GRAVITATIONAL WAVES: THE WAGER

Bernard F. Schutz
Max Planck Institute for Gravitational Physics
The Albert Einstein Institute
Potsdam, Germany
and
Department of Physics and Astronomy
University of Wales College of Cardiff, Cardiff, U.K.

Large-scale laser interferometric gravitational wave detectors now under construction offer a real prospect for making the first direct detections of gravitational waves. Whether they will do so or not before the end of the year 2001 is the subject of a wager between Bruno Bertotti and me. I present here my assessment of my chances of winning the wager. The most promising sources are spinning neutron stars and merging black holes. Neutron stars may be searched for with a single detector, whichever may be the first to operate (possibly GEO600). Confirmation could come from other detectors once they begin operating. Coalescing binary black holes must be detected by two or more detectors, but recent theoretical estimates of the merger rate are sufficiently high to encourage us to hope that LIGO and VIRGO may see one or more events per year. Whether this happens before the end of 2001 depends also on the construction schedules of these detectors!

1 Introduction

It is a great pleasure to be able to give a talk at a symposium in honour of Bruno Bertotti. His influence on the field of gravitational wave detection has been immense and unusually broad. He has made key contributions to the theory of gravitational radiation and especially of the reaction effects on sources. But he is not just a mathematical theorist: he is now leading the team that will analyze data from ESA's interplanetary missions for evidence of low-frequency gravitational waves. Behind the scenes, he has continually pushed for the development of ground-based detectors in Italy, both bars and interferometers. It is no coincidence that Italy is, with the USA, one of the two most active countries in gravitational wave detection in the world.

Against this background, it may be surprising that, when Bruno and I decided in 1993 to make a wager on the likelihood of an early detection of gravitational waves, Bruno took the pessimistic position. The wager, shown in Figure 1, sets a cutoff date of 9 December 2001, exactly 8 years after the date of the wager. It is certainly not true that Bruno hopes for a negative outcome:

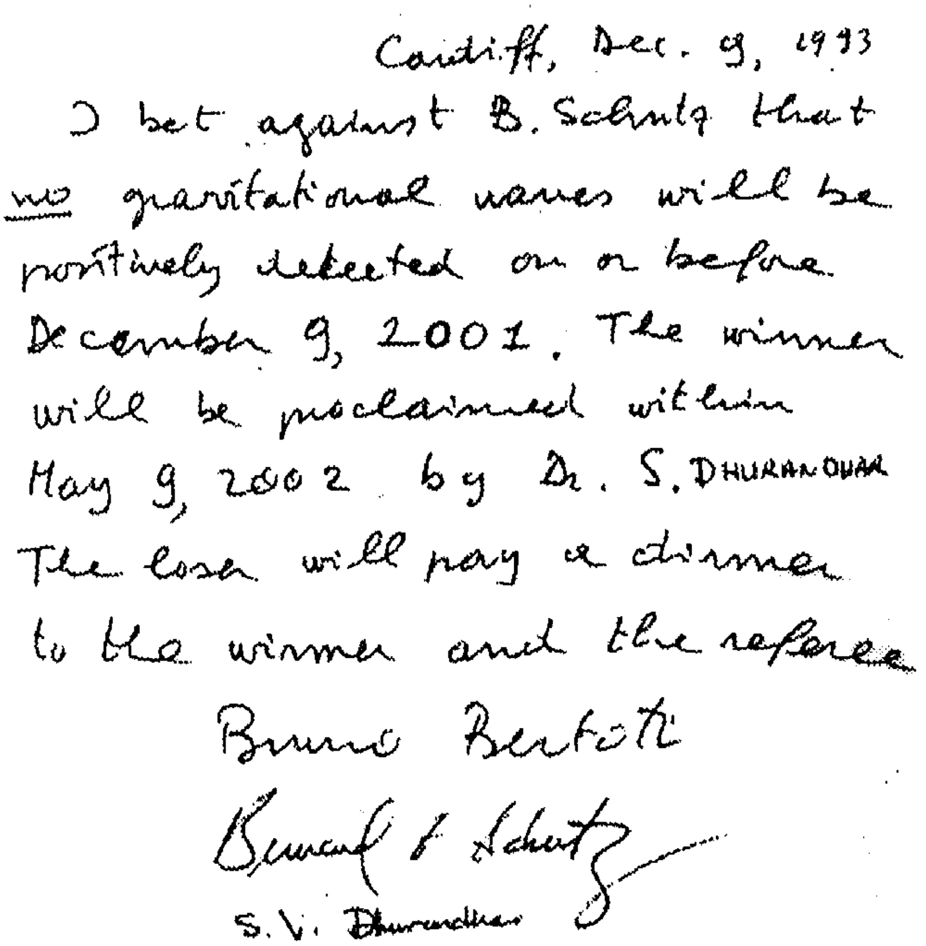
To be published in the proceedings of the September 1996 SIGRAV meeting, World Scientific, 1997.

he would be very happy to lose the cost of a dinner! But Bruno is in this for the long haul: he has never expected that the search for gravitational waves would be easy, and his enthusiasm for the chase will not be dimmed even if we do not find them quickly. I have to admit that in 1993 I expected that the interferometers now under construction would have had a couple of years of operation by 2001. Now it seems that GEO600 [1] will be ready well before 2001, but LIGO [3] may begin operations only late in 2000, and VIRGO [2] may be even later than that. So what are my chances of winning the dinner?

I call these three detector projects the *first generation interferometers*. They are of course not the first interferometers to be built: prototypes operate at Glasgow [4], Garching [5], Caltech [6], and MIT [7]. There is a large 300 m interferometer under construction in Japan, called TAMA300 [8]. In addition, there are many bar detectors in operation, the best of which are in Italy [9], and there are plans for sensitive spherical solid-mass detectors [10]. But the GEO600, LIGO, and VIRGO interferometers are the first that should reach the target strain sensitivity of 10^{-21}, which has always been the theorists' threshold, because at this sensitivity there are grounds to believe that gravitational wave events could be detected a few times per year.

An enlarged TAMA and improvements in the optical systems of the LIGO and VIRGO detectors could, after a few more years, lead to detectors that are a factor of 10 more sensitive. I would call such detectors *second generation interferometers*. On the same timescale we may see spherical detectors or large arrays of smaller bars [11] that would have astrophysically interesting sensitivity at higher frequencies, above 1 kHz.

