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PROCEEDINGS SUPPLEMENTS

Underground spherical gravitational wave detector

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Recently significant advancements have been made towards the realization of a large spherical gravitational wave detector. Research and development activities have already begun in several countries. We present here the main features and capabilities of a spherical gravitational wave detector. In particular, we discuss the interaction between a spherical antenna and cosmic rays that may require a large detector to be placed underground.

1. Introduction

Several resonant-mass gravitational wave detectors are now in continuous operation with sensitivities that should allow the detection of the strongest sources in our Galaxy and in the Local group [1]. With further improvements to these detectors and the addition of several large laser interferometers now under construction [2], the prospects for gravitational astronomy are quite good.

Many consider the next generation of resonant-mass antennas will be of spherical shape [3]. Research and development activities towards the realization of a large spherical detector have already begun in several countries, in particular Italy and the Netherlands.

A spherical antenna has a number of properties that make it an unique and interesting instrument. A sphere is equally sensitive to gravitational waves from all directions and polarizations. Only a single sphere is necessary for determining the directional information and tensorial character of a gravitational wave. Finally, because of its large mass, a sphere will have a larger cross section than the present bars (with the same resonant frequency).

The realization of a spherical detector leads to a number of possibilities. First, the large cross section and omnidirectionality broadens the number and types of observable sources, opening up the possibility of new astrophysical measurements. Second, the measurement of the direction, polarization states, and the scalar-tensor discrimination allow the study of gravitational physics. Finally, the different features and technology makes a spherical detector complementary to an interferometer. It emerges that an observatory composed of both a sphere and an interferometer will have unprecedented sensitivity and signal characterization capabilities.

A working group (SFERA) has been formed in the ROG collaboration to start an R&D activity for a spherical gravitational wave detector. We intend to carry out studies and measurements essential to define a project of a large spherical detector, 40 to 100 tons of mass. In order to define this project, it is necessary to face and solve various specific problems regarding the cryogenics, vibration isolation, signal processing, and background reduction, including the effects of cosmic rays.

Following recent computations [4], the effects

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of cosmic ray interactions in a spherical detector may set a limit to the sensitivity in an unshielded environment. Part of the SFERA R&D will be to determine if it is necessary to put the detector underground in order to reduce the background noise due to this interaction. This research will proceed in collaboration with the groups of the GRAIL project in the Netherlands.

2. Features

A gravitational wave is a traveling time-dependent deviation of the metric perturbation. The primary physical effect of a passing gravitational wave on an elastic body is to produce a time dependent "tidal" force on the material. This force will cause an observable change in the amplitude and phase of some of the vibrational modes. In order to eliminate other mechanisms that can excite these modes, the elastic body must be cooled to ultra-low temperatures (reduce Brownian motion) and mechanically isolated from the outside world.

In general relativity, the 5 quadrupole modes of vibration of an elastic sphere will strongly couple to a gravitational wave. For an ideal sphere they are degenerate, having the same eigenfrequency, and are distinguished only by their angular dependence. The effective force $F_m(t)$ that a gravitational wave will exert on a quadrupole mode m of the sphere is given by the overlap integral between the sphere's eigenfunctions $\mathbf{\Psi_m(x)}$ and the gravitational tidal force $\mathbf{f^{GW}(x,t)}$

$$\begin{aligned} F_m(t) &\equiv \int \mathbf{\Psi_m(x)} \cdot \mathbf{f^{GW}(x,t)}\, \mathbf{d^3x} \\ &= \frac{1}{2}\ddot{h}_m(t)\, M\, \chi a. \end{aligned}$$

Each spherical component of the gravitational field determines uniquely the effective force on the corresponding mode of the sphere, and they are all identical in magnitude. We can interpret the effective force $F_m(t)$ in each mode as the product of: the physical mass of the sphere M, an effective length χa (a fraction of the sphere radius), and the gravitational acceleration $\frac{1}{2}\ddot{h}_m(t)$.

By monitoring the five quadrupole modes of the sphere, one has a direct measurement of the components of the effective force on the sphere, and thus the spherical amplitudes of the gravitational wave. The standard technique for doing so on resonant detectors is to position resonant transducers on the surface of the sphere that strongly couple to the quadrupole modes. The outputs of the transducers can be combined into "mode channels" that are constructed to have a one-to-one correspondence with the quadrupole modes of the sphere and thus the spherical amplitudes of the gravitational wave [5,6]. With measurement of these amplitudes the direction and polarization of the wave can be calculated.

