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Cosmic sources of gravitational radiation

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Abstract. The most likely sources of gravitational radiation that may be seen by the large-scale laser-interferometric detectors that will soon be built around the world are reviewed. The prospects for detection are excellent, and much information can be extracted. But the coalescences of compact objects pose a problem: the two-body problem in relativity is not well enough understood to allow one to extract the most information from a detection. There is a challenge to relativists to find solutions that will be useful to gravitational wave detectors.

1. Introduction

The detection of gravitational radiation is one of the outstanding goals of modern experimental physics and observational astronomy. With its long history of slow but steady development of more and more sensitive detectors [1], it may have seemed that the goal would never be reached. But with the approval last year by the US Congress of the LIGO project [2], and the expected approval this year by the Italian and French governments of the VIRGO project [3], we can look forward to the regular observation of gravitational waves from astronomical objects before the end of this century. Elsewhere in this volume, Dr S Whitcomb of the LIGO project describes the principles by which these large-scale laser-interferometric detectors will operate. In this article, I will say a little about the kinds of sources we might see. In particular, I will describe a challenge to theoretical relativists that must be met for these detectors to be able to achieve all they are capable of.

Much has been written about the kinds of sources that these detectors could see. I refer the interested reader to some widely available reviews [1, 4, 5]. The subject is too broad to cover adequately in this paper, so I will give first a very brief discussion of the main sources that seem likely to be detected, and then concentrate on the one that presents the most direct challenge to classical relativists: calculating the orbits of the two-body problem for neutron stars or black holes in close orbits (the so-called coalescing binaries).

The confidence I expressed above that we shall soon see regular detections of gravitational waves comes from the fact that the predictions of theorists regarding the amplitudes of regularly occurring gravitational wave events should finally be matched by the sensitivity of the detectors that are now designed around laser interferometers. Readers who want more general introductions to the principles of gravitational wave detection may consult the review by Giazotto [6], the proceedings of a workshop on analysis of data [7], or the extensive collection of articles edited by Blair [8]. The Blair collection also covers modern bar detectors, and it should not be forgotten that, although such detectors can not easily be pushed to the ultimate sensitivity of

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the interferometers, there are working bars today capable of detecting rare, nearby events, and the first detection may well come from that quarter. However, it seems clear to me that, owing to their broadband nature, interferometers will be the main astronomical observatories for gravitational waves. For that reason, I concentrate here on the sorts of information that such detectors can be expected to provide.

2. Gravitational wave science

Gravitational waves are interesting for two reasons: first, they are a fundamental aspect of gravitation theory, and as such provide tests of our present theories; and second, they originate in some of the most dramatic and violent events in the universe, and they carry information about those events that often can be obtained in no other way.

2.1. Fundamentals

Although gravitational waves are often supposed to be weak, this is only half-true. They do indeed couple to detectors very weakly, which is the reason it has taken so long to develop the technology to see them. (This also means they couple weakly to intervening matter, so they reach us in virtually pristine condition.) But they carry enormous amounts of energy. The energy flux of a plane wave of amplitude h and frequency f in linearized theory is [9]

$$\mathcal{F}_{gw} = 3.2 \times 10^{-3} \left[\frac{f}{1\ \mathrm{kHz}}\right]^2 \left[\frac{h}{10^{-22}}\right]^2 \quad \mathrm{W\,m^{-2}}. \tag{1}$$

I have normalized this to the weakest burst the interferometers are likely to be able to see. Such a burst might last only one millisecond, but while it lasts it will have the same energy flux as a star of apparent magnitude −13, or equivalently it will be twice as bright as the full moon!

By integrating this equation over a sphere and over the duration τ of a burst, one gets a simple relation between the amplitude of a wave at a distance r from its source and the total radiated energy E :

$$h = 1.4 \times 10^{-21} \left[\frac{E}{10^{-2} M_\odot}\right]^{1/2} \left[\frac{f}{1\ \mathrm{kHz}}\right]^{-1} \left[\frac{\tau}{1\ \mathrm{ms}}\right] \left[\frac{r}{15\ \mathrm{Mpc}}\right]^{-1} \tag{2}$$

where I have normalized this to the distance to the Virgo cluster, in which we expect a number of possible events like this each year. This relation explains why the goal of detector-builders has always been to reach $h \sim 10^{-21}$. Present interferometer designs anticipate reaching 10^{-22}, and even lower at lower frequencies. This sensitivity opens up a much wider range of sources, which we will describe below. It is also clear from the above that with any detectable wave one is dealing with a source which is converting a sizable fraction of a solar mass into gravitational radiation energy. Such events must be rare in any volume of space.