I think that it would be very surprising indeed if second-generation interferometers did not detect gravitational waves weekly, and probably more often. But to win my bet I need the first-generation interferometers to find gravitational waves first. In this paper I will review the development of these detectors, their expected sensitivity, what kinds of gravitational waves they could detect, and what we might learn from such detections. I will conclude with more in-depth assessments of the two sources that I regard as the most promising for early detection: accreting neutron stars and merging binary black holes. Provided detector construction stays on its present schedule, I believe that the prospects are very good for the first detection of a black-hole coalescence before the end of 2001.



Cardiff, Dec. 9, 1993
I bet against B. Schulz that
no gravitational waves will be
positively detected on or before
December 9, 2001. The winner
will be proclaimed within
May 9, 2002 by Dr. S. DHURANDHAR
The loser will pay a dinner
to the winner and the referee
Bruno Bertotti
Bernard F Schutz
S. V. Dhurandhar

Figure 1: The wager between Bertotti and the present author on the time of the first detection of gravitational waves.

Table 1: First-generation interferometers

Project	Institutions	Location	Length	First obs.
GEO600	MPG, Hannover U., (D), U. Glasgow & Cardiff (GB)	Hannover	600 m.	1999
LIGO	Caltech & MIT (US)	2 det's: Hanford WA & Livingston LA	4 km	2000
VIRGO	INFN (I) & CNRS (F)	Pisa	3 km	2000-2002

2 Detector developments

2.1 *First interferometers under construction*

Three projects now under construction can be expected to begin acquiring good data in the period between 1999 and 2002. They are summarised in Table 1. The column labelled "First obs" is the year in which the detectors can be expected to make their first runs at or near their design sensitivity.

The initial sensitivity of each of these detectors will be similar; the curve for GEO600 is illustrated in Figure 2. The longer arms of LIGO and VIRGO are an advantage, but initially this will be compensated in GEO600 by using more bounces of light up and down each arm, and by implementing a further refinement called *signal recycling* that was devised by the late Brian Meers[12].

In the longer term, the ultimate sensitivity of GEO600 will be worse than that achievable by LIGO and VIRGO. This is because each reflection of light from a mirror introduces thermal vibrational noise. Using signal recycling, GEO600 can minimise this effect and tune itself to high sensitivity in narrow bandwidths. This is illustrated in Figure 3, which shows the sensitivity GEO600 could achieve in a search for sources in a small bandwidth around 600 Hz. Once this technique is perfected in GEO600, it can be transferred to LIGO and VIRGO to enable them to improve their sensitivity to levels that GEO600 cannot reach.

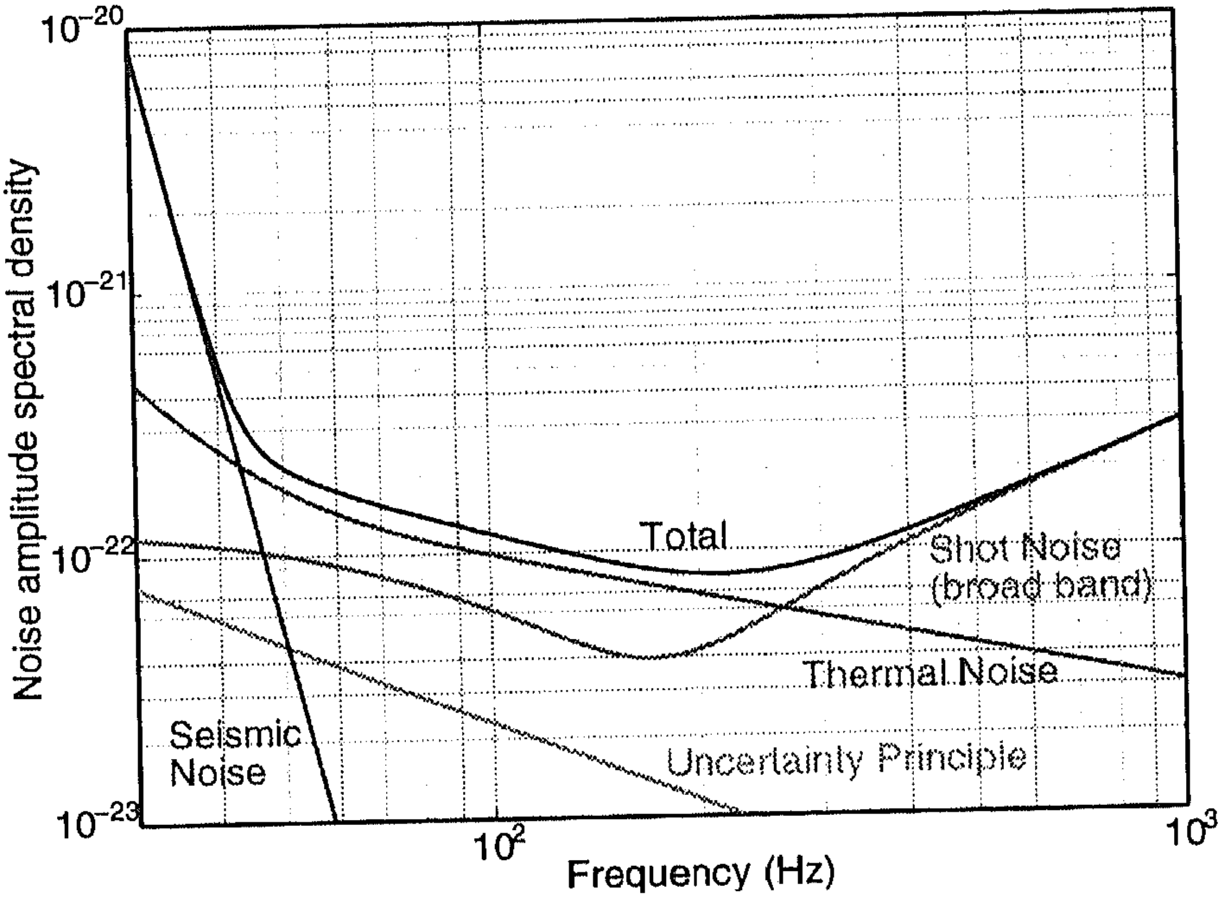


Figure 2: The wideband sensitivity of GEO600 is limited at the lowest frequencies by seismic (external vibration) noise, and below about 200 Hz by thermal vibrational noise. The shot noise curve assumes a degree of "tuning" by broadband signal recycling.

