Astrophysical sources of gravitational waves

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The interferometric detectors of gravitational waves (GW) (such as VIRGO and LIGO) will search for events in a frequency band within a few Hz and a few kHz, where several sources are expected to emit. In this talk we outline briefly the current theoretical knowledge on the emission of GW in events such as the coalescence of compact binaries, the gravitational collapse, the spinning of a neutron stars. Expected amplitudes are compared with the target sensitivity of the VIRGO/LIGO interferometric detectors.

1. INTRODUCTION

In a few years a network of interferometric gravitational waves detectors (VIRGO [1], LIGO [2], GEO600 [3], TAMA [4]) will be taking data, with the aim of observing events in a wide band of frequency (from a few Hz to a few kHz). Sources of different nature are expected to emit GW in that band. In this paper we examine four kinds of expected GW sources: the coalescing compact binaries, the supernovae, the spinning neutron stars, the stochastic background of cosmological origin. The signals emitted by these sources differ in many features: waveform (quasi-periodic, burst, periodic, stochastic), amplitude, bandwidth. Therefore completely different detection strategies are needed.

2. COALESCING BINARIES

The accurate measurement of the orbital period decay of the binary pulsar 1913+16 has provided the first indirect evidence of the existence of GW [5,6]. Due to the energy and angular momentum loss via GW emission that binary system will coalesce in about 10^8 years, emitting a *chirp* of GW: the signal sweeps up in frequency and amplitude up to the coalescence of the two stars. The coalescence of two compact binaries is the event more likely to be detected by first generation interferometers. The system is *simple* and the expected waveform can be calculated with

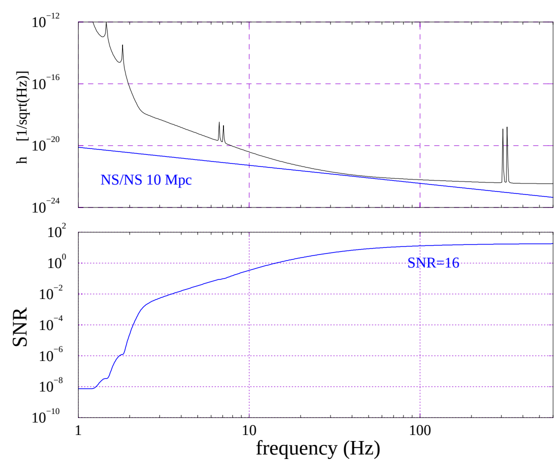

Figure 1. In the top plot the evolution of the spectral amplitude $\tilde{h}$ of the chirp from a NS/NS coalescence at 10 Mpc distance is shown (for optimal orientation with respect to the detector) and is compared with the detector sensitivity. In the bottom plot the SNR obtained by optimal filtering is shown: although the signal is always below the detector noise level one gets SNR> 1.

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great accuracy (when the two stars are not too close point mass approximation is good enough, while post-newtonian corrections have to be considered to compute the waveform in the very last phase before coalescence [7]). In the newtonian approximation the amplitude of the GW emitted in the "plus" polarization, for optimal orientation of the source, is written:

$$h_+(r,\theta,t) = 1.2\cdot 10^{-20}\left[\frac{\mathcal{M}}{M_\odot}\right]^{5/3}\left[\frac{\mathrm{Mpc}}{R}\right]\times \times\left[\frac{f(t)}{1\mathrm{kHz}}\right]^{2/3}\cos(2\pi f(t)\,t) \quad (1)$$

where the chirp mass $\mathcal{M}$ is a function of the two stars masses ($\mathcal{M}=(m_1m_2)^{3/5}/(m_1+m_2)^{1/5}$) and the frequency sweeps up according to an equation of the form:

$$f(t) = f_0(1-t/\tau)^{-3/8} \quad . \quad (2)$$

Having the templates, optimal filtering of the interferometer output can be done, increasing the signal-to-noise ratio (SNR). After producing a set of templates (depending on the stars masses) the signal can be extracted form the detector noisy output using matched filtering.

