PHYSICAL REVIEW D VOLUME 56, NUMBER 10 15 NOVEMBER 1997

ARTICLES

Search for gravitational radiation from Supernova 1993J

E. Mauceli, Z. K. Geng, W. O. Hamilton, W. W. Johnson, S. Merkowitz, A. Morse, and N. Solomonson
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803

P. Astone,[1] M. Bassan,[2] P. Bonifazi,[3] P. Carelli,[4] E. Coccia,[2] C. Cosmelli,[5] V. Fafone,[2] S. Frasca,[5] I. Modena,[2]
P. Modestino,[6] G. V. Pallottino,[5] G. Pizzella,[7] P. Rapagnani,[5] F. Ricci,[5] R. Terenzi,[3] and M. Visco[3]
[1]*Istituto Nazionale di Fisica Nucleare INFN, Rome, Italy*
[2]*University of Rome ''Tor Vergata'' and INFN, Rome, Italy*
[3]*IFSI-CNR and INFN, Frascati, Italy*
[4]*University of L'Aquila and INFN, Rome, Italy*
[5]*University of Rome ''La Sapienza'' and INFN, Rome, Italy*
[6]*Istituto Nazionale di Fisica Nucleare INFN, Frascati, Italy*
[7]*University of Rome ''Tor Vergata'' and INFN, Frascati, Italy*

(Received 27 February 1997)

The results of a coincidence search for a short burst of gravitational radiation from supernova 1993J with the Allegro and Explorer cryogenic resonant-mass detectors are reported. No detection can be claimed, but an upper limit on the possible strain amplitude from the supernova is calculated. A new method of performing coincidence searches is introduced. [S0556-2821(97)00322-6]

PACS number(s): 04.80.Nn

I. INTRODUCTION

Supernova 1993J was observed optically on March 28, 1993 [1] in NGC 3031 (M81). The supernova, at a distance of 2.0 Mpc, was the brightest (excluding 1987A) in twenty years. 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 the University of Rome) which could have come from the supernova. The detectors and the methods of data analysis used by each group to search for burst signals are described in detail elsewhere [2–4]. 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 begin at the start of March 10 (UTC day 69), and end on April 30 (UTC day 120), surrounding the optical sighting of the supernova. The long observation time of 52 days is used to get an accurate description of the nonstationary noise present in each detector. The detectors (see Table I) are essentially identical aluminum alloy cylinders with their primary quadrupole resonance near 910 Hz. 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 that gravity waves are expected to produce similar burst energies in each detector. Each group has its own methods of data analysis to search for burst signals, the result in each case being a list of candidate events characterized by an ''arrival time'' and a signal strength, referred to as the event energy. The arrival time is reported in UTC and the event energy is defined as the energy, in units of kelvin, that the burst gravitational wave would transfer to the antenna if it were initially in its ground state. The data exchanged consisted of lists of event arrival times and energies. The number of candidate events in each data set exchanged are listed in Table II.

Unfortunately, during this particular interval of time, Explorer was experiencing technical difficulties that increased its noise levels significantly. Since there were no other data available, we decided it was still worth analysis. Three sets of Explorer data were sent to LSU; one set of Allegro data was sent to the Rome group. The Explorer data sets used different vetos on the data and different methods of optimally filtering for burst signals. Two of the sets were compiled with a Wiener-Kolmogorov optimal filter [2,3] referred to as WK1 and WK2. The Wiener-Kolmogorov filter was designed to minimize the mean square error between the anticipated signal and its estimation. The WK1 filter design assumed that there were only two noise processes in the data: thermal noise due to the Brownian motion of the antenna and

TABLE I. The detectors involved in the search.

	Mass (kg)	Frequencies (Hz)	Temperature (K)	Position
Allegro	2300	896.7 920.2	4.2	30.2 N 91.2 W
Explorer	2300	904.7 921.3	2.6	46.2 N 6.1 E

TABLE II. The number of events in each data set exchanged.