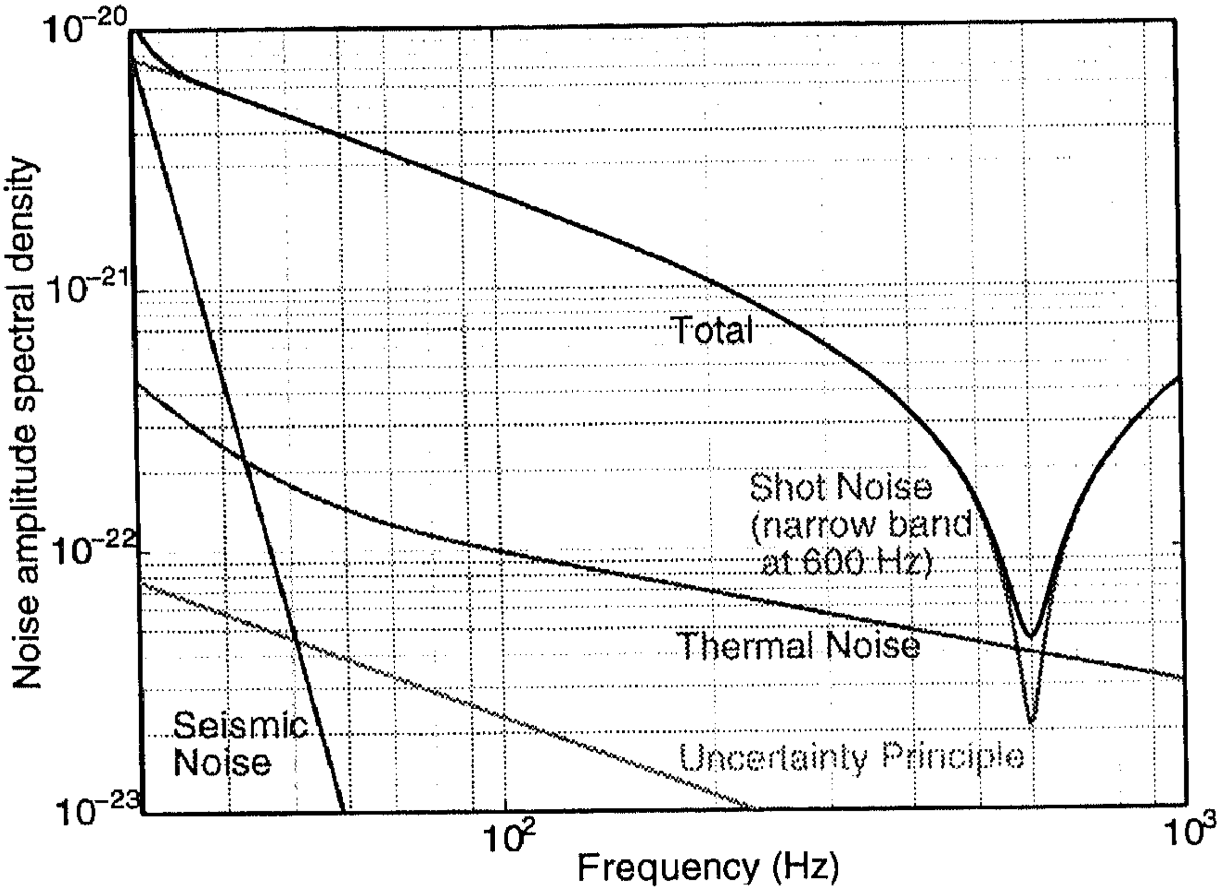


Figure 3: The ability of GEO600 to tune into a particular source is illustrated for a search at 600 Hz.

2.2 New bar detectors

The steady progress made by bar detectors gives one confidence that they can continue to be pushed towards the theoreticians' threshold level of 10^{-21}. So far, progress has been made by lowering the temperature of the bar. The coldest detector is the NAUTILUS bar in Rome[9], which at less than 100 mK is the coldest massive object that the Universe has ever seen! Operating near 1 kHz, it could provide interesting information at frequencies where interferometers do not function very well.

However, if bars of this type cannot beat the so-called "quantum limit" [13], then they must become more massive. Proposals to build spheres of up to 3 m in diameter are currently being studied seriously in a number of countries [10]. A single detector could return information from all 5 quadrupolar modes of vibration, thereby determining the direction of the source all by itself.

Very interesting from the point of view of covering the highest frequencies (above 2 kHz) is the proposal to build an array of a large number of much smaller bars or spheres[11]. This appears to be the only way that this frequency range can be studied. It is an interesting range: the normal mode vibrational frequencies of neutron stars are in this range, and recent calculations[14] have shown that detecting radiation from these modes could have an enormous impact, determining for example the equation of state of neutron matter.

3 What the first generation interferometers could tell us

There is a wide range of possible sources of gravitational waves that might have enough strength to be detected by the first generation of interferometers. In the next 3 subsections, I will describe what kinds of observations they might make and what we could learn from them. I will not consider here the likelihood of any of the sources being strong enough. I will defer that to the final section, where I will discuss that issue in detail for what I consider to be the two most likely sources.

3.1 Fundamental observations

Although we often think of the astronomical information that gravitational wave detectors can provide us about their sources, the can also draw conclusions about fundamental physics for some sources. The very *detection* of gravitational waves will confirm Einstein's theory, which we already expect is correct from the observations of the Hulse-Taylor pulsar[15].

Beyond this, it is possible to test the model of general relativity for the *polarisation* of a gravitational wave. A continuous wave (pulsar) could be tested with a single detector. For a short burst, four or more interferometers must observe it. In each case there is enough redundancy that one can test if the wave is transversely polarised, with two independent components. If the polarisation is more complicated, it could indicate that there are other gravitational fields besides the metric tensor. At the moment, the only constraint on, say, massless scalar gravitational radiation comes from the Hulse-Taylor pulsar system, which would be decaying faster if it were emitting scalar gravitational radiation as well as the tensor radiation expected in general relativity. This constraint is at the 1% level. A strong pulsar source could have a signal-to-noise ratio larger than this, and could thus set a stronger constraint.

