

# Search for gravitational radiation with the Allegro and Explorer detectors

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The results of a search for short bursts of gravitational radiation coincident between the Allegro and Explorer cryogenic resonant mass detectors with strain amplitudes greater than  $3 \times 10^{-18}$  are reported for data taken from June until December of 1991. While no significant excess of coincident events was found, an improved upper limit to the rate of gravitational wave bursts incident on Earth has been set. [S0556-2821(99)06212-8]

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## I. INTRODUCTION

A single gravitational wave detector cannot differentiate between a gravitational wave passing through an antenna and excitations due to noise. At low energies the thermal spectrum (stationary noise) masks any signal while above that a signal is indistinguishable from a burst of nonstationary noise. A number of detectors operating in coincidence can greatly reduce the noise level by demanding that an incident gravitational wave excite each antenna within a specified amount of time.

In this paper we report on the search for coincident events between the cryogenic resonant gravitational radiation detectors Allegro at Louisiana State University (LSU) and Explorer at CERN (operated by INFN) such as might be produced by the collapse of a massive star. The search involved data taken in 1991. The detectors and methods of data analysis used by each group to search for burst signals are described in detail elsewhere [1–3]. The search involved an exchange of lists of candidate events and an independent coincidence search by each group.

## II. DATA EXCHANGED

The data analyzed in this paper began at the start of June 19, 1991 (UTC day 170) and ended on December 16, 1991

(UTC day 350). There were a total of 2035 h of coincident operation over this time span.

The detectors (see Table I) are essentially identical aluminum alloy cylinders with their primary quadrupole resonance near 910 Hz. Both detectors are cooled to cryogenic temperatures to reduce thermal noise. The antennas are oriented so that their bar axes are close to parallel, and both bar axes are perpendicular to local vertical. This results in nearly identical signal reception patterns; so gravitational waves from any direction are expected to produce similar sized signals in each detector. Both detectors use resonant transducers to convert up the vibrational amplitude of the bar. The Allegro detector uses a single coil inductive transducer [4], while the Explorer detector uses a capacitive transducer [5]. Each coupled bar-transducer system has two normal modes of vibration with the resonant frequencies given in Table I.

Each group has its own methods of data analysis to search for burst gravitational waves. Such a signal is expected from, for example, the collapse of a massive star in a supernova. The result in each case is a list of candidate events characterized by an arrival time and a signal amplitude. The arrival time is reported in UTC. The signal is modeled as having a constant Fourier spectrum over a frequency range  $\delta\nu = 1/\tau_b$ , where  $\tau_b$  is roughly the duration of the burst. As a convention we adopt  $\tau_b = 10^{-3}$  s; so the Fourier spectrum of

TABLE I. The detectors involved in the search. Orientation is given in degrees from north in the direction indicated.

	Position (latitude, longitude, orientation)	Mass (kg)	Frequencies (Hz)	Temperature (K)	Sampling time (s)
Allegro	30.2 N, 91.2 W, 40.4 W	2300	896.7 920.2	4.2	0.080
Explorer	46.2 N, 6.1 E, 39.3 E	2300	904.7 921.3	2.6	0.2908

TABLE II. The number of events above threshold from each detector for 1991.

	No. of events	Time span (UTC days)
Allegro	18412	170-349
Explorer	25086	170-349

the gravitational wave is also constant across the detection bandwidth. The gravitational wave is assumed to be incident with the optimal polarization and direction. The reported signal amplitude is then given by

$$h_c = \frac{|H(\omega_R)|}{\tau_b} \quad (1)$$

where  $H(\omega_R)$  is the Fourier component of the burst at the detector resonant frequencies. The data exchanged consisted of lists of event arrival times and event amplitudes. The numbers of candidate events in each data set exchanged are listed in Table II.

Each group used a different method of optimal filtering to extract small signals from the detector noise. The Explorer data were generated by applying a Weiner-Kolmogorov filter to data sampled at 0.2908 s. The Wiener-Kolmogorov filter was designed to minimize the mean-square error between the signal and its estimation. This filter is adaptive, updating parameters based on the calculated Explorer noise spectrum every 2 h.

The Explorer data were thresholded so that only those events with amplitude greater than  $h_c = 2.3 \times 10^{-18}$  were included. Since the target signal was a short duration burst, it

was expected that the same signal amplitude would be registered in each of the resonant modes. Therefore, those events where the ratio of the measured signal strength in each mode was greater than 1.5 were vetoed from the Explorer data. Periods when the event rate exceeded 60 events/h were also eliminated from the data set, as such a high event rate was considered a sign of poor detector operation. This reduced the total operational time for Explorer from 180 days to roughly 123 days. Finally, those events which could be correlated to a seismic disturbance or other housekeeping measures were eliminated.

