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SOURCES OF GRAVITATIONAL WAVES

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ABSTRACT

Sources of low-frequency gravitational radiation are reviewed from an astrophysical point of view. Cosmological sources include the formation of massive black holes in galactic nuclei, the capture by such holes of neutron stars, the coalescence of orbiting pairs of giant black holes, and various means of producing a stochastic background of gravitational waves in the early universe. Sources local to our Galaxy include various kinds of close binaries and coalescing binaries. Gravitational wave astronomy can provide information that no other form of observing can supply; in particular, the positive identification of a cosmological background originating in the early universe would be an event as significant as was the detection of the cosmic microwave background.

I. INTRODUCTION

Almost every speaker at this Workshop who has discussed methods of detecting gravitational waves from space has included a discussion of possible sources of gravitational waves at low frequencies. My aim here is not to repeat these discussions, but to put them in their astrophysical context: why is gravitational wave astronomy interesting? A good source for further reading is Thorne (1987).

In general terms, gravitational waves open up a qualitatively new window on the universe. The information they carry reflects the large-scale mass distribution of the source on distance scales of the same order as the gravitational wavelength. By contrast, observable electromagnetic radiation is of much higher frequency, and comes from small regions: atomic size for visible wavelengths, for example. As a consequence, astrophysical modelling of large-scale structures requires assumptions that enable one to go from the small-scale to the large: assumptions of local thermodynamic equilibrium, of homogeneity, of symmetry, and so on. Gravitational waves will enable more direct modelling of the source and will be complementary to electromagnetic waves when both are available.

a) A Brief Look at Sources of High-Frequency Radiation

It will help us to look briefly first at sources of high-frequency gravitational waves, even though they are of more relevance to ground-based detectors than to space-based ones. Some of them are closely related to low-frequency sources, and if they are detected from the ground they will provide further incentive for looking from space. For a review of ground-based detection, see Schutz (1988).

1) GRAVITATIONAL COLLAPSE

Collapse to form neutron stars or black holes in the mass range 1 to 10 $M_{\odot}$ will radiate waves in the frequency range 1 to 10 kHz with an amplitude that depends on how much asymmetry there is in the collapse. These collapses, at least sometimes, result in Type II supernova explosions. The rate at which Type II supernovae occur is relatively well known, but the fraction of collapse events that produce strong enough gravitational waves is not. Since the characteristic period of the waves is proportional to the light-travel time around the collapsed object, the dominant frequency scales as $1/M$. For sufficiently large M, this source will produce low-frequency waves detectable from space. (See the article on gravitational collapse by Stark in this volume.)

2) COALESCING BINARIES

This is one of the most promising sources of waves detectable from the ground, once broadband laser detectors reach their expected sensitivity. The famous 'Binary Pulsar' PSR 1913+16 is a precursor of such a system: in some 10^8 years it will have evolved through gravitational radiation reaction into an almost perfectly circular orbit with a period of 20 msec and a separation between the stars of about 150 km. At this point it will be a strong source of gravitational waves at 100 Hz, within the expected observing window of laser-interferometric detectors. During the next 2 seconds the stars will spiral together and coalesce; before they coalesce, they will have emitted some 500 or so cycles of radiation at ever-increasing frequency. Because the signature of this radiation, or 'chirp,' is unique and predictable, it is possible to filter weak signals out of the noise of an interferometer. Consequently, coalescing binaries can be seen some 25 times further away than moderately strong gravitational collapses (supernovae). The expected event rate is very uncertain. Again, the frequency of the waves is inversely proportional to the mass of the system, so binaries consisting of massive black holes could be detected from space. So, too, might the precursor systems when the stars are still well separated, as in the present Binary Pulsar. I will return to this source in Section II.b.1 below.

3) PULSARS

Pulsars emit gravitational waves if they are non-axisymmetric. The frequency of the waves will be twice the rotation frequency of the star. We have little idea of what strength to expect from known pulsars, but it is unlikely that any slowly rotating, former pulsar would be a strong source of gravitational waves at low frequencies.

