BAR DETECTORS

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The cryogenic resonant bar detectors of gravitational waves ALLEGRO, AURIGA, EXPLORER, NAUTILUS and NIOBE are in operation and search for impulsive events. We outline their present capabilities, the foreseen upgrades and their role in a future global network together with interferometric detectors.

1 Introduction

Currently three resonant bar detectors are operating at liquid helium temperatures - ALLEGRO[1] at Baton Rouge, EXPLORER[2] at CERN and NIOBE[3] at Perth - and two are operating at He^3-He^4 refrigerator temperatures, about 100 mK - AURIGA[4] at Legnaro and NAUTILUS[5] at Frascati. Resonant detectors have comparatively narrow bandwidth but, within it, already show a sensitivity[6] for gravitational waves close to that which the large interferometric detectors are aimed at in their initial operation (Fig. 1b). The foreseen upgrades promise to open considerably the useful bandwidth and at the same time to follow interferometric detectors in their projected sensitivity enhancements. Even in the era when "advanced" interferometers will be in full operation, this facts promise to make resonant detectors an invaluable part of the world wide system of bars and interferometers. In such a system, to be considered as a global gravitational waves observatory, resonant detectors will provide: a) an observation with an independent detection technology; b) a significant increase in the overall number of detectors, a key issue in beating false alarms; c) a sensitivity to parts of the Riemann tensor to be used as vetoes[7]; and d) an independent estimate of the location of the source of candidate signals.[8]

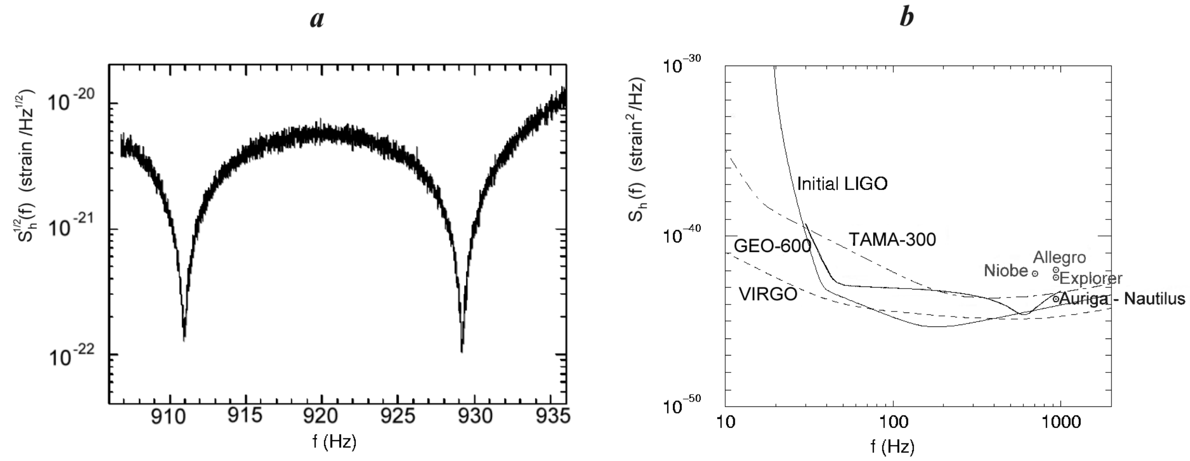

Figure 1: a) Spectral noise density of the the detector AURIGA. b) Predicted spectral noise density for the interferometric detectors under construction, the sensitivity of the currently operating bar detectors is represented by small dots.

2 Principles of operation

Fig. 2 gives a schematic of a cryogenic "bar" g.w. detector. The metric perturbation h of the wave, incoming at angle ϑ with the bar axis with polarization angle φ, drives the longitudinal resonant modes of the bar through the tidal force $(ML/\pi^2)d^2h/dt^2\ F(\vartheta,\varphi)$, where M and L are the mass and length of the bar. The antenna pattern factor $F(\vartheta,\varphi) = \sin^2\vartheta\cos(2\varphi)$ effectively modulates the response of the detector when, say, it is in relative motion with respect to a potential source and this fact can be advantageously used in dedicated searches.