Observations can also test the *speed* of gravitational waves. This depends, of course, on the mass (if any) of the graviton. At the moment, the success of Newtonian gravity's $1/r^2$ force in the Solar System and the accuracy of general relativity for the Hulse-Taylor pulsar both imply that the mass of the graviton is less than 10^{-20} eV. A particle of such a mass has a de Broglie wavelength of some 800 AU, so large that the deviation of its Yukawa-type potential from a Newtonian potential would not be detectable in Solar-System observations. Similarly, at a frequency of 1 cycle per 4 hours, the gravitons from the Hulse-Taylor system have an energy of 2×10^{-18} eV, high enough that if they had a mass of 10^{-20} eV the mass would not affect the radiation enough to be measurable. To test the speed of such a graviton, one would have to compare it with the speed of a photon. That is, one would need a source that emitted photons and gravitons at roughly the same time, and one would have to detect the time-of-arrival difference between the observations of the two kinds of radiation. If the source were emitting gravitons at 100 Hz, then their speed would be slower than that of light by enough to produce a time-difference of

$$\Delta t_{arr} = 0.1 \left(\frac{d}{1\ \mathrm{kpc}}\right)$$

A nearby source, say pulsar at 50 Hz, would show a significant phase delay between the electromagnetic and gravitational waves it it were as close as 50 pc. But this might be hard to interpret: the radio pulsations suffer a dispersive delay in the interstellar medium that would have to be known accurately, and more seriously one would not know if there were an intrinsic phase delay due to the geometry of the system (mass quadrupole axes at a different angle from the positions of the electromagnetic beams). However, for a more distant pulsar at, say, 1 kpc, there would be a delay of 5 pulse periods. This would be measurable if the pulsar glitched and the glitch was observed in both radio and the gravitational waves as it happened.

A more distant source in, say, the Virgo cluster (20 Mpc), would show a time-delay of about half an hour between photons and gravitons. If the source were a supernova, this would probably not be detectable. The optical display from a supernova comes out several hours after the collapse that produces the gravitational waves, and the uncertainty in modelling this is at least half an hour. We could pin down the collapse if we had a neutrino signal, but the Virgo cluster is too far away for that. (A supernova in our own Galaxy would be a different story.)

Perhaps the best prospect for placing constraints on the mass of the graviton is with coalescing neutron-star binaries. If they produce an observable electromagnetic burst (for example, if they are the source of gamma-ray bursts), then the delay will be 1 day for a source at 1 Gpc and a graviton mass of 10^{-20} eV. Unfortunately, the first generation of interferometers will be sensitive to such coalescences only from distances closer than the Virgo cluster, so the gamma-burst test will have to wait for the second generation of detectors.

Finally, the first generation interferometric detectors will search for a *cosmological background*, either with other detectors (bars, for example[16]) or in pairs[17]. Bars, in pairs, can also do such searches[19]. Initially their sensitivity will be poorer than limits set, for example, by observations of the millisecond pulsar[18] or indeed by nucleosynthesis limits in the early Universe. I believe that we will have to wait for the second-generation detectors and spherical bar detectors before we get genuinely sensitive searches for a background.

3.2 General astronomical observations

Excluding the stochastic background, which I argued above is unlikely to be detected by first-generation detectors, and leaving pulsars and neutron stars for the next subsection, there are two other kinds of sources that could be plentiful and detectable by the first generation: bursts of radiation from gravitational collapse, and short wavetrains from coalescing neutron-star and black-hole binaries.

A burst of gravitational waves from *gravitational collapse* could be associated with supernova explosions, but not necessarily. Numerical simulations of gravitational collapse show that it is surprisingly difficult to produce an explosion: neutrinos have to be trapped behind the shock to power it away. It may happen that stars that manage to explode will be smooth enough to trap neutrinos, whereas collapses that are highly irregular will not produce observable explosions, but will instead lead to black holes. Then gravitational radiation emission might be anti-correlated with optical emission and positively correlated with black-hole formation. These and other interesting questions can probably only be elucidated by a combination of numerical simulations and gravitational-wave observations. A first-generation interferometer would be able to detect (with a signal-to-noise ratio of 5) a gravitational wave burst at, say, 300 Hz from the Virgo cluster if it radiates about 1% of a solar mass in gravitational wave energy. This is a large amount, although not forbidden by any astronomical observations. Only observations will tell us whether we can rule out such powerful bursts.

The coalescence of two neutron stars or black holes from a binary orbit is one of the most favourable sources for interferometers to search for. The signal is narrow and sweeps upwards in frequency, taking several seconds to move through the bandwidth of a first-generation detector (several minutes for the second generation instruments). By doing matched filtering [20], one gains considerably in sensitivity. To do this satisfactorily for second-generation detectors, one needs to be able to predict the binary orbits to a high degree of accuracy, straining our present approximation methods in general relativity [21]. Recent work has considerably extended the approximations [22], and observations would therefore provide a strong test of the approximation methods and of general relativity itself. Observations would also tell us much about the statistics of the binary systems that give rise to these events, about the masses of neutron stars and black holes, about the association of gamma-ray bursts with such binaries, and about the equation of state of neutron matter [14]. The likelihood that first generation detectors will observe such events is hotly debated. I will address this question in the final section.

3.3 Observations of spinning neutron stars

A single detector could in principle detect and identify the radiation from a spinning neutron star, because the motion of the detector during an extended observation (up to one year) imprints a distinctive pattern of Doppler shifts onto the waveform. It is hoped that this pattern will not be duplicated by terrestrial noise and interference sources, so a detection at reasonable signal-to-noise would have a good chance of being a real gravitational wave. We probably would not have perfect confidence in such a detection by a single (say, the first operating) detector until the source was seen in another detector, but since such sources are long-lived, this would be just a matter of time. Searching for neutron stars, however, poses special data-analysis problems. I will return to this in the final section. There are so many different emission mechanisms and types of waveform from spinning neutron stars that I have given them a subsection of their own.

The most obvious candidate sources are *known pulsars*. These can be relatively young pulsars like the Crab or old, recycled ones like the millisecond pulsars that are found primarily in binary systems. For them to emit over an extended period of time, they must have some kind of frozen-in asymmetry. I we measure this asymmetry by an effective ellipticity δ, which is the ellipticity of an ellipsoid that has the same moment of inertia tensor as the neutron star, then the radiation amplitude from such a star will be

$$h = 2 \times 10^{-27} \left(\frac{f_{gw}}{100\ \mathrm{Hz}}\right)^2 \left(\frac{d}{1\ \mathrm{kpc}}\right)^{-1} \left(\frac{\delta}{10^{-6}}\right). \tag{1}$$

The first generation of detectors will probably not be able to go much below 10^{-25} for a reliable (5σ) identification in a data set of a few months' duration. Therefore they will be looking for pulsars with high ellipticity (10^{-4}) or pulsars that are very nearby. A positive detection would be very interesting. It would tell us what the effective ellipticity is, setting constraints on the stiffness of the crust of the star.

The radiation from known pulsars is constrained by spindown. That is, most pulsars are observed to be slowing down. This means they are losing rotational energy. By assuming that all this energy goes into gravitational radiation, we get an upper limit on the radiation amplitude emitted. This is a very strong upper limit, since we really expect that most of this energy is carried away by emitted particles and low-frequency electromagnetic waves. But it is the only limit we have. In Figure 4 I show the limits on all the pulsars in the Princeton database (as of November 1995) for which we have spindown measurements and estimates of distance, which would emit gravitational waves above 7 Hz, and whose limit is above 10^{-27}. This is compared with the expected sensitivity of the three first-generation interferometers.