4) ACCRETING NEUTRON STARS

Neutron stars in X-ray binaries can be spun up by accretion, possibly until they reach a rotation rate at which they encounter a non-axisymmetric rotational instability. As Wagoner (1984) has pointed out, further accretion will drive the instability until it has sufficient amplitude so that the gravitational waves that are radiated carry away as much angular momentum as that which is being accreted. The system then becomes a steady source of gravitational waves. Several galactic X-ray sources are candidate sources. We do not know enough about the behavior of matter at neutron star densities to predict what the frequency of this radiation should be. If X-ray observations — such as those proposed for the XLA satellite (see the talk by Wood at this meeting in Michelson and Wood, this volume) — detect low-amplitude variability in X-ray sources, ground-based detectors could search for the associated waves. Successful observations would be enormously important for neutron star (and hence for nuclear) physics. It is most unlikely that any of this radiation will be at frequencies below 10 Hz.

5) STOCHASTIC BACKGROUND

There are many postulated sources of a measureable stochastic background at kiloHertz frequencies, all of them cosmological. Perhaps the most interesting are cosmic strings, which might have acted as seeds for galaxy formation. If they did, there is a firm prediction that the gravitational wave background they would have produced should have an energy density of 10^{-7} of the closure density (Vachaspati and Vilenkin 1985). There is no preferred frequency for this background, so the waves' spectrum should be scale-invariant. Detection of this background would provide strong evidence, not only for the string model of galaxy formation, but also for the particle-physics theories that lead to strings. See the talk by Matzner at this meeting for more details on backgrounds.

b) Coalescing Binaries in More Detail

The interest in coalescing binaries of neutron stars or black holes is easier to understand if we write down the formulas for the amplitude h of the gravitational waves and the timescale τ for the coalescence of the system, in terms of the total mass M_T of the system, its reduced mass μ, the frequency f of the radiation, and the distance r to the system:

maximum h (when the system is viewed down the axis)

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

and

coalescence timescale

$$\tau := \frac{f}{\dot{f}} = 5.6 \left(\frac{M_T}{2.8\mathrm{M}_\odot}\right)^{-2/3} \left(\frac{\mu}{0.7\mathrm{M}_\odot}\right)^{-1} \left(\frac{f}{100\mathrm{Hz}}\right)^{-8/3} \text{ sec.}$$

When viewed in other directions, the binary produces a wave amplitude that is h_{max} times angular factors. A network of four broadband detectors can determine these angular factors and thereby measure h_{max}.

Notice that the product $h_{max}\tau$ depends only on r: *coalescing binaries are standard candles!* It is extremely difficult in astronomy to find observable systems that can provide reliable distance measures. Coalescing binaries are of great interest for this reason. See the talk by Wahlquist at this meeting for further discussion of these binaries in the context of space-based observations.

For low-frequency observing, there are two frequencies which are useful to remember. If one expects to observe a system consisting of two 1.4 $\mathrm{M}_\odot$ neutron stars for an observation period of 10^7 sec, then the first important number is that a binary with an initial frequency of 0.5 Hz will just reach coalescence at the end of the observing period. This is, in some sense, the optimum frequency at which to search for coalescing systems, since they are easiest to observe when they change the most in the observation period. If they are picked up at a lower frequency, they change less dramatically in 10^7 sec. Unfortunately, frequencies of 0.1 to

1 Hz are the worst from the point of view of detector noise! The second number to keep in mind is that if a system with the assumed masses has f $<7 \times 10^{-3}$ Hz, then it will not change its frequency by a measureable amount during a 10^7 sec observation. This frequency is roughly the dividing line between standard binaries and coalescing binaries from an observational point of view.