The Allegro data were filtered in the time domain by a non-adaptive filter designed to maximize the signal to noise ratio for a burst signal. The filter operated on data sampled at 80 ms. A moving threshold of 11.5 times the stationary noise level was calculated every 6 min and applied to the Allegro data. This level was chosen so that there would be roughly 100 events per day above threshold. Except for times of detector maintenance, such as liquid helium refilling, no other vetos were applied. Figures 1 and 2 show the data sets.

### III. ANALYSIS

A definition of what constitutes a coincident excitation between the two detectors involves a number of considerations, but the result is usually at least an order of magnitude larger than the light travel time between the detectors. This is due in part to uncertainty in the clocks used for timing in 1991 and to the effect of the filtering performed to extract small signals from the noise. At the time of the data exchange, it was decided that two events should be considered coincident if an event from one detector occurred within  $\pm 1.00$  s (referred to as the coincidence ‘‘window’’) of an event recorded by the other detector. This result was arrived at by applying different filtering methods to the same data set and examining the resulting coincidences from the two

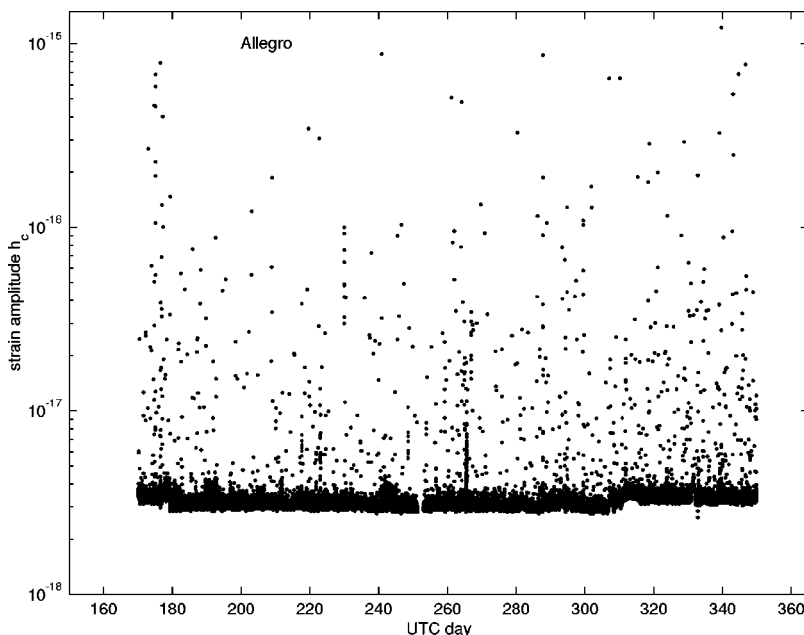


FIG. 1. Events from the Allegro detector.

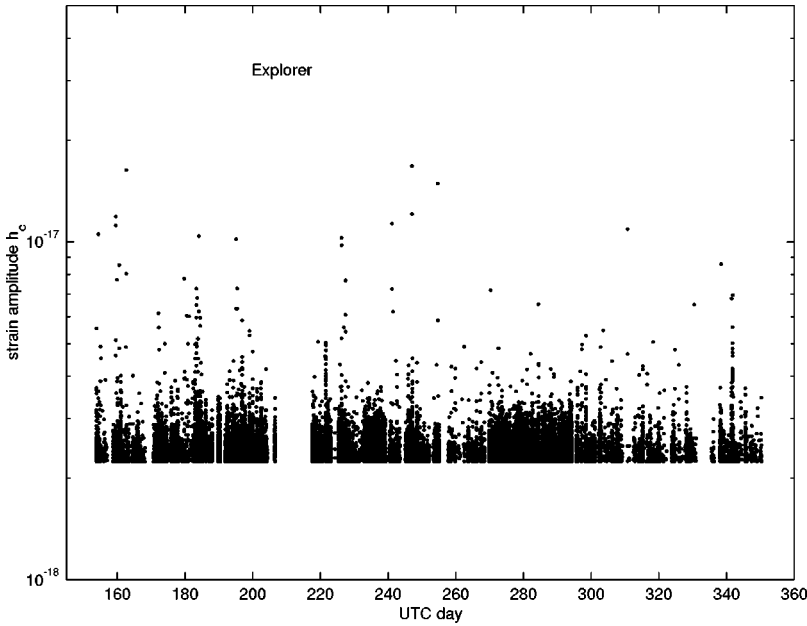


FIG. 2. Events from the Explorer detector.

