GRAVITATIONAL WAVE ASTRONOMY: A NEW WINDOW TO THE UNIVERSE

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ABSTRACT

Gravitational Wave Astronomy is about to become a new tool for the exploration and the understanding of the Universe. The attempts at gravitational wave detection where daring enterprises in the '70s but appear today as much more secure undertakings. By the end of the century we would be surprised and disappointed if gravitational waves were still undetected.

1. Introduction

In the eve of the 21st century most, if not all, of the information we get when observing the universe is due to thermal effects in astrophysically active regions, especially from the thermonuclear reactions inside the stars. This information is carried away by electromagnetic waves and is detected by earth-bound or earth-orbiting observatories. Recently, neutrino detectors changed this state of affairs although the information they supplied is still marginal. The information we get from electromagnetic observations is limited only to certain classes of astronomical processes since a number of violent but "cold" events that take place in the Universe are completely hidden from detectors of electromagnetic radiation. This is one of the reasons that led astrophysicists and theoretical physicists to turn their attention to another form of radiation which also fills the universe. This is gravitational radiation i.e. *the radiation produced by changing gravitational fields.* The frequency of such radiation depends on the time-scale of the change of the gravitational field. For example, the motion of the Earth around the Sun produces gravitational waves with frequencies of $\sim 3\times 10^{-8}$ Hz while the collapse of a super-massive star to a black-hole after a supernova explosion will produce gravitational waves with frequencies of a few kHz. We live in a Universe filled with gravitational radiation that spans a wide range of frequencies. Still, our detection abilities are hampered by its extremely low intensity. Despite the fact that gravitational forces drive the large scale evolution of the universe, they are 38 orders of magnitude weaker than electromagnetic forces. Hence, changes of the gravitational field induced by the passing gravitational waves are tiny and no present day detector can monitor them. But this situation is bound to change soon: compensating for the weakness of the signal, a new generation of huge apparatuses is under construction around the world. Within two or three years scientists expect to have the first direct evidence of the existence of gravitational waves. This will give rise to a new era for astronomy and theoretical physics, with the progressive collection of large amounts of qualitatively new information about the universe.

Despite the absence of direct detection of gravitational waves, their indirect influence has been seen and measured with such remarkable accuracy that the question of their existence can be answered unequivocally. The 1993 Nobel Prize was awarded to Hulse and Taylor for their discovery of the binary pulsar PSR1913+16 [1] and the demonstration that the binary's neutron stars are inspiraling at just the rate predicted by general relativity's theory of gravitational radiation reaction.

In the next four sections, we will discuss the nature of gravitational radiation then we will describe the present status of gravitational wave antennas, and we will outline the most interesting astrophysical sources of gravitational waves. Finally, we will discuss the types of new information we expect to get through such detection.

2. What is a Gravitational Wave?

The answer will be given in a quantitative way without direct reference to the formalism of general relativity.

In Newtonian theory the gravitational field is described by the gravitational potential U. In the neighborhood of a reference point x_0 (e.g. a gravitational wave antenna) the potential can be expanded in power series

$$U(\bar{x}) = U(x_0) - \sum_j g_j x_j + \frac{1}{2}\sum_{jk} R_{j0k0} x_j x_k + ... \tag{1}$$

where x_j are the components of the vector $\bar{x}$ from the point x_0 to the measuring point, the values g_j are the components of the *local acceleration of gravity*, and the values R_{j0k0} measure the inhomogeneity in the gravitational field at x_0. For general relativity R_{j0k0} are the components of the Riemann curvature tensor. In the Newtonian theory they are simply the second derivatives of the potential U i.e. $R_{j0k0} = \partial^2 U/\partial x_j \partial x_k$.

