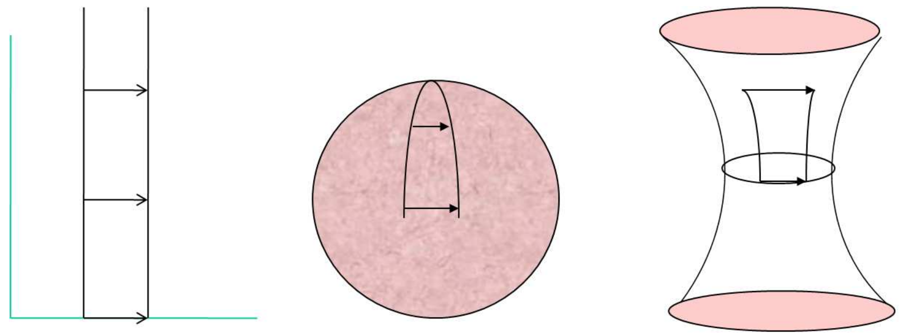

Figure 5: Geodesics move towards each other or away depending on whether the curvature is positive or negative respectively. When curvature is identically zero (see left most figure) the geodesics which are straight lines maintain the same distance between themselves.

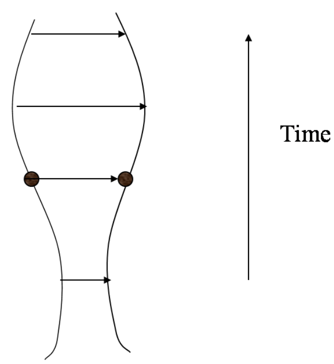

Figure 6: Connecting vector joining the worldlines of two nearby test particles subjected to a GW oscillates.

theory is actually a tensor, the situation is a little more complex. If we take the simple case of single linear polarisation, the circular ring of masses deforms at first into an ellipse and then back to the circle and again into an ellipse with its semi-major and semi-minor axes interchanged. The other linear polarisation state also deforms the circular ring into ellipses but whose axes are rotated with respect to the first polarisation by 45°. A general wave is a linear combination of the two polarised states. At the top of Fig. 7 is shown how a circular ring of test masses is distorted by one of the linear polarisations, usually called the 'plus' polarisation.

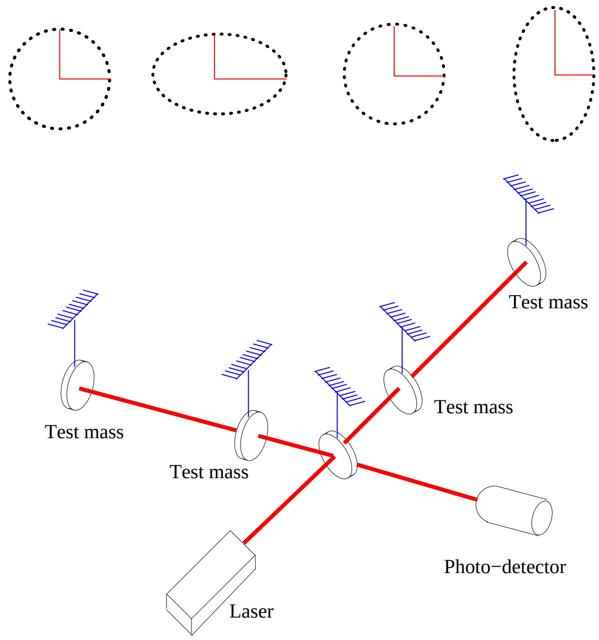

Figure 7: The top portion of the figure shows how a ring of test particles is deformed by the incidence of a plus polarised GW. The bottom portion shows a schematic diagram of a laser interferometric GW detector.

The rest of the figure 7 shows the schematic diagram of a laser interferometer. If we select two masses on this ring of test masses at right angles and consider how their distance varies 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 path difference which can be detected on a photodiode.

However, the catch is that these changes in lengths are exceedingly small. For example, a neutron star binary at distance of 100 Mpc - a typical 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_{ik}) can be estimated from the well-known Landau-Lifschitz quadrupole formula. The GW amplitude h is related to the second time derivative of the quadrupole moment (which has dimensions of energy) of the source:

$$h \sim \frac{4}{r} \, \frac{G}{c^4} \, E^{\rm kinetic}_{\rm nonspherical}, \qquad (9)$$

where r is the distance to the source, G is the gravitational constant, c the speed of light and $E^{\rm kinetic}_{\rm nonspherical}$ is the kinetic energy in the *nonspherical* motion of the source. If we consider $E^{\rm kinetic}_{\rm nonspherical}/c^2$ 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. If the change in the armlength L is δL, then,

$$\delta L \sim hL, \tag{10}$$

where h is a typical component of the metric perturbation. This result is easily obtained by integrating the geodesic deviation equation.