Detecting gravitational waves will of course confirm directly the relativistic nature of gravity. Beyond that, with a network of detectors it is possible to test the general relativity model of polarization: 4 or more detectors contain enough redundant information to allow one to look for, say, a longitudinal polarization component. If a burst of radiation arrives from a supernova explosion that is also seen optically, then the near-coincidence of the emission of the light and gravitational radiation in the explosion and the near-coincidence of their arrival at Earth allows one to set limits on the deviation of the propagation speed of gravitational waves from that of light. Perhaps most interestingly, we do expect to see occasionally the merger of two black holes from a binary orbit (see below). This is a pure-gravity problem, and can in principle be modelled on computers. Comparing models with observations will provide a stringent test of strong-field gravity theory.

2.2. *Likely sources*

The most likely sources that interferometers should observe are summarized in table 1. It is clear from the table that we have the most confidence in coalescing binaries as gravitational wave sources. This is because it is relatively easy to calculate the amplitude of the waves emitted as the stars spiral together, before they merge, and because pulsar observations in our Galaxy give reasonably secure lower limits on the event rate. This is described in more detail below. However, the other sources are very possible, and in many cases observing them would have much more impact on astronomy than would observing coalescing binaries. I shall consider each of them briefly in turn.

Table 1. Gravitational wave sources

Source	Expected	For a network of 10^{-22} detectors	
	frequency	Range	Events
Supernovae or gravitational collapse	100 Hz–10 kHz	$\sim$ 50 Mpc (uncertain)	$> 100\,\mathrm{yr}^{-1}$ (uncertain)
Coalescing binaries of compact objects	10 Hz–1 kHz	NS-NS: $\sim$ 1 Gpc (confident) BH-BH: 9 Gpc (confident)	$> 300\,\mathrm{yr}^{-1}$ (good lower limit) $\sim 10\,\mathrm{yr}^{-1}$ (uncertain)
Known pulsars (e.g. Crab Nebula)	< 60 Hz	1 kpc (uncertain)	a few objects (uncertain)
Unknown neutron stars (mostly old)	< 2 kHz	$\sim$ 100 kpc (uncertain)	10^4 objects (uncertain)
Stochastic background	any	$\Omega_{gw} \sim 10^{-9}$ or below	size very uncertain

2.2.1. *Gravitational collapse.*

The desire to detect gravitational waves emitted in supernova explosions drove the early development of detectors, but the astrophysics of supernovae is sufficiently uncertain that we still cannot say today what the likelihood of detecting such events is. It is clear from equation (2) that a wave that carries $10^{-2}M_{\odot}$ will be visible in a 10^{-22} detector at a distance of 50 Mpc from its source with a signal-to-noise ratio of 4, which might allow one to identify the event if it was seen by 3 detectors and/or had an optical identification. This is a volume of space containing more than 10^4 galaxies and several hundred supernovae per year.

Since spherical gravitational collapse emits no radiation, detections depend on events that develop significant asymmetries. These presumably would be caused by rotation. Young pulsars do not seem to rotate fast, and this argues against significant emission. On the other hand, there is evidence that some pulsars are born with high space velocities that cannot be entirely accounted for by the breakup of binary systems, and this argues that they have received a kick in the collapse event. Statistical studies of supernovae also do not provide much of a constraint: if only one supernova in 100 were unusually asymmetric, detectors might still register several per year.

On top of this, we don't know if all gravitational collapse events lead to supernova explosions: the accretion-induced collapse of a white-dwarf could emit gravitational waves without being very visible optically, and events that form large black holes may not expel much of the original star's envelope, since a large part of the progenitor star's mass must go down the hole. It may even be that rotation and asymmetry play a role in deciding which events form neutron stars and which form black holes: asymmetric events may develop weaker shocks, which produce less of an optical display and allow the recollapse of the envelope to form a black hole.