The bar is suspended by means of a cascade of intermediate masses and pendulums so to attain the largest insulation from external vibrational noise - seismic, ambient, etc. - especially in the vicinities of the frequency of the mode chosen for the detector operation. The fact that odd longitudinal modes of order n respond to g.w. as $1/n^2$ but even order modes are insentitive is of interest to get a signature of g.w. absorption. Anyway for practical reasons, all operating detectors work at their lowest longitudinal mode frequency (1 kHz, M tons and L meters); the vibrational insulation at such mode is typically some 250 db and operators may climb on the cryostat without disturbing the detector. A resonant electromechanical transducer is tuned to the bar mode to maximize the transfer of the vibrational energy of the bar to the readout electronics. The detector is thus a system of two mechanical modes. One of the kinds of transducers is a capacitor operating at constant charge and biased at electric fields just below vacuum breakdown, $10^7\ V/m$: one plate is fixed with one end face of the bar and the other is free to vibrate at a frequency tuned to that of the bar mode. The electric currents, which so originate, are coupled and transformed in magnetic fluxes via superconducting circuitry to a superconducting quantum interference device, SQUID, as a final amplifier.

The efficiency in transferring the vibrational energy of the bar into electromagnetic energy in the final amplifier is typically $10^{-4} \div 10^{-2}$ and the SQUID energy resolution at the modes frequencies is currently of the order of $10^{-30} Joule/Hz$. This last figure translates in about $\epsilon \approx 10^4\hbar$, the energy resolution of the SQUID in units of the Planck constant, not so far from the "standard quantum limit", SQL, $\epsilon = \hbar/\ln 2$.[9]

The performance of a gravitational wave detector is described mainly by its strain noise spectral density, its duty cycle, the antenna pattern, and a non-stationary "background" noise it shows in excess of the modeled one. For a resonant detector the strain noise spectral density

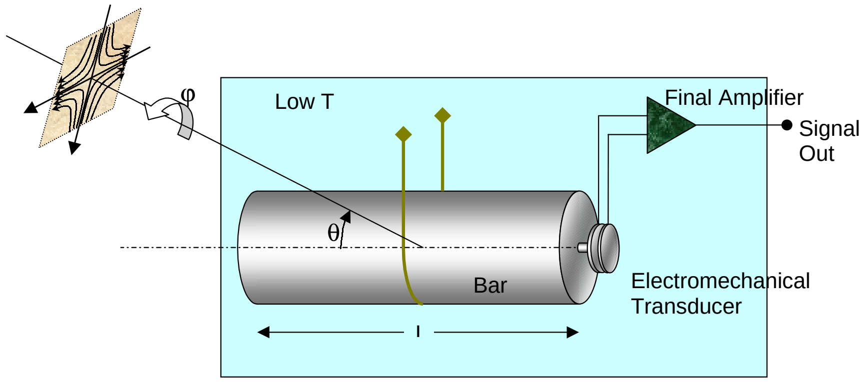

Figure 2: Schematic of a cryogenic bar detector

S_h, Fig.1a, shows two keys features: the value taken at the minima close to the two modes of resonance and the effective bandwidth around these minima where the noise performance in term of gravitational wave amplitude is best. The minima are proportional to T/Q, where T is the effective temperature of the mode, which takes into account both the Brownian noise of the mode and the back-action contribution from the transducer-amplifier chain, and Q is the mode quality factor. The effective bandwidth is then determined by the additive noise performance of the displacement transducer-amplifier chain: as the ratio between the thermal plus back-action noise and the white noise of the amplifier increases the bandwidth widens accordingly. The best experimental results have been achieved by the two ultracryogenic detectors AURIGA [4] and NAUTILUS,[5] showing minima of about $S_h \simeq 10^{-43}(Hz)^{-1}$ and effective bandwidths of the order $\Delta\nu \simeq 1\ Hz$ (Fig.1a). The duty cycle demonstrated by the operating resonant detectors is ranging from 90%, as for the liquid Helium temperature detectors, to 50%, as for the younger sub-Kelvin detectors. Another quantity used to characterize the narrow band detectors is the burst sensitivity $h_{min} = \tau_g/(S_h\Delta\nu)$, where one conventionally takes for the g.w. burst duration $\tau_g = 1\ ms$ and h_{min} is the minimum g.w. burst amplitude detectable at unity signal to noise ratio, SNR. A string of a typical week of data of AURIGA is shown in fig 3.

3 Performances and capabilities

The five detectors in operation differ in many relevant details, from materials and working temperature to type of electromechanical transducer, but their performances are presently quite similar in almost all respects; Table 1 gives a summary.

One notices that while the so called ultracryogenic ones, that is AURIGA and NAUTILUS working at $He^3 - He^4$ refrigerator temperatures, show a somewhat better spectral sensitivity at resonance, their burst sensitivity is anyway close to the others. The reason is that ultracryogenic operation is not yet fully exploited, since the final amplifier, the SQUID, is still too "hot", with $\epsilon \geq 10^4\ \hbar$. Short term upgrades concern the integration of SQUIDs with $\epsilon \leq 100\ \hbar$ [10] and should also bring along a wider bandwidth of some 50 Hz. Similar performances are expected with parametric systems [11] and with optical readouts, which use interferometric methods at low temperatures.[12]

The duty cycle given in Table 1 concerns strictly that allowed by ordinary operations of cryogenic maintenance during the same cooling down, not that due to major maintenances which require warm up of the system, with consequent interruption of operation for a few months.

