Progress in gravitational waves detection: “bar” detectors.

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Cryogenic resonant “bar” detectors have been operated for a number of years and, more recently, the network of all 5 detectors in operation worldwide has been working in coincidence, in a 4 years search of impulsive gw events in the Galaxy. Their response to cosmic rays has also been evidenced. The performance of the detectors and of the network are described here, with the result of the search in terms of upper limits and false alarm rates. The upgrades shortly due promise to extend the reach out of the detectors for violent impulsive gw events to the whole Local Group of galaxies and thus to usefully complement the upcoming interferometric detectors in the kHz frequency range.

1.INTRODUCTION

Gravitational waves are ripples in space-time, propagating at the velocity of light, which are produced by the accelerated motion of masses, much in the same way as accelerated charges produce electromagnetic waves. Compact bodies in the cosmos, moving at velocities close to that of light as black-holes and neutron stars in binary systems, are possibly the best candidates for a first direct detection from ground based detectors [1].
The detection scheme of a “bar “ detector originates from the pioneering work of Joseph Weber in the 60s [2], who constructed and operated the first room temperature detectors. Later Bill Fairbank started with Bill Hamilton the effort to cool to liquid helium temperatures and below the few tons sensitive bar mass to reduce the thermal noise and to take advantage of superconducting electronics to reduce the final amplifier noise, so that both the fundamental sources of noise would be reduced at the same time. Edoardo Amaldi had the vision with Guido Pizzella of a long baseline network, committing to develop similar detectors in Italy and, on the same tune, David Blair started a detector in Australia. As a result we now have 5 such cryogenic resonant bar detectors in the world, which have been extensively operated in coincidence in the search of violent gw burst events in the Galaxy, under the International Gravitational Event Collaboration, IGEC [3]. The detectors are: ALLEGRO at Baton Rouge , USA [4], AURIGA at INFN Legnaro, Italy [5], EXPLORER at CERN [6], NAUTILUS at INFN Frascati [6] and NIOBE at Perth, Australia [7].
I refer to the quoted web sites for a description. Here I prefer to summarize their similar performances, together with the first study of their response to cosmic rays, in §2, the achievements of the IGEC observatory in §3 and the upgrades under way in §4. Ideas, summarized in §5, are upcoming on how to progress to an “advanced” generation of ultracryogenic massive resonant detectors, to be put underground to avoid disturbances from cosmic rays, which would extend to the kHz region, beyond the “advanced” interferometric detectors due for the end of the decade, the spectral range of detection.

2. CRYOGENIC “BARS” AS GW DETECTORS

The principle of operation of “bar” detectors resides on the fact that gravitational waves 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 the orientation of the direction of propagation and of polarization of the gw relative to the bar axis, being maximal when the gw impinges perpendicularly to the bar axis, with best oriented polarization. Because of this effect, for instance, a bar detector on ground sees the Galactic Center with >50% cross section for about 75% of the day.

Two fundamental noise sources are present. One is the thermal noise in displacement of the bar ends, due to the thermodynamic fluctuations in the bar volume; as the fluctuation-dissipation says, it scales as the ratio T/MQ, where T is the bar temperature, M its mass and Q its mechanical quality factor. The Q for most materials rises as T is lowered, giving an extra bonus for a cryogenic, liquid helium, design (or, even better, for ultracryogenic, below 1K, temperatures). The other is the broadband noise of the final amplifier, which reads out the electromechanical transducer which translates the motion of the bar ends in an electric signal. This last source of noise has a natural limit due to quantum mechanics [8].

If the ratio Q/T is large enough, Q/T ~ 10^9 K^{-1}, the thermal noise in the post-detection bandwidth 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, that is to say that one can see the quantum states of a macroscopic body weighting a few tons. The bars currently in use are a factor of only 10^3-10^4 in energy above the SQL and, after the upgrades underway, a few of them should approach the SQL as close as less than a factor of 100 in energy. The sensitivity and bandwidth of resonant bars read by resonant motion transducers and linear amplifiers, as they approach the SQL, are discussed in ref [9].

The gw amplitude is given as the (adimensional) amplitude h of the "ripples" in the metric of space-time, which corresponds to the strain on matter ? l/l induced in matter by the interaction with the gw. Resonant detectors are usually characterized by their "burst sensitivity" h_b , the minimum gw burst amplitude detectable at SNR=1. In general the spectral sensitivity $S_h(f)$ as a function of detection frequency is used to characterize and compare detectors of all kinds.

Current bars, mostly of the Aluminun alloy Al5056, resonate at about 1 kHz; with M~2 t and Q~10^6, working at T ~ 0.1 – 4.2 K, they show postdetection bandwidths ~ 1 Hz, burst sensitivities h_b~2 10^{-19} and spectral sensitivities at resonance S_h(1kHz)~ 5 10^{-22} $Hz^{-1/2}$. Such a sensitivity would allow to detect violent gw events in the Galaxy, when a source like a coalescing neutron star or black-hole binary would emit some 0.01 c^2M_{sun} of energy in gw. In bar ends displacement h_b corresponds to ? l ~ 10^{-18} m. The SQL would be at the level of h_b ~ 3 10^{-21}, that is ? l ~ 10^{-20} m and correspondingly the reach out for violent gw events would go well beyond the Local Group towards the Virgo cluster of galaxies.