There is a strong possibility that radiation is being emitted by neutron stars that we do not know from pulsar observations, either because they are pulsars but are too far away to be detected by radio telescopes, or because they do not emit detectable radiation (being too old or being beamed away from the Earth or just not being emitters). For example, there are probably a handful of *very young pulsars* in the galaxy that are younger than the Crab but which are too far away, or are hidden in molecular clouds, and are not seen as pulsars. The youngest might have a gravitational wave period of 2–3 ms. To find them requires a blind search, which we will consider in the final section. It is complicated by the fact that such pulsars are likely to be spinning down rapidly, so their frequency changes by a very significant amount during the observation time. If they are found then their positions would be determined by gravitational wave observations to accuracies of order 1 arcsecond, and they would provide very interesting targets for follow-up optical and radio observations. If such pulsars are not detected in a comprehensive survey of the sky at frequencies below 500 Hz, then we will learn that ellipticities never exceed 10^{-5} (for first-generation limits) or 10^{-6} (second generation) in such stars.

There are far more *old neutron stars* in the galaxy than observed pulsars, perhaps by a factor of 100 or 1000. The nearest is therefore probably closer than 100 pc, but may have slowed down to below 10 Hz. At this frequency it would have to have a very large ellipticity to be visible to the first-generation detectors, but second-generation interferometers will have a much better chance.

Finally, neutron stars may be driven to emit gravitational radiation by accretion. This was first suggested by Wagoner[23]. I will consider this in detail in the next section. But such stars may emit their strongest radiation when they are accreting inside the envelope of a giant star, as part of the end phase of the evolution of a binary system into a compact-object binary. Such stars are called *Thorne-Zytkow stars*, because they may in the end form a Thorne-Zytkow object [24] if the inspiralling neutron star reaches the core before the envelope evaporates. Figure 4 shows the upper limit on the radiation from such a system at a distance of 1 kpc. This would be very detectable, so these are promising sources. However, since the neutron star is in a binary orbit, a blind search of the whole sky is impossible at good sensitivity. Gravitational wave searches could, on the other hand, target nearby candidate stars, such as Be-giants, which could harbour neutron stars inside their envelopes. There could be as many as 1000 such systems in the Galaxy, or a handful within a few kpc.

4 Best candidates: neutron stars and binary black holes

For different reasons, neutron stars and binary black holes seem to me to be the most likely sources to be detected by the first generation of interferometers before the end of 2001. Binary black hole coalescences may be frequent enough (if one believes recent calculations described below) that there will be a handful of events per year within range of the first detectors, particularly LIGO and VIRGO. Neutron stars are a likely candidate simply because the first detector to operate (possibly GEO600) will be able to look for nothing else reliably. It might indeed register binary black hole coalescences, but in the absence of a coincident event in another detector (bars will not be sensitive enough at the low frequencies required), it will not be able to distinguish them from the random excursions generated by the noise in the detector.

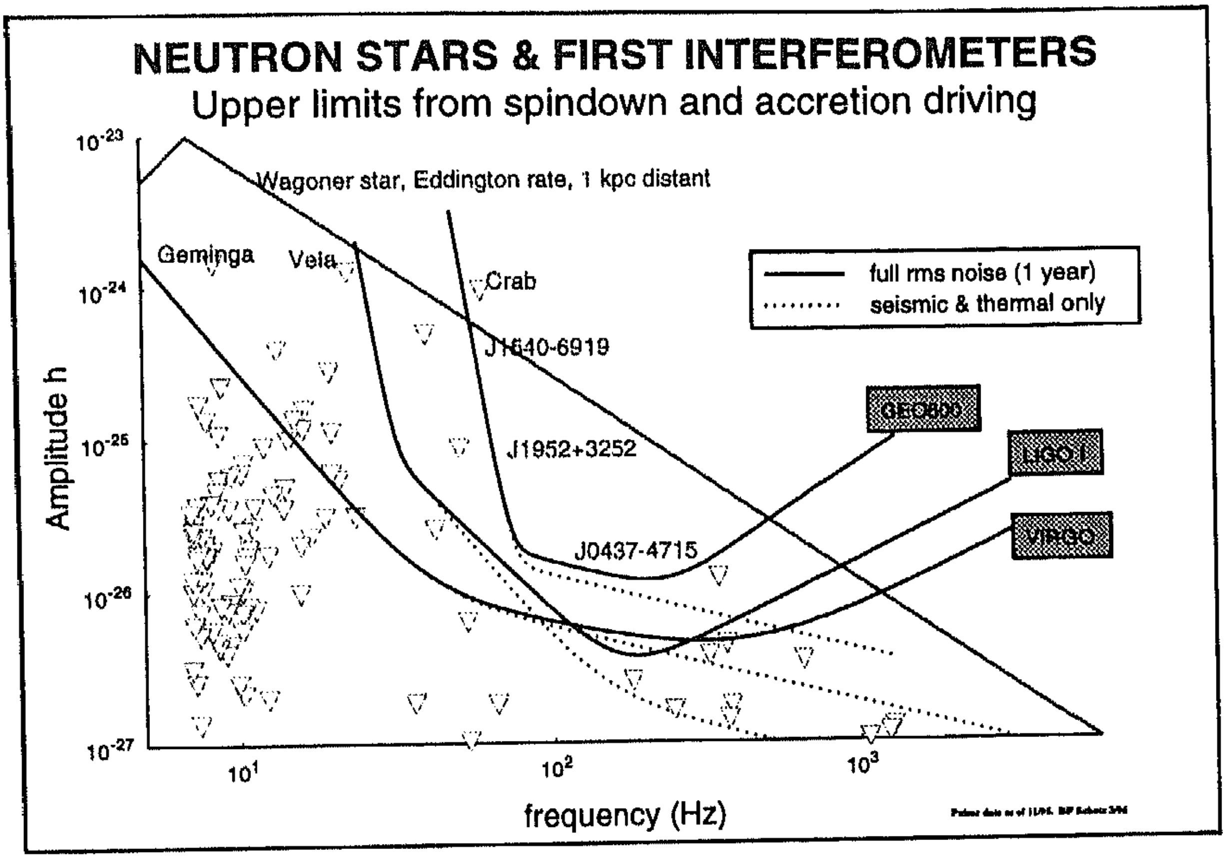


Figure 4: Spindown limits on known pulsars compared with the sensitivity of first-generation interferometers (one-year observation) and the upper limit on radiation from an accreting neutron star driven to emit by the Wagoner mechanism.

