The Search for Gravitational Waves

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Abstract

The direct detection of gravitational waves is one of the most challenging problems in experimental physics today. Sustained efforts have led to impressive advances on both theoretical and experimental fronts. This article first deals with the theoretical aspects of gravitational waves and then continues on to describe the detectors in vogue, the present status and various gravitational wave sources.

IUCAA - Preprint - 9/92; Sept. 1992

To appear in Physics Education

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Introduction

One of the greatest sources of inspiration and incentive for scientific advance has been astronomy. Born out of curiosity it has led to profound scientific achievements. There have been beneficial spin-offs, even from the days of Galileo's first telescope. In the past virtually all information about our Universe has come by way of electromagnetic radiation and the need to develop techniques for obtaining it has provided major scientific stimulus. It has recently become technically just possible to develop another window of information that of gravitational radiation. Thus a new astronomy – *gravitational wave astronomy* – is in the offing. Quite apart from checking the fundamental aspects of gravitation theories the birth of this new astronomy would provide a new window which would probe the hitherto unknown regions of the universe and complement our present view which is almost entirely based on electromagnetic radiation.

What are gravitational waves? In Einstein's theory of gravity – the general theory of relativity – gravitational waves can be described as 'ripples' in the curvature of spacetime like ocean waves on an otherwise smooth ocean surface. Gravitational waves are the gravitational analogue of electromagnetic waves such as radio waves or light. Just as accelerating electric charges produce electromagnetic waves, accelerating motions of masses produce gravitational waves. For example, waving ones arms about produces gravitational waves but they happen to be incredibly weak, too weak to be detected by current detectors or detectors planned in the near future. This is because unlike the electromagnetic interaction, the gravitational interaction is very weak, the weakest among the four known interactions. A very simple experiment to compare the strengths of electromagnetic and the gravitational interactions is the following :

Take a glass of water and raise it with your arm.

The fact that you can raise a glass of water against the Earth's gravitational pull implies that the gravitational interaction is much weaker than the electromagnetic. Why? The force in the muscles in the arm comes eventually from electromagnetic forces among the molecules that constitute the arm; while the *whole* Earth which is made of a large number of molecules as compared to those in the arm is pulling down on the glass only by gravitational forces. This incredible weakness of the gravitational interaction makes itself felt doubly, first in the generation of waves, where large bulk motions of masses produce comparatively weak waves, and then second, in the detection process, where the waves must interact with the matter constituting the detector. One therefore needs incredibly sensitive detectors to detect these waves. For fifty years after Einstein's prediction of gravitational waves in 1916, scientists considered them to be of academic interest only. But in 1960s, gravitationally collapsed neutron stars were discovered which confirmed the predictions of Chandrasekhar, Oppenheimer and Volkoff made 30 years earlier. In 1960s, Joseph Weber began his efforts to detect gravitational waves. In a decade of pioneering experiments he investigated both resonant bars and laser interferometers as detectors for gravitational radiation. His work, though inconclusive encouraged others to build second generation detectors : cryogenic resonant bars and laser interferometers with arm lengths ranging from few metres to tens of metres. It is only in recent years that scientists have seen how to build detectors of sufficient sensitivities to detect cosmic sources of gravitational radiation.

The article splits naturally into two parts. The first part mainly deals with the physical and the geometrical nature of the waves. It will be seen that the physics and the geometry are completely entwined together in a single elegant picture. The second part consists of detection aspects and the sources of gravitational waves.

I. The Nature of Gravitational Waves

1. Newton verses Einstein

Although Newton's theory of gravitation is successful in predicting the trajectories of projectiles, explaining orbits of planets to a good accuracy, etc., it however does not reconcile with the well established theory of special relativity. In Newton's theory, gravitational interaction is instantaneous: for example, if a mass particle changes its position at a given time, then its gravitational field changes throughout the universe *instantaneously.* But according to the special theory of relativity all signals must travel with a velocity less than or equal to the velocity of light - 3×10^5 kilometres/second - which is extremely large by everyday standards but none-the-less finite. Einstein's theory of general relativity on the other hand, predicts finite velocity for gravitational interaction, this velocity being none other than the velocity of light. Consequently, Newton's theory does not predict gravitational waves but Einstein's theory does. In fact, one may generically say that almost any gravitation theory consistent with the special theory of relativity will predict waves. For example, the Brans Dicke theory predicts waves (although observations of the binary pulsar PSR 1913+16 have almost ruled it out- more to follow later).

Einstein's theory is based on what is called the 'equivalence principle' which says that all massive objects experience the same acceleration in a gravitational field. Galileo was a pioneer in testing this principle when he dropped objects of different masses and compositions from the tower of Pisa in Italy. In this century, experiments have verified this principle to a high degree of accuracy, with the help of sophisticated techniques (1 part in 10^{13} or so). This principle encourages a geometric formulation of gravitation theory, since it is more economical than a description involving forces. According to Einstein, matter curves the goemetry around itself and this curvature produces force-like effects on test particles. In general relativity a gravitating body does not exert gravitational 'forces' on test particles; a test particle 'feels' the background curved geometry and moves accordingly. If the test particle has no other forces acting on it (except gravity) then it moves along the straightest path possible in that geometry. Such a path is called a *geodesic*. For example, on a simple curved surface such as a sphere, the straightest possible path is an arc of a great circle.

A simple way of contrasting the two theories is to consider planetary motion around the sun. We consider the planets as test particles responding to sun's gravity. In Newton's theory, the sun produces a gravitational field according to Newton's inverse square law, and the planets experience this force field and move according to the Newton's laws of motion. But according to Einstein the picture is conceptually quite different. The sun *curves* the space and time (these have already been married in special relativity to give a single entity *spacetime*) around it by virtue of its mass energy and the planets attempt to describe the straightest possible paths in this warped background spacetime. The two pictures are displayed in figure (1). The Newtonian picture is shown in figure 1(a) while figure 1(b) shows the spatial section of the full spacetime since it is not possible to portray the entire four dimensional spacetime. Along with the spacetime the spatial section of the spacetime also gets curved. In the figure, the planet's trajectory in spacetime is projected into this spatial section. The famous Einstein's *field* equations provide a rule which link the curvature of the spacetime to the mass-energy of the gravitating body - this is analogous to Newton's inverse square law, although the equations are far more complicated. The planets then follow geodesics in the spacetime curved by the sun (Here we have treated a planet as a test particle, thereby ignoring its gravity producing effect). Although both the theories explain planetary orbits satisfactorily, Einstein's theory agrees better with the observations. For instance, it predicts the precession of the perihelion of the orbit of the planet Mercury to a high degree of accuracy.

