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SEARCHING FOR GRAVITATIONAL WAVES

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The gravitational waves, a new tool in understanding the Universe, becomes a reality. The gravitational radiation, prediction of Einstein's general theory of relativity, has not yet been directly verified. Recent technical developments have enabled the construction of detectors with sensitivities sufficient to measure directly the radiation of astrophysical sources. These detectors will operate together as a network, taking data continuously, listening to the waves from coalescing compact binary systems, stellar collapses, pulsars and the early Universe background. The review covers the present state of gravitational radiation detection, the future detectors plans and the sources of the gravitational waves that are likely to play an important role in upcoming observations.

Гравитационные волны — новый инструмент для познания Вселенной — становятся реальностью. Гравитационное излучение, предсказанное общей теорией относительности Эйнштейна, пока еще не зарегистрировано непосредственно. Последние технические достижения позволяют создать детекторы с чувствительностью, необходимой для прямого измерения излучений астрофизических источников. Эти детекторы будут функционировать совместно как сеть, получающая данные непрерывно при прослушивании компактных систем двойных звезд, коллапсов звезд, пульсаров и фона от ранней Вселенной. Представленный обзор охватывает современное состояние детектирования гравитационного излучения, планы создания будущих детекторов и те источники гравитационных волн, которые, вероятно, будут играть важную роль в предстоящих наблюдениях.

INTRODUCTION

One of the most important theories invented in XX century is Einstein's theory of general relativity. Contrary to the theory of Newton, the gravitation in general relativity is not longer a force but an aspect of the space–time geometry. It can be described by the Einstein equation containing relationship between the matter and the curvature of space–time:

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

where $R_{\mu\nu}$ is the Ricci tensor related to the derivatives of the metric tensor; $g_{\mu\nu}$, the metric tensor; R is the contraction of the Ricci tensor; c is the speed of light; G, the gravitational constant and $T_{\mu\nu}$ is the stress-energy tensor giving the energy densities. The left side of Eq. (1) describes the curvature of space–time while the right side describes the energy and momentum contained in it.

Thus the gravity is simply the manifestation of space–time curvature induced by mass-energy distribution.

Despite of 88-year history and the fact that general relativity is our best theory explaining the phenomena of gravity, it is relatively untested comparing to other physical theories. Due to the weakness of the gravitational force the precision measurements required to test the theory were not possible when Einstein first described it and for many years thereafter. Today, such static relativistic gravity effects as precession of the periastron, gravitational lensing and gravitational redshift have been well studied.

One of the most interesting results of Einstein's theory is the prediction of gravitational waves (GW), ripples in the curvature of space–time generated by the motions of matter. Propagating at the speed of light, gravitational waves do not travel «through» space–time as such — the space–time itself is oscillating. Their strength weakens proportionally to the distance from the source.

Although some early relativists were sceptical about the existence of gravitational waves (*Gravitational waves propagate at the speed of thought* — Sir Arthur Eddington.), today their existence is no longer in doubt. The evolution of the orbit of the binary pulsar, PSR 1913 +16, can only be explained if angular momentum and energy are carried away from this system by gravitational waves, and the Nobel Prize in Physics in 1993 was awarded to Hulse and Taylor for their experimental observations and subsequent interpretations of this system [1, 2].

The most exciting prospect in this field is the direct observation of the gravitational waves. Measuring their polarization is of fundamental importance since there are theories of gravity, other than general relativity, in which the number of GW polarization states is more than two [3]. Moreover, direct observations would reveal information about astronomical systems that are not observable in any other way. This expectation is motivated by several features of the gravitational radiation, as predicted by general relativity theory:

• The GW are emitted by the coherent bulk motions of their sources, not by individual atoms, electrons or molecules as is the case for electromagnetic waves or neutrino radiation. As a result they carry a completely different information about their sources from that which is normally available from electromagnetic or neutrino observations. For example, the polarization of waves from the orbit of a binary system reveals the inclination of the orbit to the line of sight, a crucial unknown in the modelling of such systems [3].

• The GW interact with matter so weakly that they are not attenuated or scattered on their way to a detector. This means that they can reveal information about hidden regions, such as interior of a supernova explosion or the Big Bang. The GW provide also the only way to make direct observations of the black holes.

The challenge in experimental physics is the direct observation of GW by an earth or space based device. The GW change the separation of adjacent masses and this tidal effect is the basis of all present detectors. The problem for the experiment is that the predicted magnitudes of the strains in space caused by gravitational waves are of the order of 10^{-21} or lower. There are number of worldwide efforts to detect gravitational radiation by cryogenically cooled resonant-bar detectors and laser interferometers.

This overview does not attempt to cover all aspects of the subject. Instead, it briefly describes the key points of current research and cites specialized articles, where more details can be found.

The article is divided into three main parts. The first one (Sec. 1) treats the basic properties of the gravitational radiation. The second part (Sec. 2) describes the expected sources of gravitational waves that are likely to be detected. The last parts (Secs. 3 and 4) cover operation of the gravitational waves detectors, both resonant-mass and interferometer based. Future developments, like spherical antennas and a detector in space are also mentioned.

1. BASIC PROPERTIES OF GRAVITATIONAL WAVES

Although the full nonlinear Einstein equation (1) looks simple, it is not so easy to use. In general case, it leads to a set of ten nonlinear differential equations which cannot be easily solved, however they can be approximated as linear equations in the weak field limit, where the metric tensor is given by:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad |h_{\mu\nu}| \ll 1, \tag{2}$$

where $\eta_{\mu\nu}$ is the Minkowski metric of flat space and $h_{\mu\nu}$ is the small metric perturbation. Neglecting the second-order terms and using the Lorentz gauge, Eq. (1) can be expressed as follows:

$$\left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \nabla^2\right)\bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4}T_{\mu\nu}, \tag{3}$$

where $\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h_c$ and h_c is the contraction of $h_{\mu\nu}$. In the vacuum ($T_{\mu\nu} = 0$) and in a suitable coordinate system, the traceless and transverse (TT) gauge, (3) becomes a wave equation where $\bar{h}_{\mu\nu}$ has solutions in the form of waves propagating at the speed of light c. In the chosen gauge, for waves propagating in the z direction, $\bar{h}^{\mathrm{TT}}_{\mu\nu}$ can be expressed as [4]:

$$\bar{h}^{\mathrm{TT}}_{\mu\nu} = (h_+ e^+_{\mu\nu} + h_\times e^\times_{\mu\nu}) \exp\left(i\omega\left(t - \frac{z}{c}\right)\right). \tag{4}$$