II. SOURCES OF LOW-FREQUENCY GRAVITATIONAL WAVES

There is a natural division of likely sources into two categories: cosmological sources, which are strong and distant; and galactic sources, which are local but weak.

a) Cosmological Sources

1) FORMATION OF A GIANT BLACK HOLE

Many astrophysicists believe that the most plausible explanation for quasars and active galactic nuclei is that they contain massive (10^6–10^9 $M_\odot$) black holes that accrete gas and stars to fuel their activity. There is growing evidence that even so-called 'normal' galaxies like our own and Andromeda (M31) contain black holes of modest size (10^4–$10^6 M_\odot$) in their nuclei (Blandford 1987). It is not clear how such holes form, but if they form by the rapid collapse of a cluster of stars or of a single supermassive star, then, with a modest degree of non-symmetry in the collapse, they could produce amplitudes $h \sim 10^{-16}$ to 10^{-18} in the low frequency range observable from space. If a detector had a spectral noise density of 10^{-20}Hz$^{-1/2}$ (see the talk by Bender at this meeting; this might be a conservative figure), then such events could have signal-to-noise ratios (S/N) of as much as 1,000. This strong a signal would permit a detailed study of the event. If every galaxy has one such black hole formed in this way, then there could be one event per year in a detector. If no such events are seen, then either giant black holes do not exist or they form much more gradually or with good spherical symmetry.

2) STAR FALLING INTO A GIANT BLACK HOLE

If black holes power active galactic nuclei, they do so by swallowing stars and gas. Occasionally, neutron stars should fall into them. Neutron stars are compact enough not to be disrupted by tidal forces before reaching the horizon, so they will give a coherent gravitational wave burst with a frequency similar to that which the black hole gave off when if formed. Fairly reliable numerical calculations of this radiation exist (see Thorne 1987 for references), and they suggest that an event in the Virgo Cluster of galaxies would give an amplitude $h \sim 10^{-21}$ and $S/N \sim 10$. The event rate, however, is very uncertain: although the Virgo Cluster contains over 1,000 galaxies, their central black holes are quiescent and may by now have already consumed all the stars that are in orbits that take them near to the hole.

3) COALESCENCE OF GIANT BLACK HOLES

If two black holes of mass 10^6 $M_\odot$or more, collide and coalesce, they will emit radiation which is at least as strong as we have suggested above for the formation of such holes. The waveform would have a characteristic signature from which one could identify the event with some confidence. Such collisions could result from the merger of two galaxies that both contain black holes. Merged galaxies are not uncommon, especially in the centers of clusters; after the merger, dynamical friction could bring both holes to the center, where they would coalesce. Alternatively, it might be that giant black holes in the centers of galaxies themselves form, not by a single collapse, but by a sort of hierarachical merger of smaller black holes. Again, the event rate is very uncertain, but the events would be strong, $S/N \sim 1{,}000$.

4) STOCHASTIC BACKGROUND OF COSMOLOGICAL ORIGIN

Gravitational waves having frequencies below 10^{-2} Hz today may be redshifted relics of waves emitted in much earlier phases of the Big Bang. See Matzner's talk at this meeting for a full discussion of the different mechanisms which might produce such waves. Among the most interesting, observationally, are inhomogeneities associated with inflation, which might produce a scale-invariant spectrum with a spectral density $\sim 10^{-21}$ $\mathrm{Hz}^{-1/2}$ at 10^{-4} Hz; and early anisotropies, which might produce a 'line' of radiation at about 10^{-5} Hz, with spectral density 10^{-20} $\mathrm{Hz}^{-1/2}$. If these backgrounds could be detected and identified by their spectrum, they would provide the most direct evidence that the early universe was dominated by the sort of particle physics effects that are fashionable but speculative in modern cosmological theory: inflation, spontaneous symmetry breaking, cosmic strings, and so on. The implications for cosmology and physics as a whole would be fully as significant as the discovery of the cosmic microwave background was 25 years ago. Clearly, this is one of the most important gravitational wave experiments possible from space. But it may not be easy, since as we will see below there are other backgrounds due to binary stars that could obscure any cosmological background.

