Gravitational Wave Searches During the Next Two Decades

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Abstract.
Gravitational wave detectors on the ground and in space will, during the next two decades, study a rich variety of astronomical systems. The nature of the information they return places them directly on the very active interface between fundamental physics and astronomy. Sources of gravitational radiation include stellar-mass black-hole systems in our Galaxy and very massive black holes in distant galaxies. Gravitational waves from supernovae and from merging neutron stars will tell us about matter at nuclear densities. Observation of a cosmological background of gravitational waves would give us a glimpse of the Universe at the very instant of the Big Bang. In order to understand these conclusions, one must know how to estimate the gravitational radiation produced by different sources. In the first part of this lecture I review the dynamics of gravitational wave sources, and I derive simple formulas for estimating wave amplitudes and the reaction effects on sources of producing this radiation. I then describe the projects now under construction and planned that have the ability to make sensitive observations, and what they may see. Finally, in the third part of the lecture I use these estimates to discuss what we can expect to learn about fundamental physics from observations of binary systems, black holes, and the early Universe.

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1. Introduction

After a long period of development (going back to Weber [1]), gravitational wave detectors are now reaching a sensitivity that will give them a chance to detect gravitational waves regularly. With further development, say over the next two decades, their sensitivity should improve to the point where they are making several detections per day. If they follow the example set by most other branches of astronomy when they were young (such as radio, X-ray, and gamma-ray astronomy), it will not be long before gravitational wave detectors begin revealing information that will reshape our view of the Universe.

In this paper I will review the developments we can expect for detectors over the next two decades, and I will discuss the information these detectors can bring us about fundamental physics, as far as we can predict on the basis of our current understanding of astronomy. I begin in this section with a short introduction on how to understand and calculate gravitational wave emission.

There are many good reviews of the subject available. A recent review by Kip Thorne is available on the web [2]. I have given Les Houches lectures on this subject [3], and some of the transparencies I used for the present talk can be seen at the PPEUC web site [4]. Students wanting more elementary introductions may find them in Physics World magazine [5] and in an encyclopedia article [6].

2. Making waves: the physics of gravitational wave sources

The gravitational wave spectrum of space- and ground-based detection spans 8 orders of magnitude in frequency, from 10^{-4} Hz to 10^{4} Hz. This is similar to the range from high-frequency radio waves (10 GHz) to X-rays (10^{18} Hz). In this range, therefore, we should expect considerable variety. But there is also a lot that is systematic. The dynamics of most sources are dominated by their self-gravity, and their gravitational-wave amplitudes will usually be given to a good approximation by the lowest-order quadrupole approximation for radiation. This combination of two factors happily brings together the two founders of gravitation theory: Newton and Einstein. Newton tells us how, to a first approximation, self-gravitating sources behave; Einstein tells us how they radiate.

2.1. Newtonian dynamics: the natural frequency

For self-gravitating Newtonian systems, it is well-known that there is a natural dynamical frequency associated with the mean mass density ρ of the system:

$$f_{\text{dyn}} = \frac{1}{2\pi}\left(\pi G\rho\right)^{1/2} \sim \left(\frac{GM}{16\pi R^3}\right)^{1/2}, \tag{1}$$

where M is the system's mass and R its typical size. Wherever I use the symbol $\sim$ instead of $=$, I mean to indicate that there are factors of order 2 or pi left out. (In this case, the factor is $\pi/3$.) Moreover, I will always use proper frequencies (measured in Hz), not angular frequencies (radians/s) in my formulas.

It is interesting to put some numbers into this formula:

$$f_{\text{dyn}} = 32\left[\frac{M}{2.8M_\odot}\right]^{1/2}\left[\frac{R}{2\times 10^5\ \text{m}}\right]^{-3/2} \quad \text{Hz}. \tag{2}$$

Similarly, solving Equation (1) for the density, we get

$$\rho \sim 2\times 10^{14}\left[\frac{f}{30\ \text{Hz}}\right]^2\ \text{kg m}^{-3}. \tag{3}$$

Notice that, for frequencies in the range $10^{-4} - 10^4$ Hz, the density ranges from nuclear-matter density at the high end down to the density of water at the low end. This illustrates the enormous range of physics in these sources.

