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Gravitational Radiation

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INTRODUCTION

Talks on gravitational radiation at previous Texas Symposia have spanned a wide range of subjects, from efforts to detect gravitational waves to the mathematical questions concerning the quadrupole formula and the equations of motion of radiating systems. In this presentation, I have chosen to concentrate on detectors and likely sources, partly because that is where my own interests lie at the moment, but mostly because of the great deal of activity these subjects have seen in recent years, which has led to many developments that are not as well known as they should be in the relativity and astrophysics communities.

In concentrating on detectors and sources, I am ignoring other active areas of the subject. The "quadrupole controversy" that began in the late 1970s (see, e.g., Ehlers *et al.*[1] or the Texas Symposium talk on the subject ten years ago[2]) has largely abated, with many independent approaches having confirmed the validity of the formula in the Newtonian limit.[3,4] Nevertheless, there is a great deal of work on equations of motion, for example, especially with reference to relativistic binary systems (see Damour[3]).

Another area that I will not be able to cover is that of numerical relativity, which is crucially important to the reliable calculation of source strengths. A comprehensive review of that subject would require a full lecture of its own. The field is developing in two directions: (i) to redo with better accuracy and more physics the earlier spherical and axisymmetric calculations of black-hole collisions and gravitational collapse; and (ii) to push on to fully three-dimensional calculations in general relativity. For more details, see the proceedings of the recent workshop at the National Center for Supercomputer Applications.[5]

Instead, what I will be concentrating on are recent progress in detector development and the consequent broadening of our horizons with regard to what sources we believe we shall be able to see. For comprehensive reviews in greater depth, see Thorne,[6] Schutz,[7] and Blair.[8]

DETECTORS, PRESENT AND PLANNED

Bar Detectors

Bar detectors have been under development since Weber's pioneering efforts that began in the late 1950s. Present bars operate with a sensitivity of a few times 10^{-18} and bars now under development could push that to 10^{-20}. At that point, they will be close to their quantum limit and further progress will require either beating that limit (see quantum limit, although in principle possible, do not seem encouraging at this time. However, it may be possible to build bars whose quantum limit is considerably lower, near to 10^{-22} (W. Fairbank, private communication). These might be made of materials with a higher speed of sound, such as silicon carbide, allowing a larger size for a given resonant frequency. These might take bars into the same sensitivity regime as the planned laser interferometric detectors, although with much narrower bandwidth.

Laser Interferometric Detectors

The idea of using laser interferometers to detect gravitational radiation also goes back to Weber, who did not pursue it because of the limitations of the technology of the time. The first working interferometer for gravitational wave detection was built by R. L. Forward and associates at Hughes Research Laboratories.[10-12] Developments in laser and mirror technology, allied to clever ideas for the optical configuration of the detectors (such as various forms of recycling, as described by Drever,[13] Vinet *et al.*,[14] and Meers[15]), have greatly enhanced the potential sensitivity of these instruments.

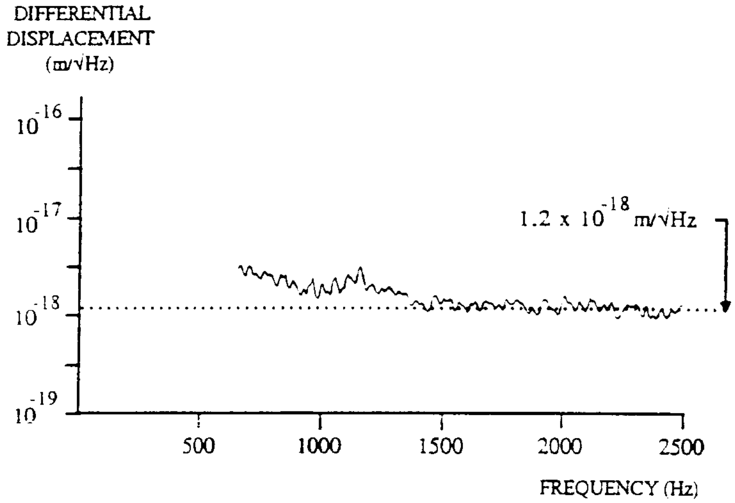
Current designs are based on arm lengths of 3–4 km. Roughly speaking, they would be built in two stages. The first stage would aim at a sensitivity of about 10^{-21} over a 1-kHz bandwidth. The second stage would implement more sophisticated optical techniques, leading to noise levels of $h \sim 10^{-22}$.

In addition, there is every expectation that the final-stage interferometers should be able to achieve good isolation from seismic noise down at least to 100 Hz and possibly as low as 10 Hz. This low-frequency observing window, coupled with the enhanced sensitivity, has made it possible to contemplate detecting a much wider range of sources than envisioned with bar detectors. The most exciting "new" source is the coalescing binary, which I will discuss in detail below.