In the following, we discuss the sensitivity of a spherical detector to a number of astrophysical sources. For this discussion we assume a 3 m diameter, 100 ton, spherical detector cooled to 50 mK, with a sensitivity corresponding to the standard quantum limit. The assumed detector is resonant at 725 Hz with a bandwidth of approximatively 100 Hz. Therefore, the detector has a spectral amplitude of $\tilde{h} = \sqrt{S_h} = 3\times10^{-24}\mathrm{Hz}^{-1/2}$ within the useful bandwidth. This translates into a burst sensitivity of $h_0^{\min} \simeq 10^{-22}$ for a 1 ms burst centered about the fundamental frequency of the sphere.

The sensitivity of our example detector would allow the detection of the gravitational wave collapses occurring in the Virgo cluster with a level of energy release of $10^{-4}M_\odot$. A very interesting burst source is the formation of black holes. When a binary whose total mass M is greater than the maximum neutron star mass coalesces the likely outcome is a mass M black hole. The excitation of a fundamental quadrupole mode of the resulting black hole generates gravitational waves lasting for a few cycles and with frequency inversely proportional to the black hole mass. For Schwarzschild black holes, our example spherical antenna is sensitive to formation of black holes with mass of the order of 15 $M_\odot$ with a signal-to-noise of several out to 200 Mpc [7].

Among the more interesting monochromatic sources for a high frequency detector is a rapidly rotating, non-axisymmetric neutron star. Assuming a reasonable neutron star distribution in space and in frequency, we can expect to detect several sources in one year observation time with nonaxisymmetry ϵ of 10^{-6} out to 1 Mpc with our example antenna [7].

Another interesting signal is the one emitted by an inspiraling and coalescing binary system of two black holes or neutron stars. It has been demonstrated that our example sphere is sensitive to a 1.4 $M_\odot$ neutron star-neutron stars inspiral out to 100 Mpc [8]. Using the second set of quadrupole modes and a double passage technique, one can determine the rate of frequency acceleration and thus the "chirp mass."

Two gravitational wave detectors with overlapping bandwidth Δf will respond to a stochastic background in a correlated way. Spherical detectors can set very interesting limits on the gravitational wave background at kHz frequencies, reaching levels below the limits set by nucleosynthesis, i.e. $\Omega_{gw} \leq 10^{-5}$. In particular, following recent estimations based on cosmological string models [9], it emerges that experimental measurements performed at the level of sensitivity attainable with large spherical detectors would be true tests of Plank-scale physics. An interesting consequence is that it may be worthwhile in the near future to move an advanced resonant mass detector near to a large interferometer, like VIRGO, to perform stochastic searches near 1 kHz.

3. Cosmic ray effect

A cosmic ray crossing the sphere produces a local overheating in the medium which can be related to a local over pressure. Such perturbations propagate acoustically throughout the detector and the net effect on each oscillation mode can be estimated. The relation between the particle energy loss dE along a path dX and the energy E_n in the n^{th} vibrational mode [10] is:

$$E_n = \frac{1}{2}\frac{l_0^2}{V}\frac{G_n^2}{\rho v^2}\gamma^2\left(\frac{dE}{dX}\right)^2, \qquad (1)$$

where l_0 is the total track length of the cosmic ray in the detector and V its the volume. γ, ρ and v are the Gruneisen's dimensionless parameter, the mass density, and the speed of sound in the medium respectively. The "form factor" G_n is related to the eigenmodes of the sphere and is expected to be of order unity.

Different kinds of particles can interact with a resonant detector: muons, electrons, and hadrons. A complete calculations of the effect due to single isolated particles muon and hadrons is in Ref. [11]. The calculations were performed using a Monte Carlo method with the GEANT package to calculate the energy absorbed in the sphere. The muon and hadron fluxes were taken from the experimental measurements.

The effects due to the interaction of multiple particles (electrons, muons, or hadrons from the core of a cosmic ray cascade) is more complicated to evaluate. This is due to the fact that the cascade produced in the atmosphere from a primary cosmic ray is a very complicated process not yet fully understood in detail and that there are technical problems due to the huge number of particles involved. We have done a rough estimation of the rate for extensive air showers and multiple hadrons using simplified hypotheses. In table 1 we summarize the results obtained in [4] for an aluminum sphere 3 meters in diameter.

There are basically two possibilities for dealing with the cosmic ray background for a single antenna: use an active veto with a cosmic ray detector or put the antenna in an underground site. The rate of the cosmic rays impinging on a 3 m sphere is of the order 2 kHz. This means it is not possible to have a veto system with a single layer of detectors signalling all the cosmic rays. This is because the resolution time of the antenna is in the range of tens of milliseconds. Therefore, the veto should be capable of selecting events with the probability of having a large fraction of energy absorbed in the antenna. This means that the veto should be capable to identify energetic muons, hadrons and showers. This should be done on the top of the antenna. In fact, due to the large mass of the sphere no secondary particles will come out from the sphere in case of interaction. A very interesting application of this detector will be the possibility to compare the direction measured from the cosmic ray detector for single particles with the one measured from the sphere using the excitations in the different modes. In this way a continuous calibration of the sphere capability to measure the direction will be possible.