The frequency of the radiation is also uncertain. The simplest assumption is that the radiation comes out as a structureless burst with a duration of about 1 ms. It would then have a broad spectrum centred on 1 kHz. This would make it visible to interferometers and to bar detectors. Indeed, if bar detectors achieve the first detection, it will most likely be on an event like this. But the timescale of the burst is sensitive to unknown nuclear physics, and it could well last longer and have a dominant frequency of some hundreds of Hz, taking it out of the range of bar detectors. Moreover, if rotation dominates the strong events, this could add structure to the signal: the energy could come out over several cycles at a lower frequency, as the deformed structure spins around. Detailed predictions of this await the development of accurate 3-D hydrodynamical codes in relativity.

With all these uncertainties, it is unlikely that we will settle the question of gravitational waves from collapse until detectors are built. Conversely, positive observations would provide a great deal of new information, and this is one of the main incentives for building detectors.

2.2.2. Coalescing binaries. If the evolution of a binary star system leads to a pair of compact objects (neutron stars or black holes) in a sufficiently close orbit, then gravitational radiation reaction will lead to the decay of the orbit and the coalescence of the objects in a cosmologically short time. We know such systems exist: the famous 'Binary Pulsar' PSR 1913+16 is one, and two others have since been found in the Galaxy. For a pair of neutron stars, when their orbital separation is about 200 km, their orbital period is 0.02 s, and their orbital motion emits gravitational radiation at a frequency of 100 Hz. This is well within the frequency bandwidth accessible to interferometric detectors, and such coalescing binaries have long been discussed as possible sources of detectable radiation [1, 10–12].

The stars will still execute nearly 200 orbits before coalescing about 2 s later, so the expected waveform lasts a long time. The orbital motion is in principle predictable, allowing one to develop accurate waveform templates with which to perform matched filtering on the detector's data stream [1]. The improvement in signal-to-noise that this brings extends the range of detectors out to about 500 Mpc [4]. The LIGO and VIRGO detectors are expected to be sensitive to below 40 Hz, which will gain them a further factor of about 2. We can therefore hope to see coalescences of two neutron stars at 1 Gpc. Even the most pessimistic estimates of event rates [13, 14] predict tens or more of events per year at this distance.

This great range can only be achieved if we have good predictions about the motion of the stars in the binary. It has recently become clear, from work done at Caltech, that we do not have an adequate model yet. I will explain this in the final section below. It will become clear there that when we can adequately model the system, we will also be able to extract a wealth of information from the gravitational wave signal: the individual masses of the two stars, the distance to the system, and in some cases even its redshift. Such information opens up new windows into neutron star structure and cosmology.

Not all binaries will consist of two neutron stars. On evolutionary grounds it is even possible that systems consisting of one neutron star and one massive black hole will be nearly as common as two-neutron-star systems [13, 14]. Such systems emit more energy and are detectable further away, so they could double the number of events detected. If this hypothesis is right, then we should soon see such a system detected in our Galaxy as a binary pulsar in orbit about a very massive companion. Systems consisting of 2 black holes must be rarer in any volume of space, but they can be detected much further away, possibly as far as the most distant known quasars.

These factors combine to make coalescing binaries the source we have the most confidence in detecting. As we shall see, the information we can extract from the gravitational waves makes them also one of the most interesting sources to detect.

2.2.3. Pulsars. Pulsars will be sources of gravitational waves if the rotation of the neutron star carries some asymmetry around with it. Asymmetries are certainly present at some level, for otherwise the electromagnetic emission from the pulsar could not be beamed. But the gravitational waves emitted by such asymmetries is not necessarily strong enough to detect. Nevertheless, the solid crust of such stars might support much larger asymmetries, and this makes looking for pulsars a very interesting prospect for laser detectors. The only limits we have at present are weak ones, set by the fact that gravitational waves must not carry away more energy than can be accounted for in the observed spin-down of the pulsars.

Unlike the sources we have considered up to now, the signal from a pulsar is steady, and so one can improve the signal-to-noise ratio by observing longer. One's sensitivity increases as the square root of the observation time. Since detectors are intended to record data 24 hours a day, every day, the problem of looking for pulsars is simply a matter of analysing sufficiently long data sets.

One can reach interesting limits on known pulsars, such as Vela and the Crab, if one uses about 3 months' worth of data. Over such a time, one must correct for the Doppler effects of the pulsar signal caused by the motion of the Earth, and one must allow for the signal itself to have some structure (caused by precession of the star, for example). But, as a recent analysis of 100 hours of data from the Garching prototype shows [15], this will not be hard to do. Indeed, one of the principal motivations for the VIRGO detector's design is to optimize it for such observations.

