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Searching for counterpart of γ-ray bursts with resonant gravitational wave detectors

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Abstract

Gamma ray bursts (GRBs) likely arise from the collapse of very massive objects or from the coalescence of compact binary systems. In both cases, also a burst of gravitational waves (GWs) should be emitted. The observation of a large number of GRB events gives the possibility of a systematic analysis of the GW detector data when searching for an association between the two emissions. Data collected by the resonant cryogenic detectors, EXPLORER and NAUTILUS, between 1991 and 1999, have been correlated with the GRB events. The analysis excludes the presence of a signal of amplitude $h \geqslant 5.4 \times 10^{-19}$, if we allow a time delay between GW burst and GRB within 10 s.

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1. Introduction

During the last decade, the observation of a large number of GRBs [1, 2], which are likely associated with catastrophic events capable of producing large GW signals, has given the possibility of systematic analysis of the GW detector data around the GRB arrival times. This is very important because GW data analysis in association with GRBs can profit from a number of useful astrophysical data (GRB time, source position, intensity etc), and both positive and negative results could be given a direct astrophysical interpretation. Cumulative data analysis techniques have been developed to detect a statistically significant association between GW signals and GRBs [4–8]. Searching for an association between the two emissions, the main difficulty arises from the theoretical uncertainty of the delay between the GRB and GW emission times. The problem can be reduced implying the data of two GW detectors and using a cross-correlation method [8] . Applying for the first time this technique to the data of two GW detectors, EXPLORER and NAUTILUS, experimental upper limits were determined for the GW burst intensity causing correlation between GWs and GRBs [9]. Analysing the data for 47 GRBs detected by BeppoSAX, the presence of GW pulses of amplitude $h \geqslant 1.2 \times 10^{-18}$ was excluded with 95% probability, within the time window of ± 400 s. Within the time window of ± 5 s, the upper limit was improved to $h = 6.5 \times 10^{-19}$. The restrictive hypothesis of the GW emission simultaneous with the GRB within a few seconds is, anyway, allowed by most of the theoretical models also taking into account the phenomenological nature of the process. Making this hypothesis implicit, several analyses have been performed [10–13]. In [12] an upper limit of $h = 1.5 \times 10^{-18}$ on the average amplitude of GW associated with GRBs was obtained with the resonant bar detector AURIGA, using 120 GRBs and an integration window of 10 s. In [13] the upper limit on the averaged gravitational wave energy released in a neighbourhood of 300 s around the GRB triggers is $h_{\mathrm{RMS}} = 1.8 \times 10^{-18}$ at 95% confidence level. According to the present knowledge, at a distance of 1 Gpc, GW burst signals of the order of $h \sim 10^{-22}$ or smaller are expected in association with GRBs. The sensitivity of the best GW detector for 1 ms GW pulse, with signal to noise ratio equal to unity, is $h \sim 4 \times 10^{-19}$ [14]. Therefore, detection of a GW signal associated with a single GRB appears hopeless. Nevertheless, the analysis of a large number of events can give useful constraints on current GRB theoretical models.

2. Data and method

The ROG Collaboration operates two resonant bar detectors: EXPLORER since 1990 at the CERN laboratory and NAUTILUS since 1995 at the INFN laboratory in Frascati. The two detectors, oriented nearly parallel, are very similar. They consist of massive cylindrical bars 3 m long and made of high quality factor aluminium alloy 5056. The GW excites the first longitudinal mode of the bar which is cooled to liquid helium temperature to reduce the thermal noise. To measure the bar strain induced by a GW, a secondary mechanical oscillator tuned to the antenna mode is mounted on one bar face (as a consequence we have two resonant modes), and a sensor measures the displacement between the secondary oscillator and the bar face. In the present analysis, the data are the output of the lock-in amplifiers tuned to the two resonant modes of the detector, taken with a sampling time of 0.2908 s and processed with an adaptive Wiener filter [15]. The Wiener filtered data represent the energy innovation (expressed in kelvin) of each of the two modes. For each data sample, the minimum energy between the two modes is taken, obtaining the 'minimum' mode time series, $E(t)$, which is the one used in this analysis. The probability distribution of $E(t)$ is

$$f(E) = \frac{1}{T_{\mathrm{eff}}} \exp\left(-\frac{E}{T_{\mathrm{eff}}}\right) \tag{1}$$