The present status of laser interferometric detectors is summarized in TABLE 2. Working prototypes with arm lengths in the range of 10–40 m have been constructed at Glasgow, Munich (Garching), Caltech, and (recently) Japan. The sensitivity of the Glasgow detector is displayed in FIGURE 2. The flat spectrum is what detector groups hope to achieve over a wider bandwidth in full-scale detectors. The vertical units

TABLE 2. Summary of the Facilities Developed at and Planned for the Active Laser Interferometric–Detector Groups

Institution	Prototype	Special Purpose	Plan for Full-Scale Project
California Institute of Technology	✓	–	✓
Massachusetts Institute of Technology	–	✓	✓
University of Glasgow	✓	–	✓
Max Planck Q. Opt. Garching	✓	–	✓
I.N.F.N. Pisa	–	✓	✓
C.N.R.S. Orsay–Paris	–	✓	✓
University of W. Australia (Perth)	–	–	✓
Tokyo	✓	–	✓
India	–	–	✓
U.S.S.R.	–	✓	✓



Present detector noise spectrum

FIGURE 2. The noise performance of the Glasgow prototype in mid-1988.

indicate the actual displacement being measured. To convert to an accuracy in *h*, multiply by the square root of the bandwidth of the expected signal (say, 1000 Hz) and divide by the arm length (10 m). This gives a sensitivity of $h \sim 4 \times 10^{-18}$, which is comparable to the cryogenic bars. This is the best displacement sensitivity of any interferometer at present, but the Munich detector has better *h* sensitivity because of its longer arm length.

Special-purpose interferometers, designed to study particular technical problems in this area, have been built at M.I.T., Paris, and Pisa. In the U.S.S.R., plans are being made to convert a low-sensitivity interferometer built for geophysical purposes into a sensitive gravitational wave laser interferometer. Various detectors have made observing runs of limited duration and a coincidence experiment lasting about one week is planned for early 1989 by Glasgow and Munich. There are no plans to run continuously, as the bars intend, because (i) the prototype interferometers are engineering testbeds for the large-scale detectors and cannot be left alone to take data for long periods and (ii) laser interferometers are difficult systems to keep locked onto a fringe and this must be done essentially by hand at the moment. Part of the design effort for large-scale detectors will go into their control systems, but this considerable effort is not likely to be devoted to the prototypes. This means that until the large-scale projects are constructed and in operation, the only systems capable of sustained operation will be the bar detectors.

Regarding future plans, the American project is presently (December 1988) engaged in a design exercise and its fully costed proposal for two detectors is expected to be submitted to the National Science Foundation in Autumn 1989. If approved, it could start in 1990. In other countries, the large cost of these instruments is a spur to international collaboration. In the United Kingdom, there is a commitment of about 25% of the money required to build a detector and discussions with possible partners in other countries are actively under way. A 1990 start to this project also does not seem unrealistic, provided a suitable partner can be found. Furthermore, in Italy, there is a sum slightly larger than the British funding committed to the project and a collaboration with France is likely. That detector would be built in Pisa. Other countries have entered the field recently: Australia, India, and Japan may well enter into partnerships with other countries to build detectors. From the scientific point of view, the more detectors the better. At least three and preferably four are required to reconstruct the gravitational wave completely, giving its intrinsic amplitude and its position on the sky. More detectors operating in coincidence will allow all the detectors to set lower thresholds against noise and thereby to see further away.

Space-based Detectors

I will not have much time to discuss detection of gravitational waves from space, but a few words are appropriate here. Methods presently used include tracking of interplanetary spacecraft and pulsar timing. Transponding to interplanetary spacecraft is sensitive to low-frequency gravitational waves, that is, from 10^{-4} to 10^{-2} Hz. Typically, this method is sensitive at the level of $h \sim 10^{-13}$, but this may improve by a factor of ten or more in the near future. (See articles in Hellings.[16]) Laser tracking could improve this to the level at which it would be likely to see the formation of giant $10^6\ M_\odot$ black holes in the centers of galaxies. See Thorne[6] for a recent review.

Pulsar timing is a technique for detecting a stochastic background of gravitational waves. The millisecond pulsar PSR 1937+214 is so stable that, from the absence of big fluctuations in its apparent period, it is possible to set upper limits on the gravitational wave field that the signals are passing through. This is most sensitive to waves with periods of the order of the time of observation. The present limit is that these waves contain an energy not more than 10^{-6} of the cosmological closure density,[6] which is tantalizingly close to the density of 10^{-7} predicted by cosmic string theory if strings seed galaxy formation.[17] This limit should improve with time, but the extent to which it does will depend on whether Earth-based clocks can be made stable enough to measure (or limit) fluctuations in the pulsar's period. At the moment, the pulsar is just about as stable as any man-made clock. Discovery of a second or third very stable millisecond pulsar would dramatically change the situation and would allow the pulsars to be used as an "interferometer" for the detection of very-low-frequency radiation.