Gravitational waves can be thought of as a *field of relative gravitational forces that propagate with the speed of light.* They make a contribution to R_{j0k0} which can be added to the Newtonian contribution. The total value of R_{j0k0} is:

$$R_{j0k0} = \partial^2 U/\partial x_j \partial x_k + \bar{R}_{j0k0} \tag{2}$$

where the contribution $\bar{R}_{j0k0}$ is dictated by general relativity. For example, a plane wave propagating in the z direction (see figure 1) has

$$\bar{R}_{x0x0} = -\bar{R}_{y0y0} = -\frac{1}{2}\ddot{h}_+\left(t - \frac{z}{c}\right) \tag{3}$$

$$\bar{R}_{x0y0} = \bar{R}_{y0x0} = -\frac{1}{2}\ddot{h}_\times\left(t - \frac{z}{c}\right) \tag{4}$$

Here h_+ and $h_\times$ are arbitrary dimensionless functions (i.e. the magnitude of the perturbations of the metric tensor $g_{\mu\nu}$) which represent the amplitude of the wave in the two orthogonal polarizations $+$ and $\times$, dots denote time derivatives and c is the speed of light. The relative forces are perpendicular to the propagation, i.e. they are transverse, just like the electromagnetic waves. An object placed in this force field will experience time-varying stresses due to the wave's relative gravitational forces which will produce mechanical strains with a magnitude of the order of the dimensionless wave amplitude h. It is in this way that gravitational waves interact with matter.

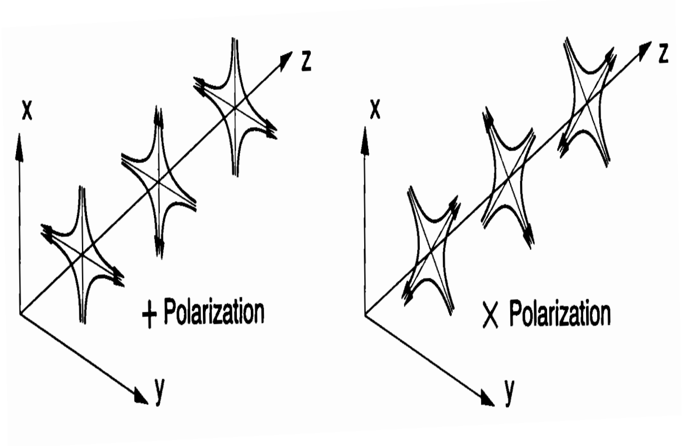

Figure 1: The force lines of the tidal field produced by a gravitational waves

The gravitational waves like the electromagnetic waves carry energy with the speed of light. The energy flux is well defined when we average over several wavelengths

$$\mathcal{F} = \frac{c^3}{16\pi G}\langle \dot{h}_+^2 + \dot{h}_\times^2 \rangle \tag{5}$$

The energy flux has properties similar to the electromagnetic waves i.e. it is conserved (the amplitude dies-of as $1/r$ and the flux as $1/r^2$) and it can be deposited in detectors. The strength of the waves can be roughly estimated using the "quadrupole formula" which says that $h \sim \ddot{Q}/r$, where $\ddot{Q}$ is the 2nd time derivative of the source's quadrupole moment and r the distance of the source from our detector. It can be shown [2] that $\ddot{Q} \sim 4E$ where E is the non-spherical part of the source's internal kinetic energy. From this we get an approximate formula for the estimation of h

$$h \sim \frac{4G}{c^4}\frac{E}{r} \tag{6}$$

Gravitational waves propagate virtually unimpeded. The only significant modification in the wave as it propagates are redshifts (Doppler, gravitational, and cosmological) and decrease in amplitude due to inverse-square-law. All other modifications as dispersion, backscatter, absorption, etc do occur, but are negligible far from the highly relativistic sources.

In all the above we have pointed out the similarities between the electromagnetic and gravitational waves but there are major differences as well.

Electromagnetic waves are oscillations of the electromagnetic field that propagate *through the spacetime* while gravitational waves are oscillations of the spacetime itself and can *act as a source for gravitation.* Electromagnetic waves are easily absorbed, scattered, and dispersed by matter while gravitational waves travel practically unscathed through all forms and amounts of intervening matter. Another important difference between the two types of waves are their range of anticipated frequencies: the electromagnetic waves have frequencies which begin at $\sim 10^7$Hz and extend upward two dozen of orders of magnitude, while astronomical gravitational waves begin at $\sim 10^4$Hz and extend downward for a dozen of of orders of magnitude.

