Anomalous signals due to cosmic rays observed by the bar gravitational wave detector NAUTILUS

2002 Class. Quantum Grav. 19 1897

(http://iopscience.iop.org/0264-9381/19/7/390)

INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **19** (2002) 1897–1903 PII: S0264-9381(02)29442-3

Anomalous signals due to cosmic rays observed by the bar gravitational wave detector NAUTILUS

P Astone[1], D Babusci[2], M Bassan[3], P Bonifazi[4], E Coccia[3], S D'Antonio[5], V Fafone[2], G Giordano[2], A Marini[2], Y Minenkov[3], I Modena[3], G Modestino[2], A Moleti[3], G V Pallottino[5], G Pizzella[6], L Quintieri[2], F Ronga[2], R Terenzi[4] and M Visco[4]

[1] Istituto Nazionale di Fisica Nucleare INFN, Rome, Italy
[2] Istituto Nazionale di Fisica Nucleare INFN, Frascati, Italy
[3] University of Rome 'Tor Vergata' and INFN, Rome, Italy
[4] IFSI-CNR and INFN, Frascati, Italy
[5] University of Rome 'La Sapienza' and INFN, Rome, Italy
[6] University of Rome 'Tor Vergata' and INFN, Frascati, Italy

E-mail: Francesco.Ronga@lnf.infn.it

Received 4 October 2001, in final form 7 December 2001
Published 18 March 2002
Online at stacks.iop.org/CQG/19/1897

Abstract

Cosmic ray showers interacting with the resonant mass gravitational wave antenna NAUTILUS, cooled down to 0.1 K, have been detected. The experimental results show large signals at a rate much greater than expected. Since August 2000 NAUTILUS has been running at $T = 1.1$ K (non-superconductor aluminium). There is evidence at the 3 standard deviation level that the rate of the large signals is dependent on the bar temperature. The rate is compatible with zero at a bar temperature of 1.1 K.

PACS numbers: 0480, 0430, 9640J

1. Introduction

The gravitational wave detector NAUTILUS has recently proved to be capable of recording signals due to the passage of cosmic rays [1, 2]. In the ongoing analysis of the data obtained with NAUTILUS in coincidence with cosmic ray detectors we found interesting new results.

The work initially done by Beron and Hofstander [3, 4], Strini and Tagliaferri [5] and refined calculations by several authors [6–10] estimated the possible acoustic effects due to the passage of particles in a metallic bar. It was predicted that for the vibrational energy in the longitudinal fundamental mode of a metallic bar with length L the following formula holds:

$$E = \frac{4}{9\pi}\frac{\gamma^2}{\rho L v^2}\left(\frac{\mathrm{d}W}{\mathrm{d}x}\right)^2 f(x,\theta) \qquad (1)$$

where E is the energy of the excited vibration mode, $\mathrm{d}W/\mathrm{d}x$ the energy loss per unit length of the particle in the bar, ρ the density, v the speed of sound in the material, $f(x,\theta)$ a function of the angle and position, $f(x,\theta) = 1$ for an orthogonal particle in the middle of the bar and γ the Grüneisen parameter (depending on the ratio of the material thermal expansion coefficient to the specific heat), which is commonly considered constant with temperature. The adopted mechanism assumes that the mechanical vibrations originate from the local thermal expansion caused by the warming up due to the energy lost by the particles crossing the material. The above formula has been recently verified with an experiment, at room temperature [11], using a small aluminium cylinder and an electron beam. It is to be noted that the gravitational wave bar used as a particle detector has characteristics very different from the usual particle detectors, because the usual detectors are sensitive only to ionization losses.

The resonant-mass gravitational wave detector NAUTILUS [12], operating at the INFN Frascati Laboratory (described elsewhere at this conference), consists of an 2300 kg aluminium bar cooled to 0.1 K, below the superconducting transition temperature [13] of 0.92 K.

NAUTILUS is equipped with a cosmic ray detector system consisting of seven layers of streamer tubes for a total of 116 counters [14]. Three superimposed layers, each with an area of 36 m^2, are located over the cryostat. Four superimposed layers are under the cryostat, each with an area of 16.5 m^2. Each counter measures the charge, which is proportional to the number of particles. The detector is able to measure particle densities up to 5000 particles/m^2 without large saturation effects and it gives a rate of showers in good agreement with the expected number [14, 15].

