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Resonant detectors for the search for gravitational waves

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Abstract. An overview of the experiments for the search for gravitational waves by means of resonant detectors is given. Since 1990 cryogenic resonant antennas have been in operation and data have been recorded by Explorer, Allegro, Niobe and Nautilus. The sensitivity for pulse detection with SNR = 1 is now $h \approx 6 \times 10^{-19}$ (corresponding to a total energy of less than 0.001 solar masses for a source in the Galactic Center). The sensitivity for monochromatic waves is $h \approx 2 \times 10^{-25}$ for one year of integration and about 7×10^{-22} Hz$^{-1/2}$ for stochastic background detection.

Large resonant detectors operating at 1 kHz might reach, in the near future, a spectral amplitude sensitivity of the order of 7×10^{-24} Hz$^{-1/2}$ and, for pulse and monochromatic wave sensitivity, respectively, $h = 3 \times 10^{-22}$ and $h \approx 10^{-27}$. Cross-correlating two such large antennas for one year can give a sensitivity for stochastic background detection of the order of 3×10^{-26} Hz$^{-1/2}$, corresponding to a ratio between the gravitational wave energy density to that needed for a closed Universe of 10^{-6}.

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1. Resonant detectors

The gravitational wave detectors used by the groups of Legnaro, Louisiana, Perth and Rome are metallic cylindrical bars, with high mechanical quality factors. In order to capture as much energy as possible the mass of the bar needs to be as large as possible. The Legnaro, LSU and Rome groups use aluminium bars $L = 3$ m long, weighing about $M = 2300$ kg with merit factors $Q > 10^6$. The Perth group uses a niobium bar (which has higher Q) resonating at 710 Hz and weighting 1.5 ton. When the bar is hit by a GW burst with amplitude $h(t)$ and very short duration τ_g, impinging perpendicular to its axis, it starts to vibrate at resonance modes that are coupled to the gravitational waves.

It is possible to show (Astone *et al* 1996) that the minimum value of h that can be detected with SNR = 1 is

$$h \approx \frac{1}{\tau_g}\sqrt{\frac{S_h}{2\pi\,\Delta f}} \tag{1}$$

where Δf is the detector bandwidth and S_h indicates the power spectrum of the noise referred to the antenna input. For a bar at the resonance frequency f_0, we have

$$S_h = \frac{\pi}{8}\frac{kT_e}{MQL^2}\frac{1}{f_0^3} \tag{2}$$

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where T_e is the thermodynamic temperature plus a term due to the back-action from the amplifier, which, with a DC SQUID amplifier, is negligible.

The bandwidth of the resonant antennas is limited only by the transducer and by the noise of the electronic amplifier, because the resonant bar responds in the same way to the excitation due to the GW and to the Brownian noise. It can be shown that the bandwidth is given by

$$\Delta f = \frac{f_0}{Q}\frac{4T_e}{T_{eff}} \tag{3}$$

where T_{eff} is the noise temperature for burst detection, that is, kT_{eff} is the minimum energy increase that can be detected with SNR = 1 after optimum filtering for very short signals.

Introducing equations (3) and (2) in (1) we obtain

$$h \approx \frac{L}{\tau_g v^2}\sqrt{\frac{kT_{eff}}{M}} \tag{4}$$

where v is the velocity of sound in the bar material ($v = 5400$ m s^{-1} in aluminium).

With $M = 2300$ kg, $L = 3$ m, $\tau_g = 1$ ms, in order to observe a GW due to a supernova at the Galactic Center (optimistically $h = 3 \times 10^{-18}$) we need $T_{eff} = 0.2$ K. If the same GW comes from the Virgo Cluster we need $T_{eff} = 1.4 \times 10^{-7}$ K.

It is interesting to compute the bandwidth for the target sensitivity. From equation (3), with $T_{eff} = 1.4 \times 10^{-7}$ K, $T = 0.1$ K and $Q = 1 \times 10^7$, we find $\Delta f \approx 300$ Hz. This compares favourably with the bandwidth of the interferometers.