A technique for the future that has been very seriously studied is the possibility of putting a laser interferometer in space. Consisting of three independent spacecraft arranged in an L-shape with arms of the order of 10^9 km, it might sit in the Earth's orbit about the sun at some distance from the Earth. With realistic laser power, it could reach a sensitivity of 10^{-22} over a bandwidth of 10^{-4}–10^{-3} Hz. This would suffice to detect many galactic binaries, including the radiation from the Binary Pulsar PSR 1913+16, as well as interesting cosmological sources, such as the formation of massive black holes in the centers of quasars.

SOURCES OF GRAVITATIONAL WAVES

Supernovae and Gravitational Collapse

Supernovae have always been the source that detector builders aimed to detect: as the most violent event in our corner of the universe, it seemed the most likely candidate for detection. Whereas coalescing binaries have to some extent displaced supernovae as the "most likely" source, at least for the laser interferometers, supernovae are still extremely important sources, particulary for the observing network of cryogenic bars in the next five years or more. Observations of supernovae, or of a gravitational collapse that is not accompanied by a strong electromagnetic outburst, would be extremely interesting for astrophysics. There is considerable uncertainty about the likely strength of gravitational waves from a supernova and I will discuss this below. However, first it is useful to see what sort of range the detectors would have for a source of a given strength.

I will characterize the source by the total energy radiated in gravitational waves during approximately one millisecond; for both 1 $M_\odot$ neutron stars and 10 $M_\odot$ black holes, this is the time scale of the biggest burst. Some kinds of gravitational collapses may give strong wave trains of much longer duration; provided that numerical calculations can provide us with predicted waveforms that we can use for pattern matching, such collapses may be even easier to detect than simple bursts of the same total energy. (This is because the radiation is likely to come out at a lower frequency; see Schutz[18] for the reason why frequency matters.) I will consider two types of burst, which I will call strong and moderate:

(i) Strong bursts contain (by definition) about 0.1 $M_\odot c^2$ of energy in the gravitational waves. This is as much as any theorist might hope for from the formation of a neutron star, but it is a much more modest amount of energy to extract from a collapse that forms a 10 $M_\odot$ black hole. Such a burst would have an amplitude of

$$h \approx 6 \times 10^{-18} \text{ in our galaxy,} \tag{1}$$

which could be seen by the cryogenic bars, or

$$h \approx 4 \times 10^{-21} \text{ in the Virgo cluster,} \tag{2}$$

which would be visible to the first-stage laser interferometers.

(ii) A moderate burst has, by my definition, ten times less energy: 0.01 $M_\odot c^2$. This is not an unreasonable amount of energy to come from a highly nonaxisymmetric rotating collapse that forms a neutron star: the binding energy released is ten times larger, so this can easily be fit into the energy budget. If a 10 $M_\odot$ black hole is formed, the "moderate" burst is not very much more than axisymmetric collapses might generate. Its amplitude is down by roughly a factor of three from that of a strong burst and, in particular,

$$h \approx 4 \times 10^{-22} \text{ at a distance of 60 Mpc.} \tag{3}$$

This would be strong enough to be seen by laser interferometers when they achieve their design goals. Moreover, a network of detectors could measure locations on the sky to an accuracy of 1° or better.[19] This distance is at least three times larger than that to the Virgo cluster, which has commonly been regarded as the minimum distance for obtaining an interesting event rate. In this volume of space, there are several starburst galaxies, where star formation and hence presumably supernovae are occurring at a much higher rate than in most galaxies. There might well be thousands of supernovae per year in the volume out to 60 Mpc. The nearest "starburst" galaxy, M82, is only 3 Mpc away and has a supernova once every few years.[20]

Now, it is time to return to the uncertainties surrounding supernovae as gravitational wave sources, which arise because a perfectly spherically symmetric collapse would produce no gravitational radiation at all. In order for a Type II supernova to produce even a moderate burst of radiation, the collapsing core must presumably become very asymmetric. The most plausible candidate for producing asymmetry is rotation. If the collapsing core contains enough angular momentum to make rotation dynamically dominant when it reaches neutron-star densities (and this is not much angular momentum—the sun has much more than this), then the nonaxisymmetric "bar mode" instability may be excited and the resulting tumbling cigar-shaped core would be a strong source of gravitational waves.