b) Galactic Sources

1) COALESCING BINARY PRECURSORS

If observing from space is confined to frequencies below 0.1 Hz, then our earlier discussion of coalescing binaries in Section I.b makes it clear that no solar-mass systems will be discovered that can be followed all the way to coalescence. However, it should be possible to see some precursors as ordinary binaries (*i.e.*, below 7×10^{-3} Hz). The Binary Pulsar system itself will be just detectable at about 10^{-4} Hz if the spectral noise density of the detector is 10^{-20} $\mathrm{Hz}^{-1/2}$. Because pulsar radiation is beamed, it is likely that there are similar systems even closer to us that we do not observe because their beams are pointed in the wrong direction. If the nearest is 2 kpc away, then it might give $S/N \sim 10$ if it is favorably oriented with respect to the detector. A precursor with a frequency of 10^{-2} Hz could be seen as far away as the Andromeda galaxy (M31) with $S/N \sim 10$. Since the number of precursor systems is very uncertain (see Schutz 1988), there is a good possibility that such a system, with a lifetime of only 10^4 years, would be seen.

2) CLOSE WHITE-DWARF BINARIES

Systems like this are associated with cataclysmic variables, Type I supernovae, and especially with models of the formation of isolated millisecond pulsars by the coalescence and subsequent collapse of the two white dwarfs. They are more numerous than neutron-star binaries, so the nearest may be considerably closer, with a $S/N \sim 100$ or more in a 10^{-20} $\mathrm{Hz}^{-1/2}$ detector.

3) INDIVIDUAL BINARIES

A number of nearby binary systems are known which produce radiation that is strong enough to be observed by space-based detectors. See Thorne (1987) and references therein for a list. This is one of the few certain sources of gravitational waves at these frequencies.

4) BACKGROUND NOISE FROM BINARIES

Another certain source is the vast number of ordinary binary systems, whose radiation reaches us from random directions and at random frequency. A single space-based detector will have little directional resolution, so below about 10^3 Hz it will be receiving waves from so many systems that they will be more closely spaced in frequency than the frequency resolution one can obtain in a 10^7sec observing run. (See Thorne 1987 or the talk by Bender at this meeting for details of the expected spectrum.) This background is of interest in its own right, since detecting it would give a measure of the distribution of periods in the binary population of the Galaxy. But it can also be a nuisance, obscuring other interesting sources. There are at least two possible ways to beat this noise. One is to obtain directional information about the gravitational waves, for example by flying two detectors. In any given solid angle, the confusion caused by the background will be reduced by the ratio of the solid angle to 4π. The second method is to make use of the fact that the 'noise' produced by these binaries is not true white noise: at any single frequency the amplitude is constant and the phase remains coherent over the observing period, since it is just the signal of a single binary system. This property may make it easier to filter for signals that do not have constant frequency, such as black hole bursts or waves from relatively massive coalescing binaries, since the 'noise' is not really stochastic.

III. CONCLUSION

There are a great variety of possible sources of gravitational waves at milliHertz frequencies. Some are rather speculative and some are essentially certain, considerably more certain in fact than any of the postulated sources detectable by ground-based detectors. Observations of, or even good upper limits on, some of these sources would contribute valuable information to astrophysical modelling of different types of binary star systems, neutron stars, quasars, active galaxies, and the early universe. In particular, the discovery of a gravitational wave background of cosmological origin would be of the greatest significance to astronomy and physics. Despite the great difficulties involved in building sensitive space-based detectors, the possible scientific returns make a strong case for going ahead with them.

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DISCUSSION

HELLINGS: Peter Bender told us to expect one galactic collapse event every 1000 years. You told us we might expect one per year. Did you assume some preferred epoch of collapse to form galaxies?

SCHUTZ: No. The difference is that Peter Bender said that if all active galaxies had giant black holes, we would get 1 even per 1000 years, while I said that if all galaxies have such black holes, then it will be 1 event per year. Peter's estimate is conservative, while mine is optimistic.

HELLINGS: When you told us the spectrum to be expected from cosmic strings was scale invariant, does that mean a flat amplitude spectrum, a flat energy spectrum, or just a broad-band spectrum that you could move anywhere you chose?

SCHUTZ: It is flat in energy per decade of frequency, so that fh(f) is constant over the whole of the frequency region we are talking about, with a possible low-frequency cutoff. This will be discussed in more detail by Richard Matzner in his talk later today.