BAR GRAVITY WAVE DETECTORS AND THE NEXT SUPERNOVA
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Abstract

Detection of neutrinos from Supernova SN1987a, opened up the possibility of coincidence measurements between neutrinos and gravity waves during the next supernova. Work is in progress toward a third generation ultralow temperature resonant-mass detector which could detect with a signal-to-noise ratio of 10, as little as $10^{-6}$ solar masses converted into gravity waves at the center of our galaxy. This opens up a new era for gravity wave detection. It has been predicted that the rate of gravitational collapse in our galaxy is as great as one every 5 years. The neutrino detectors and the gravity wave detectors acting in coincidence could extract completely new information from such an event. If they could obtain directional information, they could alert the astronomical world within a few seconds of the existence of such an event. It is important for all detectors to be on the air all the time and to be connected with a computer network that could recognize the gravitational collapse immediately.
The detection of neutrinos from supernova SN1987a (1,2) has drastically changed the future for bar gravity wave detectors. The ability to detect the neutrinos from a gravitational collapse in our galaxy means that coincidence measurements can be made with gravity wave detectors with certain knowledge that a supernova has occurred at exactly a certain time to the order of a second. Furthermore the simultaneous information which can be determined using the two modes of detection could increase greatly the information available from either one alone. For example the gravity wave should arrive with the velocity of light and be related to an exact phase of the collapse. Thus information about the arrival time of the neutrino with respect to the gravity wave could give important information about the mass of the neutrino and its escape time from the supernova. Furthermore, since neutrinos and gravity wave detectors see their signals exactly at the time of collapse, they can in principle alert the rest of the astrophysical community, within a few seconds of the initial signal of collapse, that there has been a supernova. Hopefully they could also give the direction.

This exciting possibility of simultaneous detection of gravity waves and neutrinos from the next supernova in our galaxy raise several pertinent questions. (i) How long do we have to wait for the next gravitational collapse in our galaxy? (ii) Can we be sure that we will all be on the air when the supernova comes at some completely random time? (iii) Will we have the sensitivity to see the supernova regardless of the direction from which it comes and regardless of where it comes from in our galaxy? (iv) Will we have sufficient signal to noise ratio and bandwidth to extract the maximum amount of information from this single event? (v) How much will it cost to stay on the air continuously for an unknown number of years? (vi) What else can we do with our systems while we are waiting for the next supernova? (vi) Considering the answers to these questions, is it worth it?

Let us consider each of these questions.

(i) **How long do we have to wait for the next gravitational collapse in our galaxy?** Figure 1 is a plot taken from the paper by Tammann (3) of the distribution of known supernova in our galaxy projected onto the galactic plane. It is seen that they occupy a very small percent of the volume of our galaxy. Five of the six are contained within an opening angle of $50^\circ$ centered about the sun. It is apparent from this distribution, and from a study of supernova remnants, as well as from observation of supernova in other galaxies that we do not see optically all of the gravitational collapses in our galaxy. The neutrinos could change that. From a study of other galaxies the rate of occurrence of type I and type II optical supernova in our galaxy is determined, observationally, to be about one every 20 years (3). However, the expected rate of stellar deaths in the galaxy computed using a detailed model of the distribution of stars in the disc and standard stellar evolutionary lifetimes, is one collapse every 8 years (4). Some of these collapses may be optically silent supernovae. The statistics on normal stars massive
enough to form neutron stars when they die suggest a neutron-star birthrate that could be as high as one every 4 years. A recent study (5) of the distribution of radio and X-ray pulsars and their lifetimes suggest that the stellar collapse rate in our galaxy could be one every 1 to 5 years. So the answer to question (i) is that, with neutrinos to detect them, gravitational collapses should be observable in our galaxy sufficiently often to make waiting for them very worthwhile. It is even predicted it might be as often as the 4 or 5 years a graduate student spends in graduate school.

(ii) Can we be sure that we will both be on the air when the next gravitational collapse comes at some random time? With respect to this question gravity wave bar detectors are particularly favorable. The system is expensive and difficult to build, but it is inherently very simple. It is a completely inert system isolated at very low temperatures from both the thermal and mechanical disturbances of the outside world. Even the filling with liquid helium can be replaced by a continuous helium refrigerator. We ran our system at Stanford (6) for a period of more than 2 years with no major problems of maintenance. This is also true of the next generation detectors which will be cooled to 40 millikelvin by a continuous dilution refrigerator.