The daily $SNR > 5$ rate for impulsive events is a factor $3 \div 5$ larger than expected from a Gaussian statistics and this is the unmodelled background mentioned above. With ALLEGRO it has been significantly reduced, by enhancing the insulation against microseismicity and electrical

Table 1: Summary of resonant detectors in operation

	ALLEGRO	EXPLORER	NIOBE	NAUTILUS	AURIGA
Bar Working Temp. $[K]$	4.2	2.6	5	0.1	0.2
Mechanical Q Factor	1.5×10^6	2×10^6	20×10^6	0.5×10^6	3×10^6
Strain noise $S_h^{1/2}[Hz^{-1/2}]$	10×10^{-22}	6×10^{-22}	8×10^{-22}	3×10^{-22}	2×10^{-22}
Eff. bandwidth $\Delta\nu[Hz]$	≈ 1	≈ 0.2	≈ 1	≈ 0.6	≈ 0.5
Burst strain sens. h_{min}	8×10^{-19}	8×10^{-19}	10×10^{-19}	4×10^{-19}	4×10^{-19}
Duty cycle	97%	50%	75%	60%	66%
$SNR > 5$ rate $[day^{-1}]$	100	150	75	150	200

disturbances.[13] With AURIGA attempts are made to use χ^2-tests on the output to select against spuria,[14] under the assumption that energy absorptions not originating in the bar will propagate differently along the transduction chain. Of course such a background is presently the actual limitation in the searches of rare impulsive events, which can be overcome only by having as many as possible detectors in coincidence.

The data acquisition and analysis have recently evolved under the pressure of the peculiarities of the actual data outcome, in particular the non-stationarity of the noise parameters. With AURIGA it has been introduced [15] a fast, 5 kHz, A/D conversion of the signal from the final amplifier, synchronized within 0.1 μs with UTC time, which allows on one hand a full storage of the raw data and on the other hand a fully numerical analysis, with online adaptive filters. Presently the search and reconstruction of burst events gives amplitude, time of arrival [16] and χ^2-test vetos.[14] The nature of the noise appears to be that of a quasi-stationary gaussian process, with the parameters expected from the thermal noise acting on the bar-transducer system and the amplifier noise, to which it adds the unmodelled background noise. Almost all detectors are supposed to use soon data acquisition and analysis schemes with similar overall performance.

To maximize the probability of coincidental detection, the 5 detectors in operation have been oriented with their bar axis roughly parallel to each other and all orthogonal to the earth great circle close to which they happen to stay. As for now, at $SNR = 1$, a continuous g.w. signal at about 900 Hz would be detected over an observation time of 100 days at amplitudes $h \simeq 10^{-25}$ and an impulsive g.w. signal of duration 1 ms would be detected at amplitudes $h_{min} \approx 5\times10^{-19}$. These are already interesting numbers, as they overlap with the upper range of predictions for g.w. emission from, say, rapidly rotating neutron stars with asymmetries and supernova events in the Galaxy. Presently the bars in operation, working in collaboration under the International Gravitational Event Collaboration (IGEC) agreement,[17] are able to keep a “Galactic supernova watch” with the following characteristics:
i) at $SNR > 5$ detect $\geq 10^{-3}M_\odot$ converted in g.w. at the Galactic Center;
ii) give 16hours/day of coverage of the Galactic luminous mass;
iii) suffer from a background of about 3×10^{-7} fourfold coincidences/year;
iv) resolve the burst arrival time within 1 ms;
v) give the source position in the sky within $degs$.
To throughly exploit all these capabilities, a quite demanding job on off-line data analysis is needed, which has just started.

4 Perspectives: upgrades and a global g.w. observatory

Beyond the short term upgrades, quoted above, one expects to approach the SQL and considerably expand the usable frequency band to some 100 Hz. An impulsive SQL detection would be at the level of amplitude of metric perturbation $h = 2\times10^{-21}$. This would mean that Galactic