3. Detection of Gravitational Waves.

As we mentioned earlier, a gravitational wave produces tidal forces on any object or detector through which it passes. Thus we can observe them by monitoring the strain that they produce. This can be done only for time-dependent strains and so each kind of detector is optimized for a particular frequency range. The construction of gravitational wave detectors was initiated in the 1960's by J. Weber [3] at the University of Maryland. His detectors were massive cylindrical aluminum bars, suspended and vibration-isolated in a vacuum container. They were to be set in ringing oscillations when a gravitational wave passed through. Weber's type of detectors are sensitive only in a narrow bandwidth depending on the mass and the size of the detector.

3.1 The Resonant Detectors

Weber's pioneering work has inspired many follow-up investigations and there are good prospects for a new generation of high sensitivity resonant detectors. The sensitivity of the resonant-mass detectors depends on the antenna's geometry, material and the detector's noise. Most of these detectors consist of a massive solid cylinder made of aluminum with a fundamental longitudinal frequency around 1kHz. A gravitational wave pulse incident with suitable polarization and direction will induce a dynamic strain in any odd-order longitudinal mode and the principle of operation of these detectors is based on the detection of a sudden change in the vibrational state of such a mode against the background detector noise sources (thermal noise, noise from the electronics etc).

In order to reduce the thermal noise, these detectors have to be cooled cryogenically to liquid-helium temperatures or below. Such bar detectors are now in operation in various places around the globe. The most sensitive and modern ones are AURIGA, ALTAIR and NAUTILUS in Rome, ALLEGRO in Louisiana, EXPLORER in CERN and the Australian NIOBE in Perth (for detailed reviews on resonant detectors refer to [4, 5]). These detectors have reached sensitivities around $h \sim 10^{-19}$. Although impressive in itself, such sensitivity restricts those detectors to observations of supernovae from our own Galaxy only, a quite rare event that occurs only a few times per century.

The next generation of resonant detectors is planned to operate at the same time with interferometric detectors i.e. by the year 2000. Those will be *solid spheres* up to one hundred tones, cooled down to $\sim 0.01 - 0.05K$ with sensitivity $\sim h \sim 10^{-22}$. Such detectors are planned in USA (TIGA project), in Italy (Omega project) and in Netherlands (GRAIL project). The spherical detectors have the advantage of being omnidirectional, i.e., equally sensitive to waves impinging from any direction, and they will be several times more sensitive than bars in the same frequency.

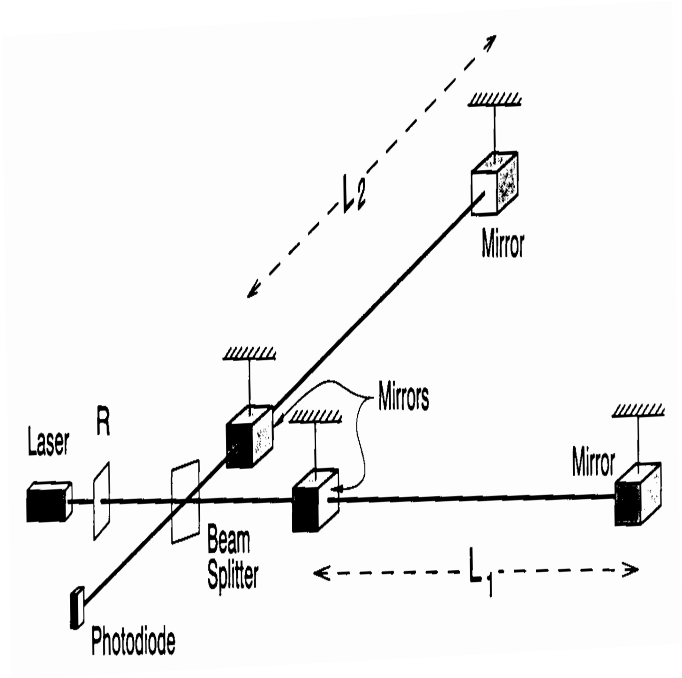

Figure 2: Schematic diagram of a laser interferometer wave detector. The fundamental idea is simple: a partially reflecting mirror splits a ray of laser light in two beams of equal amplitude propagating in orthogonal directions. The two beams are trapped into the two cavities of length L and they bounce back and forth for a few dozens of times until recombining at the photodiode. Any relative change in the distance between the mirrors will alter the optical path difference resulting in a change of the interference pattern. What we finally measure is the differential length change (figure taken from [13]).