Just as interesting as looking for known pulsars is the possibility of discovering unknown pulsars, or more accurately, unknown spinning neutron stars. These could be pulsars beamed away from the Earth or former pulsars that are no longer emitting electromagnetic radiation. To find such stars, one needs to perform an all-sky, all-frequency search. This will not be trivial. The Doppler effects mean that a separate search has to be performed for each possible 'error box' on the sky, and as the observation time lengthens and the error boxes shrink, the amount of computing required increases enormously.

It can be shown that, even on the most optimistic assumptions about computer algorithms, the computer power required increases as the *eighth* power of the improvement of sensitivity in h! [16] It is not clear yet how sensitive such a search can be made, but processing 3 months' worth of data for a full search is probably out of the question. More restricted searches, in specified frequency bands or in selected directions (such as toward a particular globular cluster), may well be possible.

2.2.4. Stochastic background. There may exist a detectable background of random gravitational waves, just as there is a cosmic background of electromagnetic waves. But, unlike the cosmic microwave background, which Smoot's lecture at this meeting showed has such an impressively thermal spectrum, detectable gravitational waves would come from a variety of interesting non-thermal processes in the early universe [1]. The most exciting prospect is that they would be generated by the same exotic physics that is being invoked to explain dark matter, galaxy formation, and the homogeneity of the universe. In Steinhardt's talk at this meeting, we saw the possible background calculated by Turner and Wilczek [17] for the cosmic radiation generated by the bubble collisions that are predicted by the extended inflation model. This radiation could be seen by interferometric detectors. Cosmic strings should also produce a detectable background, although the exact size of it is still a matter of some debate [18].

Detecting such radiation requires a cross-correlation experiment. Since in any one detector it would be indistinguishable from detector noise, one needs to have detectors close enough to each other that their response to the random waves is correlated, while their intrinsic noise is uncorrelated. They must not be further than about half a wavelength of the gravitational waves, for optimum sensitivity. The two LIGO detectors will be about 3000 km apart, which permits a search at about 50 Hz. The European GEO and VIRGO detectors would be only about 1000 km apart, allowing them a wider bandwidth and therefore a more sensitive search. There is no point in trying to cross-correlate on a transatlantic baseline.

Given its ramifications for particle physics and early cosmology, the discovery of a cosmic background of gravitational waves must be one of the most exciting possibilities offered by interferometric detectors.

3. Coalescing binaries—a challenge to relativists

3.1. Accumulating phase errors in coalescing binary orbits

When the stars are far apart, the system may be modeled as a Newtonian point-mass binary. Various authors have studied the importance of various corrections to this. Clark and Eardley [12] and Krolak [19] considered tidal and mass-exchange corrections to the orbit, and Krolak also considered the post-Newtonian effects. He concluded that post-Newtonian terms in the amplitude of the radiation were small, but possibly measurable. Although he calculated the post-Newtonian corrections to the rate at which the orbital angular velocity changes due to radiation reaction, he did not consider the effect of these corrections on the detection problem.

In an important recent paper, Kochanek [20] has reconsidered the tidal problem in greater detail, and has shown that tidal effects, while small, may accumulate to produce phase errors in the last few orbits. This means that the true orbit can go out of phase with the orbit predicted without tidal effects, rendering useless the template based on the prediction that one uses for the extraction of these signals from the noise.

The effect Kochanek found was small, and possibly marginally measurable, but the principle of the accumulating phase error has far-reaching consequences. Blanchet and Damour [21] pointed out the possibility that higher-order post-Newtonian terms in the gravitational radiation reaction expressions would produce accumulating phase effects that might be measurable, but they made no explicit calculations of their importance. Recently, Cutler *et al* [22] have shown that the post-Newtonian corrections to the standard 'quadrupole-formula' gravitational radiation reaction on the orbit produce a very significant accumulating phase error. It is easily measurable and can be used to determine much more information about the system than we had hitherto thought would be possible. The discussion below is based on their work.