4.1 Accreting pulsars

Figure 4 shows that known pulsars are not good candidates for the first generation of detectors: few of them have upper limits that are more than 5 times the noise in individual detectors, and expectations about the strength of neutron star crusts suggest that the real levels of radiation will be orders of magnitude below the upper limits. If pulsars are detected by the first generation of interferometers, then it is more likely that they will be accreting pulsars radiating through the Wagoner mechanism or young pulsars spinning down rapidly.

Young pulsars

Young pulsars have a higher spin rate than the Crab. Measurements of the braking index (the second time-derivative of the pulsar period) are hard to make, but in the two pulsars which are reliably measured (including the Crab) it is very small, suggesting that the pulse period changes linearly with time. The youngest neutron star in the Galaxy may be only about 50 years old, and its spin frequency may be around 200 Hz. This would place its gravitational radiation at 400 Hz. In between there could be as many as 20–60 pulsars in the Galaxy, radiating at frequencies where the first generation detectors are at their best. The upper limits on h at fixed dP/dt scale as $f^{1/2}$, so if we start at the Crab and push its frequency up by a factor of 4, the upper limit goes up by a factor of 2. This places it more than 200 times higher than the GEO600 noise curve at this frequency. It might be further away than the Crab, but even a factor of 3 in distance would make it hard to detect by radio measurements. To be detectable at 10σ, such a star would have to have $\delta \sim 10^{-4}$. This is somewhat larger than theory suggests is possible, but this is still the best chance for detecting young pulsars.

Wagoner stars

Wagoner's mechanism[23] makes a much more definite prediction of gravitational wave amplitudes than does the spindown-limit calculation, but it applies only to a certain class of neutron stars: accreting stars in binary systems that have been spun up to the first instability point of the CFS (gravitational-wave-driven) instability[25,26]. Further accretion simply drives this nonaxisymmetric instability to the point where gravitational waves carry off all the accreted angular momentum. The amplitude of gravitational waves from a source at a distance r, radiating approximately isotropically with a total luminosity L_{gw} and approximately monochromatically at a frequency f_{gw}, has an amplitude

[27]

$$h = 4 \times 10^{-26} \left(\frac{L_{gw}}{10^{30}\ \mathrm{W}}\right)^{1/2} \left(\frac{f_{gw}}{1\ \mathrm{kHz}}\right)^{-1} \left(\frac{r}{1\ \mathrm{kpc}}\right)^{-1} \tag{2}$$

In the Wagoner mechanism, the gravitational wave luminosity is a factor $\beta = O(1)$ times the mass-energy accretion rate $\dot{M}c^2$. For accretion at a rate of $10^{-10} M_\odot\ \mathrm{yr}^{-1}$, which is typical of X-ray binaries, the expected amplitude is

$$h = 6 \times 10^{-26} \beta^{1/2} \left(\frac{\dot{M}}{10^{-10} M_\odot\ \mathrm{yr}^{-1}}\right)^{1/2} \left(\frac{f_{gw}}{100\ \mathrm{Hz}}\right)^{-1} \left(\frac{r}{1\ \mathrm{kpc}}\right)^{-1} \tag{3}$$

In Thorne-Zytkow stars the accretion rate is likely to be closer to the Eddington rate for a neutron star, which is about $10^{-8} M_\odot\ \mathrm{yr}^{-1}$. The frequency f_{gw} is not known ahead of time: it is a property of the unstable mode, and will not equal the neutron star spin frequency. We will return below to the difficulty this makes for a search.

The amplitude of this radiation is larger for lower frequencies, essentially because the energy output is constant. This growth of h with f^{-1} cannot continue to arbitrarily small f, however. One limit on h comes from the distortion of the star: the mode amplitude should not be larger than $\delta R \sim R$. Setting $\epsilon = 1$ in Eq. (1) shows that the Wagoner mechanism reaches a maximum amplitude at a frequency no lower than 5 or 10 Hz. Modes with frequency less than this (just at the onset of the CFS instability) will grow on the same timescale as the star accretes angular momentum, so that they don't begin radiating away the full accreted angular momentum until the frequency reaches this value. These limits are shown in Figure 4.

The biggest theoretical uncertainty about the existence of such sources of gravitational radiation is the fact that viscosity competes with the CFS instability and can prevent it from having any effect. Viscosity is significantly temperature-dependent. Detailed investigations[28] suggest that there is only a limited range of temperatures inside the neutron star in which the viscosity is small enough for the star to be unstable. A newly formed star may be too hot, and known pulsars are old enough to be too cool to be subject to the instability, even if they were spinning fast enough. It is easy to calculate that a neutron star of radius 10 km will radiate at the Eddington rate when its temperature is about 3×10^7 K, so accretion cannot drive the star to a temperature much higher than this.

The Newtonian calculations of Lindblom[28] suggest that this is too cold for the instability to operate. But new fully relativistic calculations of mode frequencies[29] show that the CFS instability sets in earlier in realistic models; the calculation of the effect of viscosity in relativistic stars has not yet been done. In any case, our understanding of the interiors of neutron stars is supported by very little direct observational evidence, and so at this point it is still worth doing searches for Thorne-Zytkow stars as candidates for harbouring neutron star radiators. The problem will be to perform the search with available computer power.

Difficulty of blind searches for unknown neutron stars

In order to get good sensitivity, interferometers need to observe continuously for times of order a few months to a year, as assumed in Figure 4. During this time, the motion of the interferometer induces important Doppler shifts (phase modulation) and less-important amplitude modulations in the signal. These spread the power from the signal over such a wide bandwidth that the detector noise will hide the signal. Such sources can only be detected by removing the phase modulation. The pattern of modulation varies greatly over the sky, so a separate reduction must be made for each location. This has a good and a bad effect: the good effect is that a detected source can be located on the sky to a high precision, of the order of 1 arcsecond for a 1-year observation. The bad effect is that a search will be a very demanding task for even the most powerful computers, and it is likely that our sensitivity will ultimately be limited by the computer power rather than observing time.

The first detailed estimates of the difficulties of this detection problem was by the present author[30]. A more extensive treatment in the case of non-accreting field stars will be found in forthcoming paper by Brady, *et al*[31]. That paper concludes that a search of the whole sky for a radiating neutron star that is spinning down but is not in a binary orbit can be done with a teraflop computer only for data sets of a few days in length. To find an accreting star, which must have additional phase modulation from its orbital motion around the companion that supplies the accreting gas, would pose a hopelessly difficult all-sky search problem.