3.2 Interferometric Detectors

The laser interferometer gravitational wave detector consists of four masses which are vibrationally isolated in a shape shown in figure 2. The arm lengths are equal, and as the gravitational wave passes through the detector, it pushes the masses back and forth relative to each other creating an arm length difference ΔL. This tiny change monitored by laser interferometry in such way that the output on the photodiode is proportional to $\Delta L(t)$. A wave coming from an arbitrary direction will create an output which will be the linear combination of the two polarizations:

$$\frac{\Delta L(t)}{L} = h(t) = F_+ h_+(t) + F_\times h_\times(t) \tag{7}$$

The coefficients F_+ and $F_\times$ are of order unity and depend on the angle between the detector's plane and the line of propagation of the wave. The ultimate goal in gravity wave detection is to isolate the instrument from all other sources which can induce optical path length changes. In practice there are many technical problems which limit the performance of an interferometer. For example, seismic, mechanical and thermal noise; refractive index perturbations, scattered light mixing with the main beam etc. All these constitute problems which can in principle overcome with the use of advanced experimental techniques in the suspensions of mirrors, using vacuum pipes of length $L(= 4km!)$ for the two arms, highly stable lasers etc. But there are three fundamental limitations which follow from the quantum mechanical structure of matter. The quantum uncertainty in the mirror position, the photon counting error and the radiation pressure fluctuations. For a standard interferometer the quantum uncertainty gives a lower limit of $h \sim 10^{-23}$ which cannot be beaten by any means (cf figure 3).

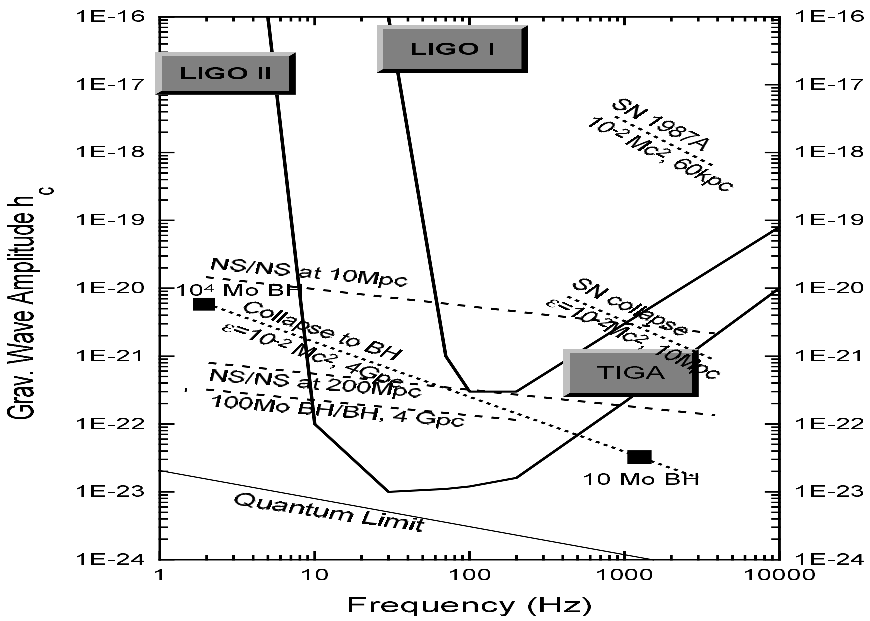

Figure 3: The sensitivity of the laser interferometers (LIGO) and spherical detectors (TIGA) for various sources of gravitational waves is plotted as function of the frequency.

