GRAVITATIONAL WAVES

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Abstract

The development of detectors for gravitational radiation has never been a more active field than it is today. Bar detectors are improving and forming an observing network, and by the end of 1989, four groups around the world will have proposed to their funding bodies the construction of large-scale laser interferometric gravitational wave detectors. I shall review the reasons for the current optimism about detecting gravitational waves, the theory of their sources, and the science that is likely to come rom this field in the next decade.

1 Introduction

Gravitational wave research goes back at least 30 years to the early efforts of Joseph Weber[1] to develop bar detectors. In these 30 years, there has not been one confirmed detection! One might be forgiven for expecting, therefore, that the field would be in the doldrums, suffering from a lack of direction; nothing could be further from the truth. The present state of the field is probably the most active and optimistic that it has ever been. There are more scientists working in it than ever before, and in 1990 funding agencies around the world seem likely to commit some $200–300M to the construction of a network of laser interferometric antennas.

What are the reasons for this activity? I can identify three:

1. *Technology* has improved dramatically over the past 30 years, so that only now is it possible to design a practical detector which ought to be able to reach theoretical predictions of signal strength and beyond.
2. *SN1987A* — the supernova that went off two years ago in the Large Magellanic Cloud — has shown that bar detectors have an important role to play today as observatories. Until the supernova exploded, bar detectors were engineering testbeds, which would often take data only long enough to determine their sensitivity, and then be shut down for further development. Because of this, none of the most sensitive detectors (cryogenic ones) were operating when the supernova went off. Their sensitivity was sufficient to have made interesting statements about the supernova, either to have seen the gravitational waves or to have set a nontrivial upper limit on them. The lesson is clear and it has been learned by the funding agencies: the present cryogenic detectors will be funded to stay on line as long as possible.
3. *Theory* has remained remarkably consistent over the years in predicting that detectors would have to reach the level of 10^{-18} strain sensitivity (the level of present bars and prototype interferometers) to detect a supernova in our Galaxy or 10^{-21} to see a good number far away. Measured against this goal, it is not surprising that gravitational waves have not yet been detected; instead, the steady improvement in the sensitivity of detectors has given encouragement to the experimentalists. In addition, the more recent realisation that coalescing compact-object binaries constitute an exciting class of observable sources has given an added impetus to the development of more sensitive detectors.

It is appropriate to review this field here at a meeting on underground physics for at least two reasons. First, there has been much discussion lately of neutrino-gravitational wave coincidences. Standard supernova theory expects such coincidences, provided the detectors are sensitive enough. Recent reports[2] of coincidences between the excitations of bar detectors and neutrinos that would appear to be simply background neutrinos before the supernova are not expected on any theory, and I will return to this later. Second, INFN supports two gravitational wave experiments, the Rome cryogenic bar experiment[3], and the Pisa laser-interferometer experiment[4]. The Rome group in fact have plans to set up an ultra-cryogenic bar detector in the Gran Sasso complex.

At the present time I would say that we stand on the threshold of gravitational wave astronomy. At least three ultra-cryogenic bar detectors are under construction. Four research groups will propose this year the construction of large-scale laser interferometric gravitational wave detectors that should attain sufficient sensitivity to detect the gravitational waves that are predicted to come from supernova explosions and the coalescence of compact-object binary systems at great distances. It is appropriate, therefore, to review the properties of these detectors and the predictions about gravitational wave sources. For further details, readers are referred to a number of reviews in the literature[5-9]. I will deal exclusively with ground-based detectors and the sources they can see. Searching for ultra-low-frequency sources with detectors in space is under active consideration (indeed, has already been done with tracking data from interplanetary spacecraft [10]). See references 5 and 6 above or the proceedings of a recent NASA-sponsored meeting[11] for details of this.

2 Bar Detectors

2.1 The current generation

Bar detectors are descendants from the first gravitational wave detector, devised by J. Weber in the early 1960's[1]. Room-temperature bars — of the type that were operating when the supernova went off in 1987 — typically have a sensitivity of $h \approx 10^{-16}$, where h is the amplitude of the wave, or alternatively the strain produced by the wave in the detector. Cryogenic bars at temperatures of 4.2 K reach to 10^{-18}. Ultra-cryogenic bars will operate at temperatures below 100 mK, and perhaps reach sensitivities approaching 10^{-20}, especially when they are operated in arrays.

2.2 The quantum limit

The principal practical problem facing bars is the well-known *quantum limit.* For a typical modern bar detector, instrumented to measure the excitation of the fundamental mode of longitudinal vibration, the energy deposited in the bar (on classical arguments) by a burst with amplitude roughly 10^{-20} is equal to the energy of one phonon associated with the vibration of that mode. It was once thought that bars could not measure gravitational wave amplitudes below this, which was called the quantum limit.

