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A.-C. Clapson, N. Leroy. Gravitational Waves: opening a window on compact objects dynamics. XXXXth Rencontres de Moriond - Very high energy phenomema in the Universe, Mar 2005, La Thuile, Italy. in2p3-00203083

HAL Id: in2p3-00203083
https://hal.in2p3.fr/in2p3-00203083

Submitted on 8 Jan 2008

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The status of VIRGO, a giant laser interferometer dedicated to gravitational wave detection, has greatly evolved in the last months. The final optical configuration is now in use, with sensitivity comparable to what was available to LIGO during its first science run. Once VIRGO is fully operational, the improved sky coverage will allow meaningful network analysis, providing source location indications. We focus on plausible astrophysical sources and the information that could be extracted from gravitational wave signal.Compact objects, from Supernovae to black hole binaries, are natural candidate sources. Observation of gravitational waves would give exclusive insights on source details, from constraints on the equation of state to source dynamics. Richer analysis could be expected in case of multi-messenger observations. These have been considered for supernovae, but should be investigated further, including for other phenomena.

1 Introduction

Gravitational waves (GW) are expected from General Relativity equations and are created by a space-time deformation from a quadrupolar acceleration of matter. There has been no direct detection yet, and their discovery should lead to a novel area in observational astrophysics. The main obstacle comes from the weak coupling of GW with matter. One of the most promising techniques is interferometry, as described in part 2.

A GW wave can be represented as the sum of two orthogonal polarizations (h_+, $h_\times$), which depend on source geometry and dynamics, and propagate with velocity c. The GW luminosity for astrophysical sources can be described by :

$$P \approx \frac{c^5}{G}\alpha^2 \left(\frac{R_s}{R}\right)^2 \left(\frac{v}{c}\right)^6 \tag{1}$$

where R is the source radius, R_S the Scharwzschild radius, v a typical velocity of the object and α a parameter describing the asymmetry of the mass distribution of the system. Relevant astro-

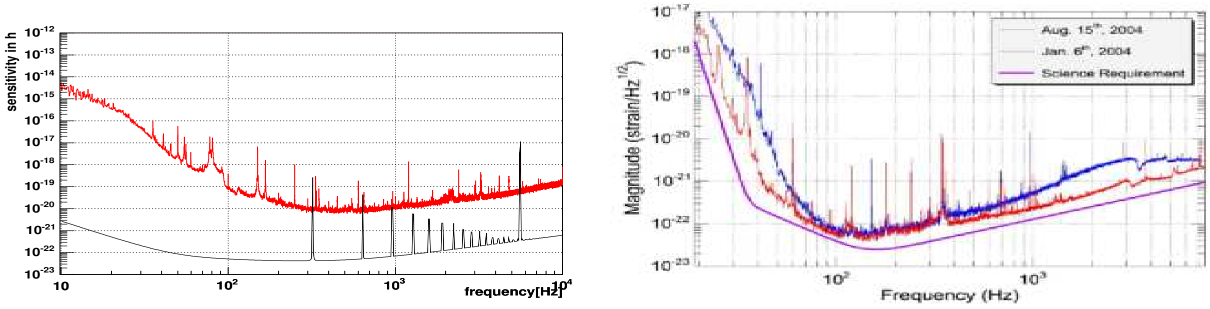

Figure 1: *(Left)* Virgo sensitivity in 2004 (upper curve) compared to the target (lower). *(Right)* LIGO sensitivity in 2004 (two upper curves) compared to target.

physical sources are objects sufficiently compact ($R \to R_S$) relativistic ($v \to c$) and asymmetric to produce waves energetic enough to be detected with present technologies.

2 Detectors and signal analysis

The most sensitive detector designs rely on a direct application of General Relativity on a system free-falling test masses. A propagating GW would modify the observable distance between the masses, as measured by the round trip of a light beam.

This thought experiment was transposed in giant ground laser interferometers, LIGO [2] and Virgo [3] being the largest. There, suspended mirrors replace the free-falling masses, and instead of a single distance, it is the length variation of the arms of a Michelson setup that gives the amplitude of the traveling GW.

The GW amplitude in the interferometer is directly obtained as the ratio between length variation (ΔL) and the light path length (L). The coupling between GW and detector depends only on source location (α and δ), source polarization (ψ) and relative orientation (l, latitude, and L, longitude) of the detector, through the beam pattern coefficients F_+ and $F_\times$:

$$h_{ITF}(t) \approx \frac{\Delta L}{L} = F_+(\alpha,\delta,\psi,l,L,t)h_+(t,source) + F_\times(\alpha,\delta,\psi,l,L,t)h_\times(t,source) \qquad (2)$$

The dependance on source location is weak, thus making interferometers non directional observatories.

As with any experiment, the sought effect is not completely isolated from noise. Three main noise sources have been identified, dominant over different part of the spectrum: seismic noise at low frequency, generated by human and seismic activity, thermal noise, between a few Hz and a few hundreds Hz, the thermally excited motion of the suspension wires and the surfaces of the mirrors, photon shot noise, up from 200Hz. Started in 1989, these projects are arriving at their design sensitivities, though not simultaneously.

This difficulty, added to the limited a priori information available on GW waveforms, greatly complicates analysis. However the detection of a known signal is widely used as a reference for method comparisons [4] and achievable limits of detection performances. Another practical limitation comes from the complex nature of the instrumental noise. Variations on all time-scales have been observed, degrading statistical separation between significant and spurious detection. The understanding of noise behaviour constitutes a critical step for confident detection.