(iii) Will we have sufficient sensitivity to see the next gravitational collapse in our galaxy regardless of the direction from which it comes and regardless of where it comes from in our galaxy? To answer this question we must estimate the size of the signal expected from a gravitational collapse in our galaxy. Although a large amount of effort has gone into calculation of gravitational collapse to a neutron star or a black hole and the gravity waves emitted, there is no consensus about the results. For a review, see Thome (7). It is likely that such collapses produce bursts with characteristic frequencies in the range $200 \text{ Hz} < f_c < 10^4 \text{ Hz}$ and efficiencies in the range $10^{-7} < \Delta E < 3 \times 10^{-3} M_0 \text{ c}^2$. For detection of such pulses with a signal to noise ratio of 10 or greater requires that the pulse detection noise temperature $T_p$ satisfy

$$T_p < 10^{-4} K \left( \frac{\Delta E}{10^{-4} M_0 \text{c}^2} \right) \left( \frac{10 \text{ kpc}}{D} \right)^2 \left( \frac{10^3 \text{ Hz}}{\Delta f} \right) \left( \frac{\Sigma}{4 \times 10^{-21} \text{ cm}^2 \text{ Hz}} \right) \quad (1)$$

where $D$ is the distance to the source, $\Delta f$ is the pulse bandwidth and $\Sigma$ is the integrated antenna cross-section. The present detector at Stanford has $T_p = 10^{-2} \text{ K}$. The next generation of ultra low temperature detectors will likely have $T_p = 10^{-5}$ to $10^{-6} \text{ K}$. Thus detection of gravitational collapses in our galaxy with $\Delta E > 10^{-6} M_0 \text{ c}^2$ will be possible.

Figure 2 is a diagram of the ultra low temperature system which will cool the antenna as much below its present temperature of 4K as it is below room temperature, 300K. This coupled with improved transducers made out of evaporated circuits of niobium which are expected to improve the electrical Q of the transducer plus a change to a three mass transducer to increase the bandwidth should make it possible to match the noise temperature of the SQUID which is $10^{-5}$ to $10^{-6} \text{ K}$. 

Fig. 1 The six historical supernovae in our galaxy projected on the galactic plane (3)

Fig. 2 0.040 K Gravity Wave Detector
To detect the supernova regardless of the direction from which it comes requires several antennas oriented in different directions more. It has been suggested that the antenna be made into a three dimensional sphere (8) with several transducers to detect the different modes excited by waves from different directions or with different polarizations. Such an antenna, if it could be built, would have also a bigger cross section by roughly a factor of 9 due to its larger mass. This would make the system sensitive to $10^{-7} \text{M}\Omega c^2$ from a collapse at the center of our galaxy.

For a fourth generation detector John Price has suggested that we make use of some of the materials that have as much as 2.5 times the velocity of sound as aluminum with roughly the same mass. Since the sensitivity of the antenna goes as $(V/c)^2$ where $V$ is the velocity of sound in the gravity wave bar such a change would improve the sensitivity by a factor of 6 due to its increased length. If the relative dimensions of the gravity wave antenna remained the same, its volume and therefore its mass would increase by $2.5^3$, making a total improvement of $2.5^5 = 10^2$, giving a sensitivity of $10^{-8} \text{M}\Omega c^2$ from a collapse in the center of our galaxy. If this material were made into a three dimensional cube or sphere the signal to noise could be improved another order of magnitude. Such an antenna would be the ultimate in bar gravity wave detectors. It would have a sensitivity of $h = 3 \times 10^{-22}$ for a millisecond pulse and would be completely three dimensional in its detection efficiency. It would have to be constructed in place like a building. John Price at Stanford is making measurements on materials and studying this problem.

(iv) **Will we have sufficient signal to noise ratio and bandwidth to extract the maximum amount of information from this single event?** The bandwidth is very important if we want to see the details of the first instance of collapse. This can be gained by proper design of a multimode detector with a possible limit of about 50% of the center frequency. It would be desirable to build a series of antennas with ever higher frequency response. With the three dimensional antenna described above the direction of the signal could be determined by the relative amplitude of the signal in the different modes, the resolution being proportional to the signal to noise ratio. The arrival time of the signal at different antennas around the world could further increase the directional resolution, limited once more by the signal to noise ratio. The answer to this question is that antennas could be built to optimize the information one could obtain from a collapse.

(v) **How much will it cost to stay on the air continuously for an unknown number of years?** As was stated in the answer to (ii) a low temperature bar detector once it is cold and running is very inexpensive and easy to maintain especially if one adds a helium refrigerator. It could be run as part of an on-going graduate research program involving graduate students. The cost of running such an experiment would be modest and comparable to other research once the development and construction phase is completed.
(vi) **What else can we do with the system while we are waiting for the next gravitational collapse?** Such a system would be very valuable for looking at any other gravitational wave signals that one could see. If one improved the system by going to high velocity of sound materials and a three dimensional system, one could even see events in the Virgo cluster. In coincidence with the laser systems the bar gravity wave detectors would make a real astronomical gravitational wave observatory.

(vii) **Considering the answers to these questions is it worth it?** The gravity wave detector as described would have a chance to contribute to one of the most important experiments in physics, the detailed observation of the next gravitational collapse. Furthermore it would serve, in the meantime, as a very good gravitational detector for unknown events. This is a new window on the Universe. It was worth the investment before the neutrino observations during SN1987a. Those observations make it an even more worthwhile project. They guarantee, if the systems are built and on the air when the next gravitational collapse in our galaxy occurs, that in the end there will be a certain payoff. Someday another star will collapse in our galaxy. Maybe tomorrow.

References

2. Bionta, R. M. *et al.*, ibid., p. 1494

This work is support by the U. S. National Science Foundation under grants PHY85-13525 and PHY85-15856