There are two possible independent polarization states which are usually denoted h_+ (plus) and $h_\times$ (cross). They are shifted in phase by $45°$. The polarization

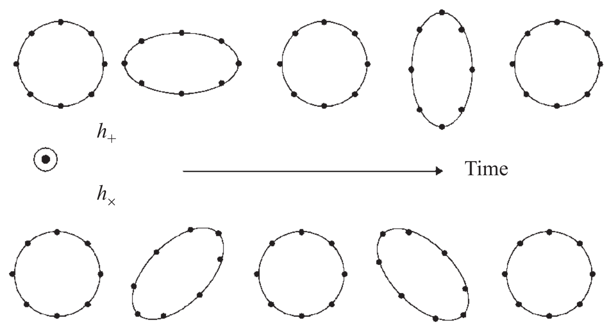

Fig. 1. The response of a ring of free test particles in the (x, y) plane to one cycle of the plus-polarized and cross-polarized GW travelling in the z direction. The ring gets deformed into one of the ellipses and returns to the circular configuration during the first half of the GW period and gets deformed into the other ellipse and back during the next half

tensors $\mathbf{e}^+$ and $\mathbf{e}^\times$ are:

$$\mathbf{e}^+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \qquad \mathbf{e}^\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.$$

It should be pointed that while the solution of Eq. (3) is simple in the vacuum, the general solution with $T_{\mu\nu} \neq 0$ is a very difficult problem which has known solutions only in a few cases.

For a pure h_+ polarization the space–time interval can be written as:

$$ds^2 = -dt^2 + (1 + h_+)dx^2 + (1 - h_+)dy^2 + dz^2. \tag{5}$$

It can be seen that such a metric produces an opposite effect on the proper distance on two transverse axes, contracting one while expanding the other. Figure 1 presents the effect of a gravitational wave on a ring of free test particles in the plane orthogonal to the wave propagation direction. The strain of the ring of diameter L, related to the wave amplitude is [4]:

$$\frac{\Delta L}{L} \sim \frac{1}{2}\bar{h}^{\mathrm{TT}}_{\mu\nu}. \tag{6}$$

Thus the deformation is proportional to the wave amplitude and to the size of the ring.

Solutions to the wave equations for $h_{\mu\nu}$ can be analyzed in a slow motion expansion (size of the source is much smaller than the wavelength) in exactly the same way as solutions to the Maxwell equations [5]. In the electromagnetism, the first radiative moment of a charge distribution is a time-varying charge dipole moment. In case of gravitational charge, mass, the corresponding dipole moment is forbidden by the momentum conservation and thus there is no time-varying dipole moment. Consequently, in general relativity there is no gravitational dipole radiation. The first gravitational radiative moment of matter distribution arises from the quadrupole moment. Thus any system with a time varying quadrupole moment $I_{\mu\nu}$ would emit GW with strain [4, 5]:

$$\bar{h}^{\rm TT}_{\mu\nu} \sim \frac{G}{r} \ddot{I}^{\rm TT}_{\mu\nu}, \tag{7}$$

where r is the distance from the source. Equation (7) is called the quadrupole-moment formula for gravitational wave generation. Two key points about that equation are: strain depends on the second time derivative of the quadrupole moment of the source, and it is inversely proportional to the distance from that source. Since the dominant channel for GW emission is quadrupolar, that process will be inefficient unless the symmetry of the source is broken by nonaxisymmetric rotation, internal stress due to inhomogeneities, an inherent asymmetry in the system, as in binary star systems, etc.

2. ASTRONOMICAL SOURCES OF GRAVITATIONAL WAVES

Astrophysics provides a variety of candidate systems which could be observable in the spectrum of gravitational waves. To be interesting from the point of view of their detection, those sources should: be sufficiently powerful, fall in the frequency band of the detectors (ranging from tens to hundreds of Hz) and occur reasonably often during the life-time of the instrument.

It should be stressed that the estimation of source strength, number or rate is difficult to make for most sources. Very often their radiation strength may depend on physics we do not know yet.

It is common to divide sources that could be strong enough to be seen in our detectors into three broad categories depending on their signal duration: bursts, periodic and stochastic waves. Bursts caused by stellar collapses last milliseconds. Inspiralling of tight binary stars can be observed over a time ranging from a few seconds to several hours. A stochastic background is predicted to be always present with a continuous frequency spectrum extending up to few tens of kHz but with the amplitude too small to be observed by the present detectors.

In the following sections only rough overview of GW astrophysical sources is given. For details of their current understanding together with predicted event rates see, for example, [6, 7] or [8].

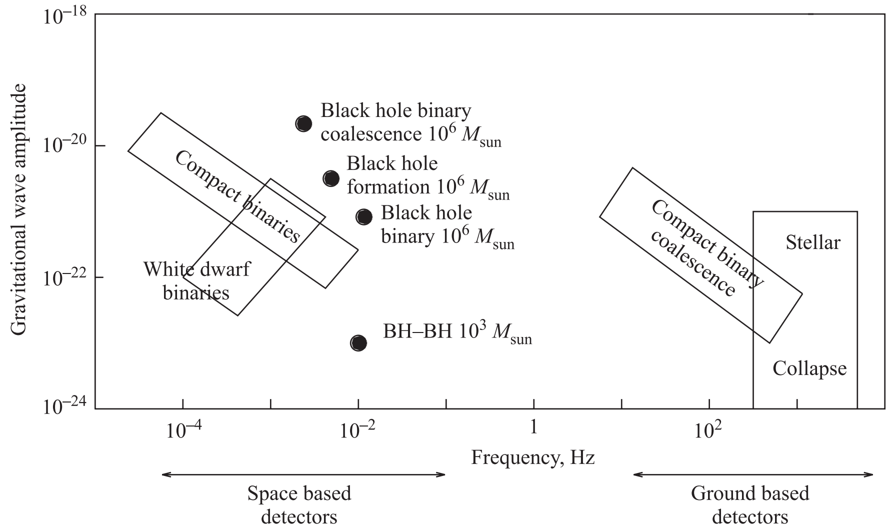

Fig. 2. Some possible sources for ground-based and space detectors (based on [9])

Signal strengths and frequency ranges for some sources possible to be detected by ground based and space detectors are shown in Fig. 2.