2. The low energy events

The rate of events due to cosmic rays in the NAUTILUS antenna was calculated using the GEANT package, developed at CERN, to simulate NAUTILUS. The muons and the electromagnetic component of the extensive air showers (EAS) were simulated using data measured at sea level. We used the CORSIKA [16] Monte Carlo, as input to GEANT, to simulate the effect of the hadrons produced by the cosmic ray interactions in the atmosphere. The results are shown in table 1.

Table 1. Calculated rate (events/day) due to cosmic rays in NAUTILUS as a function of the energy in the longitudinal fundamental mode, in Kelvin.

Energy (K)	Muons	Ext. air showers	Hadrons	Total
10^{-5}	12.7	50	24.2	87
10^{-4}	1.2	7	3	11.2
10^{-3}	0.18	0.8	0.33	1.3
10^{-2}	0.002	0.1	0.05	0.15

There is quite a large uncertainty in the calculation of the rate of the high energy events. This is due to uncertainties in the cosmic ray composition and uncertainties in the models of hadronic interactions at high energies (see later).

Since the expected signal amplitude is quite small, in our first search for signals due to cosmic rays we performed an analysis using a zero threshold method, which meant carrying out a search adding the NAUTILUS data stretches centred at the time of the cosmic ray showers [1]. The showers were selected with a cut on the particle density larger than 600 particles/m^2. No threshold in the NAUTILUS data stretches was required. The conclusion of that study was that the amplitude of the detected signal was in rough agreement with the calculations. Later

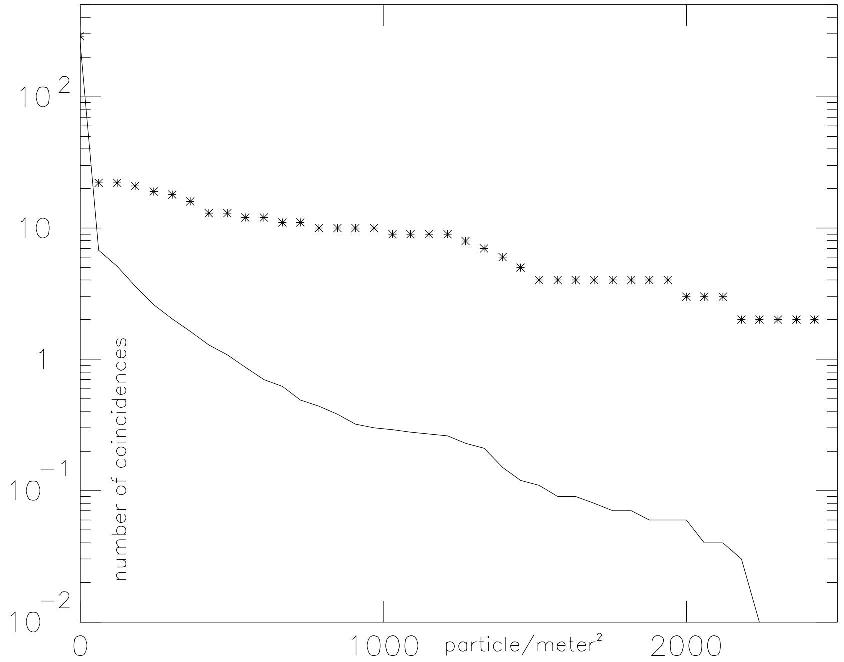

Figure 1. Coincidences between NAUTILUS and the cosmic ray detector for the dataset September–December 1998. The asterisks show the integral number of observed coincidences versus the particle density observed by the cosmic ray counters located under the NAUTILUS cryostat. The continuous line shows the estimated number of accidental coincidences.

we observed a few events having very large energy in NAUTILUS, and we therefore set about searching for coincidences between the cosmic ray detector and NAUTILUS.

3. Search for coincidences

In the present data analysis we consider NAUTILUS events defined as follows. We apply to the filtered data a threshold corresponding to signal-to-noise ratio $SNR = 19.5$, and for each threshold crossing we take the maximum value above threshold and its time of occurrence. We searched for coincidences in three different periods: September–December 1998, February–July 2000 and August 2000–August 2001. In the first two periods NAUTILUS was cooled to 0.1 K; in the last period NAUTILUS was cooled to 1.1 K and the aluminium therefore was not superconducting.