We can see the size of the effect by using the formula given by Krolak [19] for the post-Newtonian correction to the timescale for the change of the frequency of the gravitational waves:

$$\tau_f := \frac{f}{\dot{f}} = 7.8\left[\frac{f}{100\,\mathrm{Hz}}\right]^{-8/3}\left[\frac{\mathcal{M}}{\mathcal{M}_\odot}\right]^{5/6} \times\left[1-0.03\left(1+1.24\frac{\mu}{M}\right)\left(\frac{M}{M_\odot}\,\frac{f}{100\,\mathrm{Hz}}\right)^{2/3}\right]\ \mathrm{s} \tag{3}$$

where μ is the binary system's reduced mass, M its total mass, and $\mathcal{M} := \mu^{3/5}M^{2/5}$ is the so-called *chirp mass* of the binary system.† The dominant term comes from the quadrupole formula (e.g. [9]). It governs the overall timescale for the orbit. Because the rate of decay of the orbit accelerates rapidly, the actual lifetime remaining (for an ideal point-particle model with dominant quadrupole radiation reaction) is $(\frac{3}{8})\tau_f$ and the number of cycles of the waveform remaining is $(\frac{3}{5})f\tau_f$.

The next post-Newtonian correction is given by the second term inside the large square brackets. It is based on the energy loss to the next order, as calculated by Wagoner and Will [23], and is consistent with more recent calculations at the same order by Schäfer and collaborators [24, 25]. Its formal size is small, about an 8% correction for two $1.4M_\odot$ neutron stars at 100 Hz. But since it has a constant sign, it is not long before it builds up to create a phase error of π rad, which will put the real orbit out of phase with the uncorrected one.

Because this next post-Newtonian term is a slowly varying correction to the *rate of change* of the frequency, the induced phase error grows roughly *quadratically* with time. We can study this analytically within the simple approximation that df/dt is a constant, by making a Taylor expansion of the phase Φ of the waveform in time. If we denote the phase error by $\Delta\Phi$ and the correction to the rate of change of the frequency by $\Delta\dot{f}$, then the phase error builds up as

$$\Delta\Phi = \pi\Delta\dot{f}t^2.$$

The corrected waveform is completely out of phase with the quadrupole waveform when $\Delta\Phi$ reaches π, which occurs at the time I shall call t_π:

$$t_\pi = (\Delta\dot{f})^{-1/2} = 1.09\left[\frac{f}{100\,\mathrm{Hz}}\right]^{-13/6}\ \mathrm{s} \tag{4}$$

† In earlier publications, this has often been referred to as the mass parameter or the gravitational mass parameter.

where the last expression assumes, as before, a two-neutron-star binary. The number of cycles of the waveform that have elapsed in this time is roughly

$$N_\pi = f t_\pi = 109 \left[\frac{f}{100\,\mathrm{Hz}}\right]^{-7/6}$$

and the fraction of the total remaining cycles is

$$\frac{N_\pi}{N_{\mathrm{tot}}} = \frac{f t_\pi}{\frac{3}{5} f \tau_f} = 0.20 \left[\frac{f}{100\,\mathrm{Hz}}\right]^{1/2} . \tag{5}$$

This is the interesting equation. It tells us how far we can go without taking the correction term into account: the template will fail to match the real signal after about 20% of the cycles (when, incidentally, the frequency has increased only to 114 Hz). Since the enhancement of sensitivity in matched filtering is proportional to the square root of the number of cycles, we would be sacrificing about half our signal-to-noise. Of course, we know what this next correction term is, so we can match to a template based on it and expect to gain back most of the signal in the process. This means that we should be able to measure the new parameter in this term, namely the ratio μ/M and hence the individual stellar masses, with an accuracy comparable to that with which we measure the chirp mass itself. To see how far this term takes us, we need to ask about the next term that would appear in equation (3) if the post-Newtonian expansion were carried further.

The next term has been calculated by Poisson [26] and Sussman *et al* [27]. It is consistent with the radiated energy to this order as calculated by Blanchet and colleagues [21, 28]. It contains spin-orbit coupling terms and radiation backscatter. Both of these effects are only one order in v/c smaller than the previous term, so this next correction is not a very big step down in size, only about 0.2 times the previous term. This means it will require only of order $1/\sqrt{0.2}$ more time to build up to a significant effect. This would take us to roughly 50% of the cycles after reaching 100 Hz, which still is not ideal.

The situation changes dramatically at lower frequencies. Although the orbit is more Newtonian, and so the corrections are smaller, the phase errors accumulate more rapidly than the orbit shrinks. Equation (5) shows that the correction terms spoil the quadrupole template after a *smaller fraction* of the remaining number of cycles if we start out at a lower frequency. So we have the paradoxical situation that the post-Newtonian corrections are far more important to observations that begin at 10 Hz than to those that begin in the more relativistic regime of 100 Hz!