Now it is understood that by carefully choosing the observable that one measures, one can measure arbitrarily small gravitational wave amplitudes with a bar[12]. This is done basically by choosing a conjugate pair of observables that have the crucial property that if one of them is measured to arbitrarily high accuracy, the resulting disturbance to the other (via the uncertainty principle) will not feed back through the dynamical evolution of the variables to make a large uncertainty in the measured variable a moment later. Such variables can be found for harmonic oscillators, so that it is in principle possible to measure very weak gravitational waves with ordinary bar detectors.

However, no one has yet found a practical way of implementing this for bars. The variable whose uncertainty is to be "squeezed" — we say that the bar is to be placed in a *squeezed state* — is difficult to measure. Squeezing has been demonstrated to reduce the thermal noise of a bar[13], but not yet to get below the quantum limit. Until this can be done, bars of the present design will not reach below about 10^{-20}.

2.3 Observing networks

Although bars may have limitations in the long term, they remain our best — indeed essentially our only — method for detecting gravitational waves in the short term. Laser interferometers will not be ready to make observations at the 10^{-21} level for at least five years. Until then, it is very important that bar detectors should be run for as large a fraction of the time as possible.

Cryogenic (4.2 K) bars in at least two places — Stanford and Rome (at CERN) — are now being run in observing mode 24 hours a day, and groups at Louisiana State University and the University of Western Australia (Perth) expect to join them soon. This network is called GRAVNET[14].

2.4 Cross sections

Weber did the first calculation of the cross section of a bar detector to gravitational radiation, a simple calculation based upon an analogy between an elastic bar and two masses on a spring. The masses each have a mass one-half that of the bar, and the spring constant is chosen to model the elastic properties of the bar. This calculation is almost universally accepted these days (see, *e.g.* ref. [15]), and forms the basis of our estimates of sensitivity given earlier.

But recently, Weber himself has challenged this calculation[16,17], and found by a different method that certain collective effects enhance the response of the bar to gravitational waves by a factor of roughly 10^6. This has been widely criticised, notably in a paper by Preparata[18], although Weber still stoutly defends his point of view.

Recently, Preparata himself has done a different calculation involving collective effects, and reached the same conclusion as Weber, albeit for different reasons[19]. I have not seen the details of all his calculations, but it is likely that the subject of cross-sections will be widely debated in the coming year.

The implications of these calculations are, of course, immense. Not only do they give bars a great advantage over the much more expensive interferometers that are now being proposed, but they also offer the possibility of some kind of explanation of the correlations found by Pizzella and collaborators between bars and neutrino detectors.

Rather than analyse the cross-section calculations here, I would like to point out that they can be tested directly in the lab. This does not seem to have been remarked before in this debate. The key point is that the coupling of a bar to a gravitational wave must be the same as its coupling to a time-dependent near-zone Newtonian field. From the point of view of the bar, and assuming general relativity is correct (this is not being challenged by the cross-section calculations), all it is responding to is a time-dependent tidal field. The bar is very much smaller than a wavelength of the wave, so it does not see the wave structure directly. One can therefore stimulate a bar equally well by spinning a nearby dumbell, say, at the resonant frequency of the bar. By measuring the bar's excitation, one can measure its cross-section and settle the debate conclusively.

Remarkably, this experiment is now going on at CERN with the Rome bar[20]. Conceived as a fifth-force experiment to measure the Newtonian coupling, it should be able to discriminate between the two cross-sections with no difficulty. We await the results any time now.

3 Interferometric Detectors

3.1 Current detectors

It is interesting that Weber was also the first to consider laser interferometric detectors, and the first to build one was Weber's former student, R.L. Forward, who was then working for Hughes Aircraft Company[21]. The development of this approach began in earnest in the mid-1970's, after the limitations of bars caused some bar groups to change direction.

Prototype interferometers have progressed to the point where their sensitivity approaches that of the best cryogenic bars. They could be developed a bit further, but any large increase in sensitivity requires a significant increase in arm length. Unlike bars, whose length is constrained by the requirement that they remain resonant in the kiloHertz region, laser interferometers suffer no such constraint until their arm length reaches the wavelength of the gravitational waves, hundreds of kilometres. Laser detectors are broadband instruments, and this offers further advantages for observing.

Interferometers also have quantum limits on their sensitivity, but the limits occur at much smaller values of h. The primary quantum limit is the shot-noise or photon-counting limit, determined by the available laser power. We will study this in some detail below. Just as for bars, it is possible in principle to circumvent this limit by squeezing, in this case by the use of *squeezed light*[22]. Unlike the case of bars, squeezing to below the quantum limit has in fact been demonstrated, reducing shot noise by factors of up to 3 so far[23]. It is likely that squeezing will be implemented in laser interferometers in the future[24].

3.2 Proposed interferometric gravitational wave detectors

Four groups are submitting proposals for full-scale laser interferometric gravitational wave detectors in 1989. The designs all have a number of features in common. The arms of the interferometers are in the range 3–4 km. The interferometers have to sit in a good vacuum, and have to have good isolation from seismic noise. Seismic noise is likely to be relatively straightforward to eliminate above about 100 Hz, but it may need special techniques for lower frequencies.