A massive body undergoing oscillations sends out ripples in the curvature of the background spacetime analogous to the ripples produced by an oscillating object on the surface of an otherwise still pond. In this article, I will restrict myself to 'weak'(the notion of weak will be made precise later) gravitational waves propagating on a curvature free background spacetime (normally called flat spacetime), the spacetime of special relativity which ideally exists far away from all gravitating masses. These assumptions are justified on astrophysical grounds where the detectors, sources and the intermediate region can be regarded to be immersed in almost zero curvature background and the waves incident on the detector from viable astrophysical sources are weak. Then Einstein's equations which are nonlinear can be linearised and a theory akin to Maxwell's electromagnetic theory emerges. This is called the linearised theory of general relativity which is discussed later.

But to understand the phrase 'ripples in the curvature of spacetime' one needs to first understand the concept of curvature. Also the effect on test particles can be understood by studying the effect of curvature on geodesics since geodesics as we mentioned are the paths described by free test particles.

2. The Geometrical Aspect

As remarked earlier, in general relativity, mass or energy (these again have been 'married' in special relativity by the famous equation of Einstein, $E = mc^2$, known even to a barefoot pedestrian) curves the spacetime around it. This curvature is manifested in four dimensions, three of space plus one of time. However, without the help of sophisticated mathematics it is hard to directly deal with four dimensional curvature. But the concept of curvature is not hard to understand if we reduce the dimensions to two. We can easily visualise 2-dimensional surfaces embedded in the usual 3-dimensional Euclidean space. A surface is two dimensional since locally any point on the surface can be completely determined by specifying two real numbers called the *coordinates* of the point. Examples of surfaces are the plane, sphere, paraboloid, hyperboloid etc. Except the plane, all the other surfaces mentioned above are curved. The plane has zero curvature and is called 'flat'.

How do we check whether a surface is curved? We can do this in several ways. Draw a triangle on the surface. To draw a triangle one needs straight lines. Here we do the best we can by drawing geodesics. Take three points on a surface and join them by goedesics. In general we get a triangle. Take the sum of the angles of the triangle and check whether they add up to 180°. If we find even one triangle for which the angles do not add up to 180° then the surface is curved. If we draw triangles on a sphere, their sides will be arcs of great circles and the angles will add up to *more* than 180°. On a hyperboloid of one sheet the angles of a triangle drawn on it will add to *less* than 180°. The sphere and hyperboloid are curved spaces. On the other hand, for triangles drawn on a plane, the angles always add up to 180°, hence the plane is not curved or has zero curvature.

Another way to test curvature is to draw 'small' circles on the surface. Here 'small' means that the radius of the circle is small compared with scale on which the surface curves. For example, if the surface is a sphere, then the radius of the circle must be small compared with the radius of the sphere. To define a circle on a surface, take a fixed point – the centre – and throw out geodesics from the centre. The locus of these equidistant points from the centre is a 'circle'. Measure the circumference of this circle and compare it with the radius – the distance from the centre to any point on the circle – and check whether it is 2π. If not the surface is curved.

Note that all these tests for curvature involve *making measurements within the surface without any reference to the outside Euclidean space* in which it is immersed. The curvature we are talking about is called the *intrinsic* curvature. The four dimensional spacetime of Einstein is *intrinsically* curved when matter is present. Merely to contrast, a cylinder is not intrinsically curved since it passes each of the tests mentioned above for 'flatness' (the angles of any triangle drawn on it will add up to 180°), although it is *extrinsically* curved (that is why it 'looks' curved) when embedded in three dimensional Euclidean space. This distinction should be clear.

The quantity that measures the intrinsic curvature of a surface is called the Gaussian curvature K. Its generalisation to higher dimensions is a tensor called the Riemann curvature tensor. This is not a single entity like the Gaussian curvature but happens to be more complex and consists of several components. It is this tensor which enters into Einstein's field equations which relate it to the matter distribution. Thus the matter distribution determines the curvature of spacetime, the link being provided by Einstein's field equations.

Another manifestation of curvature is its effect on neighbouring geodesics. This property is of paramount importance to us since this is the principle on which gravitational wave detection is based. Neighbouring geodesics will play the role of worldlines of nearby test masses constituting the detector (A worldline is the trajectory of a particle in the 4 - dimensional spacetime. In the usual flat spacetime of special relativity with Cartesian coordinates (x, y, z, t), the world-line of a particle stationary at a space point (x_0, y_0, z_0) is a straight line passing through (x_0, y_0, z_0) parallel to the t-axis. For a particle in uniform motion, its world-line will be a straight line though tilted.). The behaviour of the geodesics will depend on the curvature waves that the masses experience.

How are neighbouring geodesics affected by curvature? Consider first a flat space i.e. space with zero curvature e.g. a plane. Consider two nearby geodesics starting out parallel. Here the geodesics are merely straightlines and if they start out parallel then they will remain parallel. In other words the perpendicular distance between the geodesics remains constant. But let us consider a sphere, for example, (see Figure 2(a)) and consider two nearby meridians starting at the equator and produced towards the North pole. The meridians are geodesics and at the equator they are perpendicular to it and hence start out parallel. The question is, however, do they remain parallel? No! The geodesics if produced will steadily move *closer* (the distance between them becomes zero when they finally meet at the North pole). This is the effect of curvature. Neighbouring geodesics starting out parallel do not retain a constant distance between themselves. This behaviour is embodied in what is called a *geodesic deviation equation* which is generally valid and in which the Riemann tensor plays a pivotal role.

For a hyperboloid of one sheet, neighbouring geodesics which start out parallel move away (see Figure 2(b)) unlike that for a sphere. This behaviour of moving towards or away from each other is decided by the sign of the Gaussian curvature K. The sign also decides whether the angles of the triangle will add up to greater or less than 180°. If $K > 0$, the angles add up to greater than 180°. Similarly, for a small circle drawn on a surface, whether the ratio of the circumference to radius is greater or less than 2π is decided by the sign of K. If K is positive, as for a sphere, the geodesics move towards each other. On the other hand, if K is negative, as for the hyperboloid, (like a saddle point) then the geodesics move away. What happens if the geodesics encounter K to be alternately positive or negative? Imagine a surface like some combination of a sphere and hyperboloid. If K is say, positive when the geodesics start parallel they will try to move towards each other, but as they progress K becomes zero and then negative so that the geodesics will tend to move apart. Therefore the geodesics will alternately move towards and away from each other. Figure 2(c) shows a surface of this kind and the geodesics display the stated behaviour.

In higher dimensions it is the relevant components of the Riemann tensor which decide the behaviour of neighbouring geodesics. If the Riemann tensor were to alternate its sign along the course of the geodesics, the distance between them would alternately increase and decrease. This naturally brings us to the effect a gravitational wave has on test particles.

3. The physical nature

To begin with, let us consider the familiar electromagnetic theory and try to draw on useful analogies. In the theory of electromagnetism, the Lorentz force equation tells us the force experienced by a charge in an electromagnetic field. An electric charge subject to a electromagnetic wave experiences a periodic force. In the simplest case of a monochromatic plane wave, the electromagnetic field components oscillate sinusoidally inducing corresponding motions in the test charges. These test charges for instance could be 'free' electrons in the conduction band of the metal of an antenna. The oscillating motions of charges give rise to oscillating currents which can further be amplified and detected. Thus electromagnetic waves can be detected.