where T_{eff}, called the *effective temperature* and expressed in kelvins, gives an estimate of the noise. We make the data selection in the following way. Given the GRB events we consider 5.5 h of GW data centred around the peak flux times on the 1024 ms trigger timescale extracted from the *Flux and Fluence Table* of *BATSE Current GRB Catalog* [3]. For each GRB we split 5.5 h into eleven 30 min stretches and choose only the stretches which have effective temperature less than 10 mK. In this way, for each GRB event, we have a variable number of accepted 30 min stretches[9]. In the present work, we use two algorithms over the selected GW data stretches synchronized using the GRB flux peak time as a common reference, in order to show a possible energy excess at zero delay time within an integration time of 10 s. In principle, the choice would imply losing sensitivity when the GW detector decay time is smaller than 10 s, which occurs about 50% of the time. Nevertheless we must consider the problem of the choice of the *arrival time* as a physical parameter in the analysis. We choose the peak time but it is not the only possible choice from the physical point of view. So, in order to also account for the residual uncertainty in the *arrival time* of GRB, the integration time of 10 s is adopted. The first algorithm computes the average of the selected data stretches corresponding to each GRB. The averaged energy at zero delay is the measured physical quantity to be compared with the background distribution of the same averages taken at all the nonzero delay times. The second algorithm differs from the first one since it measures the median of the zero-delay data instead of their average. This is important because the noise distribution of GW detector data is affected by significant non-Gaussian tails; thus, the occurrence of intense spurious noise spikes is not as infrequent as it would be for an ideal detector with Gaussian noise, and it spoils the averages much more than the medians.

3. Results

In this work cumulative algorithms were used, searching for an energy excess above the background of the GW data at the GRB arrival time. Thus the results of this analysis, in terms of signal detected or upper limits, represent the average GW flux associated with each GRB and released simultaneously with the gamma emission, within 10 s time delay, telling nothing about the possibility of a much earlier and time-scattered GW emission. The analysis, in a time period (5.5 h around the GRB time) much larger than the previous analyses, has only the purpose of a better estimation of the background. For each of the eleven 30 min intervals, 176 stretches, on average, overlap. In figure 1 the result of the application of the average algorithm is shown in the upper graph. The averaged GW detector energy is plotted versus time relative to the GRB flux peak time. In the same figure and in figure 2, the results of the application of the second algorithm are also reported, that is the median distributions. From the average and median time series shown in figure 1, $E_a(t)$ and $E_m(t)$, we consider the average and median values at zero delay, $E_a(0)$ and $E_m(0)$, and compute the time averages $\langle E_a\rangle$ and $\langle E_m\rangle$ and the standard deviations, finding for the average: $E_a(0) = 7.50$ mK, with a time average $\langle E_a\rangle = 7.21$ mK and $\sigma_a = 0.31$ mK; and for the median: $E_m(0) = 5.03$ mK, with a time average $\langle E_m\rangle = 4.61$ mK and $\sigma_m = 0.19$ mK. As we can see, the experimental standard deviation of the distribution of the average is greater than that of the distribution of the median. The ratio between them, 1.63, is larger than the analytic ratio for the exponential distribution, that is 1.44.

4. Sensitivity bound

In the frame of the Bayesian approach (see [9] and references therein), we calculate the *relative belief updating ratio* R comparing the likelihood for a model with a given signal to the likelihood when no signal is present. In the presence of a signal with energy E_s, the expected

[9] As a consequence, the GRBs selected for a given set of 30 min interval are not exactly the same as those selected in the other intervals. This fact is acceptable as long as we only consider the statistical properties of the GW detector noise.

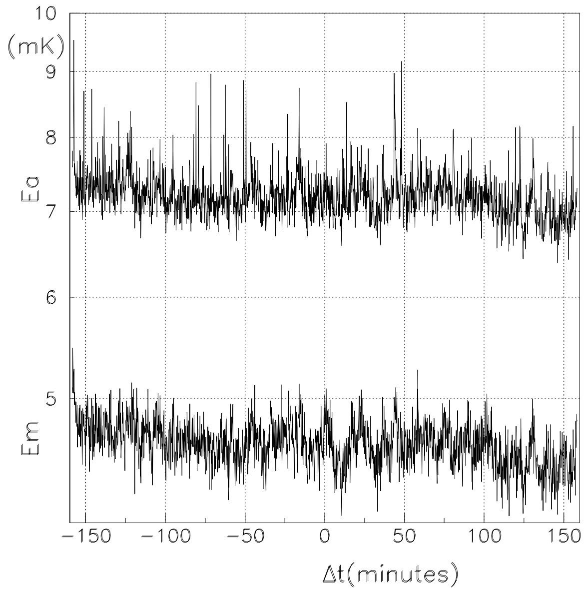

Figure 1. Cumulative average (E_a) and cumulative median (E_m) of the GW detector energy as a function of the GW–GRB delay.

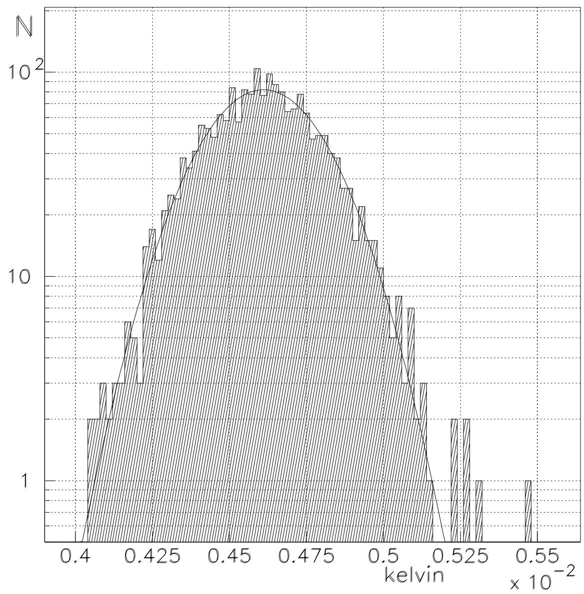

Figure 2. Distributions of the median of the GW detector energy value (see figure 1) and Gaussian fit.