The SNR is then given by:

$$\mathrm{SNR}^2 = 4\int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)}\mathrm{d}f \quad (3)$$

where $S_n(f)$ is the detector noise one-sided power spectral density and $\tilde{h}(f)$ is the signal spectral amplitude. The SNR builds up over frequency: wideband detectors are required for the detection of such events. In figure 1 the spectral amplitude of the coalescence of two neutron stars at 10 Mpc is compared with the noise spectrum of the VIRGO detector and the SNR is calculated: even if the signal amplitude is always below the noise, one gets SNR>1.

A rich physics can be done by studying the waveforms emitted by such sources:

- they are *standard candles*: both the source distance and redshift can be found out from the waveform [8];
- they are a natural lab to test gravity theories in the strong field regime [9];
- in the very last phase before the coalescence the waveform is sensitive to the matter equation of state [10].

3. SUPERNOVAE

A burst of GW (lasting a few milliseconds) is emitted during a star collapse, if the collapse is non-spherical. The collapse dynamics is poorly known (the hydrodynamics simulation codes are affected by large uncertainties). Therefore, the emitted waveform is hardly predictable and it is not possible, at present, to produce templates and try optimal filtering (some examples of waveforms can be found in [11]) . A coincidence detection (also with neutrino detectors for galactic supernovae) is then necessary in order to identify the event. The amplitude of the emitted GW is strongly dependent on the collapse dynamics. If the collapse is axisymmetric an amplitude of the order ([12] and references therein)

$$h \sim 10^{-21}\cdot\frac{30\,\mathrm{kpc}}{R} \quad (4)$$

is expected. Such event would be detected by VIRGO/LIGO only within the Galaxy, where the rate of supernovae is poor (about 1 event in 50 years). If the collapse is non-axisymmetric a far larger amplitude is expected, which can be written in the form:

$$h \sim 10^{-21}\cdot\frac{10\,\mathrm{Mpc}}{R} \quad . \quad (5)$$

Such events are detectable as far as the VIRGO cluster, where tens of events/year are expected (the fraction of non-axisymmetric events is unknown).

4. ROTATING NEUTRON STARS

Non-axisymmetric neutron stars, spinning at frequency f_{rot} emit periodic GW at frequency $f_{\mathrm{GW}} = 2f_{\mathrm{rot}}$ (actually they emit also at f_{rot}, see [13]). The expected amplitudes are weak, but the signal can be integrated for months in order to increase the SNR. Actually, to do this one has to correct the Doppler effect associated to the Earth motion. This can be easily done if the position of the source is known (which is true for the known

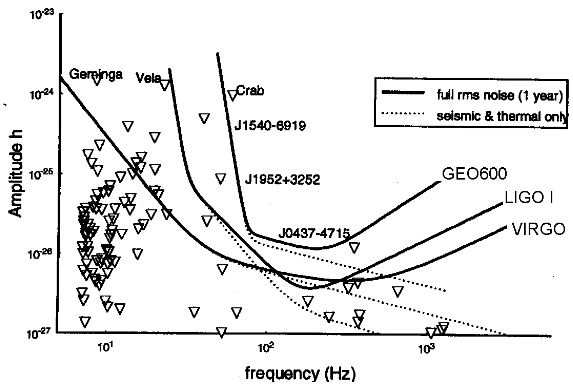

Figure 2. GW amplitude and frequency (upper limits) for a sample of galactic pulsar *vs* the target sensitivity of the first generation interferometers.

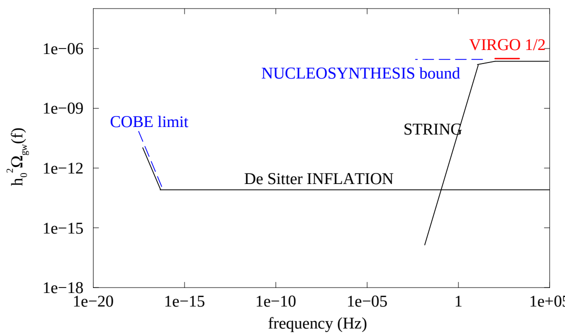

Figure 3. Spectra of stochastic GW background produced by standard exponential inflation and from a string model [16], compared with the sensitivity of two VIRGO-like correlated interferometers.

pulsars, about 700 [14]). A *blind search* of neutron star, with high frequency resolution ($O(1/\text{year})$) and covering all the possible Doppler effect parameters, is not within reach with the present computation power.