However, to detect a gravitational wave we need to use masses as test particles. But just one mass is not sufficient for the purpose, but atleast two masses are required in different locations. This again is a consequence of the equivalence principle which says that one can get rid of gravitational influence at a single point. Only relative accelerations between massive particles at different locations have a physical reality. If we take two nearby locations for the test particles, then the differential acceleration, manifests itself through the curvature of the spacetime described by the Riemann tensor. The Riemann tensor is thus responsible for the 'tidal' forces experienced by extended bodies. Geometrically, this is intimately related to the geodesic deviation equation mentioned above.

Just as a monochromatic electromagnetic wave is a sinusoidal variation of the electromagnetic field components, a monochromatic gravitational wave is a sinusoidal variation of the components of the Riemann curvature tensor. If the background spacetime has zero curvature (we are considering regions far away from all gravitating matter), then the Riemann tensor of the wave is the only source contributing to the curvature. However, if the background is curved over length scales much larger than the wavelength of the gravitational wave, then the oscillating components of the curvature tensor get added to the smooth background curvature. The picture is not unlike ripples on the surface of a ocean where the wavelength of the ripples may be few metres while the ocean curves on the length scale of thousands of kilometers , corresponding to the radius of the Earth.

Now consider two test particles in a flat (zero curvature) background at rest in a frame (x, y, z, t). The world lines of the particles will be straight lines parallel to the time-axis and thus parallel to each other. The world lines therefore maintain a constant distance between themselves. But if a gravitational wave is incident on the masses, the masses encounter a rippling curved background with the curvature alternately changing sign. Since the masses are supposed to free from any other influence except that of the gravitational wave, they describe geodesics in the spacetime of the gravitational wave. As we have seen if the geodesics encounter curvature (Riemann tensor) alternately varying in sign, the distance between the geodesics oscillates as shown in Figure 2(c). The figure can now be interpreted in a different light. The vertical direction can be thought of as the time direction and the geodesics as the world lines of the test particles A and B.

The principle of a gravitational wave detector is now apparent. If we place two or more test masses at some distance from each other then the effect of the gravitational wave is to change the distances in an oscillatory fashion. Monitoring these distances by some means will allow us to detect the wave.

4. Gravitational waves in the Linearised Einstein's theory

We will assume that the waves are weak and the background spacetime is that of special relativity corresponding to a spacetime which exists ideally far away from all matter. In Einstein's theory, the geometry of a spacetime is described in terms of a 'metric' where a metric is something which assigns infinitismal 'distances' between adjacent points in a spacetime. These 'distances' are nothing but the spacetime intervals of special relativity between nearby points. The metric has all the relevant information about the spacetime including curvature and is a dynamical variable in the theory. The Riemann curvature is obtained from the metric basically by taking its second derivatives with respect to the spacetime coordinates. Since Einstein's field equations involve the Riemann tensor, they are nonlinear, coupled, second order differential equations involving the metric. However, if the total curvatures are small we can split the metric into a 'flat' part, that of special relativity, and a 'small' curved part corresponding to the wave. In symbols we write,

$$g = \eta + h \tag{1}$$

where g is the full metric, η the flat metric of special relativity and h is that part of the metric corresponding to the curvatures. The metric is a dimensionless quantity. If we choose Cartesian coordinates then $\eta \equiv$ diag(1,1,1,-1) has the usual diagonal form. We say that the field is weak if $|h| \ll 1$. We can then justifiably retain only the first order terms in the Einstein's equations leaving out higher order corrections. This procedure linearises the equations and in a certain guage called the transverse traceless guage, the source free equations take the form,

$$\Box h = 0. \tag{2}$$

The $\Box$ is the usual wave operator, namely

$$\Box = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2},$$

where (x, y, z, t) are Cartesian coordinates and c the speed of light. This is just the usual wave equation for h in the flat background. The equation implies that the signals of the field h travel with the speed of light and that the field is massless. Also, further analysis(not embodied in this equation) shows that the waves possess just two independent polarisations. These properties are analogous to those of electromagnetic waves. However, the polarisation properties are different from an electromagnetic wave and exhibit a quadrupolar nature. To illustrate this, consider a circular ring of test particles and let a plane monochromatic gravitational wave be incident on the particles normal to the plane of the ring. A linearly polarised wave has the following effect on the ring of particles: If we start counting the phase ϕ from the initial circular shape ($\phi = 0°$), then after an elapse of a quarter period ($\phi = 90°$) the ring will have deformed into an ellipse. At half the period ($\phi = 180°$) the ring returns to its original circular shape. At three-quarters of the period ($\phi = 270°$) the ring again assumes an elliptical shape but now with its minor and major axes interchanged. A further elapse of 90° in the phase brings the configuration back to its original shape. This sequence is repeated in the subsequent cycles of the wave. Figure (3) shows the sequence of shapes the circular ring assumes for different phases of the wave.

The other orthogonal polarisation is obtained by rotating the ellipses in Figure (3) by 45°. A linear combination of these two basic linear polarisations constitutes a general monochromatic gravitational wave. The 'force-fields' (our Newtonian way of thinking!) associated with the wave are shown in the right most column of Figure(3). They can be seen to be quadrupolar and signify the spin 2 nature of gravitational field.

Here we have treated the theoretical aspects of weak gravitational waves within the framework of Einstein's theory. This however, does not mean that the theory does not predict strong gravitational waves. There are many such solutions in the literature. For the topics covered here and for further reading, see Schutz (bibliography).

II. Detection of Gravitational Waves

In the first part of the article we had discussed the geometrical and the physical nature of gravitational waves. Here, we will make use of the principles and properties of gravitational waves investigated in the first part and apply these towards the detection problem.

1. Strength of Gravitational Wave Sources

As seen in the foregoing, distances between test masses are altered when a gravitational wave interacts with them. Particles at the diametrically opposite ends of a circle of Figure (3) or alternatively, an arrangement consisting of the centre of the circle and two particles on the ring subtending a right angle at the centre, can be used as probes of gravitational waves. Both these arrangements find application in the design of the most popular gravitational wave detectors. Although, this is alright in principle, in practice the displacements are very minute indeed. In fact, for a strong source such as a supernova exploding in our galaxy, the metric perturbation $h \sim 10^{-17}$ or so. Note that the metric is dimensionless. What this implies is that if l is the distance between the masses (or l is the radius of the circle of the ring of particles), then the masses are displaced by the amount,

$$\delta l = hl \tag{4}$$

If l is 1 metre then $\delta l \sim 10^{-17}$ metre which is a one hundredth of the diameter of a nucleus! This is incredibly small and the slightest noise will mask the effect. For a typical source the h could be even smaller, a few orders of magnitude less than stated above. Therefore, the whole challenge in this game lies in systematically excluding noises. This is done by bringing the most up-to-date technology into play in terms of cryogenics, siesmic isolation, stabilized lasers, vacuum technology etc. Even after stretching the techniques to their limits, the output of the detector is still noisy. Therefore, the story far from ends here. The noisy data of the detector has to be analysed and sophisticated data analysing techniques have to be devised to extract the signal from the noise. Superfast computers are a must if the data is to be analysed in reasonable time. At IUCAA, Pune, there is a very active group working on the most burning problems on gravitational wave data analysis. So far the main thrust of the group has been on the data analysis of coalescing binaries which are the most promising sources for broadband detectors of gravitational waves. The group has strong connections with the leading groups in the world especially the one at Cardiff which happens to be centre for this activity. The group has also made use of the fast parallel computing facilities offered by C-DAC, Pune which exist on theUniversity Campus.