We summarize here the results obtained for the data of the first period [2]. We determined the number of coincidences, using a time window of 0.5 s, as a function of the particle density of the cosmic ray events; the corresponding background of accidental coincidences was estimated by performing one hundred time shifts of the NAUTILUS event times in steps of 2 s. The result is given in figure 1.

A clear excess of coincidences above background is found when the showers have particle density large enough to give a signal in the bar. There are eighteen coincidences for particle density greater than 300 particles/m^2 while the expected number of accidentals is $n = 2.1$. For a particle density greater than 600 particles/m^2 the coincidences reduce to 12, with $n = 0.78$.

We have an unexpected extremely large NAUTILUS event in coincidence with a cosmic ray event, with energy $E = 57.89$ K. The particle density of the cosmic ray detector is the largest in this dataset (3600 particles/m^2). The time of the NAUTILUS event is obtained with good accuracy from the data, given the very large value of SNR = 15 860. The time difference between the NAUTILUS event and the cosmic ray event is 6 ms within the experimental error of the NAUTILUS event, of the order of 10 ms (at present our time accuracy for the NAUTILUS apparatus has been improved). The good agreement between the two times excludes the possibilty that the large amplitude signals are due to electrical signals on the SQUID, induced by the cosmic ray showers. Using equation (1) we find that the largest NAUTILUS event requires that $W = 87$ TeV of energy be released by the shower to the bar. The 57.89 K value should be compared to the value obtained using the particle density under the hypothesis of an electromagnetic shower. In the previous study [1], focusing on the study of low energy signals, we found that this energy is given by $E = \Lambda^2\ 4.7 \times 10^{-10}$ K where Λ is the number of particles in the bar. For the largest event the above formula gives $E =$ 0.019 K, which is more than three orders of magnitude less than the recorded 58 K. Similarly we calculate energies much less than those measured using the NAUTILUS data for all the coincident events. Thus we conclude that most of the observed NAUTILUS events are not due to electromagnetic showers.

In contrast, when using the NAUTILUS low energy events we find that the electromagnetic showers account for the energy observations within a factor of 3 [1]. Moreover, the energy of the low energy signals is correlated with the cosmic ray particle density. On the other hand, no correlation with the particle density is found for the 18 large signals. This is shown in figure 2, and it confirms the conjecture that the observed large events are not due to electromagnetic showers. In conclusion, the NAUTILUS signals are associated with two distinct families of cosmic ray showers: in one family the signals can be interpreted as due to the electromagnetic component of the showers, whereas in the other the electromagnetic component of the shower does not justify the amplitude of the observed signals.

4. Possibilities to explain the high energy events

To explain the high energy events we considered the presence of hadrons inside the electromagnetic shower. The energy lost in the bar due to a single hadron could be quite large. So in the case of hadrons arriving together with the electromagnetic component, the particle density is not related to the energy in the bar. However, the rate of the events due to the hadronic component of the shower calculated in table 1 appears to disagree with our observation by more than one order of magnitude. In figure 3 the calculated numbers are compared with the integrated number of coincidences versus the NAUTILUS event energy. Using equation (1) we can express the integral number in terms of the energy delivered to the NAUTILUS bar by the cosmic rays.

In this figure we also report recent measurements of the CASCADE experiment [17] of the hadronic components of extensive air showers, number of hadronic showers versus their total energy measured with the usual particle detectors. Comparison of these measurements with the result of the Monte Carlo calculation shown in figure 3 with the error bars proves that the calculations were performed correctly, since, because of the small diameter of the bar, we expect only a few per cent of the hadronic energy to be absorbed by the bar, just as shown in figure 3. An immediate finding is that the highest energy event occurs in a time period more than one hundred times shorter than estimated under the hypothesis that the signals in the bar are due to hadrons. This big specific event could be explained as due to a large statistical fluctuation from the expected rate, but we also observe marked disagreement between predicted and observed rates for the entire distribution.