Typically, experimenters expect to develop the instruments to their full sensitivity in various stages spread over a period of 10 years or more. The first stage would reach a sensitivity level of 10^{-21} over a 1 kHz bandwidth. This would be followed by progress to 10^{-22} at kHz frequencies. In some proposals, a second detector optimised for low-frequency observing down to 100 Hz would be built as well, and there would be a final extension of sensitivity down to lower frequencies.

Briefly, the proposals are:

- *The British-German collaboration*[25]. The proposal will be for an installation with three-kilometre arms. There would be two separate interferometers in a single vacuum system. One of the interferometers would be optimised for high-frequency gravitational radiation, which means 1 kHz and above. The second would be optimised for the range 100–1000 Hz. The site of this detector has not yet been decided.
- *The Italian-French collaboration (VIRGO).* This proposal is for a single detector with three-kilometre arms. It has as a principal goal the attainment of good sensitivity at very low frequencies, perhaps down to 10 hz. It would be built on a site near Pisa.
- *The US detectors (LIGO).* At the present time it appears that the American proposal will be for two detectors, each with 4 km arms, one located on the East Coast and one on the West Coast of the USA. Inside each housing are likely to be several interferometers (perhaps 3), each of which has its optics in a separate vacuum system from the others so that working on one does not disturb the others. Two of the interferometers would be optimised for high and low frequencies, as in the British-German detector. Any other interferometer would be for special purposes, perhaps for the use of other groups that wish to do such research.
- *The Australian proposal (AIGO).* This would be built on a site near Perth, which would permit the construction of arms at least 3 km long. This proposal envisions a collaboration with the British-German group, and its design is based on the design put forward by them. A collaboration with Japan is also possible.

There are differences of detail among the designs, as one would expect of systems designed by independent groups. The principal difference is how to implement an important requirement, namely to lengthen the optical path beyond the physical size of the detector by bouncing the light up and down many times. If the bounces are kept separate, the interferometer is called a delay-line system[26]. If the bounces are superimposed, the arms become tuned cavities, and the system is of the Fabry-Perot type[27]. Both systems have advantages and disadvantages, and various hybrid designs are emerging, tailored to specific systems.

3.3 Limitations on sensitivity

The principal noise sources that affect interferometers are given below. Details can be found in the various proposals, *e.g.*[25].

- *Shot noise.* This refers to the fact that light is quantised into photons, which arrive randomly at the photodetector. This introduces an uncertainty into the measurement of the position of the fringe (or the degree of interference between the light from the two arms), which decreases as the square root of the number of photons, *i.e.* of the light power. High laser power is therefore an advantage, and various tricks will be employed to enhance the effective power, particularly the technique known as *recycling*[28]. Present designs envision that this will be the fundamental limiting factor on sensitivity above about 100 Hz, and that for pulses of broad (1 kHz) bandwidth, it is possible to achieve a limit of 10^{-22} with present technology. (See my review[29] for a simple calculation of this limit.) This figure is the basis of our estimates today of what science these detectors can do.

- *Seismic noise.* Seismic and other ground-motion noise has a spectrum that peaks at low frequencies. By passive isolation, good isolation is expected above about 100 Hz. Similar techniques work well on the prototypes and on bar detectors. The VIRGO collaboration are developing special suspension/isolation systems that may allow us to reach down even to 10 Hz. The noise reaching the detector falls off steeply with frequency, as shown in the sensitivity plots given in Figures 1 and 2 below.

- *Mirror vibrations.* The mirrors are at room temperature, so they vibrate thermally. The more reflections one uses within the arms of an interferometer, the more mirror noise there will be. This sets a lower limit of about 1 km on the size of an interferometer that could reach 10^{-22}. The effect of this noise for realistic values of the vibrational Q of the mirrors is shown in Figures 1 and 2.

- *Suspension thermal noise.* The mirrors and other optical components are suspended from their seismic isolation mounts by thin wires. There is therefore a pendulum mode of vibration of about 1 Hz that will have thermal energy at room temperature. The effect of this noise for realistic values of the Q of the suspension is shown in Figures 1 and 2.

- *Miscellaneous noise sources.* Various other kinds of noise have to be controlled: vacuum pressure fluctuations, laser noise of various kinds, light scattering from mirrors and the walls of the vacuum tube, "violin modes" of the suspension wires, acoustic noise from the environment, possible electromagnetic interference, and so on. Solutions seem to have been found for all of them.

Another possible limitation on detector performance, although not technically a noise source, is mirror heating. Although the losses per reflection from mirrors are small, the technique of recycling referred to above allows the light intensity to build up until all the laser power is being dissipated in the mirrors. The resultant heating can change the shape and index of refraction of the mirrors, which affects the quality of the interference pattern they produce. The present proposals use sufficiently small laser power to avoid this, but if it is desired to go to higher sensitivity in the future by using higher laser power, this could be a limiting factor. How easy it will be to cure will depend on developments in materials science.