Why is the h so small? The reason as mentioned earlier is the weakness of the gravitational coupling to matter. Just as electromagnetic radiation is produced by a time changing electric dipole moment, here the relevant quantity is the second time derivative of the mass quadrupole moment. This has the dimensions of energy. A formula can be written down to give an order of magnitude estimate of the strength h of a gravitational wave,

$$h \sim \frac{1}{r}\,\frac{G}{c^4}\,E^{\text{kinetic}}_{\text{nonspherical}} \tag{5}$$

where r is the distance to the source, G is the gravitational constant $\sim 6.67 \times 10^{-8}$ $\text{gm}^{-1}\text{cm}^3\text{sec}^{-2}$, c the speed of light and $E^{\text{kinetic}}_{\text{nonspherical}}$ is the kinetic energy in the *nonspherical* motion of the source. A spherically symmetric collapsing ball of matter does not produce gravitational waves since the motion has no nonspherical component. A similar situation arises in electromagnetism where a spherically symmetric motion of charge does not produce electromagnetic radiation. But unlike electromagnetism, a time changing dipole moment need not produce gravitational waves.

Can we produce gravitational waves by terrestrial means strong enough to be detected? This would certainly reduce the value of r in the formula of equation(5) but the problem now is to produce a large enough $E^{\text{kinetic}}_{\text{nonspherical}}$ to counteract the very tiny factor G/c^4. Consider a steel rod being spun laterally about its centre with a large angular velocity. The rod would produce gravitational waves. The $E^{\text{kinetic}}_{\text{nonspherical}} \sim ml^2\omega^2$, where l is the length of the rod, ω the angular velocity of the rod and m the mass of the rod. Taking $\omega \sim 10^4$ radians/second, l to be say 10 metres, $m \sim 1000$ kg. and r about 100 metres so that one is in the wave zone, the amplitude of the waves would be $h \sim 10^{-33}$! This is too small an amplitude to be detected with todays technology.

Therefore at present the only answer seems to be to look into the universe. There we can find phenomena violent enough to produce detectable gravitational waves with todays technology.

2.Detectors of Gravitational Waves

The principles discussed in the foregoing can be used to model and design detectors for gravitational waves. One can use two separated masses as in a bar, or better still a quadrupolar arrangement of three masses, the three masses being placed at the extremeties of two perpendicular baselines. I will only discuss two types of detectors whose designs have emerged after long and expert experimentation :

(a) Resonant bars,

(b) Laser interferometers.

Laser interferometers can be ground or space based but in this article I will consider only ground based detectors.

(a) Resonant Bars

Resonant bars have been under development since Joseph Weber's pioneering efforts which began in the late 1950s. More effort has gone into this type of detector than any other type. A resonant bar consists of a large, solid bar usually made of aluminium in which mechanical oscillations are produced by gravitational waves. Typical lengths of the bar are about 2 metres, masses around several tonnes and the fundamental resonant frequency around 1 kHz. The bar can be thought of as consisting of two masses coupled by a spring, when it is operating at the fundamental frequency. This means that the test masses are not free but are coupled by a spring. The action of the gravitational wave can be explained in terms of the force field diagrams of figure(3). The forces act on the bar making it alternately expand and contract setting up mechanical vibrations in it. The model of the bar as two masses coupled with a spring, is that of a forced simple harmonic oscillator. A transducer attached to its end converts the mechanical signal into an electrical one which is amplified and then recorded. Figure (4a) shows a schematic diagram of a bar. To guard against noise the bar has to be seismically isolated, supported on a thin wire, placed in vacuum and shielded from electromagnetic effects. To reduce thermal noise within the bar itself, it is cooled by liquid Helium to 4.2° K. The cooled bar belongs to todays second generation of cryogenic bars. This means that the bar has to be enclosed in several enclosures.

The sensitivity of a detector is defined as the value of the metric perturbation h, required to produce the level of noise present in the detector. With this definition in mind we can state the sensitivities or the noise levels in the present detectors and those planned in the future. Present bars operate with a sensitivity of $h \sim 10^{-18}$ and this could be pushed down an order of magnitude. Room temperature bars have sensitivities of $h \sim 10^{-16}$ or 10^{-17}. Bar detectors have been constructed in Maryland, Stanford, Lousiana, Rome, Moscow, Tokyo, China and Australia.

Besides being basically a narrow band detector, the continuous operation of the cryogenic bar presents difficulties since cooling takes a long time. Therefore, if any part in the enclosure needs to be changed the bar does not operate for a few months. These difficulties are circumvented in the laser interferometric detector described below.

(b) Laser interferometers

An alternative approach is to use widely separated test masses with distance between them being monitored by laser interferometry. Absolute length measurements are avoided by constructing two perpendicular baselines at the ends of which test masses are suspended freely. The arrangement is that of a Michelson interferometer with test masses being placed at the ends of its arms. Such a system has many advantages over bar detectors:

(i) The system can be scaled up in size to enhance the sensitivity since as we have seen the distance the masses move relative to each other is proportional to the distance initially existing between them ($\delta l \sim hl$). The proposed detectors around the globe have arm lengths 3 to 4 km.

(ii) Since the masses are freely suspended, the system is inherently wideband and has more versatility and wider applicability.

(iii) The quadrupolar arrangement is tuned to the quadrupolar nature of the waves. Therefore polarisation information is more conveniently obtained. Also technical working difficulties are reduced due to the absence of cryogenics.

Figure (4b) shows a schematic diagram of a laser interferometer. The test masses are the mirrors which reflect the laser beam. The test masses are seismically isolated as in the case of the bar. The whole system of mirrors and laser beams are housed in vacuum $\sim 10^{-8}$ Torr within vacuum tanks and pipes. The idea being to reduce noise from various factors.

As we know from the theory of radio antennas, for efficient functioning the size of the antenna should be about half the wavelength of the waves to be detected. Since the Einstein's linearised theory of gravity is formally similar to electrodynamics, the same principle holds. For a median frequency of 1 kHz, the wavelength is $\sim$ 300 km the size of the detector should be $\sim$ 150 km. Since it is practically impossible to build an interferometer with this arm length, the required path length is obtained by folding the light path within each arm by arranging several bounces of the beam between the mirrors. High quality mirrors are needed to achieve a large number of bounces to get the necessary path length.