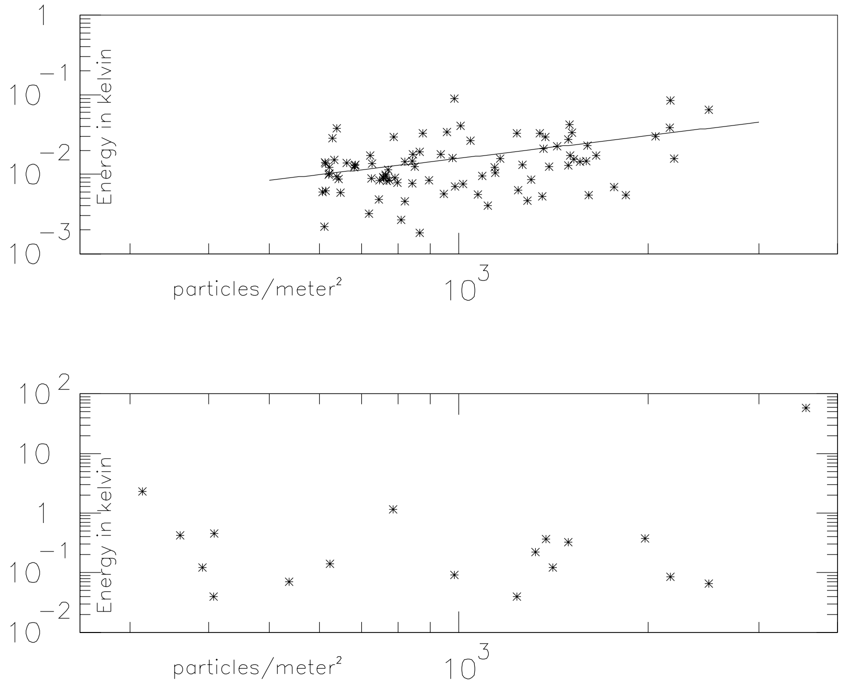

Figure 2. Correlation between the NAUTILUS signals and the cosmic ray particle density. The upper graph shows the correlation of the NAUTILUS energy at zero delay (with respect to the cosmic ray events) versus the corresponding cosmic ray particle density, for the 92 data points considered in [1]. The correlation coefficient is 0.30, with a probability of being accidental of less than 1%. On the other hand the lower plot shows no correlation between the energy of the NAUTILUS coincident events analysed in this paper and the corresponding cosmic ray particle density. The dataset is August–December 1998.

In conclusion, our observations exceed the expectation for hadronic showers by more than one order of magnitude.

Other possibilities to explain our observations must be considered, such as anomalous composition of cosmic rays (the observed showers might include other particles, like nuclearites [8, 19, 20] or Q-balls [21]).

We must also consider the possibility that formula (1) does not always apply, either because the Grüneisen coefficient might be larger at the temperature of NAUTILUS when the aluminium is a superconductor and the specific heat rapidly approaches zero, or because the impact of a particle could trigger non-elastic audiofrequency vibrational modes with a much larger energy release. This has already been suggested [18] for the case of the interaction with gravitational waves, to explain cross-sections higher than calculated.

However, the agreement we found for the low energy signals between experiment and calculation [1] using equation (1) requires the breaking of the thermoacoustical model to occur rather infrequently.

The favoured hypothesis is currently the one related to an anomalous behaviour of the superconductor aluminium. In fact, since August 2000 NAUTLUS has been running at a temperature higher than the critical temperature for aluminium. The result of the coincidence analysis for the overall NAUTILUS data is shown in table 2. In order to have direct comparison the event selection is very similar to the one for the 1998 data (noise temperature less than