For the detection of monochromatic waves the sensitivity is given by (Astone *et al* 1996)

$$h = \sqrt{\frac{2S_h(f)}{t_m}} = \sqrt{\frac{\pi kT_e}{MQv^2 f_0 t_m}} \tag{5}$$

where h is the amplitude of the wave that can be detected with SNR = 1 and t_m is the duration of the measurement. The first equality is valid at any frequency, the second one only at the resonance.

A resonant detector can also measure the gravitational stochastic background. The relationship between the density ratio Ω and the power spectrum S_h is

$$\Omega = \frac{4\pi^2}{3}\frac{f^3}{H^2}S_h(f) \tag{6}$$

where H is the Hubble constant.

In addition to the bars other new projects for resonant detectors are beginning. Most of the groups considered above (as well as two other groups, one in Brazil and the one in Holland) are considering the possibility of starting new experiments with resonant antennas. The idea is to use spherical detectors that have, basically, two advantages with respect to other detectors: (i) it is possible to use much heavier antennas, since an aluminium sphere with a diameter of 3 m weighs 38 tons, against 2.3 ton of the available 3 m long cylinders; (ii) the spherical detector is sensitive to GWs coming from all directions and with any degree of polarization.

In fact, one sphere is equivalent to five bars properly oriented on the Earth's surface, each one with a mass $\frac{3}{4}$ of the mass of the sphere (Coccia 1994). Estimations of the sensitivity for a 3 m sphere resonating at 1000 Hz and cooled at 20 mK, give, for 1 ms bursts, $h \approx 3 \times 10^{-22}$. The spectral amplitude sensitivity would be 7×10^{-24} Hz$^{-1/2}$ and the sensitivity for monochromatic waves should approach $h \approx 10^{-27}$.

2. Operation of the resonant detectors and preliminary results

The resonant bars (Astone *et al* 1993, Blair *et al* 1994, Geng *et al* 1994) are the only detectors that have been in continuous operation since 1990. They have reached a burst sensitivity, with SNR = 1, of the order of $h \approx 6 \times 10^{-19}$ and a spectral amplitude sensitivity of less than 1×10^{-21} Hz$^{-1/2}$. In one year of continuous operation, with such a spectral amplitude sensitivity, they can detect monochromatic waves with an amplitude of $h \approx 2 \times 10^{-25}$ (Astone 1996).

Coincidence experiments were performed between Allegro and Explorer. No gravitational wave events were found during a period of 122 days in 1991 with amplitude greater than $h \approx 4 \times 10^{-18}$. Coincidences were also searched in the period from day 180 to day 280 of 1995 between the antenna Explorer and the antenna Niobe. A coincidence excess was found of about a dozen events over the 100 days. To confirm this last result, however, additional data analysis is required and work is in progress.

More recently two ultracryogenic resonant antennas have entered operation: Nautilus (Astone *et al* 1994) in Frascati (Rome) and Auriga (Cerdonio *et al* 1994) at Legnaro (Padua). These two antennas operate in coincidence for the search of wave bursts and for the measurement of the stochastic background.

In Tokyo a resonant antenna of a particular shape has been realized (Suzuki 1994), resonating at about 60 Hz, that can detect gravitational waves possibly emitted by the Crab pulsar. The sensitivity so far reached is $h > 2 \times 10^{-22}$, whilst the optimistic expected value is of the order of 10^{-24}.

Table 1.