2.1. Supernovae. Although it is difficult to predict the waveform or amplitude expected from that event, the supernovae (SN) have long been considered as the primary source of the GW. Because we have no observational evidence we can only guess how nonspherical the collapse can be and how large fraction of the energy released is radiated in GW and thus the intensity of the radiation. Even modern computers are not able to perform realistic simulations of gravitational collapse in three dimensions since it is difficult to include all the important processes.

A burst signal consists of a very short single event (a few ms), with one or very few cycles, frequencies centred on 1 kHz, or anywhere between ~ 100 Hz and a few kHz and a large range of waveforms [10]. The strongest GW emission is predicted to come from a nonaxisymmetric collapse [11]. In that case the GW amplitude can be as large as:

$$h \sim 10^{-21} \frac{10\ \mathrm{Mpc}}{r}, \tag{8}$$

where r is the distance from the source. Several SN per year are expected out of the distance 10 Mpc. The fraction of nonaxisymmetric collapses is unknown.

It should be mentioned that coincident detection with neutrino and/or optical observatories will greatly increase confidence of the measurements in that case.

The methods were also proposed to determine absolute neutrino masses from the simultaneous observations of bursts of neutrinos and GW emitted during a stellar collapse [12].

The observation of GW from supernovae could enable studying details of its dynamics, which is still unknown today, and studying nuclear physics of high density.

For detailed description of algorithms for detection of burst-like signals see [13].

2.2. Binary Systems. Our best known sources of GW are binary systems consisting of two compact, stellar mass objects — neutron stars (NS) or black holes (BH). The stars spin around each other. Such systems have a large, time varying quadrupole moment, which makes them a strong GW radiation source. The gravitational radiation carries away orbital binding energy and orbital angular momentum, which leads to faster and more compact orbit. Since the radiated power increases as the orbit decreases, the system will then decay at an increasing rate, radiation amplitude, frequency and power, until the components coalesce. This signal is predicted with good accuracy by the theory except for the final, merging phase.

It is the radiation from the final moments of inspiral before the coalescence of binary systems, that is seen as an important source for present interferometric detectors. The GW from coalescence of binary stars are roughly 10^{-21} in strain amplitude at frequency of $10{-}10^3$ Hz for $1.4\ M_{\odot}$ pair at 200 Mpc away. Its event rate is expected at 3 events/y within 200 Mpc [14].

The inspiral waveforms are determined to high accuracy by only a few, clean parameters: the so-called «chirp mass» ($M_C \equiv (M_1 M_2)^{3/5}/(M_1{+}M_2)^{1/5}$, where M_1 and M_2 are the two stars masses), the distance to the source, and the orbital inclination. The shrinking time observation from gravitational radiation gives the chirp mass. The amplitude of the radiation measurement leaves only one unknown — the distance r to the source. This is another way in which GW observations are complementary to electromagnetic ones, providing information that is hard to obtain electromagnetically. The observations of coalescing compact object binaries could allow one to measure the Hubble constant (the standard candle method) [15–17] or other cosmological parameters as the cosmological constant Λ or the Universe density parameter Ω_0 [18]. The GW detection from compact binary inspiral can be also used for high precision tests of general relativity [19].

As the waveform of signals from coalescing binaries is well known, the detection of those GW can be done by using the pattern recognition technique called matched filtering, based on matching the output from the detector to expected waveform (template). As the radiation from a binary system depends on the chirp mass and it might arrive with an arbitrary phase, several thousands of related templates must be separately applied to the data to cover the whole family of signals [20].

The binary neutron star systems can be also stochastic and burst sources. A large population of them in our Galaxy, with orbital periods in the range from days to minutes, can produce a stochastic background in the frequency band $\sim 10^{-2}$–10^{-5} Hz. Individual systems far from coalescence can produce nearly monochromatic waves at any frequency up to 0.1 Hz. The binary system merging phase can be another possible source of GW bursts. Characteristic of such an event is similar to the one from supernovae.

2.3. Pulsars. The nonaxisymmetric rotating neutron stars radiate periodic GW [21]. The strength of the emission depends on the degree of asymmetry. The emission is characterized by three parameters: the polar ellipticity ϵ_p, the equatorial ellipticity ϵ_e and the wobble angle θ_w between the principal axis of inertia and the axis of rotation. Thus the star emits GW at $f_1 = 2f_{\rm rot}$, twice the rotation frequency, with $h \sim \epsilon_e$ and the wobble angle couples to ϵ_p to produce waves with $f_2 = f_{\rm spin} + f_{\rm prec}$ (where $f_{\rm prec}$ is the precession frequency) with $h \sim \epsilon_p \theta_w$. More than 700 pulsars are known in our Galaxy, most of them emitting GW below 10 Hz. Unfortunately because of their emitting properties and orientation in space, most of them stay invisible from the Earth in the electromagnetic spectrum. For typical masses and reasonable momenta of inertia, the GW predicted amplitude from the spinning NS is:

$$h \sim 6 \cdot 10^{-25} \left(\frac{f_{\rm rot}}{500\ \text{Hz}}\right) \left(\frac{1\ \text{kpc}}{r}\right) \left(\frac{\epsilon_e \text{ or } \epsilon_p\theta_w}{10^{-6}}\right). \tag{9}$$

An upper limit of $\epsilon_e, \epsilon_p \sim 10^{-4}$ has been suggested for the ellipticity [22].

There are other mechanisms in rotating NS causing GW radiation as NS spin precession or excited NS oscillation (r-mode instability) [6, 23].

