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The search for Gravitational Waves: Status and perspectives

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Summary. — In this paper we give an overview of the present status and future perspectives of the search for gravitational waves. Gravitational Waves (GW) are predicted by the General Theory of the Relativity and, due to their very weak interaction with matter, can be an invaluable tool to look to the universe up to its very first moments. On the other hand, these same characteristics make their detection very difficult to achieve, and, at present, we have only indirect proof of their existence. In the last years the techniques adopted to directly detect GWs converged to laser interferometers. A world network of kilometer-scale laser interferometers is presently taking data but their sensitivity does not seem enough to give results in reasonable times. To this purpose all the presently working interferometers have plans to enhancement in the next few years and second-generation detectors, both ground and space based, are already in the design phase.

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PACS `95.55.Ym` – Gravitational radiation detectors; mass spectrometers; and other instrumentation and techniques.

1. – Introduction to Gravitational Waves

The General Relativity equations for the gravitational field, if one considers a linearized perturbed metric $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $\eta_{\mu\nu} = \mathrm{diag}(-1,1,1,1)$ and $|h_{\mu\nu}| \ll 1$, give rise to ondulatory solutions: $\Box h_{\mu\nu} = 0 \Rightarrow h_{\mu\nu} = A_{\mu\nu} e^{k^\alpha x_\alpha}$. Considering the symmetry, the transversality and a gauge condition one obtains that in the so-called *Traceless Tranverse gauge*, only two possible degrees of freedom are available. The two remaining oscillatory modes are generally referred as h_+ and $h_\times$ due to the way they act on a ring of "free falling" masses orthogonal to the direction of propagation. The mode h_+ stretches the ring alternatively along two orthogonal axes, while the $h_\times$ along two axes rotated by 45° with respect to the + polarization.

To give an idea of the smallness of the coupling constant of GW with respect to other interactions, take into account that weak interactions couple with $g_f = 1.17 \cdot 10^{-5}\,\mathrm{GeV}^{-2}$, in the same units, gravitation couples through $G = 6.707 \cdot 10^{-39}\,\mathrm{GeV}^{-2}$. This means that although the events producing GW are very energetic, the waves almost do not interact, and thus propagate unperturbed. This makes GW an ideal medium for information transport from inside very opaque energetic events (*e.g.*, SuperNova explosions) and from the very beginning of the Universe.

The generation of gravitational waves depends on the time derivatives of the quadrupole momentum of the source $Q_{\mu\nu}$, thus on the asymmetry of the source. In fact the emitted power can be written as: $P = G/5c^5\langle\dddot{Q}_{\mu\nu}\dddot{Q}^{\mu\nu}\rangle \approx \epsilon c^5/G(R_s/R)^2(v/c)^6$, ϵ being an asymmetry parameter and R_s/R a compactness parameter varying from 1 for black holes to 0.3 for neutron stars to 10^{-4} for white dwarves. From the previous equation it is clear that to have an effective production of GWs, the source must be compact, fast and asymmetric. The amplitude of the GWs received at a distance r from the source is proportional to $\ddot{Q}_{\mu\nu}$ and inversely proportional to r, so that it can be estimated that for the coalescence of two orbiting neutron stars at the distance of 10 Mpc (the Virgo cluster), an amplitude of 10^{-21} can be expected.

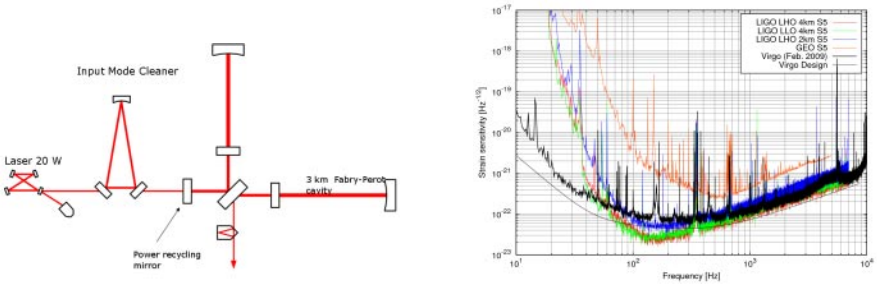
2. – Past and present experiments to detect GWs

The first proof of the existence of GWs is the decrease of the period of the binary pulsar PSR1913-16, that is exactly as predicted by the emission of GWs from the system. This observation gave the Nobel prize to R. Hulse and J. Taylor in 1993. The direct observation of GWs was initially seeked in 1966 by J. Weber, who built an antenna consisting of a 2 m long 1 m diameter aluminium cilynder instrumented to detect length changes up to 10^{-16} m. Despite the claim for evidence of GW signals [1], neither Weber's nor any other successive "bar" antenna was proven to have detected GWs.

Interferometric wave detection was originally proposed by R. Weiss [2]. In his paper he described a modified Michelson interferometer, using freely suspended test masses at the ends of the arms. This is the technique used by all the present-day GW observatories around the World. The idea is that,being the GW radiation quadrupolar, when it impinges on a Michelson interferometer with the proper polarization, one arm is stretched, while the other is reduced. If L is the arm length, it can be shown that the difference in length of the two arms due to a GW of amplitude h is given by $\Delta L \approx \frac{1}{2}hL$. Thus, to measure $h \approx 10^{-21}$, with a kilometre-scale interferometer, a $\Delta L \approx 10^{-18}$ must be controlled.

A world-wide network of kilometre- scale interfeometers is nowadays taking data. It is composed by the 3 km armlength VIRGO interferometer [3] in Cascina near Pisa, Italy, the two 4 km LIGO [4], in Hanford (WA, USA) and in Livingston (LA, USA), the 600 m GEO600 in Germany. A coincident data taking has already been run in 2007, and the LIGO Scientific Community (LSC) and VIRGO signed a MoU to exchange data in such a way that the four interfeometers can be considered as an unique observatory. To these interferometers the 300 m Japanese TAMA300 interferometer can be also added.