Data set	Number of events
WK1	36513
WK2	11012
AM	16754
Allegro	4363

white amplifier noise. The WK2 filter was adaptive, updating parameters based on the calculated Explorer noise spectrum every two hours. Both filters operated on data sampled every 0.29 s. These data sets are shown in Figs. 1 and 2.

The third data set from the Rome group was compiled using an adaptive-matched (AM) optimal filter [2,3], designed to provide the maximum signal to noise ratio for an input δ function signal. As did the WK2 filter, the AM filter used the actual data to calculate the noise power spectrum every two hours. The AM filter operated on data sampled at 4.54 ms, much higher that that of the Wiener filters. The AM events are shown in Fig. 3 and the Allegro events in Fig. 4. 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. Allegro's sampling time was 8 ms.

The difficulty in searching for coincident events is that for purely random data there are going to be coincidences which have nothing to do with gravity waves. The number of these ''accidental'' coincidences is estimated by

$$N_{\mathrm{acc}}=N_1 N_2 \frac{\delta t}{T_{\mathrm{obs}}}, \tag{1}$$

where N_1, N_2 are the number of events in each data set, δt is the coincidence window, and T_{obs} is the observation time over which both detectors are operational. For the WK1-Allegro event lists, the number of accidental coincidences calculated with Eq. (1) is 71. Such a large number of accidentals can easily mask a real detection, or cause the erroneous claim of a detection. In an effort to reduce the possibility of the latter occurrence, a new procedure to look for coincident events was proposed by the LSU group. Called the ''single blind'' coincidence search technique, it involved making one change to the event lists before exchange. Each event time in each list of events was shifted in a circular manner by an amount S. If D is the duration of the comparison interval (52 days), then the time-shift S is applied to the data as S mod D. Events shifted past the end of the comparison interval are ''wrapped around'' to the beginning. To undo the time shift and return the true event times, the *conjugate* to $S(\equiv D-S)$ needs to be added to the false times so as to continue shifting the events around to their true values. The value of the time shift used to generate the exchanged lists was not disclosed to the other group. Instead, a list of 100 possible time shifts was exchanged with the data, only one of which when applied to the data, would return the true event times. The other 99 were generated randomly. Using this procedure, it becomes much more difficult for a particular choice of selection criteria to skew the results of a coincidence search.

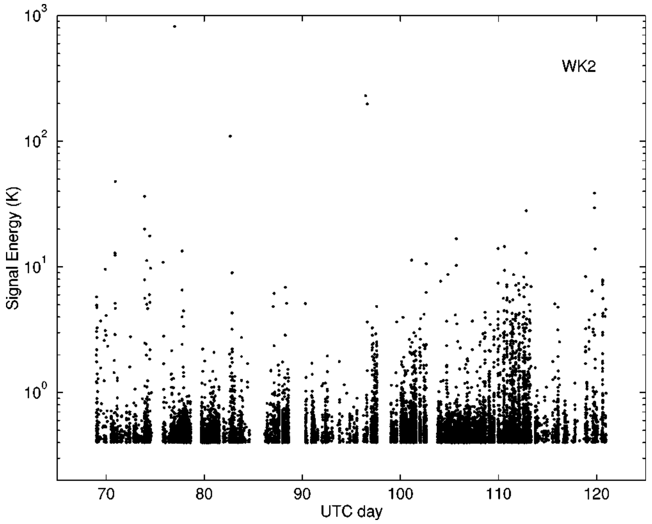

FIG. 2. The shifted event times and energies received by the LSU group for the WK2 Explorer data set.