Recently, according to predictions, the sensitivity of bars to cosmic rays has been demonstrated [10], indicating that, as they may get close to the SQL, operation underground would be compulsory.

3. THE "5-BARS" NETWORK IN OPERATION.

The detectors are oriented with their axes parallel to each other and each locally orthogonal to a great circle, which happens to pass very close to the various locations. Having thus all their antenna patterns oriented coherently, the coincidence probability is maximized.

All the projects exchange data under the International Gravitational Events Collaboration - IGEC - agreement [3] to search for coincidental impulsive gw events, that is any signal of nearly constant spectral amplitude over the resonant modes of each detector, which are some 20 Hz apart around ~900 Hz (NIOBE is however at 700 Hz). The network is sensitive to millisecond bursts of any shape such as those from the final coalescence, merger and ringdown of black-hole binaries of total mass below some 15 *M*sun,, the final coalescence of binary neutron stars systems (as it will be in 100 million years the famous binary pulsar 1913+16, which shoed evidence for gw *emission*) and the birth and cool down of neutron stars and black holes in supernovae.

The team caring for each detector in the network has the responsibility to produce lists of 'burst events'. The periods of 'on' time of the detector are identified, during which the noise shows up as a quasi-stationary Gaussian process, plus a limited number of 'background' events, about 100/day (for all detectors, except ALLEGRO which has only a few 'background' events per day). Optimal filtering with ? -like templates is used to extract, from the raw data, the time series of the candidate 'events'.

Each team performs tests of its choice on the events list to veto spurious ones, when coincidental with local disturbances, and self-consistency tests. The timing accuracy within the network is kept to better than 1 μs, UTC time. The filter time correlation, for all detectors, is of the order of 1 s.

A threshold is applied at SNR = 3–5 in amplitude, which would correspond, for actual gw signals, to 0.04–0.11 Msun converted in a millisecond burst at a distance of 10 kpc, in case of optimal direction and polarization with respect to the antenna pattern.. The 'event list' is then exchanged, with the following mandatory declarations:

• Fourier magnitude H(f) in Hz^{-1} of the 'event' amplitude h(t), averaged over the resonant modes of average frequency f
• universal time (UTC) of the 'event' arrival;
• START–STOP of the detector's accepted data;
• detector's noise, Hrms at 'event' time.

The coincidence window is set considering the joint overlap of the error bars on timing of the various detectors and is typically of 1s.

Tests have been performed to look at the statistics of the events and their correlations, if any [10, 11].
The first IGEC search [10, 11 and in preparation] concerns a large part of the period June 1 1997 to December 2000, with common observation times of about 640 days for twofold, 140 days for threefold and 20 days for fourfold coincidence analysis. For about 1280 days at least one detector was "on".

The noise between all the detectors, either nearby or far apart, is found to be not correlated, a feature which gives confidence in the effectiveness of the coincidence searches in reducing the 'background' ambient noise. The false alarm rate is mainly influenced by a non-modeled 'background' noise, which represents the actual limit in the network sensitivity. However, while the rate of accidentals can be as large as a few per week for twofold coincidences, as soon as three or more detectors are in coincidence, the false alarm rate goes easily below one event per century, $< 10^{-4}$ event/year for threefold coincidences and $<10^{-6}$ event/year for fourfold coincidences.
With detector thresholds in the interval $h = 3–5\ 10^{-18}$ the main results are:
• the rate of accidentals for twofold coincidences fully agrees with predictions;
• no candidate gw signal has been found over the period of threefold coincidences;
• upper limits of about $h = 4\ 10^{-18}$ can be continuously given for the GW flux at the detector network at each time, assuming optimal direction and polarization, using data from as many detectors (one to four) as they were on air at any time. These data can be of use in connection with astronomical triggers, such as neutrinos, ? -bursts, etc to set upper limits within specific models.

The agreement between observed and predicted twofold accidentals is very robust. In fact, two different methods have been used to predict the corresponding rates: (a) as the event rates of the detectors are not correlated, one can assume the process is point Poisson and thus estimate the frequency of the accidentals, with textbooks formulae; (b) one can artificially shift in time the output of each detector with respect to any other and then count, for each trial, the coincidences found. Identical results are obtained with the two methods: no excess of twofold coincidences has been observed at the level of about $h = 4\ 10^{-18}$ over the period of time with at least two detectors in coincidence.

4. UPGRADES FOR THE DETECTORS OF THE IGEC OBSERVATORY.

All the detectors are expected to be substantially upgraded over the next year or so, to increase the 'on' time and the sensitivity, under programs already funded.