4.2 Global network of interferometric detectors

The USA has been at the forefront in building large scale detectors. The LIGO project has built three detectors, two of armlength 4 km and one of armlength 2 km at two sites about 3000 km apart at Hanford, Washington and at Livingston, Louisiana. The 2 km detector is at Hanford. These initial detectors have had several science runs and the design sensitivity has not only been reached but surpassed. The goal of this initial stage was mainly to vindicate the technologies involved in attaining the design sensitivities. However, even with these initial sensitivities, several astrophysically interesting upper limits have been surpassed which were previously obtained from conventional astronomies.

Now the next phase is to build advanced detectors with state of the art technologies which will be capable of observing GW sources and doing GW astronomy. With these future goals a radical decision has been taken by the LIGO project, that of building one of its detectors outside US either in Australia or India. The reason for this decision by the US 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 localization of the GW source.

In Europe the large-scale project is the VIRGO project of Italy and France which has built a 3 km armlength detector. After commissioning of the project in 2007, it also had science runs. The GEO600 is a German-British project and whose detector has been built near Hannover, Germany with an armlength of 600 metres. One of the goals of GEO600 is to develop advanced technologies required for the next generation detectors with the aim of achieving higher sensitivity.

Japan was the first (around 2000) to have a large scale detector of 300 m armlength - the TAMA300 detector under the TAMA project - operating continuously at high sensitivity in the range of $h \sim 10^{-20}$. Now Japan plans to construct a cryogenic inteferometric detector called the LCGT (Large-scale Cryogenic Gravitational wave Telescope) which has been recently funded. The purpose of the cryogenics is to reduce the thermal noise in the mirrors and the suspensions. But this technology is by no means straight forward and will test the skills of the experimenters.

There are 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/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 a fraction of a Hz. 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 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.

Figure 8 shows the strain sensivity for the LIGO Louisiana Observatory (LLO) [3].

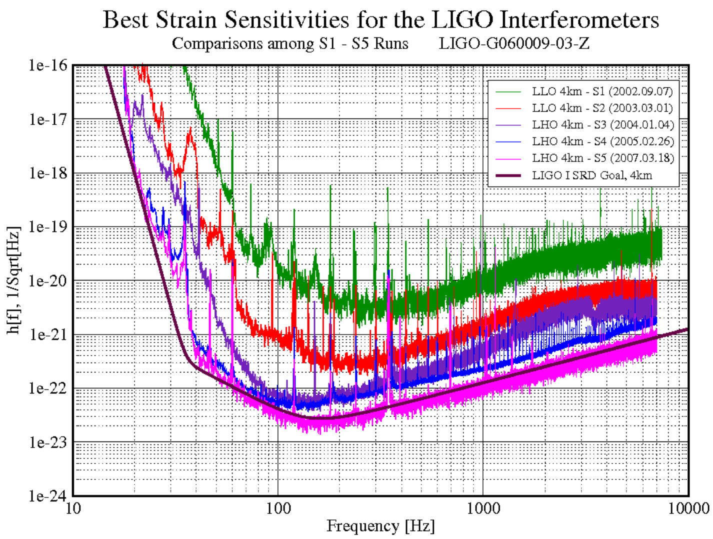

Figure 8: The improvement in the sensitivity of the LIGO Louisiana detector over the last decade. Sensitivity curves are shown for science runs S1-S5.

Building a network of widely separated detectors is most crucial since such a network will not only increase our confidence in a detection event but moreover localise the source in the sky and also provide information on the orientation of the GW source through polarisation measurements.

5 Sources of GW

Several types of GW sources have been envisaged 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 coalescence phase; supernovae explosions – 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.

Coalescing binaries have been considered highly promising sources not only because of the enormous GW energy they emit, but also because they are clean systems to model; the inspiral waveform can be computed accurately to several post-Newtonian orders [4] 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 [5]. Hierarchical search algorithms have been designed and are being improved to reduce the cost over a flat search. In the recent past, 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 [6]. This extension of the waveform leads to a higher signal-to-noise ratio (SNR) in the extraction of the signal from detector noise.

Another important burst source of GW is the supernova. It is difficult to reliably compute the waveforms for supernovae, because complex physical processes are involved in the collapse and the resulting GW emission. This limits the data analysis and optimal signal extraction.