3.4 Squeezed light

The photon shot noise limit is not a fundamental limit; it is a quantum limit that can be beaten by squeezing techniques[24] that have already been demonstrated in the lab[23]. It is not impossible that the presently proposed detectors could be pushed to 3×10^{-23} with no increase in laser power. This factor of 3 translates into a factor of 27 in the volume of space that can be reached, and therefore into a factor of 27 in the event rate for detected gravitational waves.

4 Sources of Gravitational Waves

As we will see below, the maximum amplitude of gravitational waves expected from sources in our Galaxy is 10^{-18}, and that only once every decade or so. The maximum amplitude expected from extragalactic sources that might occur more than once per year is 10^{-21}, which could come from supernovae in the Virgo Cluster, where there are several thousand galaxies. The proposed designs are aimed at providing amplitude sensitivity ten times better than this.

4.1 The worldwide gravitational wave network

Gravitational wave detectors cannot operate alone; detections must be confirmed by coincidences between two separated detectors. But two detectors alone cannot supply enough information to reconstruct the gravitational wave itself, *i.e.* to infer its amplitude, polarisation, and direction of travel. Solving this "inverse problem" is crucial to getting scientific information from the detectors, and it requires at least three detectors around the world. In order to allow for non-optimal orientation, operational down-time, special-purpose uses such as narrow-banding, and detector development, the goal of the worldwide detector community is to have detectors at four separated sites as a sensible minimum, and five as a highly desirable next step.

Since detector sensitivity is limited by internal and local noise sources, presumably uncorrelated between separated sites, coincidence experiments have a lower false-alarm rate (noise-generated coincidence rate) at a given threshold than individual detectors do. For a given false-alarm rate (we adopt once per year for our estimates in this review), the more detectors a network has, the lower will be the threshold it can operate at. Thus, each additional detector improves the performance of all the others. These considerations plus the formidable complexity of laser interferometric detectors account for the highly cooperative spirit that exists among the various gravitational wave groups today.

The following list of sources of gravitational waves is by no means exhaustive, but it contains those that are the most likely to be detected, based on our present understanding of them. The uncertainties are to a large extent the justification for building detectors; if we knew all about the sources we would not want to build detectors to study them!

4.2 Supernovae

Supernovae, or more generally gravitational collapses, have been the primary goal of gravitational wave detector development. Supernovae occur in supergiant stars whose cores are supported by electron degeneracy pressure because they have exhausted their nuclear fuel. When the mass of the core builds up to the maximum that can be supported, it collapses to neutron-star densities. If the collapse halts there, a rebound will occur that drives off the outer envelope of the star. This causes the optical display that we see as a supernova. The neutrino signal that we see comes partly from the conversion of protons and electrons into neutrons, but mainly from the thermal gas of neutrinos in equilibrium with other particles in the collapsed core, where they are trapped for the first second or so.

If the collapse is spherical, there will be no gravitational radiation. An attractive way to achieve nonsphericity is through rotation. If the core has sufficient angular momentum — it does not need much if it is conserved during the collapse — then rotational instabilities will deform the core into a tumbling cigar-shaped object that could even fission into two lumps. The tumbling and orbital motion should be strong radiators. The energy available is large, plausibly up to $0.1M_\odot$ in extreme cases. A more moderate guess is that nonaxisymmetric collapse will give perhaps $0.01M_\odot$.

We know little about the precise waveform to expect, but on general grounds one expects that the burst may last about a millisecond and have very little structure. If the burst has $0.01M_\odot$ energy and comes from Virgo, it would have an amplitude greater than 10^{-21}. A network of detectors would be able to identify such a burst reliably as far away as 40–50 Mpc. This is three times the distance to Virgo and is a volume of space in which there are perhaps a thousand supernovae per year. If only a small fraction are very nonaxisymmetric, there could still be a good event rate in our detectors.

The amount of rotation in a typical collapse is hard to predict, but the case for occasional events in which rotation dominates would be strong if the report of a pulsar in the remnant of SN1987A, with a pulse period of nearly 2 kHz, is confirmed[30]. Studies of neutron star models show that a star rotating that fast must either still be subject to a slowly-growing gravitational wave instability, or else it must be very close to such an instability[31]. It would be very hard to form such a star without its having undergone nonaxisymmetric deformation, with the emission of considerable gravitational wave energy either as a burst or over a relatively few cycles of rotation. The data in which the pulsar was discovered are extremely clean, and can be fit with a simple model: remove the Doppler shifts produced by the Earth's motion and fit the residual frequency shifts with a Keplerian orbit (which suggests that the pulsar has an orbiting Jupiter-sized object near it). The fit is so good[32] that it is very hard to reject this data, despite the fact that it is hard (but not impossible[33]) to explain theoretically and the fact that the pulsar has not yet been seen again. This suggests that the case for strong rotation and strong gravitational radiation from some supernovae is a good one.