However, one can contemplate a *targeted* search, where specific positions are searched for orbiting stars. Since the timescale for the completion of the Thorne-Zytkow process may be 10^5 yr or more, the time-scale for the intrinsic frequency of the star may be much longer than assumed by Brady, *et al*, and this again reduces the parameter space that must be searched. Moreover, the orbital of the star can be taken to be circular, if it is inside the envelope of the companion: eccentricity will rapidly dissipate.

In a recent paper[32]. I concluded that a search using 3 months' data would require treating about 10^{14} different parameter sets for each target star. Each parameter set requires something like a Fourier transform of the data. This is less than an all-sky search with such a data set[31], but still not within reach of modern computers. Therefore one will have to use much shorter data sets or adopt hierarchical (multi-stage) search techniques, as described in [31]. These are under investigation.

4.2 Black hole coalescence

Why black holes and not neutron stars?

Most discussions of coalescing binaries as gravitational wave sources have emphasized the detection of neutron-star binaries. This is because we have direct evidence of such systems (such as the Hulse-Taylor system). Moreover, coalescences are rare in any volume of space, so detectors have to be sensitive enough to see events well beyond the Virgo cluster to achieve an acceptable event rate for neutron stars. However, because of their larger mass, black-hole binaries emit stronger radiation, and are therefore detectable in a larger volume of space. Their space density is certainly less than that of neutron star binaries, but their detection rate might still in principle be comparable or even higher. A number of recent theoretical calculations[33,34,35,36] have suggested that the event rate for black holes may indeed be higher, and in fact so high that even first-generation detectors will have a chance to see these events. We will describe these below.

Range of detection

Black-hole binaries of two $10M_\odot$ black holes can be detected about 5 times further away than binaries consisting of two $1.4M_\odot$ neutron stars. At a signal-to-noise ratio of 5, GEO600 could see such sources out to 30 Mpc, 50% further than the Virgo cluster. LIGO and VIRGO could each see them at 100 Mpc. (The second-generation LIGO could reach to 3 Gpc, or redshifts of order 1). Such detections need to be made in coincidence, but by 2001 there should be 3 and possibly 4 detectors in operation for long periods of time.

Distribution in space

The only observational constraint on coalescing binaries comes from the statistics of observed binary pulsars in our Galaxy. Assuming the Galaxy to be typical, and assuming that the three neutron-star binaries we observe are representative of the general population, it is possible to make estimates of the coalescence rate in volumes of space containing many galaxies. There have been many such estimates, which carefully take into account all the known selection effects in searches for binary pulsars. The most recent such estimate, by Lorimer and Van den Heuvel[37], suggests that there should be about 3 coalescences per year of a Hulse-Taylor binary out to about 100 Mpc. This is, of course, a lower limit on the event rate, since there could be other populations of stars not represented by the galactic neutron-star binary population, which could contribute to the event rate.

In fact, this is just what the theoretical calculations predict[33,34,35,36]. They consistently give rates for neutron-star coalescence that are 10 to 100 times higher than the observational lower limits. If one accepts the neutron-star estimates, then one wants to predict an associated event rate for black holes. It is easy to see why black-hole binaries may have a relatively high rate. While observed X-ray binaries suggest that black holes are formed in only a few percent of gravitational collapses, black hole formation has a stabilizing effect on binary orbits. If a supernova in a binary leads to a neutron star, then much more than half of the mass of the pre-supernova star will be lost, and the effect will be to disrupt the system: it will no longer have enough self-gravity to keep it bound. Only if the neutron star gets a kick in a favourable direction can the binary survive. But if a black hole is formed, there is less chance of disrupting the system, because a much larger fraction of the mass of the pre-supernova star remains in the black hole. This effect is multiplied again if a second black hole forms. Therefore, while two gravitational collapses may have a relatively small probability (10^{-4}) of producing two black holes, there is a much higher probability that the binary system will survive, so the coalescence rate for black holes could be as high as 1/3rd to 1/10th of the rate for neutron stars.

Extensive simulations with a variety of parameter choices have led Lipunov and collaborators[35,36] to conclude that the space density of black hole coalescences might be comparable to that of neutron stars, and that the rate for neutron stars is about 10 times higher than the statistics of binary pulsars suggests. This puts the nearest coalescence of either type in one year at a distance of 30 Mpc. If this is true, then even GEO600 has a chance of detecting one event at 5σ per year, and first-generation LIGO and VIRGO should see several.

5 Conclusions

What are the prospects for winning my bet with Bruno? By the end of 2001, GEO600 may have had two or three years of observing, gradually building up the sensitivity of its searches over the whole sky and increasing its sensitivity for selected targets. It may spend part of that time in narrow-band mode, with enhanced sensitivity in a range where the youngest pulsars may be found, and where the Wagoner mechanism produces strong radiation. If the Wagoner mechanism operates at all in Thorne-Zytkow stars, then it seems to me that GEO600 is likely to find it. If young neutron stars can radiate strongly, then GEO600 has some chance of seeing them. But GEO600 will have to wait for LIGO and VIRGO in order to look for black hole coalescences.

Bibliography

1. Danzmann, K., "GEO 600 – A 600-m Laser Interferometric Gravitational Wave Antenna", in Coccia, E., Pizzella, G., Ronga, F., eds., *Gravitational Wave Experiments*, (World Scientific, Singapore, 1995), p. 100–111.
2. Man, C.N., Brillet, A., Cregut, O., Marraud, A., Shoemaker, D., and Vinet, J.Y., "The Virgo Project: a Progress Report", in Blair, D., Buckingham, M.J., eds., *The Fifth Marcel Grossmann Meeting*, (World Scientific, Singapore, 1989), p. 1787–1801.
3. Abramovici, A., Althouse, W.E., Drever, R.W.P., Gursel, Y., Kawamura, S., Raab, F.J., Shoemaker, D., Sievers, L., Spero, R.E., Thorne, K.S., Vogt, R.E., Weiss, R., Whitcomb, S.E., and Zucker, M.E., "LIGO: The Laser Interferometer Gravitational-Wave Observatory", *Science*, **256**, 325–333 (1992).
4. Ward, H, Hough, J, Kerr, G A, Mackenzie, N L, Mangan, J B, Meers, B J, Newton, G P, Robertson, D I, and Robertson, N A, "The Glasgow gravitational wave detector - present progress and future plans", in Michelson, P.F., Hu, En-Ke, Pizzella, G., *Experimental Gravitational Physics*, (World Scientific, Singapore, 1991), p. 322–327.
5. Maischberger, K, Ruediger, A, Schilling, R, Schnupp, L, Winkler, W, and Leuchs, G, "Status of the Garching 30 meter prototype for a large gravitational wave detector", in Michelson, P.F., Hu, En-Ke, Pizzella, G., *Experimental Gravitational Physics*, (World Scientific, Singapore, 1991), p. 316–321.
6. Raab, F. J., "The LIGO Project: Progress and Prospects", in Coccia, E., Pizzella, G., Ronga, F., eds., *Gravitational Wave Experiments*, (World Scientific, Singapore, 1995), p. 70–85.
7. Benford, R, Burka, M, Christensen, N, Eisgruber, M, Fritschel, P, Jeffries, A, Kovalik, J, Linsay, P, Livas, J, Saulson, P, and Weiss, R, "Progress on the MIT 5-Meter Interferometer", in Michelson, P.F., Hu, En-Ke, Pizzella, G., *Experimental Gravitational Physics*, (World Scientific, Singapore, 1991), p. 312–315.