Table 1
The number of cosmic ray events per day calculated from a Monte Carlo simulation for a 3 m diameter aluminum sphere.

Mode energy threshold (K)	ev./day muons	ev./day hadrons	ev./day (EAS)	ev./day multi had.	ev./day total
10^{-6}	10870	8200	535	–	19600
10^{-5}	940	1110	100	22	2180
10^{-4}	84	120	19	20	245
10^{-3}	10	12	4	17	43
10^{-2}	0.5	1.3	0.6	2	4.4

Another solution is to shield the antenna from the electromagnetic and hadronic components of the cosmic ray with absorber and use detectors only for energetic muons (for example a TRD).

In another scenario, two sphere detector could be built. In this case a further and better reduction in the accidental noise will come from the use of the two detectors in coincidence. However, the cosmic rays will still put intrinsic limitations in the search for rare signals. For example in the same ideal noise hypothesis and for a coincidence window of 50 ms we have an accidental rate of 70 ev/year (due to cosmic rays) with a threshold of 10^{-2} K. The conclusion is that the cosmic rays are a strong limitation in the performance of a spherical detector. This effect should be eliminated to reach the best limit sensitivity.

In Fig. 1 we illustrate the number of accidental burst events due to cosmic rays for the various scenarios discussed above. The R&D program in this particular field will focus on a better evaluation of the effects due to cosmic ray cascades, simulations of the cosmic ray excitation of the sphere in the different modes, further analysis of the NAUTILUS cosmic ray detector, and a better understanding of the thermo-mechanical model. This work will be in strong contact with the GRAIL group that is currently doing a test experiment.

4. Conclusions

In the last few years significant advances have been made towards the realization of a spherical antenna. Significant barriers have already been overcome. Cooling large masses to ultra-low temperatures for long periods of time is possible and was demonstrated by the operation of the 2.5 ton NAUTILUS antenna at 100 mK since December 1995 [12]. The 5 quadrupole modes of a real spherical mass are independent and have the required high mechanical Q at ultra-low temperatures [13]. Practicality of the truncated icosahedral symmetry for the positioning of the transducers was demonstrated and coupling of multiple resonant transducers with the 5 quadrupole modes of a spherical mass is understood [14]. The possibility of obtaining large pieces of material suitable for use as spherical antennas was investigated. Large pieces of Al5056 with high quality factors [13] can be obtained by means of explosive bonding, and high quality factors of CuAl alloys (which can be cast in large pieces) were measured [15].

Interest in spherical gravitational wave detectors is present in Australia, Brazil, Italy, Japan, Netherlands, Spain, and USA. A collaboration between these groups was formed several years ago called OMEGA (OMnidirectional Experiments with Gravitational Antennas). In particular, coordinated research efforts are already in progress in Italy and the Netherlands.

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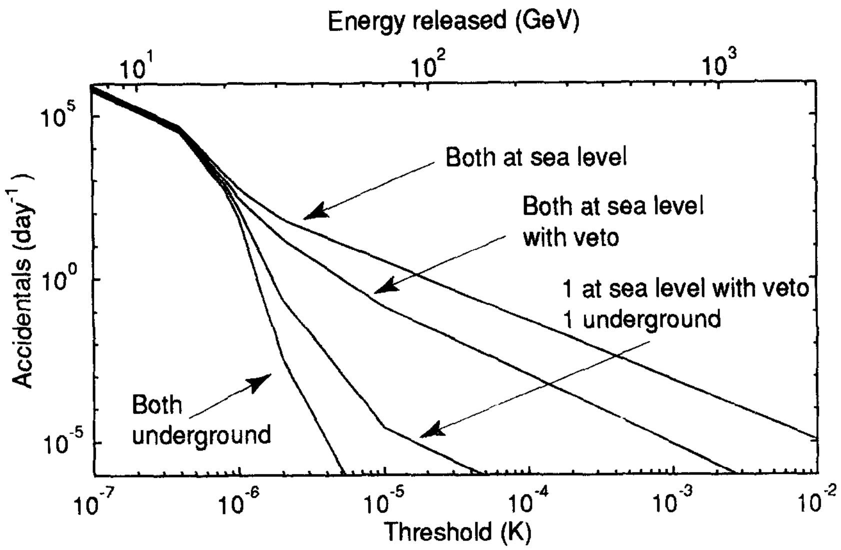

Figure 1. The number of accidental coincidences per day as a function of the detector burst threshold for different pairs of 40 ton aluminum spherical detectors.

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