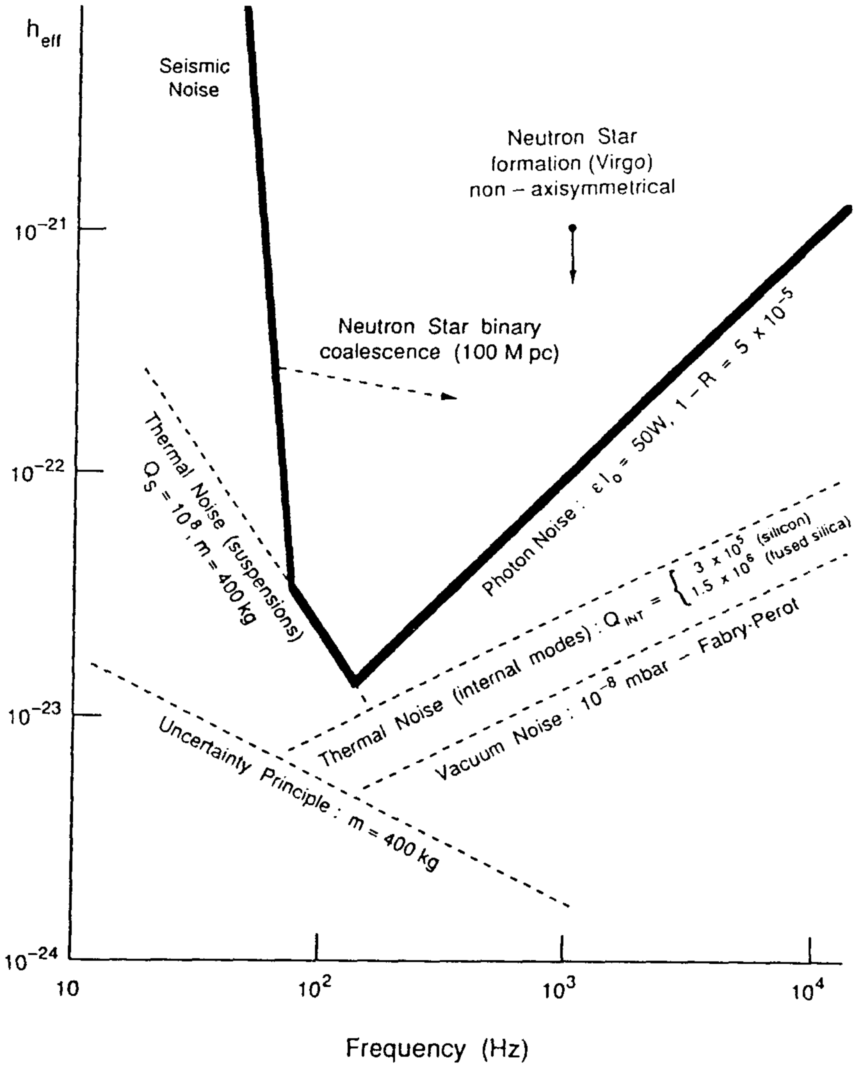

Figure 1: The sensitivity $h_{\rm eff}$ to short bursts of radiation of a 10^{-22} detector optimised for observing at frequency f. A number of interesting possible sources are shown. The effects that give rise to the sensitivity limits are indicated. (For an explanation of $h_{\rm eff}$, see Section (4.3.1).) Taken from Ref. [25].

4.3 Coalescing binaries

Since most stars begin as members of binary star systems, it is likely that a substantial fraction remain binary after the individual stars have completed their evolution and become either white dwarfs, neutron stars, or black holes. A small number of these will have been brought so close together during earlier phases of binary evolution that their orbital lifetime against the loss of energy to gravitational radiation is less than the age of the universe. Such systems will coalesce in an astronomically short time. Systems containing white dwarfs are not of interest for ground-based detectors, since they coalesce before their orbital radiation reaches a frequency accessible from the ground. (They would be visible from space.) But those composed of highly compact objects — neutron stars and/or black holes — can produce observable radiation.

4.3.1 How we detect coalescing binaries — matched filtering

Coalescing binaries give off a great deal of energy before they coalesce. As the radiation from a system consisting of two $1.4\,M_\odot$ neutron stars changes from 100 to 200 Hz, the waves carry away some $5 \times 10^{-3}\,M_\odot c^2$ in energy, comparable to a decent supernova burst. Because this energy is spread out over many cycles, the waves' amplitude is smaller than one would expect from a supernova. Nevertheless, by the technique of *matched filtering* it is possible to attain a much higher signal-to-noise ratio than for a comparable supernova.

For matched filtering, the sensitivity increases roughly as the square root of the number of cycles in the waveform. When comparing different burst sources for detectability, one needs to take this factor into account. This is why we plot an effective h in Figure 1, which is the amplitude a broadband burst would have to have to achieve the same signal-to-noise ratio as the filtered signal will have.