Pulsars are quasi-periodic sources: sinusoidal frequency modulated by the Doppler effect of the Earth and of the source, changes in time (spin-down of the source) and the detector pattern. The signal is much weaker than from the burst sources but in principle one can take advantage of periodicity for long-term integration to extract signal from noise. This requires accurate knowledge of mentioned frequency modulations to maintain the coherent integration.

New information about physics of neutron stars and their evolution is expected if gravitational radiation from that source is observed.

2.4. Stochastic Background. A stochastic GW signal differs from that of the burst and periodic sources discussed above. It is random in character and as not generated by an isolated source, it is not incident on the detector from a single direction and has not a characteristic waveform. Its main property will be therefore the frequency spectrum.

A stochastic background of GW could be generated by processes in the early history of the Universe [24]. Those GW have not lost memory of the conditions in which they have been produced, still retain in their spectrum, typical frequency and intensity, bringing us important information on the state of the very early Universe, and therefore on physics at correspondingly high energies, which cannot be accessed experimentally in another way. This is the so-called cosmological stochastic background. It extends through the entire frequency range and could be as low as 10^{-18} Hz and so high as $1{-}10^4$ Hz. Various sources of GW from the early Universe have been hypothesized. The most interesting background is that predicted by the Big Bang, an analogue of the microwave cosmic background radiation.

A stochastic background could also be produced by phase transitions in the early Universe [25] and the cosmic strings [26]. These processes are expected to generate a background which has different spectrum and strength than the one coming from the Big Bang. Thus a stochastic background measurements will provide a good test for the present cosmological models.

Another source of a stochastic GW background is the superposition of a large population of binary stars in our and other galaxies [27]. By studying the spectrum of that background it is possible to make a census of compact objects distributed over astronomical distances. This is the so-called astrophysical stochastic background.

The intensity of a GW stochastic background can be characterized by the dimensionless quantity [24, 28]:

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm gw}(f)}{d\ \ln\ f}, \tag{10}$$

where $\rho_{\rm gw}(f)$ is the GW radiation energy density and ρ_c is the critical energy density required to close the universe:

$$\rho_c(f) = \frac{3H_0^2}{8\pi G}, \tag{11}$$

where H_0 is the Hubble constant. Usually it is convenient to work with $h_{100}^2\Omega_{\rm gw}$, where $h_{100} = H_0/(100\ {\rm km/s/Mpc})$, which is independent of H_0 value.

Most inflationary models predict a flat $\Omega_{\rm gw}(f)$ spectrum. Other models, such as string cosmologies have very different predictions [8]. The background from the Big Bang nucleosynthesis is limited by $h_{100}^2\Omega_{\rm gw}(f > 10^{-8}\ {\rm Hz}) \leqslant 10^{-5}$ [24].

In fact the stochastic signal can be treated as just another detector noise. To make distinction between stochastic radiation and the detector noise, studying correlations of the output of two detectors is needed. Such two detectors must be close enough to experience the same random wave field.

3. RESONANT-MASS DETECTORS

The first GW detector was built by Joseph Weber during the early 1960s. The detector, the so-called bar, consisted of a large suspended bar of aluminium, with resonant frequency of about 1 kHz. The tidal forces due to gravitational radiation would excite the normal modes of the bar. The oscillation of the bar after it had been excited could be measured by a series of piezoelectric crystals mounted on it. The output of the system was put on a chart recorder like those used to record earthquakes. The signals seemed to show the presence of gravitational waves. Weber claimed evidence for observation of gravitational waves based on coincident signals from two bars separated by 1000 km [29, 30]. Although the strength of his signals was very much in excess of what was expected, resonant bar research is still an active field, and the fundamental Weber concept remains almost unchanged. In the following years, various experimenters built more sensitive bars, including low-temperature bars. Those detectors have a disadvantage of being sensitive only to signals in a narrow band around their resonant frequency.

3.1. Principle of Resonant-Mass Detector Operation. The resonant-mass detectors are basically very sensitive oscillators, capable of detecting changes in their vibrational amplitude. The principle of operation of the bar detectors is based on the fact that GW would excite the quadrupolar resonant modes of a massive cylinder. The largest cross section is shown by the fundamental longitudinal mode, which is thus the only one used for detection. The cross section depends on orientation of the GW propagation direction and GW polarization in respect to the bar axis, being maximal when the GW travels perpendicularly to the bar axis and is polarized along it.

A typical bar detector consists of a cylinder of aluminium with a length $L \sim 3$ m, a resonant frequency of order $f \sim 500$ Hz to 1.5 kHz, and a mass $M \sim 2$ t. A short gravitational burst with $h \sim 10^{-21}$ will make the bar vibrate with an amplitude:

$$\Delta L_{\rm gw} \sim hL \sim 10^{-21}\ \text{m}. \qquad (12)$$

To detect this signal, an auxiliary oscillator with a mass in the kg range is attached to one of the bar faces, and its resonance frequency tuned to that of the sensitive mode of the bar in order to have a strong privileged coupling. This transducer is in turn electrically coupled (with a variety of solutions: capacitive, inductive, microwave, optical) to an external readout. A transducer converts the bar's mechanical energy into electrical energy, and an amplifier increases the electrical signal to record it.

The output channel of a gravitational wave detector is always alive with random fluctuations of noise, even in the absence of GW signal. The performance of the detector is characterized by the strain sensitivity $\widetilde{h}_f$:

$$\widetilde{h}_f = \sqrt{S_n(f)}, \qquad (13)$$

where $S_n(f)$ is the power spectral density of the noise, $\widetilde{h}_f$ has dimension $\text{Hz}^{-1/2}$.

3.2. Main Sources of Noise in Resonant-Mass Detectors. Three fundamental noise sources are usually considered for the resonant-mass antennas.

Thermal noise, due to the thermodynamic fluctuations in the bar volume causing displacement of the bar ends. The r.m.s. amplitude of the bar vibrations due to those fluctuations during the averaging time τ is [4]:

$$\langle \Delta L_{\rm th}^2 \rangle_\tau^{1/2} = (kT/4\pi^2 M f^2)^{1/2} (2\pi f \tau / Q)^{1/2}, \qquad (14)$$

here T is the bar temperature; Q, the bar quality factor (the number of radians of oscillations required for its energy to dump by $1/e$); k, the Boltzmann constant; M, mass of the bar. Thus from Eq. (14) it can be seen that high sensitivity (small thermal noise) requires large bar mass M, large bar quality factor Q and low bar temperature T. The time of integration should be short.