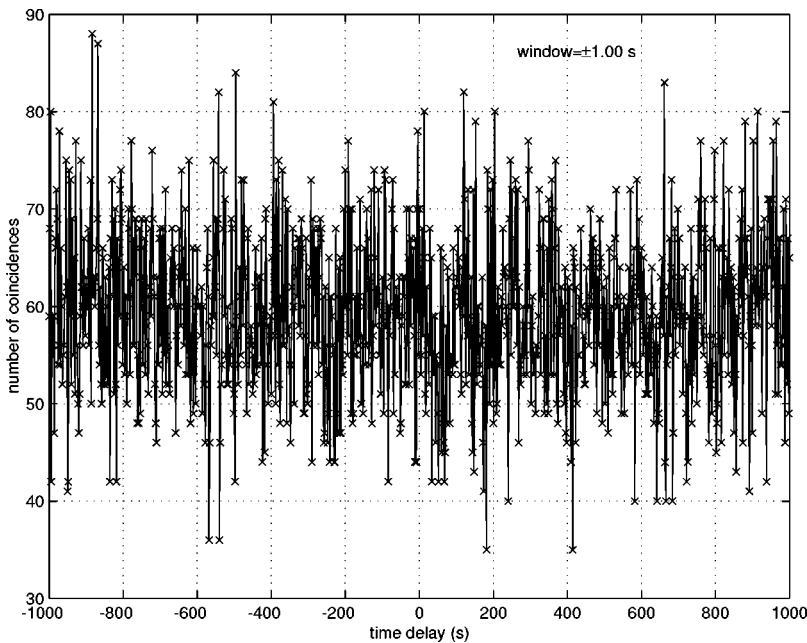
analyses of the same data [6]. A more recent analysis [7] has led to the conclusion that the coincidence window should be taken as small as possible. The limiting factor is the largest sampling time of the participating detectors. For this experiment that was 0.2908 s for the Explorer data, resulting in a coincidence window of  $\pm 0.29$  s. For the sake of completeness and for consistency with previously reported results [8], we present the results for both choices of the coincidence window.

The difficulty in searching for coincident events is that for purely random data there are going to be coincidences which are not produced by gravitational waves. If the event rates in each detector are stationary, then the average number of these “accidental” coincidences are accurately estimated by

$$n_{acc} = n_1 n_2 \frac{\Delta t}{T_{obs}} \quad (2)$$

where  $n_1$  and  $n_2$  are the number of events from each detector,  $T_{obs}$  is the total observing time, and  $\Delta t$  is the coincidence window (equal to twice the stated time since each window is defined as  $\pm$  some time interval). Gravitational wave signals present in the data would cause the observed number of coincidences to exceed the number of accidentals.

However, as can be seen in Figs. 1 and 2, the event rates were not stationary in the two detectors over the 6 months of data taking. One then expects Eq. (2) to be only a rough approximation to the expected number of coincidences. The

FIG. 3. The time delay histogram for Allegro-Explorer coincidences ( $\pm 0.29$  s).

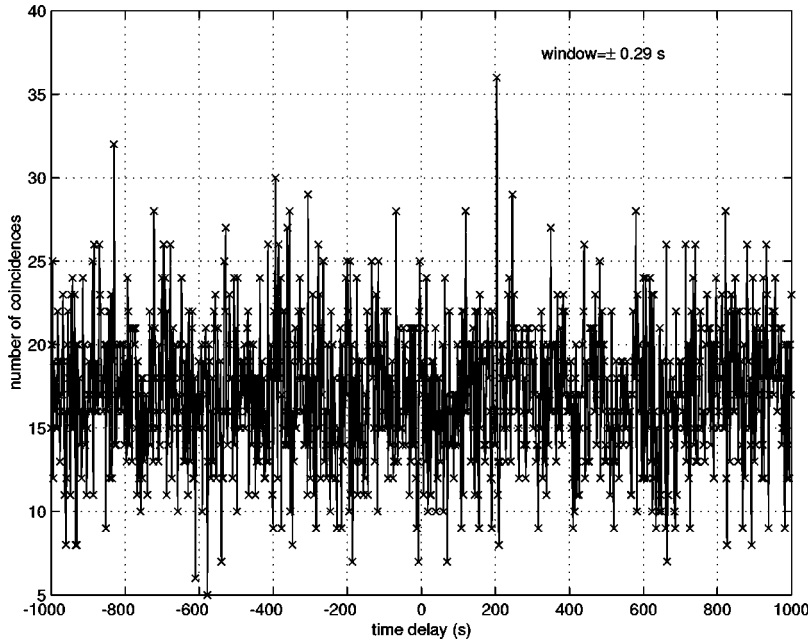


FIG. 4. The time delay histogram for Allegro-Explorer coincidences ( $\pm 1.00$  s).

question is how should those coincidences which are actually observed be interpreted? The following section describes the analysis techniques used here (see also [9] and [10]) to address this issue.