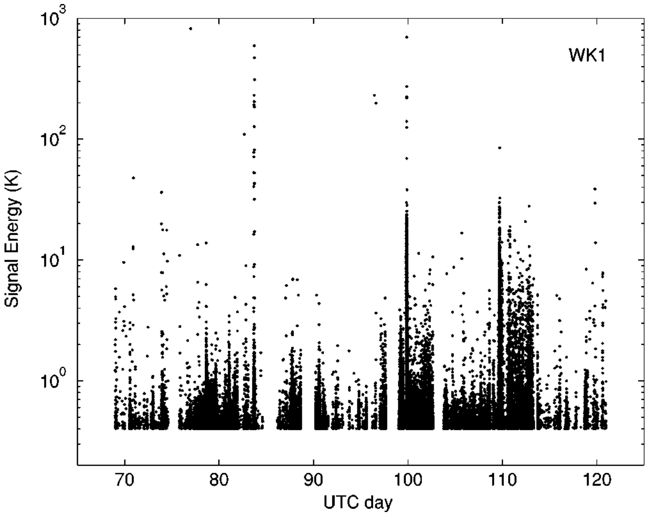

FIG. 1. The shifted event times and energies received by the LSU group for the WK1 Explorer data set.

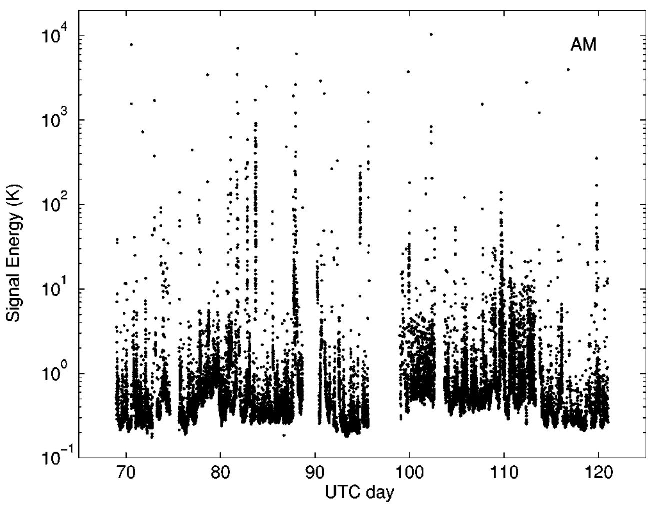

FIG. 3. The shifted event times and energies received by the LSU group for the AM Explorer data set.

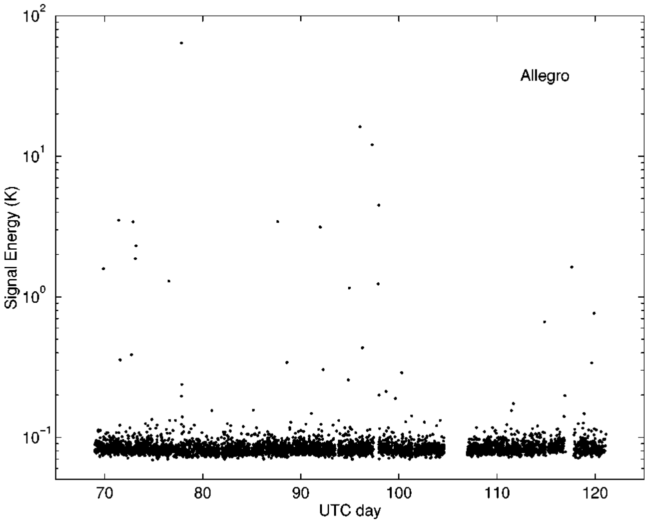

FIG. 4. The true event times and energies for the Allegro data.

III. COINCIDENCE ANALYSIS

To begin the coincidence analysis, one of the time shifts from the list of 100 was added to all the event times from one of the Explorer data sets as described above. The resulting shifted times were compared to the true Allegro event times and all coincidences recorded. Events were considered coincident between the two detectors if they fell within ±1 second of each other [5]. This procedure was repeated for each of the remaining 99 time shifts, and then for the other two Explorer data sets, resulting in three sets of coincident events (WK1-Allegro, WK2-Allegro, AM-Allegro), each set including the coincidences from all 100 time shifts.