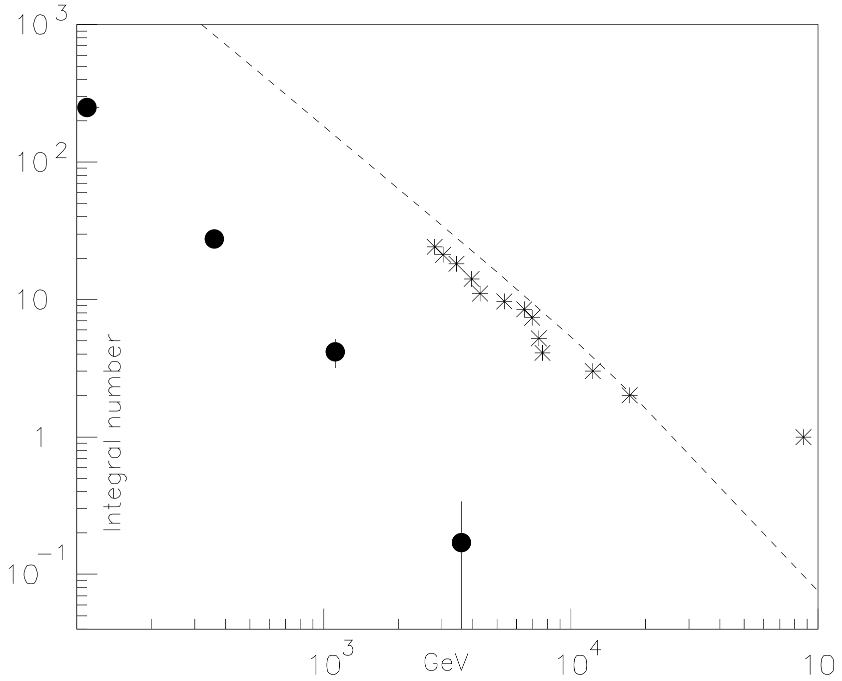

Figure 3. Comparison between calculations and measurements. The asterisks indicate the integrated number of coincident events versus the energy delivered by the cosmic ray to the bar, expressed in GeV units, to be compared with the black points having error bars, which give the number of events due to hadrons we expect in the NAUTILUS bar as result of our Monte Carlo calculation. The errors are the statistical errors of this calculation. The dashed line is the experimental integral spectrum for the hadronic component of the showers for the 83.4 days of observation, obtained by the CASCADE experiment [17]. This line is reported to show the consistency between our Monte Carlo simulation and the measurement of the CASCADE experiment, taking into account the small fraction of energy contained in the NAUTILUS bar (a few per cent). See text.

Table 2. Coincidences cosmic rays—NAUTILUS for superconductor and non-superconductor aluminium.

Data	Bar temperature	Days	Events	Accidentals	Rate (ev/day)
Sept–Dec 1998	0.1	83.4	18	2	0.19 ± 0.051
Feb–Jul 2000	0.1	31.8	13	2.3	0.33 ± 0.11
Total $T = 0.1$ K	0.1	115.2	31	4.3	0.23 ± 0.048
Aug 2000–Aug 2001	1.1	65.7	6	3.4	0.04 ± 0.04

10 mK, signal-to-noise ratio larger than 19.5, particle density larger than 300 particles/m^2). This table offers evidence at about the three σ level that the rate is related to the aluminium temperature, which supports the hypothesis that equation (1) for a fraction of the cosmic ray events does not apply to the superconductor aluminium.

The reason for this possible anomalous behaviour of superconductor aluminium is under investigation: we have proposed a dedicated experiment to check equation (1) at lower temperatures using an electron particle beam hitting a superconductor aluminium bar.

References

[1] Astone P *et al* 2000 *Phys. Rev. Lett.* **84** 14
[2] Astone P *et al* 2001 *Phys. Lett.* B **499** 16
[3] Beron B L and Hofstander R 1969 *Phys. Rev. Lett.* **23** 184
[4] Beron B L, Boughn S P, Hamilton W O, Hofstander R and Tartin T W 1970 *IEEE Trans. Nucl. Sci.* **17** 65
[5] Grassi Strini A M, Strini G and Tagliaferri G 1980 *J. Appl. Phys.* **51** 849
[6] Allega A M and Cabibbo N 1983 *Lett. Nuovo Cimento* **83** 263
[7] Bernard C, De Rujula A and Lautrup B 1984 *Nucl. Phys.* B **242** 93
[8] De Rujula A and Glashow S L 1984 *Nature* **312** 734
[9] Amaldi E and Pizzella G 1986 *Nuovo Cimento* **9** 612
[10] Liu G and Barish B 1988 *Phys. Rev. Lett.* **61** 271
[11] van Albada G D *et al* 2000 *Rev. Sci. Instrum.* **71** 1345
[12] Astone P *et al* (ROG Collaboration) 1997 *Astropart. Phys.* **7** 231
[13] Coccia E and Niinikoski T 1983 *J. Phys. E: Sci. Instrum.* **16** 695
[14] Coccia E *et al* 1995 *Nucl. Instrum. Methods* A **335** 624
[15] Cocconi G 1961 *Encyclopedia of Physics* vol 46 ed S Flugge (Berlin: Springer) p 228
[16] Heck D *et al* 1998 *Report FZKA* 6019 Forschungszentrum Karlsruhe
[17] Horandel J R *et al* 1999 *Int. Cosmic Ray Conf.* (*Salt Lake City*) vol 1 p 337
[18] Fitzgerald E R 1974 *Nature* **252** 638
[19] Witten E 1984 *Phys. Rev.* D **30** 272
[20] Astone P *et al* 1993 *Phys. Rev.* D **47** 4770
[21] Coleman S 1985 *Nucl. Phys.* B **262**