The standard analysis technique to search for coincident events has been referred to in the literature as the “experimental probability” [6]. Instead of using Eq. (2) to estimate the number of accidental coincidences, one measures it experimentally by shifting the event times in one of the two data sets by an amount  $\delta t$  (called the time delay) and determining the number of coincidences  $n(\delta t)$ . A plot of  $n(\delta t)$  vs  $\delta t$  is referred to as a “time delay histogram.” Repeating for  $N$  different values of the time delay, the expected number of coincidences is simply the sample mean of the  $N-1$  values of  $n(\delta t)$  at delays other than  $\delta t=0$ ,

$$\bar{n} = \frac{1}{N-1} \sum_{\delta t} n(\delta t). \quad (3)$$

Since there is no signal at delays other than  $\delta t=0$ , the number of coincidences at these delays can be considered an experimental estimation of the parent distribution from which the accidental coincidences are drawn. For detectors with stationary event rates the parent distribution is Poisson with a mean given by Eq. (2). The number of coincidences at zero delay can then be compared to the experimental distribution. If enough gravitational waves are present in the data,  $n(0)$  will lie outside of the distribution.

By counting the delays at which the number of accidental coincidences equals or exceeds the number at zero delay ( $n_{>}$ ), one can measure experimentally the probability that the coincidences at zero delay occurred by chance,

$$p_{\text{expt}} = n_{>} / (N-1), \quad (4)$$

and hence the term “experimental probability” for this type of analysis.

#### IV. RESULTS

Figures 3 and 4 show the time-delay histograms for each choice of coincidence window with  $N=1001$ . The 1001 time delays were chosen to run from  $-1000$  s to  $1000$  s in increments of 2 s. The sample mean ( $\bar{n}$ ) and the number of coincidences at zero delay [ $n(0)$ ] for each choice of the coincidence window are given in Table III. Also listed are the number of accidentals ( $n_{acc}$ ) calculated from Eq. (2) and the values listed in Table II, and the experimental probability calculated by Eq. (4).

The measured parent distribution of the accidentals for each choice of coincidence window is shown in Fig. 5, along with a Poisson distribution generated using the measured sample mean. As can be seen, even though the event rates in each detector are not constant over time, the measured accidentals distribution is well matched by the Poisson distribution. This is also supported by the good agreement between the measured number of accidentals ( $\bar{n}$ ) and the number expected from purely Poisson statistics ( $n_{acc}$ ). For a window of

TABLE III. The number of coincidences at zero delay  $n(0)$ , the measured ( $\bar{n}$ ) and estimated ( $n_{acc}$ ) values for the accidental coincidences, and the experimental probability that the coincidences at zero delay were drawn from the accidentals distribution ( $p_{\text{expt}}$ ).

Data set	$n(0)$	$\bar{n}$	$n_{acc}$	$p_{\text{expt}}$
Allegro-Explorer ( $\pm 0.29$ s)	19	17.1	17.2	0.36
Allegro-Explorer ( $\pm 1.00$ s)	70	59.3	59.4	0.11