Matched filtering requires that we know the amplitude of the signals expected from coalescing binaries. The maximum amplitude, taken over all orientations of the binary and the detector, is

$$h_{max} = 3.6 \times 10^{-23} \left(\frac{M_T}{2.8M_\odot}\right)^{2/3} \left(\frac{\mu}{0.7M_\odot}\right) \left(\frac{f}{100\text{Hz}}\right)^{2/3} \left(\frac{100\text{Mpc}}{r}\right), \tag{1}$$

where M_T is the total mass of the binary and μ its reduced mass, and where r is its distance and f the frequency at which it is radiating (twice its instantaneous orbital frequency).

Although the amplitude looks small, matched filtering can bring up the signal-to-noise ratio in this case by as much as a factor of 25. Moreover, the sensitivity of detectors is better at the lower frequencies of coalescing binary signals. This means that coalescing binaries can be seen as far away as 650 Mpc, much further away than supernovae, provided detectors can operate down to 100 Hz. (For comparison, at this sort of distance one can see only the brightest galaxies with big optical telescopes.) If seismic noise can be eliminated down to 40 Hz, this range is roughly doubled to 1.3 Gpc.

Notice that the masses of the stars influence the amplitude of radiation only through the combination

$$\mathcal{M} = \mu^{3/5} M_T^{2/5}, \tag{2}$$

which we call the *mass parameter* of the binary system. Remarkably, the mass parameter also determines how fast the frequency of the signal increases as the orbit decays:

$$\frac{f}{\dot{f}} = 7.8 \left(\frac{f}{100\ \mathrm{Hz}} \right)^{8/3} \left(\frac{\mathcal{M}}{M_\odot} \right)^{5/6} \ \mathrm{s}. \tag{3}$$

Equations (1) and (3) contain an important relation: the masses of the stars enter only via the mass parameter $\mathcal{M}$. By measuring the signal amplitudes and the rate of change of the frequency, the two equations can be combined to yield a single unknown, the distance to the source. In fact there is not enough information from a single detector to determine the maximum signal amplitude used in Eq. (1), but a network of three detectors could do so. In this way, *coalescing binaries become distance indicators*, and this has important implications for astronomy, to which we return later.

Not all binaries will consist of neutron stars. The statistics of X-ray binaries suggest that perhaps one percent will contain a black hole of roughly $14 M_\odot$; it is possible that a further one percent of these might consist of two such black holes. The signal-to-noise ratio of the two-black hole system would be some 6.3 times larger than that of two neutron stars at the same distance, so the range for detecting binary black holes would be more than 4 Gpc, approaching a cosmological redshift of 0.5.

The maximum range of the detector is not the whole story, since orientation-dependent effects will reduce the probability that any given coalescence will be seen. Tinto[34] has made a detailed study of these effects in a network of 4 or 5 detectors. The influence of tidal, mass-exchange, and post-Newtonian effects on the quality of the predicted waveform have been considered in detail by Krolak[35]. All our conclusions here take full account of these two papers.

4.3.2 How many coalescences might we see?

There is one well-known binary coalescence *precursor* system in our Galaxy: the famous Binary Pulsar, PSR 1913+16, which has a remaining lifetime of about 10^8 years before it will coalesce. Importantly, a second such system, PSR 2127+11C, has very recently been discovered in the globular cluster M15[36]. Its pulse and orbital characteristics are remarkably similar to those of the classic binary, PSR 1913+16, but we will have to wait for a measurement of the periastron shift before we can be sure it is the same sort of system.

It is also possible that PSR 0021-72A, in the globular cluster 47 Tuc, is also a precursor with a short lifetime[37]. Unfortunately, this pulsar is at the limit of detectability, and exhibits a number of unexplained features, so it is too soon to draw conclusions about it.

The event rate out to any distance is very uncertain, since our estimates rely on the precursor systems we can see. Based on PSR 1913+16, Clark, *et al*[38], concluded that the most likely value for the rate is probably 3 events per year out to a distance of 100 Mpc, which would give an event rate in a network of some 40–80 events per year. I have elsewhere estimated[39] that this rate may be uncertain by a factor of 100 either way, allowing a detection rate that could range from one every two years up to several thousand per year. The more recently discovered precursors mentioned above raise this rate somewhat and reduce the uncertainties in it. Further searches now going on will reduce the uncertainties even more.

4.4 Pulsars and other continuous-wave sources

There are many possible long-lived or continuous sources of gravitational radiation in the frequency range accessible to our proposed detector. These include pulsars with "lumps" in their crust; unstable pulsars spinning down after having been formed with too large an angular velocity; and unstable accreting neutron stars where the instability is being driven by the accretion of angular momentum ("Wagoner stars"[40]).

The sensitivity of a detector to such long wavetrains increases as the square root of the time of observation. If the dominant source of noise were photon shot noise, the sensitivity would be extremely good. However, it appears that thermal mirror vibrations will dominate or at best equal photon noise in this case, unless materials with extremely high Q can be found. As Figure (2) shows, thermal noise may dominate the photon noise by a factor of perhaps 5.