There are two problems making this scenario quantitative. The first is that numerical calculations are not yet good enough to predict how much radiation will come from a core with a given amount of angular momentum. As computers improve, this problem will probably be solved, but it will not be easy: detailed nuclear physics and neutrino transport need to be included. A first step in this direction is described by Bludman in his report at this symposium. The second problem is that we do not know what initial conditions are likely: how much rotation does the precollapse degenerate core typically have? Observations of pulsars suggest that they may be formed with relatively slow rotation rates: the Crab pulsar is young and may never have been rotating near to its breakup velocity. This argues that there is little rotation in a collapsing core. On the other hand, SN1987a offers some suggestion that rotation may have been important in its collapse: polarization measurements[21] suggest that the expanding cloud has an elliptical shape, and the axis of the ellipse lines up with the direction to the mysterious "spot" that appeared in speckle photographs.[22,23] Rotation must be a strong candidate for the mechanism that produces these alignments.

There are other important questions that need more work before they can be answered. The radiation that can be expected from Type I supernovae is also uncertain: if the exploding star completely disintegrates, then none can be expected. However, if occasionally a neutron "cinder" is left behind, then the original star probably has enough angular momentum to produce a strongly deformed core.

Another question is whether there are electromagnetically quiet collapses: do all gravitational collapses result in visible supernovae? The statistics of stellar births, deaths, supernovae, and pulsars are not good enough to exclude this possibility. On theoretical grounds, there is some reason to think that quiet collapses may be common. Current successful Type II supernova models are delicately balanced: the escaping neutrinos provide only just enough energy to power the shock outwards through the envelope and blow off the envelope. If we have a strongly rotating collapse, the lower core densities and longer time scale may weaken the shock and prevent it from blowing off the outer shell. Thus, there could be an anticorrelation between electromagnetic and gravitational radiation intensities from a gravitational collapse: the strongest gravitational wave emitters may have the weakest explosions and may therefore even go on to form black holes.

It may be that only gravitational wave observations of supernovae will settle some of these questions. However, it would surprise me if the answers conspired to give no observations of bursts in laser interferometer detectors. Of all the supernovae out to 60 Mpc, if even only 1% produces moderate bursts, the network could register tens of events per year. Moreover, strong bursts could be seen to nearly 200 Mpc. There may be hundreds of black holes like Cygnus X-1 formed per year in that volume.

Gravitational Waves from SN1987a

It is one of the great frustrations of gravitational wave astronomers that the cryogenic bars were not taking data at the time of the supernova. What sort of waves would have been expected? Even if the burst was exceptionally strong, say, 1.0 $M_\odot c^2$ of energy in the radiation itself, its amplitude would have been only about $h \sim 5 \times 10^{-18}$, just within the range of the cryogenic bars. The room-temperature bars at Rome and Maryland were sensitive at about 3×10^{-17}. No significant coincidences were reported between them at the time of the supernova (as defined by the time of arrival of the bursts of neutrinos in any of the neutrino detectors).

However, it has been reported that there were excess correlations between events in the neutrino detectors and the excitation of the bar detectors 1.2 s before each neutrino event, over a two-hour period including the supernova, and Pizzella describes the latest results on that elsewhere in this volume. I will remark here only that if these events are gravitational waves from the Large Magellanic Cloud, then each event, even at the 1σ level in a 3×10^{-17} detector, would represent the release of about 40 $M_\odot c^2$ of energy in gravitational radiation. Therefore, they cannot be gravitational waves if general relativity is correct and their source is physically associated with the supernova. Other plausible theories of gravity can be excluded as well.[24]

Coalescing Compact-Object Binaries

In its final moments some 10^8 years from now, the "Binary Pulsar" PSR 1913+16 will be a pair of neutron stars in a perfectly circular orbit that is decaying rapidly because of gravitational radiation reaction. The orbit is well approximated as a simple Newtonian point-particle orbit with quadrupole radiation reaction.[25] Tidal, post-Newtonian, or other effects do not begin to make it deviate from this behavior until the gravitational waves have a frequency of some 500 Hz or so.[26,27]

As was first pointed out in a remarkable early paper by Forward and Berman,[28] these sources are good candidates for detection by broadband detectors. The energy carried off by the waves from the orbit will be enormous: some 6×10^{-3} $M_\odot c^2$ as the radiation frequency rises from 100 to 200 Hz. Moreover, the very predictable wave train allows matched filtering to be applied to the data, which allows us to dig into the noise and see these systems at very great distances.