Today, there are various prototypes around the world (CALTECH, MIT, Glasgow, Munich) with an arm length L of a few tenths of meters which have reached sensitivities of the order $h \sim 10^{-18}$. Soon, before the turn of the century, various detectors will start their operations around the world. GEO600 is a German-British detector with 600m arm length (Hannover), LIGO is the USA project with two detectors (Louisiana and Washington) with arm lengths of 4 km. In Pisa there will be an Italian-French detector called VIRGO with arm lengths of 3 km, while prototype detectors of a few hundred meters are under construction in Japan (TAMA-300) and Australia. In figure 3 the sensitivity of LIGO is shown in the first phase of its operation (LIGO I) and the anticipated sensitivity after fine tuning and introduction of new technology (LIGO II).

As it is apparent from the figure 3, laser interferometers are broadband detectors and they are sensitive from 10Hz and onwards. Below 10Hz it is difficult, if not impossible, to improve the sensitivity because of the earth's seismic noise and this is one good reason for the construction of space interferometers.

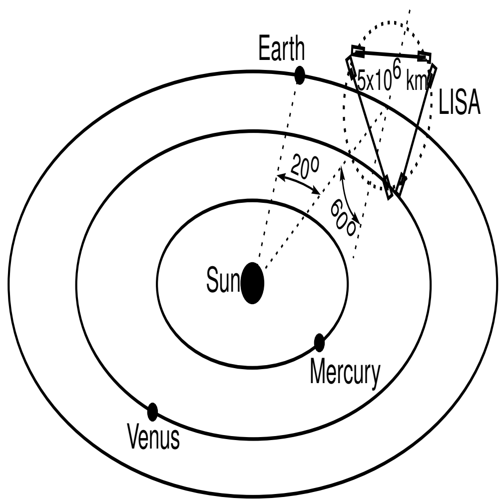

Figure 4: Proposed LISA orbit

3.3 Interferometers in space (LISA)

The primary objective of LISA (Laser Interferometer Space Antenna) is to observe low frequency gravitational waves (0.1mHz to 1 Hz) with sensitivity of the order of $h \sim 10^{-22}$. This sensitivity will be sufficient for detection of galactic binaries, including the radiation from the binary pulsar PSR 1913+14, as well as interesting cosmological sources, such as the formation of massive black holes in the centers of quasars.

LISA consists of a cluster of six spacecrafts in the same heliocentric orbit as Earth, which would follow 20^0 behind the Earth (figure 4). The spacecrafts will fly in pairs and each pair will be placed at the vertex of an equilateral triangle that is inclined at an angle of 60^0 to the Earth's orbital plane [6]. The length of the arms will be 5×10^5Km. LISA has been approved to fly as an ESA Cornerstone Mission around the year 2017.

4. Astrophysical Sources of Gravitational Waves

Every astrophysical process which results in the change of the gravitational field of a system produces gravitational waves. Nevertheless, only those processes which happen in relatively small areas of the Universe and involve high mass concentrations and high velocities produce gravitational waves which are expected to be detectable. The detectability of an event depends very much on the a-priori knowledge we have about the generation of the gravitational waves. In gravitational collapse we have limited information about the shape of the emitted waveform and thus the signal must be strong enough to stand above the noise of the detector. On the other hand events for which the waveforms can be modeled quite well (like binary coalescence and pulsars) can be detected even if the signal is much weaker than the detectors noise, for example by using matched filtering techniques [7].