The present laser interferometers are prototypes of arm lengths in the range 10–40 metres with sensitivities $h \sim 10^{-18}$ or 10^{-19}. The currently planned detectors with arm lengths in kilometres are expected to have sensitivities of $h \sim 10^{-22}$ or 10^{-23}. The band width of these detectors will range from 100 Hz to 2000 Hz. The lower limit may further be reduced to 10 Hz by using sophisticated seismic isolation techniques. The wide band operation of the laser interferometer has brought into our range of detection a wide variety of sources.

Prototype laser interferometers have been built in Caltech, Glasgow, Munich and Japan. However, constructing a full scale kilometre length detector has placed large demands on funds, technology and expert manpower. The full experiment needs input from several diverse fields in physics and engineering such as vibration isolation techniques, lasers and laser optics, vacuum technology, data processing and superfast computing etc. Therefore, expert manpower from diverse areas has to work together in fruitful unison. This has encouraged several international collaborations to meet these challenging demands. US on its own is in the process of constructing two detectors of 4 km armlength (the LIGO project).

3. Sources of gravitational radiation

As seen earlier terrestrial sources are ruled out (In equation (5) the factor G/c^4 sitting in front demolishes everything but the strongest!). However, there are many violent phenomena occuring in the universe and these could generate gravitational waves of appreciable amplitude which lie within our detection capabilities. The supernova being a highly violent event, became the most likely candidate for detection in the early days. But now with the broad band detectors of today, other sources such as coalescing binaries are claiming more attention. Other promising sources of gravitational waves are pulsars, blackholes and stochastic waves from the early universe. I will now discuss some of these sources.

(a) Supernovae

Astrophysically, the detection of electromagnetically quiet supernovae would be extremely important. Since matter is more or less transparent to these waves, they pass through matter with impunity where in similar circumstances electromagnetic waves would be blocked. A supernova burst could release as much as 10^{53} or 10^{54} ergs of energy. The strength of the gravitational waves emitted depends on the degree of non-sphericity in the bulk motion of the material (equation (5)). A strong burst occuring in our galaxy can produce at Earth an amplitude $h \sim 10^{-17}$ or 10^{-18} which is detectable even by the present day bars and prototype laser interferometric detectors. However, such bursts are very rare. Recent estimates show that in our galaxy a supernova may explode on an average of once in 20 or 30 years although it may not be seen electromagnetically. Therefore we are forced to look outside our galaxy, say, to the Virgo cluster which contains tens of thousands of galaxies, which would dramatically increase the event rate. But the catch is that the amplitude would be reduced by a factor of thousand say, since a typical source would be thousand times more distant as compared to the one in our galaxy. Hence the expected $h \sim 10^{-21}$. Todays bars and prototypes are not sensitive enough to detect such small amplitudes but the full scale interferometers are expected to have sufficient sensitivities for the purpose.

(b) Coalescing binaries

A coalescing binary consists of two compact stars such as neutron stars or blackholes which revolve around each other emitting strong gravitational waves. This continuous loss of energy in the form of gravitational radiation, makes them spiral into each other finally coalescing into a single object, with a powerful burst. The waveform is basically sinusoidal, with the frequency and amplitude increasing as the stars coalesce. Broad band detectors are best suited to detect this source since the signal runs through practically all frequencies. The well known 'Hulse-Taylor' binary pulsar PSR 1913+16 is a typical example of such a system. Another such system, PSR 2127+11C has been found in the globular cluster M15. The Hulse-Taylor pulsar will coalesce in about 10^8 years. Hence we may mistakenly conclude that the events are extremely rare. However, by using special techniques of data analysis, it is possible to detect coalescing binaries to a great distance with a full scale laser interferometer. We may be be able to 'see' as far as 500 mega-parsecs with such a detector. (Astronomers use a unit of distance called a parsec which is $\sim 3 \times 10^{18}$ cm. A mega parsec is a million parsecs. To get an idea, the nearest star from us is about 1.3 parsecs, the size of our galaxy is about 40,000 parsecs and the Virgo cluster is about 18 megaparsecs away from us.) Therefore, the volume scanned by a detector when looking for coalescing binaries is very large indeed and undoes the large timescale of 10^8 years. Hence, the the occurence of events is not so rare afterall.

The main advantage one has for this source is that its waveform can be predicted to a high degree of certainty. Special data analysis techniques such as matched filtering can be used to extract the signal from the noise. Active work in developing efficient, fast algorithms, which use sophisticated mathematical techniques, for processing coalescing binary signals is in progress at IUCAA, Pune. The power of intensive mathematical analysis is apparent from the following: For online data anaysis of coalescing binary signals, for reasonable values of parameters the computing speed was estimated to be in tens of gigaflops (1 megaflop is a million floating point operations per second. A gigaflop is a thousand megaflops.)

But recent work at IUCAA shows that by using certain mathematical tricks this speed can be brought down to 100 to 200 megaflops which is surely in the range of todays computers. On the C-DAC machine a speed of 85 megaflops has been obtained with another 50 percent scope for improvement.

(c) Pulsars

Pulsars are rotating neutron stars. Asymmetry about their axis of rotation results in their generating single frequency gravitational waves. The asymmetry may be in the form of ellipticity which is defined as 1 minus the ratio of semi-minor-axis to semi-major-axis. For a pulsar 10 kiloparsecs away, with ellipticity of 10^{-6} emitting gravitational waves at 100 Hz the value of $h \sim 10^{-27}$. This is certainly far below the sensitivity level of even the LIGO whose sensitivity would be 10^{-23}. But integrating the signal for a few months can result in an acceptable signal-to noise ratio. The key result of signal analysis is that the signal-to-noise ratio is proportional to the square-root of the number of cycles in the data train. One therefore needs a data train of 10^9 cycles. For a frequency of 100 Hz the length of the data train is 10^7 seconds which is a few months.

Consider a similar calculation for the terrestrial source considered before. Since the h for the rotating rod is about 10^{-33} we need to integrate 10^{20} cycles just to get to the noise level in the LIGO. Assuming a frequency of about few kHz, the data train would have to be 10^{17} seconds long which is 10^{10} years! - the age of the Universe.

(d) Stochastic sources

Among the several stochastic sources, the most interesting 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.They provided the seeds on which the galaxies condensed. 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}. The amplitude scales inversely as the frequency until the wavelength reaches about 100 or 200 megaparsecs. This means that at low frequencies the amplitude can get quite large. However, for ground based detectors the siesmic noise is also very large and the advantage is lost. Detectors in space would be ideal for these type of low frequency sources since the noise at low frequencies in such detectors is quite low.

This radiation will look like noise and hence specifically designed methods will be needed to detect it. The idea is to use atleast two aligned interferometers in the same place and cross-correlate their outputs for a sufficiently long integration time. This makes the outputs identical as far as the signal is concerned. The noise component however will be uncorrelated.

This kind of radiation has the famous electromagnetic analogue in the 'microwave background', although the microwave background is produced at a much later epoch in the evolution of the universe.