The original Weber bar operated at room temperature, but the most advanced detectors today — NAUTILUS [31] and AURIGA [32] — operate at $T \sim 100$ mK. With that temperature, high Q ($\sim 10^6$) in its fundamental mode and averaging time for GW burst ~ 1 ms, the bars today can approach the goal of detection at $h = 10^{-20}$ or slightly below [8].

Sensor noise is due to the noise of the final amplifier, which reads out the electromechanical transducer translating the motion of the bar ends into an electric signal. Amplifiers introduce noise and this makes small amplitudes harder to measure. The amplitudes of vibration are the largest in the resonance band near f, so amplifier noise limits the detector sensitivity to gravitational wave frequencies near f. But if the noise is small, then the measurement bandwidth about f can be much larger than the resonant bandwidth f/Q. Today, typical measurement bandwidths are 1 Hz, about 1000 times larger than the resonant bandwidths. In the near future, it is hoped to extend these to 10 Hz or even to 100 Hz [8].

Quantum noise. If the ratio Q/T is large enough, $Q/T \sim 10^9$ K^{-1}, the thermal noise gets smaller than the quantum noise and the whole system attains the so-called Standard Quantum Limit (SQL): one can detect excitation energies of the bar resonance of the order of just one quantum of vibration.

The bars currently in use are above the SQL but after upgrades a few of them should approach the SQL [33]. Recently, the sensitivity of bars to cosmic rays has been demonstrated [34], indicating that, as they may get close to the SQL, underground operation would be compulsory.

3.3. Overview of Existing and Future Bar Detectors. Cryogenic resonant bar detectors have been operated for a number of years (since 1990) and recently, the network of detectors works in coincidence, in search of impulsive GW events in the Galaxy. There are five bar detectors in long term operation: ALLEGRO [35] at Baton Rouge in US, AURIGA [32] at Legnaro in Italy, EXPLORER [36] at CERN, NAUTILUS [31] at Frascati in Italy, and NIOBE [37] at Perth in Australia, and since 1997 they have joint in a single international data exchange and coincidence search community, known as IGEC (International Gravitational Event Collaboration) [38].

The five detectors in IGEC have rather similar schemes. They are made mostly of the aluminium alloy Al5056 (NIOBE is made of niobium), resonate at about 1 kHz; have $M \sim 2$ t and $Q \sim 10^6$, working at $T \sim$ $0.1{-}4.2$ K, they show post-detection bandwidths ~ 1 Hz, have burst sensitivities $h \sim 2 \cdot 10^{-19}$ and strain sensitivities at resonance $\widetilde{h}_f(1 \text{ kHz}) \sim (5{-}10) \cdot 10^{-22}$ Hz$^{-1/2}$.

The axes of all bars are aligned within a few degrees of one another, so that the chance of coincidence detection is maximized. The network is sensitive to millisecond bursts of any shape such as those from the final coalescence, merger and ringdown of BH binaries of total mass below some 15 $M_\odot$, the final coalescence of binary neutron stars systems and supernovae. The bars may usefully complement in the kHz frequency range the initial interferometers. The IGEC is well prepared to correlate data with interferometric detectors, as by statute it is open to collaborate with any team producing data usable for coincidental searches for GW signals.

For the future, one can expect that bars will remain fairly narrowband detectors, and that they will have difficulty getting below a sensitivity limit of 10^{-21}. Those limitations motivated groups to explore the intrinsically wideband technique of laser interferometry. However, resonant-mass detectors have a future in construction of large spheres: TIGA (project proposed by the US gravitational-wave group), GRAIL (project underway at NIKHEF, the Netherlands), OMEGA (proposed by the Rome gravitational-wave group, Italy). It was recognized that a sphere is a very natural shape for resonant-mass detector. In a cylindrical bar only the first longitudinal mode of vibration interacts strongly with the GW, and consequently only one wave parameter can be measured: the amplitude of a combination of the polarization states. A free sphere has five degenerate quadrupole modes of vibration that will interact strongly with GW. The fivefold degeneracy of the quadrupole modes enables the determination of the GW amplitudes of two polarization states and the two angles of the source detection [39,40] which could be obtained with five different resonant bars. The problem of attaching mechanical resonators to the detector suggests a truncated icosahedral geometry rather than a sphere. The spheres could reach approximately one order of magnitude better in the sensitivity compared to the resonant bars.

Recently, hollow spheres have been proposed [41] with the strain sensitivity even of the order of 10^{-24} Hz$^{-1/2}$. Another idea which is discussed is a wideband dual sphere detector [42] in which the relative surface displacements between two concentric freely suspended spheres, as they vibrate independently under the GW excitation, are read by nonresonant optomechanical transducer. The spectral sensitivity in the kHz frequency range would be comparable or even better than the second generation interferometers.

4. INTERFEROMETRIC DETECTORS

The resonant bar detectors have sensitivity limited to very narrow bandwidths. In the year 1962 two theorists in the Soviet Union, Gertsenshtein and Pustovoit [43] introduced concept in which an interferometer could be used to detect gravitational waves. However, the first realistic feasibility study had been performed by Weiss [44] in 1972. In the same period, Forward [45, 46] built the first prototype in Malibu. This technique is based on the Michelson interferometer and is particularly suited to the detection of gravitational waves as they have a quadrupole nature. GW propagating perpendicular to the plane of the interferometer will result in one arm of the interferometer being increased in length while the other arm is decreased and vice versa. This results in a small change in the interference pattern of the light observed at the interferometer output. Laser interferometers offer the possibility of very high sensitivities over a wide range of frequency. A typical design specification allows a reasonable probability for detecting sources with a noise level in strain sensitivities smaller than $2 \cdot 10^{-23}$ $\mathrm{Hz}^{-1/2}$.