Figure 5 shows the Allegro event energies plotted against the Explorer event energies for the coincidences from WK1-Allegro and WK2-Allegro. Coincidences from all the time shifts are plotted on the same graph. Figure 6 shows the same information for the AM-Allegro coincidences. Both detectors have credible calibrating procedures [2,4] so we might expect similar estimates of the energy deposited, within some range due to the addition of Gaussian noise to the signal and also due to the peculiarities of the optimal filter used. Keeping this in mind we somewhat arbitrarily declared that we expected to see a coincident event from a real gravity wave lie within the solid lines in Figs. 5 and 6. The width shown is significantly wider than it would be if the uncertainty was associated with the stationary noise alone.

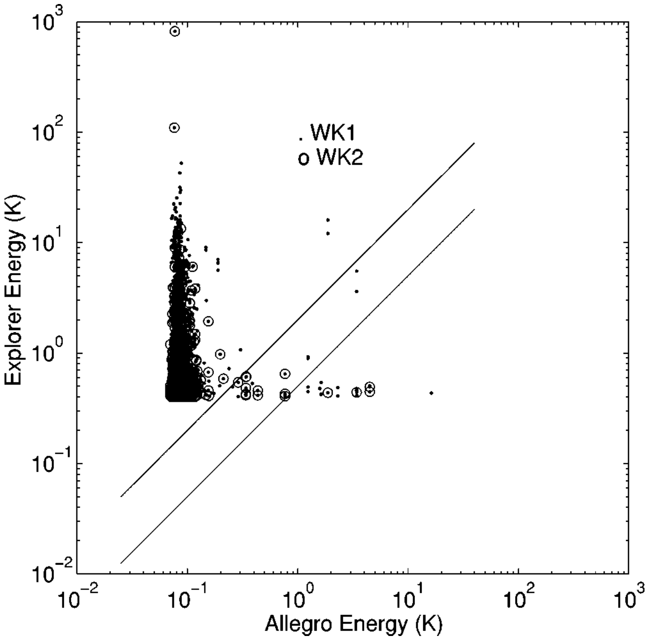

FIG. 5. The Allegro energy plotted against the Explorer energy. The data plotted are all the events coincident in time between Allegro, WK1, and WK2. Candidates for gravity waves lie between the solid lines.

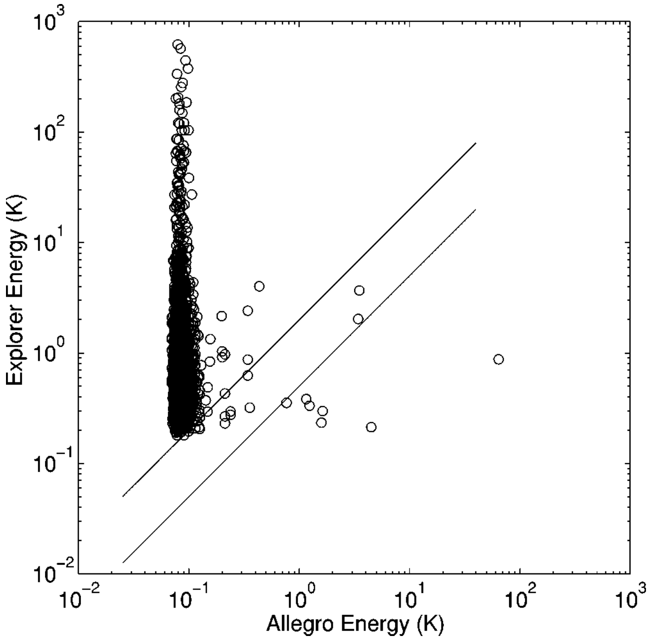

FIG. 6. Same as Fig. 5 but using the AM data set for coincidences with Allegro.

There were only two such events with energy above the noise in the WK1-Allegro coincidence set. They were from the same time-shifted data set, but from a noisy period of Explorer which overlapped with one of the larger Allegro events. They do not appear in the WK2-Allegro coincidence set, making them unlikely gravity wave candidates. All of the other coincidences have energies that do not emerge from the noise. A similar plot of coincidences between the Allegro data and the AM data (Fig. 6) shows two separate events that have a correlation in energy well above the noise. One coincidence involved time-shifting the AM data by 10.57 days and the other by 7.03 days. Since this was a ‘‘blind’’ exchange of data, we did not know the real time-shift so there was no *a priori* way to declare either one a gravity wave detection. This example demonstrates the useful property of this method in searching for gravity waves. If either one of these events was from the real time shift, the fact that the other was not provided an experimental estimate of the probability that such a coincidence happened by chance. After this null result was confirmed by the Rome group, the time shifts which returned the true event times were exchanged. None of the previously mentioned time shifts was the real one.