4.Concluding remarks

The direct detection of gravitational waves is one of the most challenging problems in experimental physics today. The sustained efforts to detect gravitational waves has led to impressive advances and what previously appeared to be a fantasy has now turned into a realisable expectation. Several detectors are being planned with a sensitivity goal which promises a significant chance of detection. In the past two decades or so, one is struck by the enormous advance made in our theoretical understanding of gravitational waves. One is even more impressed by the progress made by experimentalists to invent, design and strive for detectors with greater sensitivities. A new astronomy is in the offing which promises to bring us information complementary to the one we have from the electromagnetic window.

There is no doubt that the quest will succeed. The only question is when.

Bibliography

For further general information the reader may consult the literature below:

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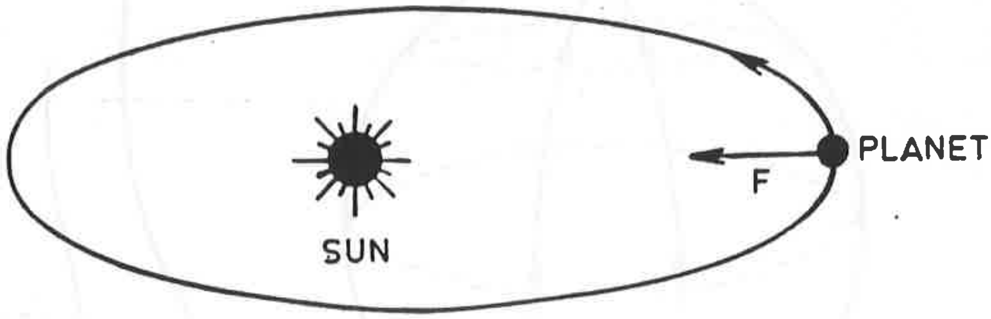
4. *Interferometric Gravity Wave Detector: Phase I Developmental Work and Experiments* a IUCAA-CAT report 1991.