4.1. Principle of Interferometer Operation. Interferometers use laser light to measure changes in the difference between the lengths of two perpendicular arms. A simple interferometer design is presented in Fig. 3. The light coming from a laser is split into two distinct paths ended by mirrors (test masses), reflected and recombined on the beam-splitter where the interference occurs. In the absence of

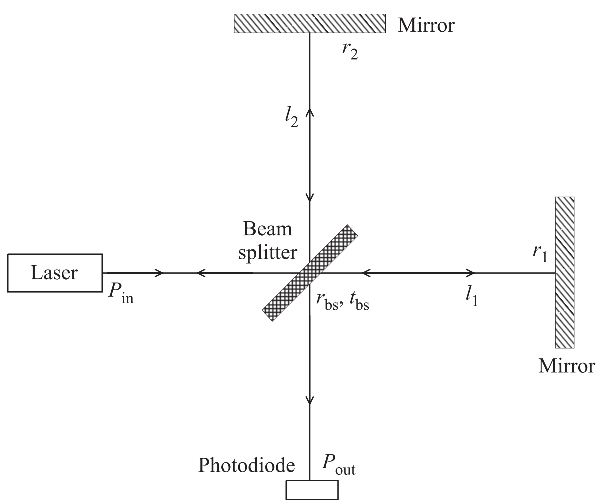

Fig. 3. The Michelson interferometer — schematic diagram

gravitational waves, the field $\psi_{\rm out}$ seen by the photodiode is:

$$\psi_{\rm out} = -\psi_{\rm in} r_{\rm bs} t_{\rm bs} (r_1\, {\rm e}^{2ikl_1} + r_2\, {\rm e}^{2ikl_2}), \tag{15}$$

where $r_{\rm bs}$, $t_{\rm bs}$ are the reflection and transmission coefficients of the beam-splitter; k is the wave number ($k = 2\pi/\lambda$, where λ is the laser wavelength); r_1, r_2 are the reflectivities of the end mirrors. The power $P_{\rm out}$ seen by the photodiode is:

$$P_{\rm out} = |\psi_{\rm out}|^2 = P_{\rm in} r_{\rm bs}^2 t_{\rm bs}^2 (r_1^2 + r_2^2)(1 + C\, \cos(2k\delta l)), \tag{16}$$

where $\delta l = l_1 - l_2$, and the contrast C is defined by:

$$C = \frac{P_{\rm out}^{\rm max} - P_{\rm out}^{\rm min}}{P_{\rm out}^{\rm max} + P_{\rm out}^{\rm min}} = \frac{2r_1 r_2}{r_1^2 + r_2^2}. \tag{17}$$

In a perfect interferometer, the contrast, which quantifies the imperfections of the optical components, is equal to one. Then if $2k\delta l = (2n+1)\pi$, we say that the interferometer is tuned at a dark fringe. The present interferometers work with such adjusting.

In the case of a gravitational wave with a «+» polarization propagating perpendicularly to the interferometer plane with arms along x and y directions, the lengths l_1 and l_2 will be slightly changed:

$$l_1' = l_1 + \frac{1}{2} h_+(t) l_1, \quad l_2' = l_2 - \frac{1}{2} h_+(t) l_2. \tag{18}$$

Considering $|h_+| \ll 1$, $r_{\rm bs}^2 = t_{\rm bs}^2 = 1/2$ (the beam-splitter well balanced) and $r_1 = r_2 \simeq 1$:

$$P_{\rm out} = P_0 + \Delta P_{\rm gw}(t), \tag{19}$$

$$P_0 = \frac{P_{\rm in}}{2}(1 + C\, \cos(2k\delta l)), \tag{20}$$

$$\Delta P_{\rm gw}(t) = \frac{P_{\rm in}}{2} C k h_+(t)(l_1 + l_2)\, \sin(2k\delta l). \tag{21}$$

If $h_+(t)$ is not zero there is a time-varying component $\Delta P_{\rm gw}(t)$ and the passage of the gravitational wave changes the power seen by the photodiode at the output of the interferometer. The power variation is proportional to the amplitude of the wave, to the average length of the arms and to the inverse of the laser wavelength.

If the waves are coming from overhead or underfoot and the axes of the plus polarization coincide with the arms directions, then it is the waves' plus polarization that drives the masses, and $\Delta L(t)/L = h_+(t)$ but in general both polarizations of the wave influence the test masses and the interferometer's output is a linear combination of the two wave fields:

$$\Delta l(t)/l = F_+ h_+(t) + F_\times h_\times(t) \equiv h(t). \tag{22}$$

The coefficients F_+ and $F_\times$ depend in a quadrupolar manner on the direction to the source and the orientation of the detector. They describe the so-called «antenna pattern» [3].

A detector with an arm length of $l = 4$ km responds to a gravitational wave with an amplitude of 10^{-21} with

$$\Delta l_{\text{gw}} \sim hl \sim 4 \cdot 10^{-18} \text{ m}. \tag{23}$$

Light takes only about 10^{-5} s to go up and down one arm, much less than the typical period of gravitational waves of interest. Therefore, it is beneficial to arrange for the light to remain in an arm longer, e.g., for 100 round-trips. This increases an effective path length by 100 and hence the shift in the position of a given phase of the light beam will be of the order of 10^{-16} m. Most interferometers keep the light in the arms for this time by setting up optical cavities in the arms with low-transmissivity mirrors; these are called Fabry–Perot cavities. Interferometer test masses (mirrors) at present are made of transparent fused silica, though other materials might be used in the future. Most of the recombined light goes back toward the laser where it can be returned to the interferometer by a «light-recycling mirror».

4.2. Main Sources of Noise in Interferometric Detectors. Fundamentally it should be possible to build systems using laser interferometry to monitor strains in space which are only limited by the Heisenberg uncertainty principle; however there are other practical issues which must be taken into account. There are several sources of noise against which a measurement must compete. The main sources of noise are seismic noise dominant at low frequencies, thermal noise at midfrequencies and shot noise at high frequencies. The three main noise sources are presented in Fig 4.