As I mentioned above, the sensitivity achievable on a continuous source increases with the square root of the observation time τ. One might contemplate narrow-banding a detector (which can be achieved with special optical techniques[28,41,42]) for a period of up to a few months in order to make an important observation; a significantly longer observation might not be desirable, given the importance of searching for bursts and for continuous sources at other frequencies.

There may be pulsars in the solar neighbourhood that are not visible electromagnetically (because they are beamed elsewhere or because they are old and radio-quiet), but which could still be radiating gravitational waves. But the problem of conducting an all-sky search for such signals is formidable: the Earth's motion produces Doppler effects that need to be removed from any observations lasting longer than about 30 minutes, and these corrections are different for each different location on the sky. The longer an observation lasts, the better will be its directional resolution, and therefore the greater will be the number of possible locations that have to be looked at. For example, an observation lasting 10^7 s would be able to define the location of a pulsar to an accuracy of 0.2 arcsec[43], better than optical observations can do using ground-based telescopes.

If we wanted to search the whole sky for such pulsars, simply performing the data analysis on 4 months' worth of data over a 1 kHz bandwidth would be beyond the capacity of present and foreseeable computers[39], because one would have to search separately all 0.2-arcsec-square boxes on the sky: some 10^{13} in all. Given the data set of some 10^{10} points, it is not hard to see why this is impossible at present. Instead, the detectors will perform searches of more limited sensitivity, such as all-sky searches limited to narrow frequency bands and/or short observation times.

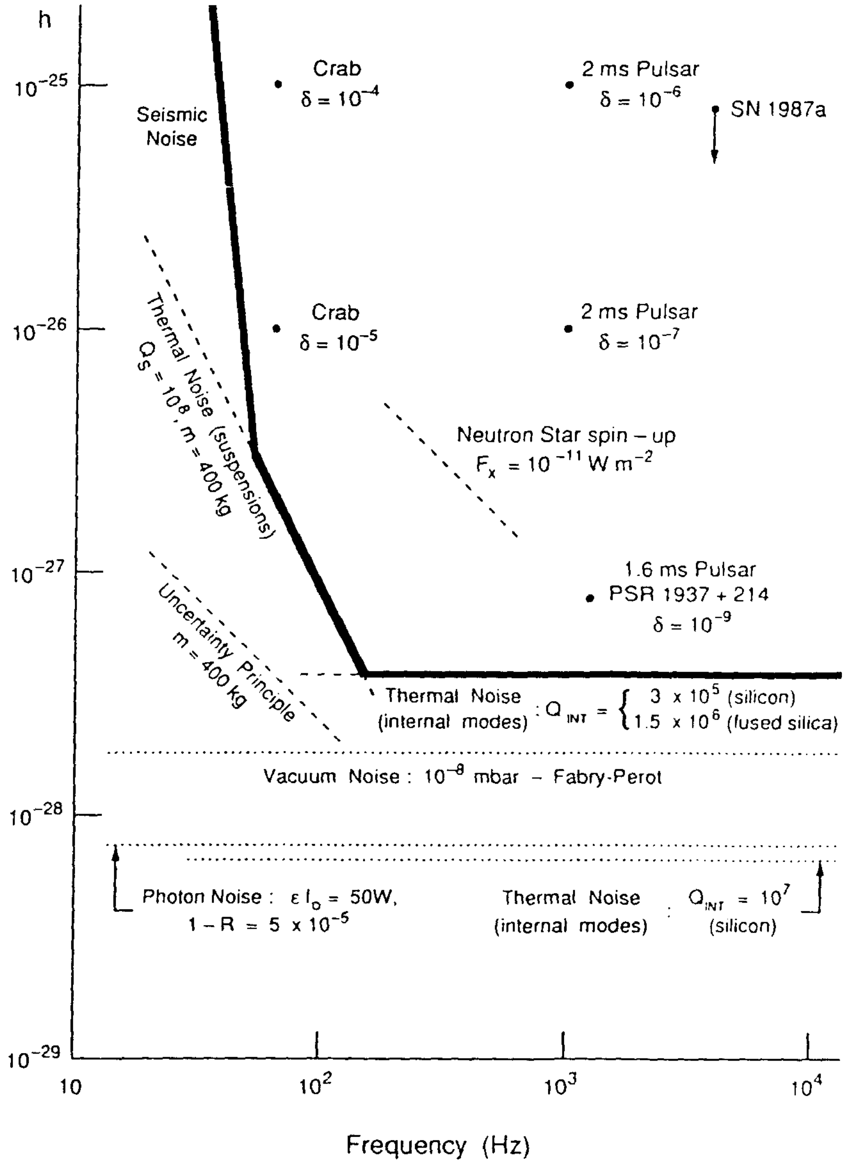

Figure 2: Sensitivity of a 10^{-22} detector to continuous wavetrains, assuming an integration time of 10^7 s. Depending on the Q of the mirror material that can be achieved, either mirror noise will dominate or it will be comparable to shot noise. Taken from Ref. [25].