The maximum amplitude is along the axis of the orbital angular momentum. These gravitational waves have amplitude,

$$h_{\max} = 3.6 \times 10^{-23}\left(\frac{M_T}{2.8\ M_\odot}\right)^{2/3}\left(\frac{\mu}{0.7\ M_\odot}\right)\left(\frac{f}{100\ \mathrm{Hz}}\right)^{2/3}\left(\frac{100\ \mathrm{Mpc}}{r}\right), \tag{4}$$

where M_T is the total mass and μ is the reduced mass of the binary. The amplitude in other directions is reduced by angular factors of order 1 and the detected amplitude is further reduced by antenna-pattern effects. With a network of three or four laser interferometers, it will be possible to unravel the angular factors and reconstruct $h_{\max}$ from the observations.

The orbit decays due to gravitational radiation reaction and the orbital period decreases. The formal coalescence time scale is given by

$$\tau := \frac{f}{\dot{f}} = 5.6\left(\frac{M_T}{2.8\,M_\odot}\right)^{-2/3}\left(\frac{\mu}{0.7\,M_\odot}\right)^{-1}\left(\frac{f}{100\text{ Hz}}\right)^{-8/3}\text{ s.} \tag{5}$$

The true time to coalescence is three-eighths of this. If we look at these two equations, we see that the way that the (generally unknown) stellar masses enter the relations is the same in both cases. Therefore, the product of the two observables is independent of the masses: $h_{\max}\tau$ depends only on r, the distance to the binary.[29] Coalescing binaries are therefore standard candles and this makes them useful for many purposes, including the determination of Hubble's constant.[29] I will return to this below.

Conversely, detection of the coalescing binary does not determine the individual masses of the stars. It only tells us the mass parameter of the system, defined by

$$\mathcal{M} = m_1^{3/5} m_2^{3/5}/(m_1 + m_2)^{1/5} \tag{6}$$

or, equivalently, by the more transparent formula,

$$\mathcal{M}^{5/3} = \mu M_T^{2/3}. \tag{7}$$

Only if the signal is strong enough to detect post-Newtonian orbital effects in the waveform will it be possible to determine the individual stellar masses.[27]

By using pattern-matching techniques, it should be possible for the second-stage laser interferometers to detect coalescing binaries out as far as 1 Gpc, where the cosmological redshift is 0.1–0.2.[6,30] A network of four detectors would detect 5–10% of all the sources in this volume.[31]

As with gravitational collapse, there are considerable uncertainties about coalescing binaries as gravitational wave sources. The most important is their event rate. An early estimate suggested there would be 3 per year out to 100 Mpc.[32] If we extrapolate this to our expected range of 1 Gpc and allow for the fraction we expect to detect, we find that this gives an event rate in the network of detectors of 150–300 per year.

However, the Clark *et al.*[32] event rate is based on a number of assumptions, not least of which is that the one coalescing binary precursor system that we do observe—the Binary Pulsar—is representative of its class. We would learn much more about the event rate if we could discover other precursors. In this connection, the recently discovered binary pulsar in the globular cluster 47 Tuc is potentially very important,[33] but we must await confirmed measurements of the orbital elements and their rates of change. At the moment, I would estimate that it would be fair to say that the event rate is uncertain by a factor of 10–100 either way. Even the pessimistic lower bound would give a few events per year in a network of detectors. This is why I feel that coalescing binaries are the most likely source that laser interferometers will detect in the long run.

Another approach to understanding coalescing binaries is to study their evolutionary history. How many binary evolutionary paths could lead to systems with two compact objects close enough to have an orbital lifetime less than 10^{10} years? What fraction of them could contain black holes of 10 $M_\odot$ or more? If the fraction of compact X-ray binaries in our galaxy having black holes is typical of coalescing binary precursors, then perhaps 1% of coalescences would involve a neutron star and a black hole, whereas 10^{-4} might involve two black holes. Because systems with two 14 $M_\odot$ black holes could be seen roughly ten times further away than two-neutron-star systems, they could account for as much as 10% of the total number of systems detected. Another question concerning the formation of coalescing binary precursors is whether conditions in evolved globular clusters lead to the formation of such systems more often than in the disk of the galaxy. It is interesting that 47 Tuc is one of the most centrally condensed clusters, and it may have just undergone central core collapse and reheating by the formation of a few dozen binary stars. If a good fraction of globular clusters go through this cycle many times, how often will coalescing binary precursors be formed?

It might be possible to get further information about coalescing binaries if we knew what the coalescence event looked like in electromagnetic radiation. An interesting suggestion by Blinnikov *et al.*[34] is that, in a system with unequal-mass neutron stars, the more massive star will strip the less massive one and this will go on until the less massive one reaches the minimum mass of a neutron star, about 0.1 $M_\odot$. At this point, the small neutron star is unbound and will explode. What will this explosion look like? Will it look like a weak Type I supernova? Will it give a detectable X-ray or gamma-ray burst? What will happen to the primary star? If it accepts all the mass shed by the secondary, it may exceed the upper limit on the mass of a neutron star and it may collapse to a black hole. Theoretical study of these questions could shed considerable light on the question of whether coalescing binaries will be detected frequently or at all.