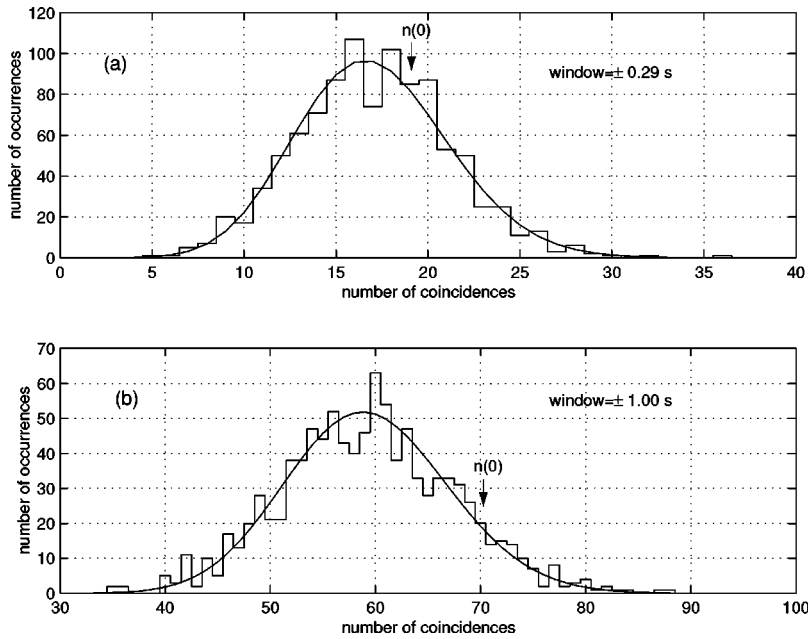


FIG. 5. (a) The accidentals distribution derived from Fig. 3. (b) The accidentals distribution derived from Fig. 4.

$\pm 0.29$  s, the number of coincidences at zero delay is near the mean of the distribution shown in Fig. 5(a) with an experimental probability of 36%. We therefore infer that for this choice of coincidence window, the coincidences at zero delay are samples drawn from the accidentals distribution shown in Fig. 5(a). For a window of  $\pm 1.00$  s, the number of coincidences at zero delay is slightly greater than the mean of the distribution. The corresponding experimental probability is 11%, still too large to claim a discovery. Again we infer that the slight excess of coincidences at zero delay is drawn from the accidentals distribution shown in Fig. 5(b).

Interpreting these conclusions as a null result, we used this information to calculate the upper limit to the possible flux of gravitational wave bursts incident on Earth. The procedure is described in detail in [9]. The number of coincidences at zero delay is assumed to be drawn from one of two distributions. If these coincidences are due to noise alone,  $n(0)$  is a sample from a Poisson process with mean  $\bar{n}$  determined by Eq. (3). If a signal is present,  $n(0)$  is a sample drawn from two independent Poisson processes, events due to detector noise and events due to coincident signals. The mean of this distribution is given by the sum of  $\bar{n}$  and the mean number of coincident events due to gravitational waves (explicitly the rate of coincidences due to gravitational waves multiplied by the observation time). By setting false alarm and false dismissal levels (both were set to 0.05), the mean rate of coincidences due to gravitational waves was determined. This is not yet the desired quantity, as not all incident gravitational waves will cause coincident detection. A Monte Carlo simulation was used to determine the probability that a gravitational wave of a particular amplitude would cause coincident events in the detectors. The distribution of sources was assumed to be isotropic with a random distribution of polarization. Combining these two pieces of information resulted in the upper limit, at a 95% confidence level, which is shown as a function of signal amplitude in Fig. 6 [8]. For comparison we also show the upper limit

obtained with the Stanford antenna alone in 1982 [11] and with the Explorer detector alone in 1991 [1].

## V. CONCLUSION

No significant coincident excitations were observed between the Explorer and Allegro gravitational wave detectors from June until December of 1991. From this result we have set an upper limit on the rate of gravitational wave bursts incident on Earth that is significantly lower than has been previously observed.

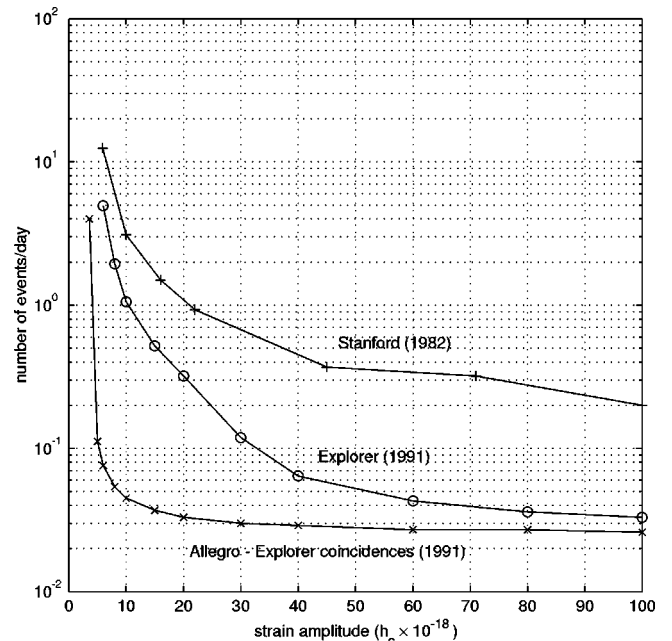


FIG. 6. Upper limit to the rate of gravitational wave bursts incident on Earth.

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