4.1 Coalescing binary systems

Coalescing compact binary systems consisting of neutron stars or/and black holes are probably the most important potential sources for laser interferometers. They may also be detectable in the future by the new spherical resonant detectors. What makes them detectable is our ability to model reasonably well the waveforms expected from the inspiral phase, as the two compact objects get closer and closer because of the emission of gravitational waves by their orbital motion [1]. The Hulse-Taylor binary pulsar is an example of a NS/NS binary whose waves could be measured by LIGO/VIRGO, if we were to wait long enough ($\sim 10^8$ years). At present the gravitational waves emitted by this binary are at a frequency of $\sim 10^{-4}$Hz i.e. far outside the bandwidth of ground based laser interferometers. But, as the orbit shrinks, due to the emission of gravitational waves, the frequency increases and when for example the separation of the two neutron stars becomes about 150Km (after 3.5×10^8 years) the system will have an orbital period of 20ms and in less than a few minutes will coalesce. In general, for a typical NS/NS binary with mass of its components around $1.4M_\odot$ each, the detectable signal by LIGO/VIRGO will last around 15 minutes as the orbital frequency will increase from 5 to 500 Hz (the frequency of the gravitational waves will be twice the orbital frequency).

Because the strongest radiation is produced near periastron, when the acceleration is greatest, the radiation reaction is also strongest at this time, which results in circularisation of the orbit. The gravitational wave luminosity of a binary system (m_1, m_2) in circular orbit can be estimated by the quadrupole formula:

$$L = \frac{32G^4}{5c^5}\frac{(m_1 m_2)^2(m_1+m_2)}{a^5} \tag{8}$$

where a is the separation of the two stars while the increasing wave frequency f as

[1] There are still various problems related to the modeling of the binary evolutions [8, 9], which are not unbeatable [10]

a function of time is given by:

$$f(t) = \left(\frac{c^3}{G}\right)^{5/8} \frac{1}{\pi} \left(\frac{5}{256} \frac{1}{\mathcal{M}^{5/3}} \frac{1}{t - t_0}\right)^{3/8} \tag{9}$$

where $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$. The typical wave amplitude for a NS/NS binary system emitting gravitational waves at the frequency of 100Hz will be:

$$h \sim 10^{-23} \left(\frac{\mathcal{M}}{M_\odot}\right)^{5/3} \left(\frac{f}{100Hz}\right)^{2/3} \left(\frac{100Mpc}{r}\right) \tag{10}$$

Since in the 15 minutes we expect to detect $n = 16,000$ cycles of waveform oscillation the characteristic amplitude $h_c = h\sqrt{n}$ which practically matters for detection will practically increase the above number by 2 orders and such waves can be detected by LIGO/VIRGO, while with next generation of LIGO such systems can be detectable even further than 1Gpc.

There is an uncertainty regarding the event rate of coalescing binaries, the estimates are based mainly on careful studies of pulsar detection in binary systems [11, 12] and the theory of binary evolution which range for a birth rate of $10^{-6} - 10^{-4}$/year in our Galaxy. The general current belief is that we should expect from the advanced interferometers (LIGO II) a rate of several up to hundred NS/NS coalescences per year out to 200Mpc [13]. For the event rate BH/BH or NS/BH coalescence there is not yet a very good estimation.

In the case of the infall of a star M_S into a massive black hole the characteristic frequency f_c is determined by the light travel "diameter" of the event horizon, so depends only on the black hole mass, M_{BH}.

$$f_c \sim 1kHz \left(\frac{10M_\odot}{M_{BH}}\right) \tag{11}$$

The amplitude depends only on the non-spherical component of the kinetic energy (cf eqn (6)) so depends only on the stellar mass

$$h \sim 2 \times 10^{-21} \left(\frac{M_S}{M_\odot}\right) \left(\frac{10Mpc}{r}\right) \tag{12}$$

This problem have been studied in detail in the last 30 years using black-hole perturbation theory [14], the signal from such a process is usually a short burst since most of the energy is emitted during the final stages of the plunge when the star falls from $4M$ to $2M$ (remember that the radius of a black hole is $2M$). The signal can be longer and the total energy emitted as gravitational waves can be an order of magnitude larger if the star is counter rotating during the infall. The gravitational waves emitted from the excitation of the "quasi normal mode" perturbations of black holes contain precise information on the black hole mass and angular momentum. Thus a gravitational wave signal can give surprisingly detailed information on existing black holes as well as on forming black holes. Recent, numerical solution of the head on collision of two equal-mass black holes verified that even in this highly asymmetric case the results of the perturbation theory mentioned earlier are still valid [15]. The general case of BH/BH coalescence (no head-on collision) is not well studied and we have not exact waveforms for the signals emitted during the late stages of black-holes coalescence. There is currently a "Grand Challenge" project underway in the USA to simulate the 3-dimensional spiraling coalescence of black holes [16].