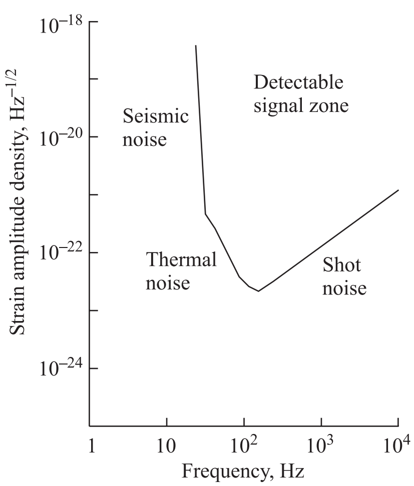

Fig. 4. Various contributions to the exemplary interferometer noise floor. Plotted horizontally is GW frequency, plotted vertically is $\widetilde{h}(f)$, the square root of the spectral density of the detector output $h(t) = \Delta l/l$ in absence of GW

Ground vibrations are connected to external mechanical vibration which must be screened out. Interferometers bounce light back and forth between mirrors, and so each reflection introduces further vibrational noise. Seismic noise follows a spectrum in all three dimensions close to $10^{-7}/f^2$ mHz$^{-1/2}$ [9] and thus if the motion of each mirror has to be less than $3 \cdot 10^{-20}$ mHz$^{-1/2}$ at a frequency of 30 Hz, then the level of seismic noise isolation required at that level in the horizontal direction is greater than 10^9 [9]. At frequencies above 10 Hz the protection of the mirrors from the seismic vibrations is done by the suspension/isolation systems based on pendula [47]. Each pendulum has a normal-mode frequency f_0 around few Hz and is a good mechanical filter for frequencies above its natural frequency. When seismic noise with frequency f tries to drive this harmonic oscillator far above its resonant frequency the amplitude of its response is attenuated relative to the driving motion by a factor $(f_0/f)^2$. Thus a stack of four or five pendula is enough to provide the required isolation. A multiple pendulum system is hung from a plate mounted on passive, rubber isolation mounts or on an active (electromechanical) antivibration system. These systems can be very sophisticated as in VIRGO detector [49].

Thermal noise is connected to the vibrations of the mirrors and to the last stage of their suspensions. Unlike bars, interferometers operate only at frequencies far from the resonant frequency. The operating range of the detector lies between the resonances of the mirrors (several kHz) and their pendulum suspensions (few Hz). In order to keep the off-resonance thermal noise as low as possible, the mechanical loss factors of the material of the mirrors and of the fibres or wires used to suspend them need to be kept low [28]. This is achieved if the quality factors Q of the mirrors and pendulum are as high as possible. By ensuring that both kinds of oscillations have very high Q, one can confine most of the vibration energy to a small bandwidth around the resonant frequency, so that at the measurement frequencies the vibration amplitudes are small. This allows interferometers to operate at the room temperature, but mechanical Q of 10^7 or higher are required, and this is technically demanding. The solution is to use fused silica masses hung by fused silica fibres. Also the use of other materials such as sapphire may be possible due to its excellent mechanical quality factor ($Q > 10^8$) and high thermal conductivity.

Shot noise corresponds to the fact that the photons that are used for interferometry are quantized, and so they arrive at random and make random fluctuations in the light intensity that can look like a GW signal. The more photons one uses, the smoother will be the interference signal. As a random process, the error improves with the square-root of the number of photons. In order that $\Delta l_{\rm shot}$ should be low one needs large light power, far beyond the output of any continuous laser. Light-recycling techniques overcome this problem, by using light efficiently. An interferometer has actually two places where light leaves. One is where the interference is measured. The other goes back toward the input laser.

The mirrors are of good quality, only one part in 10^3 or less of the light is lost during a 1 ms storage time. By placing a power-recycling mirror in front of the laser, one can reflect this wasted light back in, allowing power to build up in the arms until the laser merely resupplies the mirror losses. This can dramatically reduce the power requirement for the laser. The first interferometers will work with laser powers of 5–10 W.

4.3. Present and Upcoming Interferometers. Two largest interferometers are being commissioned or have started taking data. The American LIGO [48] project consists of two detector systems, 2 and 4 km arm interferometers in the same vacuum envelope in Hanford, Washington State, and one, 4 km arm, in Livingston, Louisiana. The French/Italian VIRGO [49] detector of 3 km arm length at Cascina near Pisa is the second working interferometer. It should be noted that this detector uses five-stage multipendulum systems for the suspension of its test masses and is specially designed to be able to operate down to approximately 10 Hz. At the same time two other, smaller interferometers were built — TAMA300 in Japan [50] and GEO600 in Germany [51].

All the systems mentioned above are designed to use resonant cavities in the arms of the detectors, standard wire sling techniques for suspending the test masses, and are to be illuminated by infrared light from a Nd:YAG laser. The German/British project, GEO600, for a 600 m detector near Hannover is different. It makes use of a four pass delay line system with advanced optical signal enhancement techniques, utilizes very low loss fused silica suspensions for the test masses, and should have a sensitivity at frequencies above a few hundred Hz comparable to the first phases of VIRGO and LIGO. Illumination is again by infrared light, provided by a 10 W single frequency YAG laser. GEO600 and TAMA300 detectors will be important also for developing the techniques needed by second generation experiments.

It should be noted that in order to improve the confidence level of any detection and to obtain the location of the source, a number of interferometers are required worldwide. Thus an international network of gravitational wave interferometer detectors is now under construction. Interferometers are plagued by non-Gaussian noise, e.g., due to sudden strain releases in the wires that suspend the masses. This noise prevents a single interferometer from detecting with confidence short-duration gravitational-wave bursts (though it might be possible for a single interferometer to search for the periodic waves from known pulsars). The non-Gaussian noise can be removed by cross correlating two, or preferably three or more, interferometers that are networked together at widely separated sites.

LIGO alone, with its two sites which have parallel arms, will be able to detect an incoming gravitational wave, measure one of its two waveforms, and (from the time delay between the two sites) locate its source. LIGO and VIRGO together, operating as a coordinated international network, will be able to locate the source (via time delays plus the interferometers' patterns) and to monitor both waveforms $h_+(t)$ and $h_\times(t)$.

There are already designs prepared for the first upgrades of the existing detectors in 2006. Their sensitivity is likely to be improved by an order of magnitude with a better low-frequency performance. In particular a significant reduction of thermal noise will be obtained using fused silica fibres in the mirrors suspensions, increasing laser power up to 100 W (decrease of the shot noise), and using sapphire mirrors.