This ended the ‘‘blind’’ search, with no claim made to

TABLE III. The possible supernova events.

	Event time (UTC day)	Explorer energy (K)	Allegro energy (K)
WK1	87.1096	0.4767	0.0990
	87.3400	0.8088	0.0790
	87.3607	0.5597	0.0790
	87.3885	0.4092	0.0870
AM	87.7414	0.5375	0.0740
	87.8450	0.3500	0.0810

have detected gravitational radiation from the supernova. Next the real time shifts were exchanged so that an estimate to the upper limit of the burst strain from the supernova could be made. First optical sighting of the supernova was at about 87.89 UT [1]. The coincident events between WK1-Allegro and AM-Allegro from day 87 are listed in Table III. The WK1-Allegro coincident event nearest the supernova occurs 12 hours before the first optical sighting, a very generous estimate of the uncertainty in the arrival time of the gravity wave and the first photons. The situation for the AM-Allegro coincidences is more encouraging as both events are within a couple of hours of the first optical sighting. We chose the largest of the two events from the AM-Allegro list to set the upper limit.

For a gravity wave incident with optimal direction and polarization, both Allegro and Explorer relate the Fourier coefficient of the strain amplitude at the bar resonant frequency to the energy deposited in the detector by [6]

$$\tilde{h} \sim 8 \times 10^{-18} \sqrt{T}.$$

Here T is the energy deposited when the gravity wave arrives at the detector with the optimal polarization and direction. In the nonoptimal case, the energy deposited in the detector is

$$T' = \sin^2 \theta \cos^2(2\phi) T,$$

where θ is the angle of incidence of the incoming wave to the bar axis and ϕ is the unknown angle between the polarization state of the wave and the bar axis. For the time in question, $\sin^2\theta \sim 1/2$ and we replaced $\cos^2(2\phi)$ with 1/2 since ϕ is unknown. Making these substitutions and setting $T' = 0.5375$ K we arrived at an upper limit to the burst strain from the supernova of $\tilde{h} \sim 10^{-17}$. For a source at a distance of 2 Mpc, roughly 10^3 solar masses would have to be converted into gravitational radiation by the supernova to produce this strain, an unrealistically large amount.

IV. CONCLUSION

An effective method for searching for coincident events which appears to reduce the possibility of a false detection has been described. There is no statistically significant evidence for the detection of a gravity wave from supernova 1993J with amplitude at the Earth larger than $\tilde{h} = 10^{-17}$.

ACKNOWLEDGMENTS

The LSU group was supported by the National Science Foundation under Grant No. PHY-9311731.

---

[1] International Astronomical Union, Circular No. 5731, Supernova 1993J in NGC 3031, 1993.

[2] P. Astone *et al.*, Phys. Rev. D **47**, 362 (1993).

[3] P. Astone *et al.*, Nuovo Cimento C **17**, 713 (1994).

[4] E. Mauceli, Z. Geng, W. Hamilton, W. Johnson, S. Merkowitz, A. Morse, B. Price, and N. Solomonson, Phys. Rev. D **54**, 1264 (1996).

[5] P. Astone, G. Pizzella, and ROG Collaboration, *Coincidences in gravitational wave experiments* (Laboratori Nazionali di-Frascati, 1995), p. 1.

[6] W. O. Hamilton, *Real performance & real promise, resonant mass detectors of gravitational waves*, in Proceedings of the Seventh Marcel Grossmann Conference on General Relativity and Gravitation, Stanford, 1994, edited by R. T. Jantzen, G. Mac Keiser, and Remo Ruffini (World Scientific, Singapore, 1996).