Nowadays five instruments exist, all in the Northern hemisphere, with different sensitivities. Full sky coverage, direction reconstruction [5] and high detection significance will not be possible until a full network (of at least 3 instruments) is operating.

3 Astrophysical sources

A variety of astrophysical processes meet the criteria summed up in (1) and are good GW sources candidates. We briefly consider the most efficient source types considered so far. Arguments for complementary GW emitting processes, including strange star quakes[6], disk dynamics and matter jets [7], have flourished recently but all predicting lower amplitudes than the models presented below.

3.1 Binary systems

A system composed of two compact objects (neutron stars and/or black holes) in close orbits constitutes a case study for the existence of GW: due to energy dissipation through GW emission, the general relativity predicts the coalescence of the objects and their merger into a single one. Predictions for this energy dissipation have been verified on the binary pulsar PSR 1913+16. Coalescence GW signals are the most finely modelled waveforms, see[8] for details. The amplitude is approximated by [9] :

$$h = 4.1\,10^{-21}\left(\frac{\mu}{M_\odot}\right)^{1/2}\left(\frac{M}{M_\odot}\right)^{1/3}\left(\frac{10\,Mpc}{d}\right)\left(\frac{100\,Hz}{f}\right)^{1/6} \qquad (3)$$

with $\mu = \frac{M_1 M_2}{M_1+M_2}$ the reduced mass, M the total system mass, d the distance to the source and f the wave frequency. Taking into account the performances of analysis methods, it is possible to estimate [10] the detection distance for current instruments using $\mathcal{M} = \mu^{3/5}M^{2/5}$:

$$d \approx 20Mpc\left(\frac{\mathcal{M}}{1.22M_\odot}\right)^{5/6} \qquad (4)$$

For binaries including a neutron star, the coalescence phase might also be accessible via the pulsar signal, for favorable configurations. The merging phase, however, is a commonly used model for short gamma-ray bursts [7].

3.2 Core collapse

Supernovae (type II) are prototypes for this category of sources. With the merger phase of a binary system, these are supposedly the most efficient predicted GW emitters. Waveforms for such short ($\tau < 1s$) signals cannot be precisely predicted and they have proved very sensitive to model details in numerical relativity simulations, see [12] and references therein.
An order of magnitude estimation of the amplitude of the wave for a core collapse gives [9]:

$$h = 2.7\,10^{-24}\left(\frac{\Delta E_{GW}}{10^{-8}M_\odot c^2}\right)^{-1/2}\left(\frac{1\,kHz}{f}\right)^{-1/2}\left(\frac{10\,kpc}{d}\right) \qquad (5)$$

Supernovae are known luminous sources of both photons and neutrinos. These messengers do not inform us on the same part of the object dynamics. Adding gravitational waves again completes the picture on the physics involved: core dynamics will transcribe in GW, while the initial expansion of the envelop is best marked by neutrinos, and the subsequent, already well documented, evolution is told by electromagnetic radiations [13].

3.3 Periodic sources

Neutron star with a slight ellipticity α qualify as GW emitters, with a frequency radiation at twice the rotation frequency, and an amplitude of the order[11]:

$$h = 6\,10^{-26}\left(\frac{f}{500\,Hz}\right)^{2}\left(\frac{10\,kpc}{d}\right)\left(\frac{\alpha}{10^{-6}}\right) \qquad (6)$$

source type	NS - NS	NS - BH	BH - BH	Core collapse	QPS (a)
galac. evt rate (y^{-1})	$\sim 2\,10^{-5}$	$< 10^{-5}$	$< 10^{-5}$	10^{-2}	-
detect. evt rate (y^{-1})(b)	$5\,10^{-3}$ to 0.3	$< 10^{-1}$	$< 10^{-1}$	10^{-2}	$>$ 1 year (c)
max. detect. dist. (d)	20 Mpc	42 Mpc	100 Mpc	10 kpc	?
frequency (Hz)	10^3 (LSO)(e)	10^2 (LSO)	10	$200 - 10^3$	$\leq$ 200 Hz (f)

Table 1: Parameter estimates for potential sources.(a) Quasi periodic sources.(b) At present sensibility.(c) Required integration time.(d) Using 1.4 $M_\odot$ NS and 10 $M_\odot BH$.(e) Last Stable Orbit.(f) Monochromatic sources.

While pulsar emissions exist for some neutrons only, and are strongly beamed, it is expected that GW emission will be more accessible. Both messengers provide information on dynamics and possibly equation of state.

Periodic GW emission could also come from quasi normal mode oscillation of neutron stars and black holes[15]. Notably, gravitational wave emission is the only desexcitation channel for black holes.

4 Conclusions

Several instruments are now made available for a direct detection of gravitational waves. In the coming years upgrades on kilo-metric interferometers should expand by a factor 10 their observable horizon, to scan a volume of Universe 1000 times larger than today. This and further sensitivity improvements would give access to the densest part of astrophysical systems, which is opaque to electromagnetic radiation.

Additional sources will be made accessible with the launch of the space mission LISA[16], targeted on very low frequency signals (10^{-4} Hz to 1 Hz).

As sketched here, understanding of high energy phenomena has much to gain from multi-messenger astronomy, combining gravitational waves, neutrinos and full-spectrum electromagnetic radiation.

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