In order to extract all the information in these terms that detectors operating below 40 Hz can offer [29], it will be necessary to find the post-Newtonian corrections that are smaller than the backscatter correction assumed above by a factor of $100/40 = 2.5$, in other words to go beyond that correction by at least one further order. It may be necessary to go further beyond that if, as Thorne and colleagues suspect, the post-Newtonian scheme does not converge well at higher order.

It is well to emphasize that what we have been discussing is the best way to extract information from the signals, not the way to detect them. Even if we do not know the details of terms in the post-Newtonian expansion, it would still be possible to build a family of templates that were simply expansions of $\dot{f}$ in powers of f with arbitrary coefficients, and use those to find signals. They would find signals with good efficiency. But then we would not know how to interpret the values of the coefficients that best matched a given signal unless we could relate them to a post-Newtonian expansion.

3.2. *Beyond the quadrupole formula*

The problem with going higher in the post-Newtonian scheme is, as most relativists will appreciate, that it may not be practical to do the calculation. The algebra increases exponentially with order. The challenge facing relativity now may be to find alternatives to this.

A possible alternative way of calculating the orbit is to do it fully numerically. While possible in principle, this is not realistic at present, because the regime in which one wants the result is the nearly-Newtonian one, where the separations are large and the timescales long. This would demand a relativistic 3-D integration with a huge grid and a huge number of time-steps. Even then, it is not clear how accurate one could keep the calculation: the grid spacing may need to be kept small if terms as small as those we are talking about are to be obtained.

Perhaps there are hybrid methods for doing the calculation. One might, for example, calculate the two-body orbit problem for relatively nearby stars, for many different separations, and then numerically fit some plausible scaling to extrapolate the results to the more Newtonian regime. Alternatively, one might find a hybrid numerical-analytic scheme in which the near-zone calculation is done numerically but the matching to the radiation zone is done analytically.

None of these alternatives seems practical in the immediate future, but we can be consoled by the fact that we probably have 8 to 10 years before the templates will be required at this level of accuracy. Can relativists make faster progress on the two-body problem than experimentalists will make on detector sensitivity?

3.3. *The payoff: what we learn from coalescing binaries*

There is much to be gained from solving this problem. This comes from two factors. First, a fully post-Newtonian or relativistic filter will depend on both stellar masses, and so detecting the system means being able to measure (or at least estimate) the masses of the two components. Second, if three or more gravitational wave detectors measure the same signal, then by triangulation among them the direction to the source and the intrinsic amplitude h of the waves may be determined. From this one can infer the distance to the source [30]. It is not hard to see that if one knows the distance and the masses, then the following become possible.

• Direct identification of black holes. There will be some coalescences between black holes and neutron stars and probably between two black holes. With good measurements of the individual masses, the identification of black holes will be relatively secure.

• Deduction of the neutron star mass function. Are all neutron stars really of mass $1.4M_\odot$, as binary pulsar observations suggest? Coalescing binary observations would rapidly build up the statistics, and this would have implications for stellar evolution, supernova theory, and possibly for nuclear physics and the neutron star equation of state.

• Measurement of Hubble's constant and q_0. If all neutron stars do have a mass of $1.4M_\odot$, then coalescing binaries at cosmological distances will show apparent masses that are redshifted [31], and from the known true mass one can deduce the redshift. Given the distance, one can then calibrate cosmological parameters.

• The large scale mass distribution in the Universe. Coalescences are typically separated by a few hundred megaparsecs, which is an interesting distance scale for cosmological structure on which we have few measurements at present. Seeing significant clustering on this scale would have striking implications for particle physics and galaxy formation hypotheses.

• Coincidences with gamma ray bursts. Now that we know that gamma ray bursts are isotropic and most likely at cosmological distances [32], the most conservative model for bursts is that they arise in the coalescences of two neutron stars or a neutron star and a black hole. Coordinating observations between gravitational wave detectors and gamma ray detectors could provide a great deal of new information and substantially increase the range of objects detected by their gravitational waves [33].