If coalescing binaries are detected at the rate predicted by Clark *et al.*, they become very interesting for astronomy:

- Nearby events (within 100 Mpc) could be used to determine Hubble's constant with an accuracy of a few percent. Our recent estimates of the accuracy of the angular positions that a network will be able to infer are much better than I assumed when I first suggested this method.[29] It may take only a handful of events to pin down H_0 this way.
- If we detect a few hundred events per year from 500 Mpc and beyond, each with a distance and an angular position, we can do statistical studies of the stellar distribution on scales not heretofore possible. Gravitational waves are not obscured by any intervening matter, so they represent an ideal survey medium.
- Each coalescing binary event gives us a measure of the masses of the component stars, the mass parameter $\mathcal{M} = \mu^{3/5} M_T^{2/5}$. Statistical studies of this could help us infer the neutron star mass function.
- Coalescences involving black holes could be the most reliable method available for positive identification of black holes. Those involving two black holes can be modeled by computers and therefore provide a test of general relativity.
- Coalescences of two black holes seen at $z \sim 1.0$ are bound to give us new statistical information about conditions at that epoch. They also may be candidates for gravitational lensing.[27] The different lensed components could not be resolved spatially, but the events would arrive at different times; thus, the time-delay would be known extremely accurately (to less than a second). The

elliptical polarization of the generic coalescing binary gravitational wave would allow us to distinguish positive from inverted images.

FIGURE 3 summarizes the great variation in the effective ranges of expected gravitational wave detectors when looking at supernovae and coalescing binaries.

As a sobering final thought on the subject, let us recall that it will be some time before abundant data on coalescing binaries become available: if the Clark *et al.* event rate is correct, then only when laser interferometers reach a sensitivity of 10^{-22} can they begin to do serious observing. This may be ten years from now.

Other Sources: Pulsars and the Stochastic Background

Pulsars

Pulsars are particularly interesting sources to search for because the gravitational radiation they may emit will not be beamed: the statistics of a "complete" search of the solar neighborhood would not be affected by the uncertainties due to beaming factors that afflict radio searches. Moreover, because the radiation would presumably be due to crustal deformations, old radio-quiet pulsars could still in principle be sources of gravitational waves. On the other hand, there is considerable doubt about the amplitude of any gravitational waves that may be emitted and it may be that only by observing gravitational waves from pulsars or setting upper limits on their amplitudes will we be able to settle the question.

Present observational limits come from the Tokyo experiment,[35] which can reach down to about $h \sim 3 \times 10^{-22}$ at 60 Hz. (The dominant quadrupole radiation will come out at twice the frequency of rotation of the pulsar, just as it does for binary systems.) This limit is far above an indirect one of 10^{-24}, which is the maximum allowed if the entire spindown of the Crab pulsar is due to its losing energy to gravitational waves. Interferometers in their ultimate configuration could in principle reach to 10^{-27} at 60 Hz, provided they can beat the seismic noise at such a low frequency.

Finding known pulsars is one thing; making an all-sky search in gravitational waves is another. The primary problem is that long integration times (typically, 10^7 s) are required and, during such long times, the Earth's various motions produce very significant Doppler shifts in the pulsar signal. Moreover, these shifts depend on the position of the pulsar in the sky. Removing these shifts is computationally prohibitive for a search by a single detector.[36] However, a less-sensitive all-sky search is possible using cross-correlation of three or more interferometers. Gursel and Tinto[19] have shown how to remove the effects of different instrumental polarizations in order to reach the maximum sensitivity. Their method works provided the detectors are sufficiently close that there is no significant Doppler shift of the signal in one relative to the other. For millisecond pulsars, the detectors need to be within about 600 km of one another, but a worldwide network could search for pulsars efficiently below 100 Hz.

Wagoner Stars

Wagoner[37] pointed out that an accreting neutron star that is spun up to the angular velocity at which a nonaxisymmetric mode of the star becomes unstable to gravitational radiation (a CFS instability: see Thorne[6] and Schutz[38]) will become a gravitational wave beacon, emitting gravitational waves at exactly the rate required to carry off any further accreted angular momentum. Such a source would be an X-ray source as well and, in fact, the gravitational wave luminosity would be proportional to the X-ray luminosity. There are several galactic X-ray sources in which this scenario is possible and whose luminosity is large enough to suggest that interferometers could see their gravitational waves, most particularly Sco X-1.[6] They could be searched for in the same way as for pulsars.