Most of the known pulsars emit in the low frequency region (1-10 Hz). Figure 2 shows the upper limit on the amplitude for a sample of known pulsars, compared with the target sensitivity of the first generation interferometric detectors. A certain number of pulsars would be detectable, especially with VIRGO. These upper limits have been calculated assuming that the observed period slowdown is entirely due to GW emission. Therefore the real amplitudes can be orders of magnitude smaller than the upper limit. The wave amplitude can be expressed in the form:

$$h \sim 6 \cdot 10^{-25} \left(\frac{f_{\rm rot}}{500\,\rm Hz}\right)^2 \left(\frac{1\,\rm kpc}{r}\right) \left(\frac{\epsilon}{10^{-6}}\right) \qquad (6)$$

where the parameter ϵ measures the deviation from axisimmetry. Theoretical estimates yield the upper limit $\epsilon \lesssim 10^{-5}$ ([15] and references therein).

5. STOCHASTIC BACKGROUND

The uncoherent contributions of all the possible GW sources of the universe will show up as a stochastic background of GW. Moreover, a background of cosmological origin, taking the imprinting of the early cosmological dynamics is expected to fill the universe. The detection of such spectrum can permit to discriminate between different cosmological models. The stochastic background is characterized by the quantity:

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm gw}(f)}{{\rm d}\ln f} \qquad (7)$$

Two correlated detectors are necessary to distinguish the stochastic signal from the noise. As an example, we consider two different models and compared the spectra produced:

- **standard inflation:** if the expansion is exponential (de Sitter inflation) a flat spectrum (over a huge range of frequencies) is produced. The quadrupolar anisotropy in the CMBR measured by COBE sets a limit on the amplitude, which is many orders of magnitude below the sensitivity of two correlated VIRGO-like interferometers.

- **string models:** string models can produce spectra which bypass the COBE limit and reach a considerable amplitude in the VIRGO/LIGO detection band (see figure

3). Such spectra can be detectable by the second generation interferometers.

6. CONCLUSIONS

According to the present theoretical knowledge, the coalescence of two compact stars, the star collapse and the spinning of a non-axisymmetric neutron stars are events in which GW are emitted. The present estimates of the expected rates and GW amplitudes seem to indicate that the first generation interferometric detectors may aim to the first detection. On the other hand, a further enhancement of the detectors sensitivity (second generation detectors) is required in order to increase the statistics and be able to begin a *gravitational waves astronomy.*

REFERENCES

1. C.Bradaschia *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **289**, 518 (1992).
2. A.Abramovici *et al.*, *Science*, **256**, 325 (1992).
3. J.Hough *et al.*, GEO600 Proposal (unpublished, 1994).
4. K.Kuroda *et al.*, *Proc. of the 1st International Conference on GW: Sources and Detectors*, F.Fidecaro and I.Ciufolini eds., World Scientific (1997).
5. J.Taylor, *Rev. Mod. Phys.*, **63** (1994).
6. R.Hulse, *Rev. Mod. Phys.*, **63** (1994).
7. L.Blanchet, *et al.*, *Class. Quantum Grav.*, **13** (1996).
8. B.Schutz, *Nature*, **323** (1986).
9. T.Damour, G.Esposito Farèse, gr-qc/9803031.
10. C.Cutler, *et al.*, *Phys. Rev. Lett.*, **70** (1993).
11. T.Zwerger, E.Müller, http://www.mpa-garching.mpg.de/ẽwald/GRAV/grav.html
12. K.S.Thorne, gr-qc/9506084 (1995).
13. M.Zimmermann, *Phys. Rev.*, **D21**, 891-898 (1990).
14. J.Taylor, *et al.*, *Ap. J. Suppl.*, **88** (1993), http://pulsar.princeton.edu
15. É.É.Flanagan, gr-qc/9804024 (1998).
16. A.Buonanno, M.Maggiore, C.Ungarelli, *Phys. Rev.*, **D55**, 3330 (1997).