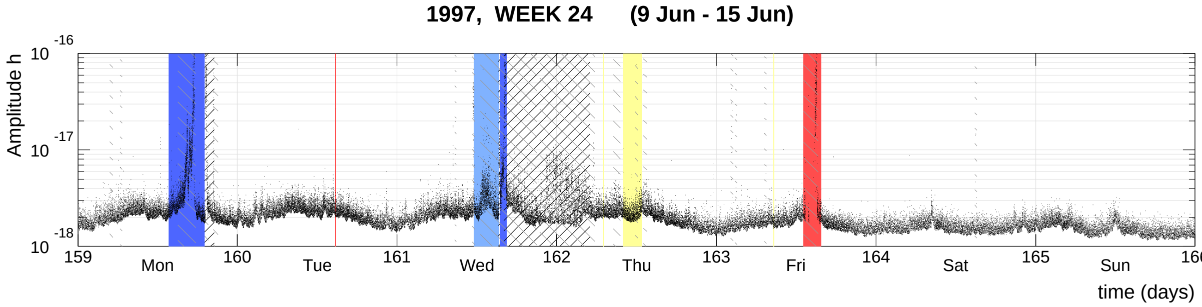

Figure 3: One week of burst events above a threshold $h > 3h_{min}$. Two kinds of vetoes are represented, which cover known maintenance activities (plain bands) and automatically determined noisy periods (dashed bands).

supernovae would be detectable, even if of poor efficiency, 10^{-6} $M_{\odot}$ in g.w. conversion, and that large efficiency supernovae and neutron stars and black-hole mergers in the Virgo Cluster would also be detectable. The bandwidth would be appreciably open: i) to allow searches of stochastic background by correlating the outputs of nearby enough detectors, as just AURIGA and NAUTILUS are [18] ii) to allow searches of continuous sources giving spectral metric perturbations amplitudes at the detectors $S_h \simeq 10^{-46}$ Hz^{-1}, that is amplitudes $h \geq 5 \times 10^{-27}$ over 100 days integration time, in some 100 Hz around 1 kHz. A larger effective bandwidth is a must for detecting signatures of the wave, as its propagation speed and its incoming direction; as this is possible by measuring the arrival time of the signal in more detectors with sub-millisecond accuracy,[16] bandwidths > 30 Hz are needed to do this for the low $SNR \leq 10$ signals expected.

For all g.w. signals - impulsive, continuous and stochastic - the SNR gets enhanced, if the mass of the detector increases. Long ago it has been proposed [19] that a spherical mechanical resonator, when the responses of its five quadrupolar modes are suitably correlated, would give a massive omnidirectional g.w. detector, actually able to identify the direction of propagation of the wave. Recently the idea has been revived [20] and the study of materials and cooling methods has led to the notion that it would be feasible [21] to cool at 10 mK a Cu-Al sphere of 3 m diameter, weighting some 100 $tons$. So, in addition to the all-sky coverage, one would get a significant increase in cross section of almost one order of magnitude, pushing the burst sensitivity to $h_{min} \simeq 10^{-22}$ and all other sensitivity numbers accordingly. Possibly, at these levels of sensitivity, high energy cosmic rays may become a problem,[22] which would be overcome by locating the detector in an underground laboratory, as for instance the GranSasso INFN Nat.Lab. in Italy.

For any detection, it would be quite convincing if the signal would be seen by detectors based on different principles of operation and different construction technologies. It is natural to propose that all the upcoming interferometric detectors - LIGO, VIRGO, GEO and TAMA - collaborate, from "initial" to "advanced" operation, for correlated signal searches, in a global network, together with the most sensitive resonant mass detectors, the bars now, the sphere in the future. With such a network for instance it could be possible to solve the so called inverse problem, for searches of burst signals, by a straightforward extension of the exercise worked out for a "6 bars" network.[7] A spherical detector could enter the network, as "advanced" detector in place of the bars, contributing in a similar way to the solution of the inverse problem. These solutions give also signatures of symmetries of the g.w. Riemann tensor, as tracelessness and transversality, which could be used as vetos against spuria. As interferometers are intrinsically insensitive to the trace of the g.w. Riemann tensor, again resonant detectors are crucially complementary in the global network. Given burst sensitivities $h_{min} = 10^{-21} \div 10^{-22}$, as expected when enhancing performance beyond the "initial" for all detectors, such a global network would detect g.w.bursts of 0.1 $M_{\odot}$ out to $100 \div 1000$ Mpc, having full sky coverage, allowing reconstruction of polarization and direction of propagation, giving the arrival time to less than 1 ms, together with tests on the velocity of the waves and on the Riemann symmetries quoted above. Using such a global network, undoubdtly one should be able to work out solutions of the inverse problem with similar merits also for other kind of searches, as emissions from continuous sources and "chirps" from coalescing binaries.

We finally notice that the enhancements in sensitivity both of resonant mass and of interferometric detectors are in principle boundless. As the interaction of gravitational waves with a SQL detector is expected to be that of a classic wave packet with a quantum system, the SQL is only a limit for the use of "classical" measurement methods, not an intrinsic limit for the ultimate sensitivity.[23]

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