The optical scheme of the VIRGO interferometer is shown in fig. 1(a). Final mirrors as well as the beam splitter and other optics are mounted on active pendular suspensions in order to cut away as much as seismic noise is possible. Each arm consists of a Fabry-Perot cavity where light is reflected back and forth several times before escaping thus enhancing the effective arm length (by a factor called *finesse* depending on mirrors' reflectivity). A recycling mirror re-inject in the interferometer the power reflected back to the input. A similar design with higher finesse cavities and less performant suspensions is adopted by LIGO interferometers.



(a) (b)

Fig. 1. – (a) Optical design of the VIRGO interferometer: the mode cleaner ensures that a single mode beam is injected in the interferometer. (b) Comparison of the sensitivities of the LIGO and VIRGO interferometers.

To attain high sensitivity, the interferometers are controlled both at the local mirror level and globally by means of active digital controls running with a control loop frequency of the order of 10 kHz [5]. A comparison of the VIRGO and LIGO sensitivities is shown in fig. 1(b). LIGO is better performing at medium frequencies ($\sim 100\,\text{Hz}$) due to higher finesse, while at low frequency ($< 40\,\text{Hz}$) VIRGO is more sensitive due to its suspensions. At high frequency the sensitivity is dominated by the laser Shott noise, depending on laser power.

LIGO has reached its design goal and VIRGO is approaching. In the next year a new network data taking will be run, involving the four interfeometers. The advantages of a network observation are multiple: to reject single instrument false alarms, to locate sources through triangulation, to cover a larger portion of the sky for a longer time, to deconvolve the instrument response from the signals and get signal parameters. To be better prepared to this coincident data taking, both VIRGO and LIGO are making some enhancements. VIRGO has installed a system to compensate the deformation of mirrors due to the heating induced by the laser beam and is installing a new last stage of suspension and has been renamed VIRGO+. LIGO is installing an active suspension system and a few other upgrades (renamed Enhanced LIGO).

3. – Second-generation GW detectors

With the present interferometers' sensitivity a low event rate can be expected (10^{-1}–10^{-2} evt/year), so, to increase the chance of the first detection and to open the way to GW astronomy we want to enhance the sensitivity by a factor 10 (and the detection rate by a factor 1000). To this purpose, second-generation detectors are under way. Advanced LIGO has already been funded by NSF and Advanced VIRGO (AdV) is undergoing the project review phase by the funding agencies.

The passage from VIRGO+ to AdV is a major step, consisting in the substitution of the mirrors with heavier and more reflective ones, installation of *non-degenerate* recycling cavities avoiding other modes to resonate in the cavity, installation of a high-power (200 W) pre-stabilized laser, and changing the last stage of suspension. Similarly, Advanced LIGO is planned to install a new system of active multipendular suspensions, change the laser and the end mirrors and add an output mode cleaner. AdV should enter in the commisioning phase at the end of 2013 to start running mid 2014, Advanced LIGO starts installation in 2011 and will be ready to run together with AdV in 2014.

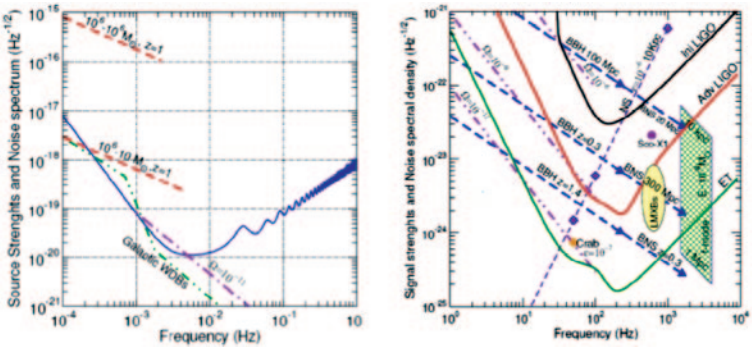


Fig. 2. – Right panel: noise amplitude spectrum in three generations of ground-based interferometers. Only initial and advanced LIGO and third-generation detector sensitivities are shown. Also shown are the expected amplitude spectra of various astrophysical sources. Left panel: same as the right for the LISA detector.

The most advanced plans along these lines are with the Japanese Large-scale Cryogenic Gravitational-wave Telescope (LCGT) and the Australian International Gravitational Observatory (AIGO). Possibilities for a detector in India (INDIGO) are also being studied.

4. – Third-generation and space detectors

To go further in sensitivity and to lower frequencies a new generation of interferometers is already under study (see fig. 2). The next multikilometre interferometric detector—Einstein Telescope—(ET) is thought to be installed underground to fight the Newtonian noise, and cryogenic to beat thermal noise. A large part of the European GW community is involved, but it is still not clear where this detector will be built. Construction of ET could begin as early as 2017, with commissioning in 2022.

In a more advanced stage of design is the ESA-NASA Laser Interferometric Space Antenna (LISA) [6]. It is a constellation of 3 satellites orbiting as an equilateral triangle with a $5 \cdot 10^6$ km side on a heliocentric orbit following the Earth's orbit by 20°. Each spacecraft contains two lasers and two free-falling proof masses and works as an optical transponder phase-locked with the light (a few pW) coming from the remote satellites. The satellites will follow the proof masses by means of micro-thrusters. LISA has a pathfinder [7] mission scheduled to be launched in 2011 to test its main technology with a single spacecraft. On the basis of the pathfinder results, LISA will be launched in 2018-2020.

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