(a) NEWTONIAN PICTURE



(b) EINSTEINIAN PICTURE

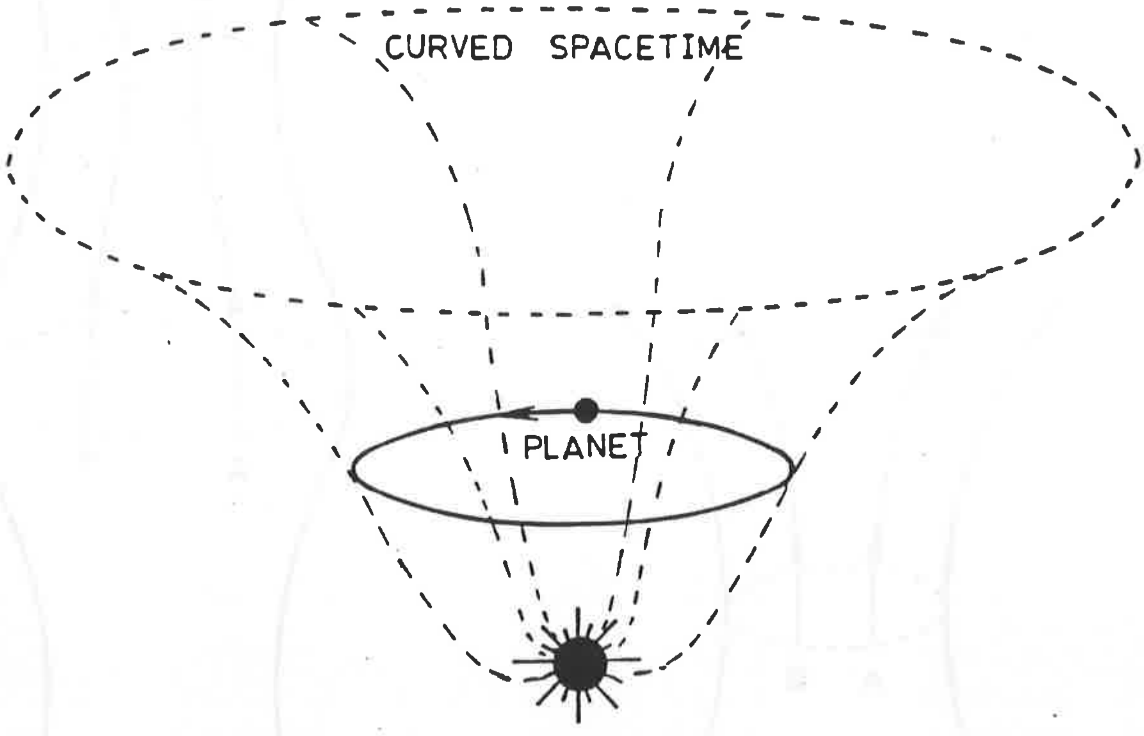


Figure 1

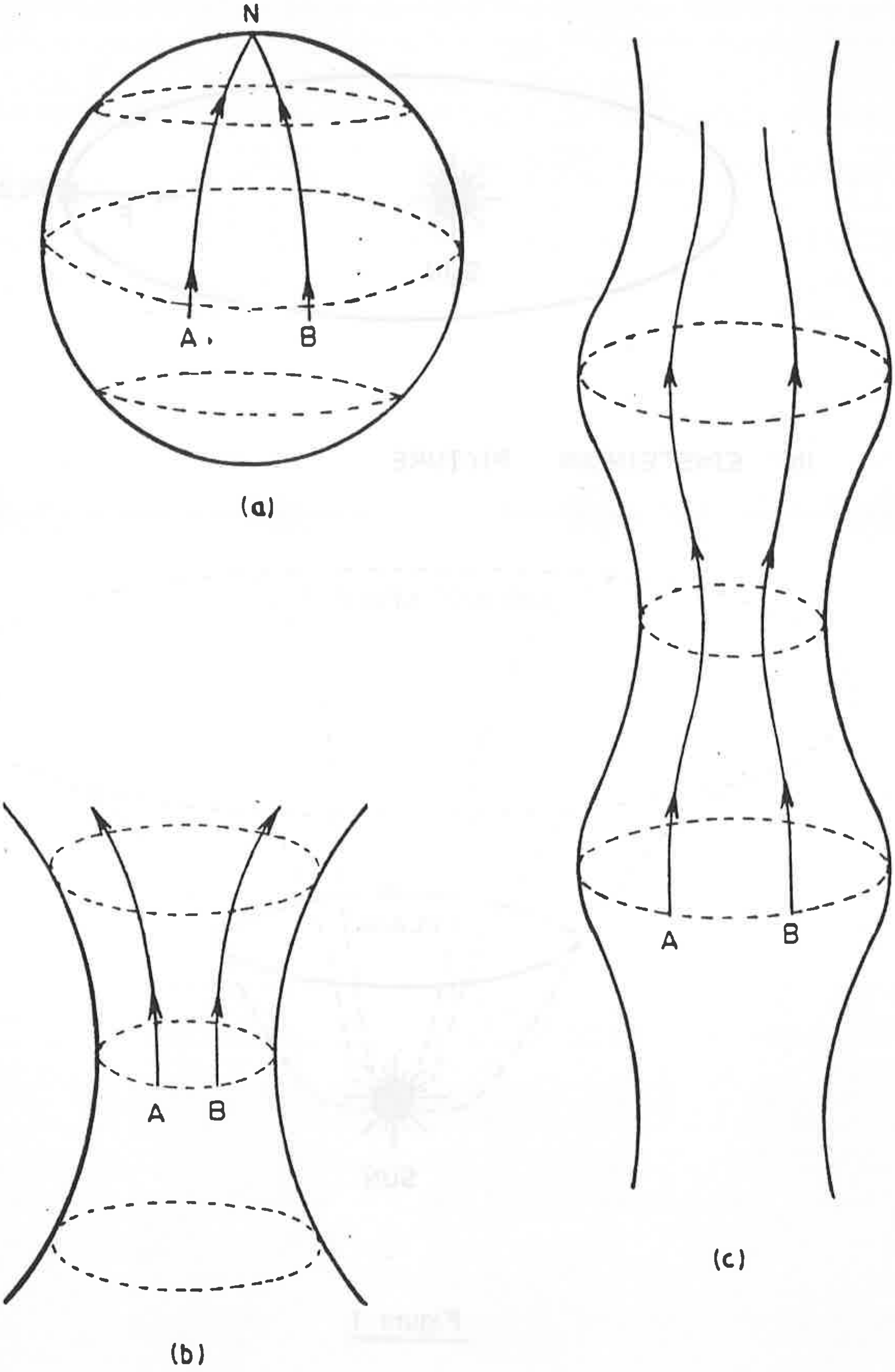


Figure.2

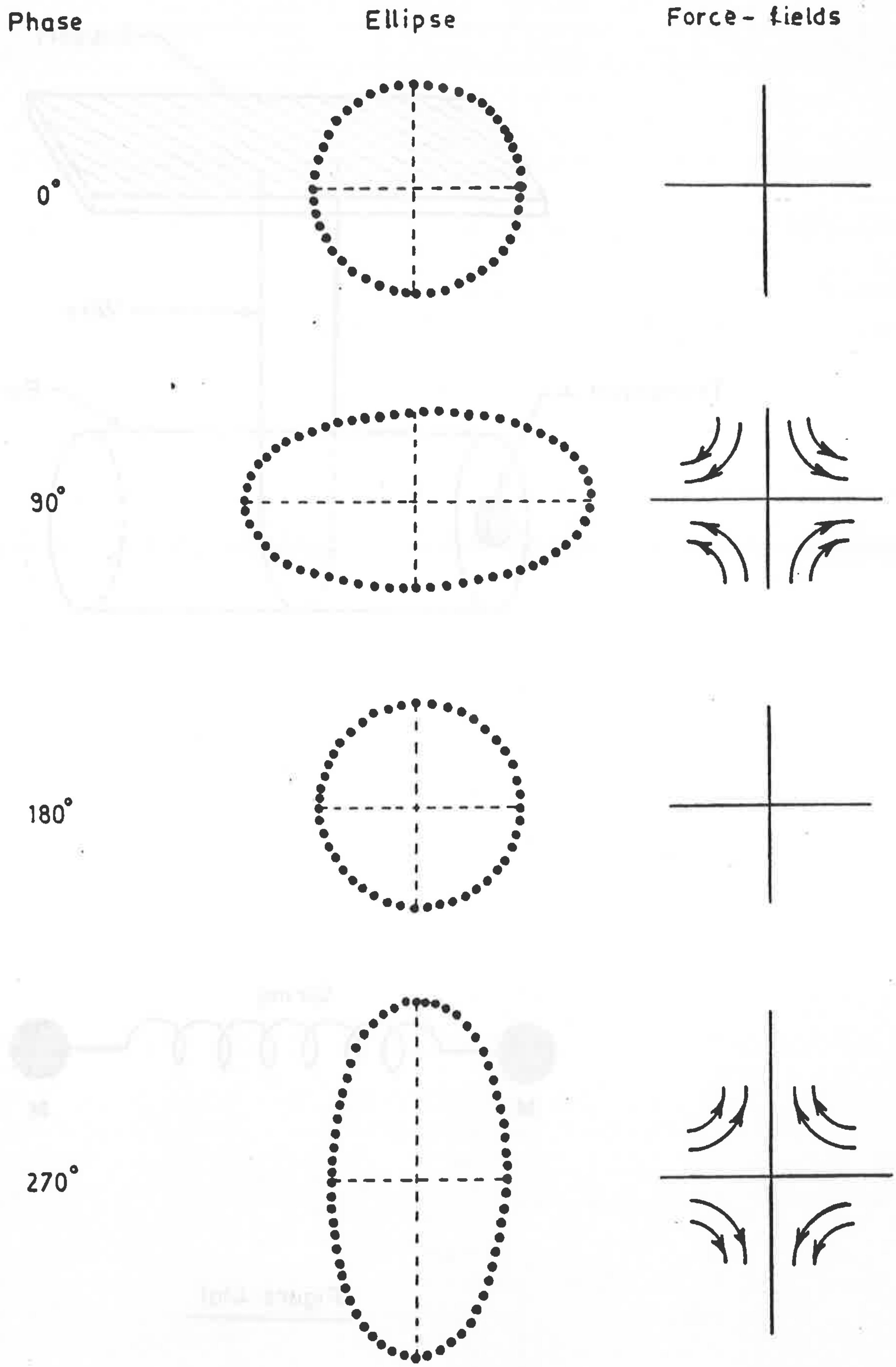
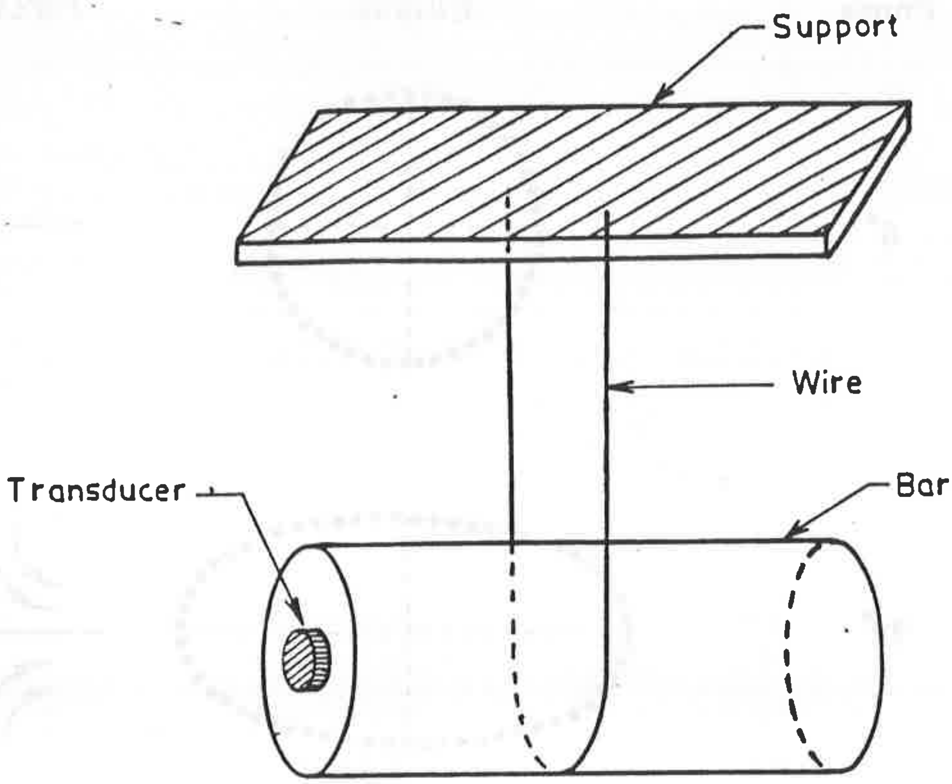