For the 'on' time a number of improvements in the cryogenics, as continuous liquid helium refills, are going to minimize maintenance stops.
For the sensitivity: (a) the non-modeled 'background' noise will be reduced by new designs of the vibration insulations and of the mechanical links to the bar needed for thermal linking; (b) the so-called 'standard quantum limit' in the short-term 'Gaussian' sensitivity will be approached with the upgraded transducers and final amplifiers which each team is actively and successfully developing. This will enable the detection of events delivering just a few tens of quanta of vibration energy to the bar. At the same time, the bandwidth will open up to many tens of hertz around the resonances.
This will immediately allow a resolution <1 ms in the arrival time of the bursts: the coincidence window will be narrowed and the time of flight of candidate gw signals across the network will become measurable.

All in all, these upgrades should allow a significant enhancement of the reach out of the IGEC observatory, which, taking as a reference the ringdown signal of black holes of about 15 M_{sun}, would go from the current 100 Kpc to as far as 50 Mpc.

Thus the 'bars' may usefully complement in the kilohertz 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 of gw signals.

Until now the IGEC dedicated its efforts only to searches of "burst" gw signals, but other searches can and will be implemented, in particular of continous signals, of correlations with ? -bursts [12] and of stochastic background.

5. “ADVANCED” ULTRACRYOGENIC DETECTORS

Massive, high mechanical quality factor, spherical resonators have attracted the interest of the “bar” community by a long time, as prospective “advanced” detectors. The main attractive features are:

• the cross section is larger as the ratio of the masses with respect to the bar, which, to be at equal resonant frequency, would have length equal to the sphere diameter; for the same material this is a factor about 20 [13];

• the detection is omnidirectional and it is possible to reconstruct the direction and polarization of the incoming signal [14]; in fact, two spherical detectors at a distance would be, in principle, a complete GW ‘observatory’ [15] and, if the distance is properly chosen, one can maximize the correlation in the detection of the stochastic background [16];

• the cross section of the second quadrupolar mode is of the same order as that of the first; this would allow an interesting procedure of detection, for instance, of the final coalescence of neutron stars binaries, when the signal excites the two modes at subsequent times [17].

Hollow spheres, equipped with resonant transducers at the SQL [18], would reach out to beyond 100 Mpc, the scale at which a few events/year are expected.

Recently, a new scheme has been proposed [19], in which the relative surface displacements between two concentric freely suspended spheres, as they vibrate independently under the gw excitation, are read by non-resonant optomechanical transducers. The new concept has many interesting features, the main one of which is that, due to the fact that the Fabry-Perot cavity of the transducer can be short, say 1 cm, the finesse can be very high, $F > 3\ 10^5$, without degradation of the gw signal, and thus one can, in principle, reach the SQL at an overall displacement noise level of the readout which allows a bandwidth quite open ? f~f. The spectral sensitivity in the kHz frequency range would be comparable or better than the “advanced” interferometric detectors due by the end of the decade.

In conclusion, one may envisage that, with LISA, with the ‘advanced’ interferometric detectors and with the ‘advanced’ cryogenic resonant mass detectors, one would cover, for one of the most interesting signals, the coalescence of black holes, the whole mass spectrum from millions of M_{sun} to a few M_{sun}.

REFERENCES

1. for a comprehensive review on gw sources vs gw detectors see: K.S.Thorne gr-qc9506086
2. J.Weber, Phys.Rev. 117 (1960) 306
3. http://www.igec.lnl.infn.it
4. http://gravity.phys.lsu.edu
5. http://www.auriga.lnl.infn.it
6. http://www.roma1.infn.it/rog/
7. http://gravity.pd.uwa.edu.au
8. H.Heffner, Proc.IRE 50 (1962) 1604
9. J.C.Price, Phys.Rev. D36 (1987) 3555
10. G.A.Prodi *et al* Int.Journ.Mod.Phys. 9 (2000) 237
11. Z.A.Allen *et al* Phys,Rev.Letters 85 (2000) 5046
12. P.Tricarico *et al* Phys. Rev. D 63, (2001) 08200
13. R.V. Wagoner and H.J.Paik Proc. Int. Symp. Experimental Gravitation , Accademia Nazionale dei Lincei, Rome (1976) 257
14. C.Z. Zhou and P.F. Michelson Phys. Rev. D 51 (1995) 2517; M.M.Merkovitz and W,W.Johnson Phys. Rev. D 56 (1997) 7513; J.A.Lobo Mon. Not. R. Astron. Soc. 316 (2000) 173
15. M.Cerdonio M *et al* Proc. 1st E Amaldi Int. Meeting GW Experiments , World Scientific, Singapore (1995) 176; E.Coccia *et al* Phys. Rev. D 52 (1995) 3735
16. S.Vitale S et al Phys. Rev. D 55 (1997) 1741
17. E.Coccia and V. Fafone Phys. Lett. A 213 (1997) 16
18. E.Coccia *et al* Phys. Rev. D 57 (1998) 2051
19. M. Cerdonio *et al.* Phys. Rev. Letters 87 (2001) 031101