This formula for the relation between frequency and density is valid to a first approximation in general relativity as well. It governs the orbits of binary stars, the orbital and escape velocity near self-gravitating masses, the frequency of the fundamental mode of vibration of a self-gravitating mass, and essentially all other processes where self-gravitation determines the structure and dynamics of the system. If we change the frequency into a velocity,

$$v_{\text{dyn}} = 2\pi f_{\text{dyn}} R, \tag{4}$$

and then we set this to the speed of light, we deduce:

$$v_{\text{dyn}} = c \qquad \Longrightarrow \qquad R \sim GM/c^2. \tag{5}$$

This is, to within a factor of 2 (our accuracy) the equation for an object whose gravitational escape speed is the speed of light: a black hole.

2.2. *Einstein: the quadrupole formula*

Gravitational waves are described by a *dimensionless* wave amplitude, conventionally called h, which describes the way that the waves interact with a detector (or with anything else they pass through). It is easiest to see what happens to an idealised detector, consisting of two free particles in empty space, far from any ordinary gravitational fields. Their separation is

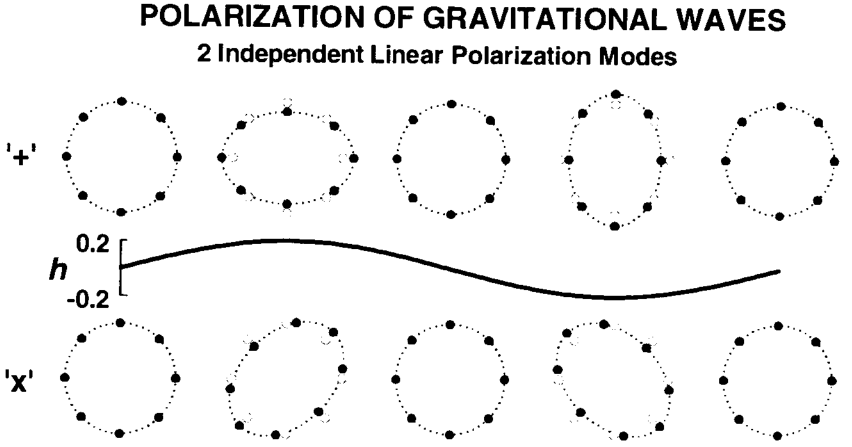

Figure 1. Illustration of gravitational wave polarisation. The diagram shows a ring of free particles in empty space responding to a wave incident from above. The wave in the top row has what is called "+" polarisation, stretching in the x-direction while compressing in the y-direction, then reversing. The bottom diagram illustrates the "×" polarisation, rotated by 45°. Any other polarisation state of a wave travelling in this direction is a linear combination of these two. Notice that the amplitude h is the ratio of the distortion to the original size, so that the *shape* of the ellipses will be independent of their size.

L. This will change because of the gravitational forces carried by a wave. A wave that arrives with a suitable orientation and polarisation will change L by an amount $\delta L = \frac{1}{2}hL$. Because h is the ratio of two lengths, a larger detector will have a larger displacement. This is part of the reason that the detectors now under construction are being built on kilometre scales.

The orientation of the waves matters because they are transverse. Like electromagnetic waves, they act only in the plane perpendicular to the direction of propagation of the wave. Their polarisation matters too: there are two independent polarisation states, described in Figure 1. Although the effect of the wave in this illustration is large, the real situation is different: we need to be able to detect relative length changes of less than one part in 10^{21} to see realistic gravitational waves a few times per year.

Radiation of gravitational waves is, to a first approximation, given by

Einstein's quadrupole formula, which gives the amplitude h of the wave at a distance r from its source in terms of an integral over the source, which is assumed to be described well enough by Newtonian gravity. To avoid complications of tensor analysis, which a full study in general relativity would require, I just write the approximate formula as

$$h = \frac{2G}{c^4 r}\frac{d^2}{dt^2}Q, \tag{6}$$

where the quadrupole moment Q (sometimes also called I) is the largest of the components of the trace-free second mass moment of the system:

$$Q = \max_{jk} \int \rho \left(x_j x_k - \frac{1}{3} x^2 \delta_{jk} \right) d^3x. \tag{7}$$

For estimation purposes we shall use an even simpler version of this formula which makes order-of-magnitude estimates of the integrand in Equation (7) and ignores the indices there. Ignoring the indices means that we get *upper limits* on the amplitude of the waves, since the projections and the removal of the trace (the term containing the 1/3 term in Equation (7)) can eliminate components that our estimate will include. The simpler estimator is:

$$\left|\ddot{Q}\right| \leq \frac{d^2}{dt^2} \int \rho x^2 d^3x \sim \int \rho v_{\rm dyn}^2 d^3x \sim Mv^2, \tag{8}$$

where M is the total mass of the source and $v$dyn is given by Equation (4).