4.5 Unpredicted sources

There are many other possible sources of gravitational radiation, especially including several possible sources of a stochastic gravitational wave background. But it is hard to believe that we will not also find things we simply did not predict. As with the opening of any other window in astronomy, one can be confident that there will be unexpected sources of gravitational waves at some level. If they are strong enough to stand out above the broadband noise, then they will be readily detected and studied.

5 Impact on Astrophysics

In this section I will describe where in physics and astrophysics the data from detectors could have its greatest impact.

We will begin our list with three new tests of relativistic gravity that observations of gravitational waves can perform. In this role, gravitational wave detectors function as fundamental physics experiments.

- *Test of gravitational wave polarisation.* Simply seeing gravitational waves would, of course, be a milestone for relativistic gravity. But many theories predict gravitational waves, and a network of detectors can distinguish among them. With four or more detectors, one has redundant information in the observations with which to reconstruct the amplitude, polarisation, and direction of the wave. If these data are self-consistent, then general relativity provides a good model of the wave, particularly of its polarisation properties. If they are not self-consistent, then a different theory of gravity may be necessary.

- *Speed of propagation of gravitational waves.* If a supernova at 15 Mpc were seen optically and detected by the gravitational wave network, there should be less than a day's delay between the gravitational wave and the optical detections, provided the gravitational wave travels at the same speed as the light from the supernova. Over a travel time of some 45 million years, the coincident arrival of the waves within a day would establish that their speeds were equal to within one part in 10^{10}.

- *Test of strong-field gravity.* A further test can be made if black hole coalescing binaries are detected. Computer simulation should soon be accurate enough to make detailed predictions of the dynamics of the merger of the holes, and of the radiation they emit, with only a few parameters (such as the masses, spins, total angular momentum, and impact parameter of the collision). Given a reasonable signal-to-noise ratio, matching the observations to the predictions could provide a stringent test of strong-field gravity.

Now we turn to the astrophysical "return" on the investment these detectors would require.

- *Morphology of the supernova core.* Observations of bursts from gravitational collapses tell us a number of things about supernovae themselves. We could learn how many collapses do not produce visible supernovae; how often rotation plays an important role in the collapse; whether the collapse has formed a neutron star or a black hole; and what the mass and angular momentum of the compact object are.

- *Neutron star equation of state.* This is one of the most important areas where gravitational wave astronomy can provide information that is crucial to nuclear physics: the interactions of neutrons in these conditions are poorly understood and inaccessible to laboratory experiments. Supernova gravitational wave observations constrain the equation of state by telling us what the timescale of collapse and rebound is, what the mass and angular velocity of any neutron star formed in the collapse might be, and what the upper mass limit of neutron stars is. If neutrino observations are available, then together with the gravitational wave observations they might strongly constrain models of the shock: whether it is "prompt" or " delayed". Coalescing binaries similarly offer information on neutron star masses (through the mass parameter $\mathcal{M}$) and on mass exchange once the initial point-mass approximation breaks down. Observations of pulsars radiating from frozen-in mass deformations constrain the solid crust equations of state.

- *Compact-object statistics.* It is very hard to devise unbiased indicators of the numbers and distribution of pulsars, old neutron stars, and black holes. Observations of gravitational waves from supernovae and coalescing binaries can give a new measure of the mass functions of these populations and of their formation rate. Searches for unknown pulsars, if successful, could give a relatively unbiased indication of their distribution in the solar neighbourhood.

- *Hubble's constant.* If the event rate of coalescing binaries is sufficient to give a few per year from within 100 Mpc, then the fact (noted in Section (4.3.1) above) that coalescing binaries are reliable distance indicators allows one to measure Hubble's constant to within a few percent in a year or two of observations[44]. This in turn will determine the age of the universe and the distance scale to external galaxies.

- *Cosmological mass distribution.* Given a reasonable event rate, coalescing binaries are good tracers of the stellar distribution out to 500 Mpc or (for black holes) a few Gpc. Their distribution would indicate structure out to 500 Mpc on length scales of 10–100 Mpc or so, scales on which we have little information at present. This would provide a stringent test of the homogeneity and isotropy of the universe.

- *The early universe.* By confirming or ruling out a stochastic background of gravitational radiation as predicted by cosmic string theory, gravitational wave observations can be crucial to the cosmic string theory of galaxy formation. If other backgrounds are detected, they will have to be explained by some physics in the early universe. If the explanation has to do with phase transitions, for example, then this would have implications for particle physics; if an early generation of very massive objects is the cause, then this has implications for galaxy formation as well.

- *Follow-up observations.* Once gravitational wave sources have been identified by the detectors, astronomers will want to look at them with optical, radio, X-ray, and other telescopes. These follow-up observations will be a further source of important information. They require the gravitational wave network to provide a position for the source, which it can do to within a degree or so for burst sources at threshold, and with more accuracy for stronger sources. In addition, the network ought to be able to identify a supernova event within an hour of its arrival in the detectors, enough time to notify optical astronomers who would like to catch its first optical brightening, which would occur any time from a couple of hours to a day after the gravitational wave signal.

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