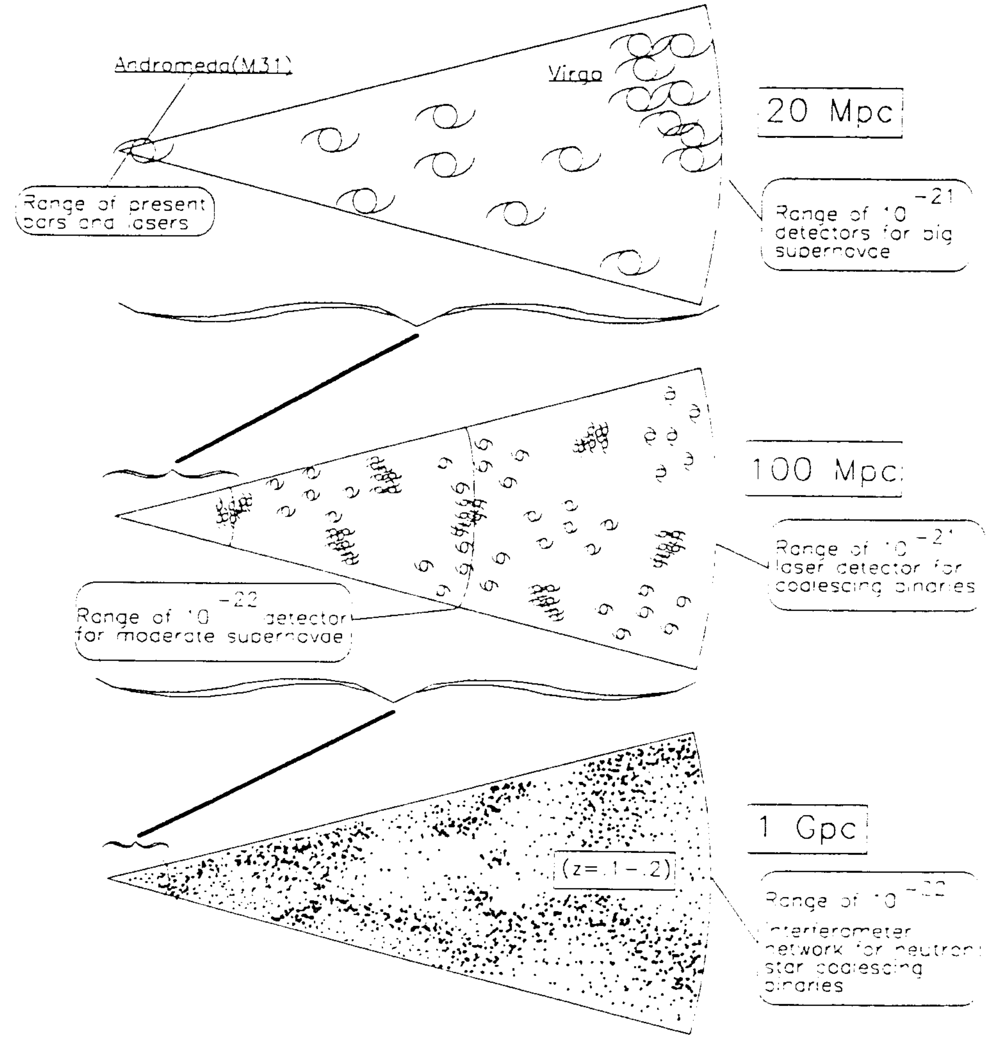


FIGURE 3. Wedge-shaped sections of the universe displayed on different scales to indicate the ranges of different detectors for supernovae and coalescing binaries. The observer sits at the apex of the cone.

Stochastic Background

A stochastic background can also be found by cross-correlation between detectors. The detectors should be no more than a reduced wavelength of the gravitational waves apart for maximum sensitivity. There are many possible sources for such backgrounds: cosmic strings;[17,39] very massive objects—VMOs—formed in the early universe;[40] or phase transitions in the early universe.[6] In particular, the cosmic string scenario makes a fairly definite prediction of the energy density of the background: if cosmic strings are seeds for galaxy formation, then the gravitational radiation they produce as they decay should contain at present about 10^{-7} of the closure density. Laser interferometers could reach to 10^{-9} of closure, so they could test this prediction at 100 Hz. It also may be tested soon by observations of very stable millisecond pulsars, but this would be at low frequencies (10^{-9} Hz) and it will depend on progress in the development of very stable laboratory clocks.