			Present sensitivity		Target sensitivity			
	Start	Main characteristics	Δf (Hz)	Sensitivity for 1 ms bursts	Δf (Hz)	Sensitivity for 1 ms bursts	Spectral amplitude (Hz$^{-1/2}$)	Ω (min)
Allegro USA	1970 (1991)	$M = 2300$ kg $T = 4$ K	1	6×10^{-19}	50	1×10^{-20}	7×10^{-22}	
Auriga Legnaro	1989	$M = 2300$ kg $T = 0.1$ K			50	3×10^{-21}	7×10^{-23}	4×10^{-5} 920 Hz
Explorer Rome	1971 (1990)	$M = 2300$ kg $T = 2$ K	1	6×10^{-19}	50	1×10^{-20}	7×10^{-22}	
Grail Holland	1994	$M = 15$ ton $T = 0.02$ K			50	6×10^{-22} omni-directional	1×10^{-23}	2×10^{-6} 1 kHz
Nautilus Frascati	1986 (1995)	$M = 2300$ kg $T = 0.1$ K	1	6×10^{-19}	50	3×10^{-21}	7×10^{-23}	4×10^{-5} 920 Hz
Niobe Australia	1978 (1993)	$M = 1500$ kg $T = 6$ K	1	6×10^{-19}	50	1×10^{-20}	7×10^{-22}	
Tokyo (Crab)	1975 (1991)	$M = 1200$ kg $T = 4.2$ K	10^{-4}	2×10^{-22} continuous h	10^{-4}	2×10^{-24} continuous h		
Grail Omega Tiga	R&D now	$M = 40$ ton $T = 0.02$ K			50	3×10^{-22} omni-directional	7×10^{-24}	1×10^{-6} 1 kHz

In table 1 we indicate the present and expected sensitivity for various antennas. The burst sensitivity can be made larger than that now available by improving the transducers, that is, by increasing their bandwidth. Note that a new group in Holland is beginning a gravitational wave experiment with a resonant spherical detector.

In the first column we have indicated the time when the experiment actually started to be designed and, in parentheses, when it started, although with a sensitivity below the target one, to produce new data.

The last column indicates the minimum gravitational wave density ratio Ω (with respect to the critical density) that can be determined with two equal near detectors operating continuously for one year using equation (5), with $H = 100$ km s^{-1} Mpc^{-1}.

Finally, in the last row we have reported the expected performances of the experiments with spherical detectors that are being planned. The target sensitivity for all resonant detectors has been evaluated assuming that wide-band transducers will become available in the near future (Bassan and Pizzella 1996).

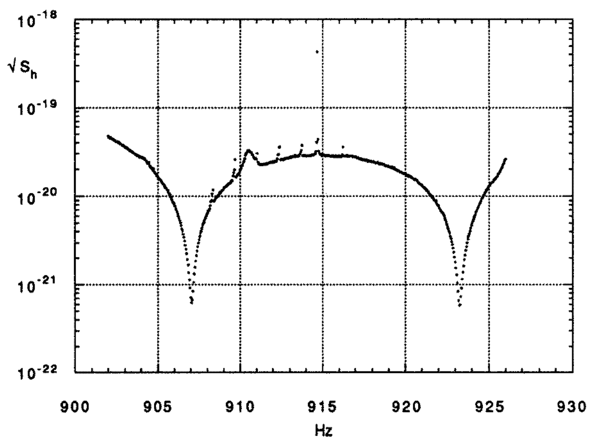

Figure 1. Sensitivity to stochastic GW background with SNR = 1 for Explorer. $T =$ 2.4 K, $M = 2300$ kg, $Q = 5 \times 10^6$, average spectrum over 36 h (Astone *et al* 1996).

For the experiments already performed we show in figure 1 the experimental spectral amplitude noise of Explorer reported at the detectors' input. We notice the value of 7×10^{-22} Hz$^{-1/2}$ at the two resonances of the detector.

From the data shown in the figure, even with a single detector one can deduce an upper limit for the stochastic gravitational waves background in the Universe, although the sensitivity is not yet satisfactory. It is found (Astone *et al* 1996) that $\Omega < 300$.

3. Conclusions

We remark that, in order to reach the target sensitivity, further development of the present techniques is needed. Since it is not possible to guess to what extent a technique can be implemented, it remains very difficult to foresee the time when the above detectors will be sensitive enough to observe gravitational collapses occurring at Virgo cluster distances.

As far as the comparison with the interferometric antennas is concerned, it is our opinion that the two techniques complement each other, the interferometers being more suited for frequencies below 1 kHz, the resonant detectors being more sensitive at 1 kHz and above.

However, it is important, in conclusion, to realize that there are at present sensitive resonant antennas in operation, with a duty cycle that is of the order of 50%, and that they are taking data in an unexplored field of physics.

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