Figure . 3

RESONANT BAR



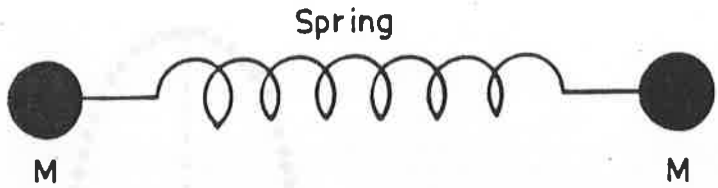
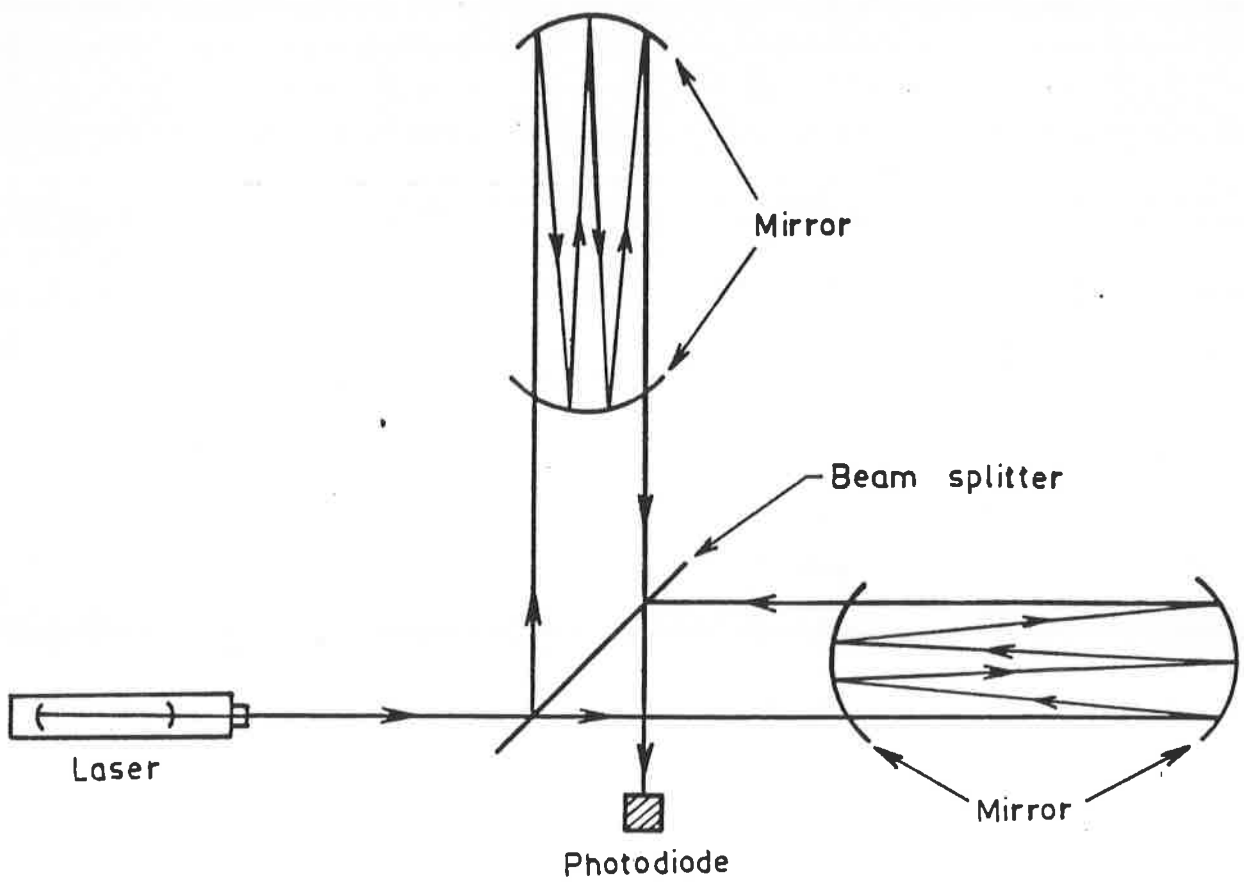


Figure. 4(a)

LASER INTERFEROMETER



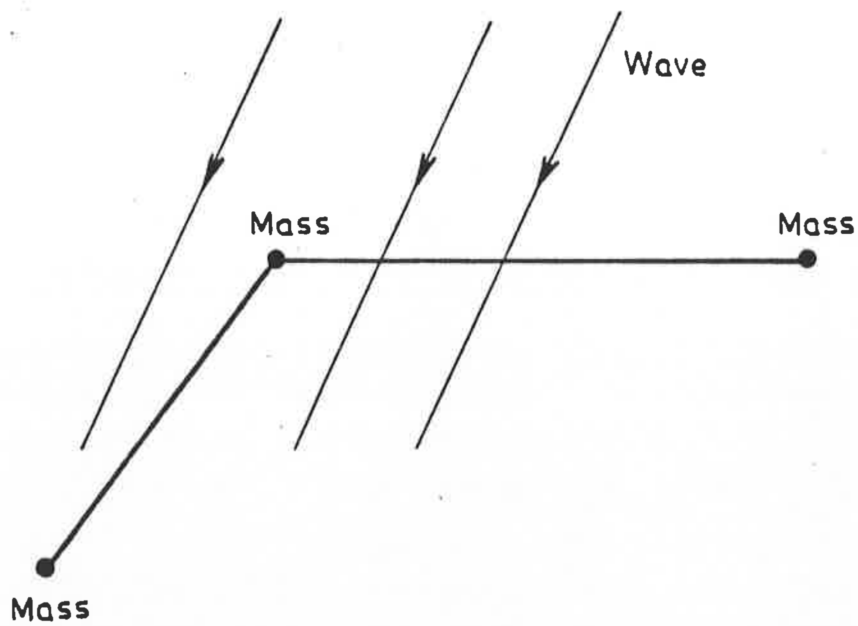


Figure 4(b)