Low-Frequency Sources

Although I have concentrated on sources of gravitational waves at frequencies above about 50 Hz, which would be observable from the ground, there is considerable interest at present in the design of space-based detectors that can reach as low as $h = 10^{-22}$ at 10^{-3} Hz.[16] There are a number of interesting sources at these frequencies that made the development of such detectors desirable. These include:

- Formation and coalescence of black holes of mass greater than $10^6\ M_\odot$ in the centers of galaxies.
- Binary systems in our galaxy: there are many systems with periods of a few hours or less that could in principle be observed. Binaries consisting of two white dwarfs are particularly interesting.[41] Neutron-star binaries that will eventually coalesce could be identified at a much earlier stage of their evolution. In fact, there are so many binaries in this frequency range that they will become a nuisance, acting as a noise background against which it will be harder to detect bursts from massive black-hole events in distant galaxies.
- Stars falling into nearby galactic black holes. Even nearby galaxies may have "dead" black holes in their nuclei and neutron stars may occasionally fall into them. Such an encounter would emit a detectable burst of radiation.

For more details, see Thorne[6] and Schutz.[18,42]

A GRAVITATIONAL WAVE ASTRONOMER'S SHOPPING LIST OF ASTROPHYSICAL PROBLEMS

There are many questions that lead to uncertainties in our predictions about gravitational wave sources that do not need to wait for gravitational wave observations before they can be solved. The following very personal "shopping list" is offered in the hope that it will encourage astrophysicists to give some needed attention to these problems during the time when the large laser interferometers are being constructed. The list is by no means exhaustive; it simply represents the problems that I personally would most like to see progress on during the next five years:

- Incorporate significant rotation into supernova collapse models. Although this is a long-term goal of numerical general relativity, present highly developed spherical collapse codes that do the nuclear physics correctly could be modified within Newtonian gravity to examine rotation. Even an extension and updating of the work of Müller and Hillebrandt[43] on axisymmetric collapse would be very useful. We would especially want to treat neutrino transport correctly (see Bludman in this volume). Given the well known sensitivity of present collapse/supernova models to details of the nuclear physics, it would be interesting to see how realistic amounts of rotation might modify the picture.

- Are there electromagnetically quiet gravitational collapses? If we have confidence in at least a spherically symmetric collapse code, then it would be interesting to explore some sort of reasonable parameter space of initial conditions and physical uncertainties to see whether there is a class of stars that could collapse without a big explosion.
- Model the coalescence of two neutron stars from circular orbits. There are really three phases of coalescence that need to be better understood:
  - Model the interactions of the stars once they are too close to be treated as point masses. This could be attacked with analytic calculations and numerically. As a numerical problem, it is one of the most demanding goals that could be set for a numerical relativity program. Head-on collisions of neutron stars have been treated by Evans,[44] and a remarkable first attempt within Newtonian gravity at modeling coalescence of two stars that start out in roughly circular orbits with their surfaces in contact has been reported by Nakamura and Oohara.[45] As computers improve and more physics can be put in, we would like to see tidal effects and mass transfer modeled accurately. Is there a long "coasting" stage in which the orbital frequency is roughly constant as mass is transferred? Such models would help us to extend the filters we use for digging coalescence signals out of the noise beyond the point-mass stage, increasing the range of any detectors and improving the signal-to-noise ratio of any detection. This would have the further effect of improving the determination of the angular position and distance of any event.
  - Model the explosion of a mini-neutron star. The late stage of mass transfer between two neutron stars or a neutron star and a black hole may result in the stripping of a neutron star down to its minimum mass, at which point it would explode. What would such an explosion look like? Are there observational tests or searches we could perform?
  - Model the subsequent development of the primary star in the binary. If the secondary explodes because it has too little mass, does the primary in its turn collapse because it gains too much? What electromagnetic radiation would such a collapse produce? Given that the primary is probably rotating rapidly because of the accreted angular momentum, does its collapse produce a long wave train of gravitational waves? If so, then numerical predictions of this wave train can be used to produce filters for the incoming data that will aid in detecting any collapses that may follow detected coalescing binary events.

- What is the coalescing binary event rate? It may be possible to provide much more confident predictions of this from studies of binary star evolution and from observational tests of the predictions of coalescence models, such as models for the explosion of mini-neutron stars.

In his summary of the first Texas Symposium, Peter Bergman[46] wrote that we could hope that gravitational waves will be detected, but only in the "rather distant future". Twenty-five years later, that hope is rather more concrete. If the funding authorities cooperate and if our predictions regarding gravitational wave sources are not too far wrong, then in the *foreseeable* future—maybe at the 19th Texas Symposium in 1998, maybe well before—we should have a talk, not just about gravitational wave detectors, but about gravitational wave astronomy. In the meantime, it is not just the gravitational wave experimentalists who will be working hard: the more theoretical understanding we have about likely gravitational wave sources, the easier it will be to dig their radiation out of the noise when the detectors come on line.

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