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References

[1] Thorne K S 1987 Gravitational Radiation *300 Years of Gravitation* ed S W Hawking and J Hartle (Cambridge: Cambridge University Press) pp 330–458
[2] Abramovici A *et al* 1992 LIGO: The Laser Interferometer Gravitational-Wave Observatory *Science* **256** 325–333
[3] Bradaschia C *et al* 1990 The Virgo project—a wide band antenna for gravitational-wave detection *Nucl. Instrum. Methods* A 518–25
[4] Schutz B F 1989 Gravitational wave sources and their detectability *Class. Quantum Grav.* **6** 1761–80
[5] Schutz B F 1989 Gravitational radiation *Ann. NY Acad. Sci.* **571** 27–43
[6] Giazotto A 1989 *Phys. Rep.* **182** 365–425
[7] Schutz B F 1989 (ed) *Gravitational Wave Data Analysis* (Dordrecht: Kluwer)
[8] Blair D G 1991 (ed) *The Detection of Gravitational Waves* (Cambridge: Cambridge University Press)
[9] Misner C W, Thorne K S and Wheeler J L 1973 *Gravitation* (San Francisco: Freeman)
[10] Forward R L and Berman D 1967 Gravitational-radiation detection range for binary stellar systems *Phys. Rev. Lett.* **18** 1071–4
[11] Dyson F J 1963 Gravitational machines *Interstellar Communication: the Search for Extraterrestrial Life* ed A G W Cameron (New York: Benjamin) pp 115–20
[12] Clark J P A and Eardley D M 1977 *Astrophys. J.* **215** 315
[13] Narayan R, Piran T and Shemi A 1991 Neutron star and black hole binaries in the Galaxy *Astrophys. J.* **379** L17
[14] Phinney E S 1991 The rate of neutron star binary mergers in the Universe: minimal predictions for gravity wave detectors *Astrophys. J.* **380** L17
[15] Niebauer T M, Rüdiger A, Schilling R, Schnupp L, Winkler W and Danzmann K 1992 A pulsar search using data compression with the Garching gravitational wave detector *Preprint* Max Planck Institute for Quantum Optics, Garching
[16] Schutz B F 1991 Data processing analysis and storage for interferometric antennas *The Detection of Gravitational Waves* ed D G Blair (Cambridge: Cambridge University Press) pp 406–52
[17] Turner M S and Wilczek F 1990 Relic gravitational waves and extended inflation *Phys. Rev. Lett.* **65** 3080–3
[18] Allen B and Shellard E P S 1992 Gravitational radiation from cosmic strings *Phys. Rev.* D **45** 1898–912

[19] Krolak A 1989 Coalescing binaries to post-Newtonian order *Gravitational Wave Data Analysis* ed B F Schutz (Dordrecht: Kluwer) pp 59–69
[20] Kochanek C S 1992 Coalescing binary neutron stars *Astrophys. J.* to be published
[21] Blanchet L and Damour T 1988 Tail-transported temporal correlations in the dynamics of a gravitating system *Phys. Rev.* D **37** 1410–35
[22] Cutler C 1993 The last three minutes: issues in the measurement of colaescing compact binaries by LIGO *Phys. Rev. Lett.* (submitted)
[23] Wagoner R V and Will C M 1976 *Astrophys. J.* **210** 764
[24] Blanchet L and Schäfer G 1989 *Mon. Not. R. Astron. Soc.* **239** 845
[25] Junker W and Schaefer G 1992 Binary systems: higher order gravitational radiation damping and wave emission *Mon. Not. R. Astron. Soc.* **254** 146–64
[26] Poisson E 1993 in preparation
[27] Sussman G J, Thorne K S and Apostolatos T A 1993 in preparation
[28] Blanchet L and Schafer G 1990 Higher-order gravitational radiation losses in binary systems *Mon. Not. R. Astron. Soc.* **239** 845–67 (Corrigendum: **242** 704)
[29] Dhurandhar S V, Krolak A and Lobo J A 1989 Detection of gravitational waves from a coalescing binary system—effect of thermal noise on efficiency of the detector *Mon. Not. R. Astron. Soc.* **237** 333–40
[30] Schutz B F 1986 Determining the Hubble constant from gravitational wave observations *Nature* **323** 310–1
[31] Krolak A and Schutz B F 1987 Coalescing binaries—probe of the universe *Gen. Rel. Grav.* **19** 1163–71
[32] Meegan C A, Fishman G J, Wilson R B and Paciesas W S 1992 Spatial distribution of gamma-ray bursts observed by BATSE *Nature* **355** 143–5
[33] Nicholson D and Schutz B F 1992 in preparation