Of course, this is an upper limit because not all the mass needs to move in such a way that it gives off gravitational radiation. Spherical motions, for example, radiate *nothing.* One way of approximating Equation (6), then, would be to take only the *nonspherical* part of the kinetic energy $Mv^2/2$ in Equation (8), which leads to

$$h \sim \frac{4G}{c^4 r} K_{\rm nonspherical}, \tag{9}$$

where $K_{\rm nonspherical}$ is the non-spherical part of the system's kinetic energy. This is a good generally-applicable estimate ([2]).

If all the mass of the system is involved in the motion, and the velocity is determined by self-gravity (this excludes radiation from a small lump on a spinning neutron star, where only the mass of the eccentricity radiates and the relevant velocity is the rotation speed of the star, which could be much smaller than the dynamical speed), then we can use the virial theorem to simplify this even further, giving us an *upper bound* that is usually fairly close to the correct value for many sources:

$$h \leq \frac{2G^2M^2}{c^4 rR} \sim 2\frac{GM}{Rc^2}\frac{GM}{rc^2}. \tag{10}$$

This is a very simple formula that was first derived in the context of a scalar approximation to relativistic gravity ([7]). It gives an upper limit on the gravitational wave amplitude in terms of the product of two (dimensionless) Newtonian gravitational potentials: the typical internal potential of the system, GM/Rc^2, and the external potential at the observer's location, GM/rc^2. Since the internal potential must be smaller than about 1 (or the system would form a black hole), we see that the gravitational wave amplitude must be smaller than the dimensionless Newtonian potential of the system: waves are a small disturbance in the Newtonian field, not a replacement of it.

This formula only gives an upper bound on the wave amplitude, but this is not as bad as it might seem. The real amplitude can fall below this only if the source has some kind of symmetry that does not allow it to radiate fully (such as a nearly-spherical system), or if the frequency is not given by the natural frequency but by a smaller internal frequency, such as the rotational frequency of a spinning star. But for highly asymmetric source, and in particular for the binary black hole systems that are interesting and important sources across the frequency band, this formula is not an upper bound: it is a realistic estimate.

Normally, the frequency of the radiation is twice the natural frequency of the system, essentially because if v depends on time as $\exp 2\pi i f t$ in Equation (8), then the factor of v^2 in the integrand has time-dependence $\exp 4\pi i f t$. It is not always the case that gravitational waves come off at twice the natural dynamical frequency, but these exceptions need not concern us here. Accordingly, we will take

$$f_{\mathrm{gw}} = 2f_{\mathrm{dyn}} \sim \left(\frac{GM}{4\pi R^3}\right)^{1/2}. \tag{11}$$

With some interesting values for space-based detectors, Equation (10) becomes

$$\begin{aligned} h &\leq 2.6\times 10^{-22}\left[\frac{M}{2M_\odot}\right]^2\left[\frac{R}{2\times 10^8\ \mathrm{m}}\right]^{-1} \\ &\qquad \times\left[\frac{r}{10\ \mathrm{kpc}}\right]^{-1} \\ &\qquad (10^3\ \mathrm{s\ compact\ binary\ at\ galactic\ centre}). \end{aligned} \tag{12}$$

$$\begin{aligned} h &\leq 2\times 10^{-20} z\left[\frac{M}{2\times 10^6 M_\odot}\right]^2\left[\frac{R}{6\times 10^9\ \mathrm{m}}\right]^{-1} \\ &\qquad (\mathrm{massive\ bh\text{-}binary\ at\ redshift}\ z=1), \end{aligned} \tag{13}$$

where I have assumed a value for the Hubble parameter of $H_0 = 60\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$.

2.3. Energy loss to radiation

Waves carry off energy, and this is important for some of the systems we will discuss. One might think that this would be a hard thing to estimate, but this is not really the case. Relativists argued for decades over whether gravitational waves really did carry energy, because when one looks at the question in the full nonlinear theory of general relativity it becomes a difficult one. But work in the 1950s and 1960s by H. Bondi, R. Penrose, R. Isaacson, S. Chandrasekhar, and others put the arguments to rest by showing that general relativity does indeed transmit energy from one place to another via gravitational radiation, and in fact that the formula for the amount of energy is very similar to those in other classical field theories of physics — electromagnetism and scalar fields, for example.