Continuous wave sources pose one of the most computationally intensive problems in GW data analysis [7]. A rapidly rotating asymmetrical neutron star is a source of continuous gravitational waves. Long integration times, typically of the order of a few months or years are needed to build up sufficient signal power. Earth's motion around itself, the sun and the moon Doppler modulates the signal, the Doppler modulation being dependent on the direction of the GW source. Thus, coherent extraction of the signal whose direction and frequency is unknown is impossibly computationally expensive. The parameter space is very large, and a blind survey requires extremely large computational resources. However, targeted searches are computationally viable, for example, if the direction to the source is known. In this context, LMXBs are extremely interesting candidate sources for Earth-based detectors. Several systems would be detectable by enhanced LIGO operating in the narrow-band configuration. The asymmetry of a neutron star can occur in various ways such as crustal deformation, intense magnetic fields not aligned with the rotation axis or the Chandrasekhar-Friedman-Schutz instability. This instability is in fact driven by GW emission and consists of strong hydrodynamic waves in the star's surface layers. This phenomenon results in significant gravitational radiation.

To detect stochastic background one needs a network of detectors, ideally say two detectors preferably identically oriented and close to one another. The stochastic background arises from a host of unresolved independent GW sources and can be characterised only in terms of its statistical properties. The strength of the source is given by the quantity $\Omega_{\rm GW}(f)$ which is defined as the energy-density of GW per unit logarithmic frequency interval divided by $\rho_{\rm critical}$, the energy density required to close the Universe.

The signal is extracted by cross-correlating the outputs from two different detectors. The data analysis technique is based on the premise that the signal in the two detectors is correlated while their noises are not. This situation demands opposing requirements: for a well correlated signal, the detectors should be coaligned and nearby, while independence in the noise requires them to be geographically well separated. Nevertheless, two kinds of data-analysis methods have been proposed (i) a full-sky search [8] - but this drastically limits the bandwidth, (ii) a radiometric search in which the sky is scanned pixel by pixel - since a small part of the sky is searched at a time, it allows for larger bandwidth, and more importantly includes the bandwidth in which the current detectors are most sensitive, thus potentially leading to a large SNR [9]. Moreover, with this method a detailed map of the sky is obtained.

Apart from these sources, there can be burst sources of GW from mergers or explosions or collapses which may or may not be seen electromagnetically but nevertheless deserve attention. In this case time-frequency methods are the appropriate methods which look for excess power in a given time-frequency box.

6 The IndIGO project

There is a twenty year old legacy in GW data analysis at IUCAA, Pune and waveform modelling at RRI, Bangalore. This makes India an attractive partner for collaborative projects from the global point of view even when it means going experimental. This is because several of the students from these groups have returned to India and joined various institutions as faculty. The community for analysing the detector data *already exists* in India. Recently, in 2009, an Indian Initiative in Gravitational Wave Astronomy (IndIGO) has begun whose goal is to promote and foster gravitational wave astronomy in India and join in the worldwide quest to observe gravitational waves. Apart from the data analysis this initiative includes the all important experimental aspect. Accordingly a modest beginning has been made by IndIGO with TIFR, Mumbai approving a 3 metre prototype on which Indian experimenters can get first hand experience and develop expert manpower. This project has already been funded. An IndIGO consortium has been formed with scientists from leading institutions which include TIFR, RRCAT, RRI, IUCAA, few IISERs, few IITs, Delhi University and CMI, and also including scientists (mainly Indian) working abroad. In order to further this effort the first goal is to muster up sufficient expert and skilled manpower which will be able to launch this activity. It will mean India getting into this worldwide challenging experiment.

Since the data analysis community already exists, a high performance supercomputing facility is being proposed by IUCAA in the 12th 5 year plan. This will also act as a data centre and facilitate the analysis of international GW data, specifically LIGO-Virgo data. Such a prototype facility already exists at IUCAA and will be enhanced in the future. The proposal in the near future is to build an internationally competitive facility.

7 Conclusion

GW astronomy is now knocking at our doors. The initial detectors have not only reached their promised sensitivities but have surpassed them. The advanced detectors will start operating in few years time and the era of gravitational wave astronomy would then have truly begun. From the astrophysical knowledge that we possess as of now, one should expect a fair rate of gravitational wave events that one should be able to observe. An important recent proposal of the US is to build one of its detectors geographically far from the US soil. A detector far away and out of the plane of other detectors in US and Europe would greatly benefit the search of gravitational waves. One possibility is Australia given Australia's efforts of obtaining a site near Perth and experimental expertise. The other possibility could be India where a data analysing community already exists. India has a 20 year old legacy in gravitational wave data analysis at IUCAA, Pune and wave form modelling at RRI, Bengaluru, and recently a three metre prototype detector at T.I.F.R., Mumbai has been funded. Apart from the groundbased detectors, there is also the prospect of the space-based detectors such as LISA which will bring in important astrophysical information at low frequencies complementing the ground-based detectors. The future looks bright for GW astronomy.

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