4.2 Pulsars

Spinning neutron stars emit gravitational waves via two different mechanisms. Newborn pulsars would radiate in strong bursts of gravitational radiation, thereby reducing quickly their deviations from axisymmetry. (This is due to the radiation reaction experienced by radiating sources).

More importantly, from the viewpoint of detecting gravitational waves, they would emit continuous gravitational radiation if they are non axisymmetric, with a frequency equal to twice the spinning frequency [17]. If we idealize the neutron star as a slightly deformed, homogeneous sphere with a moment of inertia I and rotational frequency f we obtain for the power radiated

$$L_{GW} = \frac{32G}{5c^5} I^2 \epsilon^2 \left(2\pi f\right)^6 \tag{13}$$

where $\epsilon = \theta_\omega \epsilon_0$, θ_ω being the so-called *wobble* angle, which describes the misalignment between the star's rotation and symmetry axes and ϵ_0 is the *oblateness*. For typical neutron-star masses and moments of inertia, the wave amplitude is

$$h \sim 6 \times 10^{-25} \left(\frac{f_{rot}}{500Hz}\right)^2 \left(\frac{1kpc}{r}\right) \left(\frac{\epsilon}{10^{-6}}\right) \tag{14}$$

The deepest searches for these nearly periodic waves will be performed by narrow-band detectors, i.e. either resonant-mass antennas or laser interferometers working in dual-recycling mode [4]. There is some uncertainty about the existence of such spinning neutron stars, although there are reasons to suspect that several physical mechanisms might generate ellipticities which can radiate detectable signals. For example, the magnetic fields that are trapped inside the superconducting cores could produce such ellipticities. Accretion onto spinning neutron stars can drive precession and produce measurable waves. Finally, newborn, very fast rotating neutron stars may experience an instability driven by gravitational radiation-reaction. This CFS (Chandrasekhar [18], Friedman, Schutz [19]) instability is also a potential source of gravitational waves.

The signal from a pulsar is basically periodic, however because it is very weak (cf eqn (14)) the procedure of extracting such a signal from the noise is quite laborious since we may have to integrate the data for several months. This means that the small corrections induced by Earth's motion around the Sun and the spin-down of the pulsar should be taken into account [20].

4.3 Supernovae and the birth of neutron stars and black holes

When the nuclear fuel of a massive star is exhausted it collapses to form a neutron star or a black hole. Supernova collapse is one of the most violent events known in astronomy and was the motivation for building the resonant mass antennas. They are still considered a primary source of gravitational waves even for the new generation of resonant detectors.

Despite more than 30 years worth of efforts, astrophysicists are far from a definite understanding of the details of collapse and explosion. There are great uncertainties about the details of the core collapse and there is probably a variety of collapse scenarios.

The collapse releases an enormous amount of gravitational radiation (it is of the order of the binding energy of a neutron star) about $\sim 0.1 M_{\odot} c^2$. Although the largest part of this energy will be carried away by neutrinos there is still a huge amount of energy which can be radiated away as gravitational waves. The key question that concerns us is: What is the magnitude of d^3Q/dt^3 during a collapse, or from equation (6), what is the kinetic energy of the non-spherical motion? There are many possibilities, very little astrophysical evidence to give guidance, and extreme technical difficulties in calculating the bulk properties of degenerate matter during collapse. We believe that the main source of non-sphericity during collapse is angular momentum. During the collapse the angular frequency of the collapsing core rises rapidly and it may pass through a succession of states as for example becoming an increasingly oblate spheroid, it may evolve to a bar mode instability and evolve for a short period into a binary neutron star system or alternatively it may develop a pancake instability and break up into several parts which will finally coalesce. There are also other ways that gravitational waves can be emitted during the collapse in addition to radiation due to initial asymmetries, for example the possible fragmentation of the core into several large "chunks" which later fall onto the central compact object can be a potential source of additional gravitational waves. Finally, considerable deviations from symmetry are expected due to the non-symmetric emission of neutrinos which are responsible for the observed pulsar recoil.