background is

$$E_b = E_n + E_s, \tag{2}$$

where E_n, due to noise, is evaluated using the quantity $\langle E_m \rangle$ previously measured with the median algorithm, which is $\log 2$ smaller than the average value. We have also to take into account a factor due to the choice of the integration time. As we explain in section 2, we

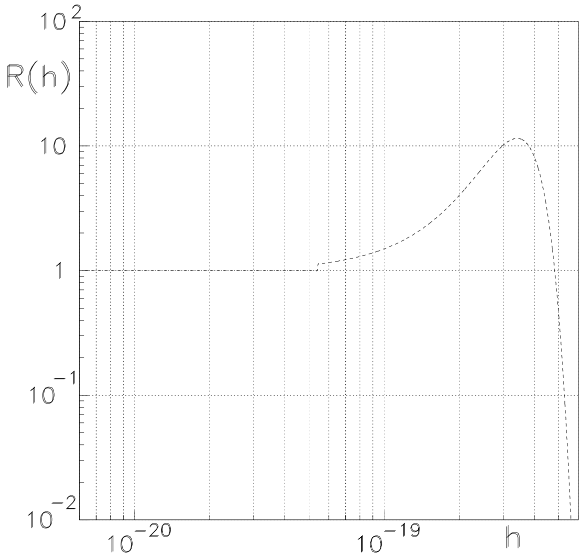

Figure 3. *Relative belief ratio* as a function of the dimensionless amplitude h.

adopted 10 s while the signal due to a GW burst is usually shorter than this value. We evaluated this sensitivity loss in a factor 3. Thus

$$E_n = C\langle E_m\rangle, \tag{3}$$

with $C = 3/\log 2$. Applying the same considerations at the measurement at zero time delay, E_0, and at the corresponding standard deviation σ, we have $E_0 = CE_m(0)$ and $\sigma = C\sigma_m$. Thus the expected normal distribution is

$$f(E_0|E_s) \sim \exp(-(E_0 - (E_n + E_s))^2/2\sigma^2), \tag{4}$$

and the *relative belief updating ratio R*

$$R(E_s) = \frac{f(E_0|E_s)}{f(E_0|E_s = 0)} = \exp\left(-\left(E_s^2 - 2E_0E_s + 2E_nE_s\right)/2\sigma^2\right) \tag{5}$$

which becomes

$$\exp\left(-\left(E^{*2} - 2E_m(0)E^* + 2\langle E_m\rangle E^*\right)/2\sigma_m^2\right), \tag{6}$$

where $E^* \equiv E_s/C$. For our detectors, the relationship between burst energy E (in kelvin) and the dimensionless amplitude h is given by [16]

$$E = \frac{h^2}{(7.97\times10^{-18})^2}\left(\frac{\tau_{\mathrm{gw}}}{1\ \mathrm{ms}}\right)^2 \quad \mathrm{K} \tag{7}$$

where τ_{gw} is the duration of the GW burst, conventionally assumed to be $\tau_{\mathrm{gw}} = 0.001$ s, which means that we consider a flat spectrum up to 1 kHz. The function R, in terms of the amplitude h, is shown in figure 3. We remark that the range $R(h) \sim 1$ corresponds to the region where the experiment is not sensitive enough, so nothing can be learned by the experiment in this range of h. The value $h_{\max} = 3.5\times10^{-19}$ is the value which maximizes R that is the likelihood. $R_{\max} = 11$ gives, only in a rough approximation, how much the belief for $h = h_{\max}$ increases with respect to $h = 0$. In fact, the amount of belief increase depends on the *prior belief*. If a person believes that only values of $h \leqslant 10^{-20}$ were reasonable, this experiment would not affect his convictions. Thus, the above result of $h \neq 0$ can be appreciated only in the case that we can conceive a model which admits the value $h_{\max}$. We can put a sensitivity bound [9] at $R(h) = 0.05$, which means that the model with such a signal is 20 times less likely than the model in the absence of a signal, we have

$$h(5\%) = 5.4 \times 10^{-19}. \tag{8}$$

5. Conclusion

Making the hypothesis of the GW emission simultaneous with the GRB within 10 s, data analysis of the GW cryogenic bars has been performed. Using a large data sample, and a robust filter, the median algorithm, several hours of real data background have been constructed. The presence of signals of amplitude $h \geqslant 5.4 \times 10^{-19}$ is excluded within a time delay of 10 s. Although the sensitivity is still insufficient to expect the detection of signals associated with GRBs, assuming their cosmological origin, the measurement can give interesting indications for further investigations.

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