8. Tsubono, K., "300-m Laser Interferometer Gravitational Wave Detector (TAMA300) in Japan", in Coccia, E., Pizzella, G., Ronga, F., eds., *Gravitational Wave Experiments*, (World Scientific, Singapore, 1995), p. 112–114.
9. Coccia, E., "The NAUTILUS Experiment", in Coccia, E., Pizzella, G., Ronga, F., eds., *Gravitational Wave Experiments*, (World Scientific, Singapore, 1995), p. 161–175.
10. Coccia, E., Fafone, V., Frossati, G., "On the Design of Ultralow Temperature Spherical Gravitational Wave Detectors", in Coccia, E., Pizzella, G., Ronga, F., eds., *Gravitational Wave Experiments*, (World Scientific, Singapore, 1995), p. 463–478.
11. Papa, M.A., Frasca, S., "Local Array of High Frequency Antennas", in Coccia, E., Pizzella, G., Ronga, F., eds., *Gravitational Wave Experiments*, (World Scientific, Singapore, 1995), p. 443–448.
12. Meers, B.J., "Recycling in laser-interferometric gravitational-wave detectors", *Phys. Rev. D*, **38**, 2317–2326 (1988).
13. Thorne, K.S., Drever, R.W.P., Caves, C.M., Zimmerman, M., and Sandberg, V.D., *Phys. Rev. Lett.*, **40**, 667 (1978).
14. Andersson, N.A., and Kokkotas, K.D., "Gravitational Waves and Pulsating Stars — What Can We Learn from Future Observations?", *Phys. Rev. Lett.*, **77**, 4134–4137.
15. Taylor, J. H., *Rev. Mod. Phys.*, **66**, 711 (1994).
16. Astone, P., Lobo, J.A., Schutz, B.F., "Coincidence Experiments Between Interferometric and Resonant Bar Detectors of Gravitational Waves", *Class. Quant. Grav.*, **11**, 2093–2112 (1994).
17. Flanagan, E.E., *Phys. Rev.*, **D48**, 2389 (1993).
18. Kaspi, V.M., Taylor, J.H., and Ryba, M.F., "High-precision timing of millisecond pulsars. 3. Long-term monitoring of PSRs B1885+09 and B1937+21", *Astrophys. J.*, **428**, 713–728 (1994).
19. Compton, K.A., *(PhD Thesis)*, (University of Wales, Cardiff, 1996).
20. Schutz, B.F., "The Detection of Gravitational Waves", in Marck, J.-A., Lasota, J.-P., eds., *Relativistic Gravitation and Gravitational Radiation*, (Cambridge University Press, 1996).
21. Cutler, C., Apostolatos, T.A, Bildsten, L., Finn, L.S., Flanagan, E.E., Kennefick, D., Markovic, D.M., Ori, A., Poisson, E., Sussman, G.J., Thorne, K.S., "The Last Three Minutes: Issues in Gravitational Wave Measurements of Coalescing Binaries", *Phys. Rev. Lett.*, **70**, 2984–2987 (1993).
22. Blanchet, L., "Gravitational radiation from relativistic sources", in Marck, J.-A., Lasota, J.-P., eds., *Relativistic Gravitation and Gravita-*

tional Radiation, (Cambridge University Press, 1996).

23. Wagoner, R. V., *Astrophys. J.*, **278**, 345 (1984).
24. Thorne, K.S., and Zytkow, A., *Astrophys. J.*, **212**, 832 (1977).
25. Chandrasekhar, S., *Phys. Rev. Lett.*, **24**, 611 (1970).
26. Friedman, J.L., Schutz, B.F., "Secular Instability of Rotating Newtonian Stars", *Astrophys. J.*, **222**, 281–296 (1978).
27. Misner, C. W., Thorne, K. S., Wheeler, J. L., *Gravitation*, (Freeman, San Francisco, 1973).
28. Lindblom, L., and Mendell, G., *Astrophys. J.*, **444**, 804-809 (1995).
29. Stergioulas, N., *The Structure and Stability of Rotating Relativistic Stars* (PhD Thesis, University of Wisconsin-Milwaukee, 1996).
30. Schutz, B.F., "Data Processing Analysis and Storage for Interferometric Antennas", in Blair, D.G., ed., *The Detection of Gravitational Waves*, (Cambridge University Press, Cambridge England, 1991), p. 406–452.
31. Brady, P., Creighton, T., Cutler, C., and Schutz, B.F., "Searching for periodic sources with LIGO", submitted for publication (gr-qc9702050).
32. Schutz, B.F., in Krolak, A., ed., *Mathematics of Gravitation. II. Gravitational Wave Detection*, (Banach Center, Warsaw, 1997).
33. Tutukov A V, and Yungelson L R, *Mon. Not. R. astron. Soc.*, **260**, 675 (1993).
34. Yamaoka H, Shigeyama T, and Nomoto K, *Astron. Astrophys.*, **267**, 433 (1993).
35. Lipunov, V.M., Postnov, K.A.; Prokhorov, M.E., "First LIGO events: binary black holes mergings", (Sternberg Astron. Institut Moscow, 1996),
36. Lipunov, V.M., Postnov, K.A.; Prokhorov, M.E., "Formation and coalescence of relativistic binary stars", *Mon. Not. Roy. Astr. Soc.*, , (1996).
37. Lorimer, D., and van den Heuvel, E.P.J., "On the galactic and cosmic merger rate of double neutron stars", *Mon. Not. Roy. Astr. Soc.*, **283**, L37–L39 (1996).