While the first generation detectors could detect GW, the second generation will have a much greater assurance of success. Beyond that, new technologies that may be needed for the third generation detectors are under study. This may involve cooled mirrors, ultra-massive mirrors, etc. [8].

To cover the low-frequency region, where many interesting signals are expected, but which on the Earth is unaccessible because of seismic noise, it is planned to use GW effect on the Doppler shift of radar signals transported back from spacecraft such as Ulysses [8]. However, the most promising way is to send an interferometer into space. This is the NASA and ESA project LISA [52]. It would open up the frequency window between 0.1 mHz and 0.1 Hz. LISA would consists of an array of 3 drag free spacecraft at the vertices of an equilateral triangle of length of side $5 \cdot 10^6$ km, and this cluster is placed in an Earth-like orbit at a distance of 1 AU from the Sun, and 20 degrees behind the Earth (Fig. 5). Test masses inside the spacecraft (two in each spacecraft) form the end points of three separate but not independent interferometers. Each single two-arm Michelson-type interferometer is formed from a vertex and the masses in two remote spacecrafts. The three-interferometer configuration provides redundancy against component failure, gives better detection probability, and allows

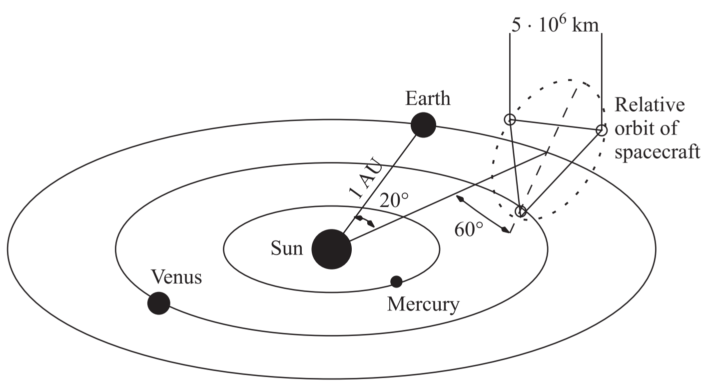

Fig. 5. The scheme of LISA's orbital configuration (based on [9])

the determination of polarization of the incoming radiation. There are no simple mirrors in the spacecraft, the reflected light would be too weak. Instead, LISA will have optical transponders: light from the one spacecraft's on-board laser will be received at another, which will then send back light from its own laser locked exactly to the phase of the incoming signal. If approved by Congress, LISA will begin development in 2004, with a planned launch in 2011 and duration of five years.

The main noise sources for LISA are fluctuations in solar radiation pressure and pressure from the solar wind. To minimize these, LISA incorporates draft-free technology. Interferometry is referenced to an internal test mass that falls freely, not attached to the spacecraft. The job of spacecraft is to shield this mass from external disturbances.

An interesting feature of LISA is that, as it rotates in its orbit, its sensitivity to different directions changes. Thus LISA can test the isotropy of the stochastic background.

CONCLUSIONS

The next few years will witness the opening of the gravitational window for observing the Universe using a worldwide network of detectors. The network of five bar detectors have been working since 1997. Several large scale interferometric instruments are being commissioned or have started their science runs.

For the moment there is no evidence for the gravitational wave detection but it is important to have in mind that the present detectors are the first generation of large scale instruments, and in that sense they represent pioneering effort. At the level of sensitivity that is reached, there is no guaranteed source of detection however, the most luminous sources of radiation can be seen. The present GW detectors open the way to the second and third generation interferometers and resonant spheres with the much better sensitivities. It is the second and third phase of operation that will be most interesting from the astrophysical point of view.

So far only upper limit results were delivered by the present detectors. The LIGO first scientific run S1 (September 2002) set the best upper limits on the GW from some of the prime source categories. It should be pointed out that during S1, LIGO was not operating at its eventual design sensitivity and no source detection was expected. The GEO600 interferometer also operated during S1. The second science run (S2) in coincidence with TAMA300 interferometer, where 10 times improvement in sensitivity was achieved, took place in February–April 2003 and the results should be published soon.

The present upper limits for GW sources are as follows:

• The upper limit on binary neutron star coalescence rate from the first LIGO science run: R 90% (Milky Way) $< 170/\mathrm{y}$ [53]. The best previously published observational limit was obtained using data from the 40 m LIGO prototype at Caltech [54], R 90% (Milky Way) $< 4400/\mathrm{y}$. The expected theoretical galactic rate is 10^{-6}–$5 \cdot 10^{-4}/\mathrm{y}$ [55].

• The upper limit on the strength of periodic gravitational waves from PSR J1939 + 2134 (with 95% CL) from LIGO S1 [56] is $h < 1.4 \cdot 10^{-22}$ with ellipticity $< 2.7 \cdot 10^{-4}$. Previous results are $h < 3 \cdot 10^{-20}$ for PSR 1939 + 2134 [57] using an interferometer, and $h < 3 \cdot 10^{-24}$ for an untargeted search toward the centre of the Galaxy at a frequency constrained by the resonant bar Explorer [58].

• Stochastic upper limit from LIGO S1 (90% CL) [59] is: $h^2_{100}\Omega_{\rm gw}(40{-}314\ \mathrm{Hz}) < 23$. Previous result is $h^2_{100}\Omega_{\rm gw}(900\ \mathrm{Hz}) < 60$ from Nautilus and Explorer correlated data [60].

The monitoring of GW is likely to provide us with a view of astrophysical phenomena and objects that will be extremely difficult or impossible to observe by conventional electromagnetic means. Aside from demonstrating the existence of black holes and revealing a wealth of data on supernovae and neutron stars, gravitational wave observations could also provide an independent means of estimating cosmological distances and help further our understanding of how the universe came to be the way it looks today. Moreover, it might be able to detect possible gravitational waves from unidentified phenomena and unknown astronomical objects, which may introduce new physics never considered before. As John Haldane said: *«My own suspicion is that the Universe is no stranger than we suppose, but stranger than we can suppose».*

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