A conservative estimation will give an effective amplitude $h_c = h\sqrt{n} = h\sqrt{ft}$ (n: is the number of cycles, f: the frequency of the wave and t: the timescale of the process) [21]

$$h_c \sim 3 \times 10^{-21} \left(\frac{E}{10^{-6} M_{\odot} c^2}\right)^{1/2} \left(\frac{2kHz}{f}\right)^{1/2} \left(\frac{50kpc}{r}\right) \tag{15}$$

$$\sim 3 \times 10^{-18} \left(\frac{E}{10^{3} M_{\odot} c^2}\right)^{1/2} \left(\frac{1mHz}{f}\right)^{1/2} \left(\frac{3Gpc}{r}\right) \tag{16}$$

The first estimate is for stellar collapse while the second is for galactic size collapse i.e. formation of a huge black hole in the center of galaxies. This estimate, besides being very conservative, does not describe completely the details of the collapse.

The final object of the collapse, be it a black-hole or a neutron star, will finally settle into a, possibly rotating, equilibrium configuration. It will not do so, though, before the violent emission of gravitational waves in certain characteristic frequencies [22]. Recent results [23, 21, 24] from the study of these stellar vibrations showed that there could be more energy radiated away than was previously conjectured. This possibility prompts for more detailed studies of the 3 dimensional gravitational collapse in the framework of general relativity.

4.4 Stochastic gravitational-wave background

The violent processes in the early universe should have produced a stochastic background of gravitational waves which can extend in a wide range of frequencies ($10^{-18} - 10^{4} Hz$). The more interesting background would be that produced during the bing bang itself, nevertheless stochastic background could also have been produced by phase transitions in the early universe. If the detectors do detect a gravitational wave background of cosmological origin, this will carry with it a picture of the universe as it was about 10^{-22} seconds after the big bang. This will represent a tremendous step forward in our knowledge of the very early phases of the Universe. Finally, the vibrations of cosmic strings, that theorists believe that were produced in the early universe in large numbers, would produce gravitational waves in a wide range of frequencies. Such waves can be ideal sources for LISA. For an extensive review on stochastic gravitational-wave background refer to [25].

5. The significance of gravitational wave detection.

There is a vast amount of information that can be collected from the gravitational wave observatories. The direct detection of gravitational waves is by itself a major challenge for our present days technology. Such detection signals our ability to measure signals of unprecedented smallness. Also, there is a variety of theories for gravity which predict gravitational waves. The detection will provide us with unique information about the polarization of the waves which is different for each theory [26] and in this way we will pick up the right theory for gravity.

Bellow I just mention without detailed analysis the information that we expect to mine out from the detection of gravitational waves (for a detailed presentation refer to [27]).

- Measure other predictions of general relativity (gravitomagnetism etc).
- Study binary star evolution (LIGO, VIRGO, Resonant Bars & Spheres).
- Discover new single and binary neutron stars (LISA, LIGO, VIRGO, Resonant Spheres).
- Study nuclear astrophysics in neutron stars and supernovae [21, 22] (LIGO, VIRGO, Resonant Bars & Spheres).
- Find massive ($10^{6} M_{\odot}$) black holes in galaxies (LISA).

- Direct observation of single black-holes formed in the centers of Galaxies or quasars (LISA).
- Measure of the cosmological background radiation of the Big-Bang (LIGO, VIRGO, LISA, Resonant Bars & Spheres).
- Measure of Hubble constant H_0 [28] and the deceleration parameter q_0.
- Study particle physics in the early universe.

Gravitational Wave Astronomy is likely to be one of the most productive research areas in the first decades of the next century. Although we already envision the image of the universe that we are likely to confront, we should not underestimate the ability of the universe to surprise us. Gravitational wave detectors may follow the footsteps of radio telescopes and the X-ray detectors which have revealed much more that even the most optimistic Astronomer fifty years ago could imagine.

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