In particular, the energy flux carried by a wave is proportional to the square of the time-derivative of the amplitude[2] h:

$$F \propto \dot{h}^2.$$

The constant of proportionality must get the dimensions right, and it can only be made up of pure numbers and the fundamental constants G and c. Remembering that h is dimensionless, the dimensions of F (energy per unit time per unit area) determine the way it depends on G and c:

$$F \propto \frac{c^3}{G}\dot{h}^2.$$

The remaining constant is not something that can be deduced by analogy with other theories: it is the only part of this formula that comes from the full tensor theory. I simply quote it here without proof:

$$F_{\rm gw} = \frac{1}{32\pi}\frac{c^3}{G}\dot{h}^2 \qquad \text{for each polarisation.} \tag{14}$$

Because the constant c^3/G has a large value in SI units, this flux can be surprisingly large. For example, for the weakest burst of radiation that the *ground-based* detectors anticipate detecting in the near future, we use $h = 1 \times 10^{-22}$ and $f = 1$ kHz. Then the flux is (allowing for two equally strong polarisations)

$$F_{\rm gw} = 3\ {\rm mW\ m^{-2}c}\left[\frac{\rm h}{1\times 10^{-22}}\right]^2\left[\frac{\rm f}{1\ {\rm kHz}}\right]^2,$$

[2] In electromagnetism, for example, the relevant field is the vector potential, and its time-derivative is proportional to the electric field in the wave, $\vec{E}$. Then the rule given here would make the flux proportional to $\vec{E}\cdot\vec{E}$, which is the magnitude of the Poynting flux *for a wave*, up to constants of proportionality.

which is twice than the energy flux on Earth from the full Moon. So for the roughly 1 ms that this source is radiating, it is the brightest object in the night sky!

Unfortunately, all that energy goes right through the detector, and so the detector's response is woefully small. But even this cloud has an important silver lining: the waves have also gone right through everything else that might have been between their source and us, and have done so with negligible scattering and absorption. Gravitational waves are the ultimate unbiased information transmitter.

Assuming two equally strong polarisations generally (this is still within our factor-of-two uncertainties), using $\dot{h} = 2\pi f h$, taking $f = f_{\rm gw} = 2f_{\rm dyn}$ [from Equation (1))], and getting h from Equation (10), we find

$$F_{\rm gw} \leq \frac{c^5}{4Gr^2}\left(\frac{GM}{Rc^2}\right)^5 . \tag{15}$$

If we again approximate the radiation as being isotropic, we can integrate this over a sphere of radius r to get the total luminosity of the source,

$$L_{\rm gw} \leq \frac{\pi c^5}{G}\left(\frac{GM}{Rc^2}\right)^5 . \tag{16}$$

Notice that this is a very strong function of the internal compactness of the source: a source with $GM/Rc^2 \sim 0.2$ (as a neutron star) would radiate 10^{25} times the power of one with the compactness of the Sun ($GM/Rc^2 \sim 2 \times 10^{-6}$)! The natural luminosity in this equation of

$$L_{\rm natural} = \frac{c^5}{G} = 3.6 \times 10^{52}\ \rm W$$

is enormously large, and Equation (16) shows that it is an *upper limit* on the luminosity of any gravitational wave source.

For many purposes, the important consideration regarding energy radiated is the time-scale: how long does it take for the gravitational energy loss to manifest itself in a significant way? The energy is typically lost from the gravitational potential energy of the source $E_{\rm grav} = GM^2/R$ (or from its kinetic energy: to within our factors of two, these are the same, by the virial theorem). So the timescale on which observable changes occur is

$$T_{\rm gw} = \frac{E_{\rm grav}}{L_{\rm gw}} \geq \frac{R}{\pi c}\left(\frac{GM}{Rc^2}\right)^{-3} . \tag{17}$$

$$\geq 70 \left[\frac{M}{2.8M_\odot}\right]^{-3}\left[\frac{R}{2\times 10^5\ \rm m}\right]^4 \rm s$$

(for a very compact binary). (18)

This gives the timescale as a multiple of the light-crossing time, R/c. The dynamical timescale $1/f_{\rm dyn}$ might be a more relevant comparison, which leads us to the dimensionless product

$$T_{\rm gw} f_{\rm gw} \geq \frac{1}{(4\pi^3)^{1/2}} \left(\frac{GM}{Rc^2}\right)^{-5/2} . \tag{19}$$

This example illustrates one of the most spectacular sources that ground-based detectors will look for: coalescences of neutron stars in orbit around one another. Once the orbital radiation becomes detectable from the ground (a few tens of Hz), the system has only minutes or seconds to live before the stars coalesce.

2.4. Dynamics in a nutshell

The most important formulas above can be summarised in a single diagram, which shows a number of relevant lines as a function of the mass M and size R of a the source. Figure 2 shows lines of constant frequency $f_{\rm gw} = 2f_{\rm dyn}$ in the mass-radius plane for 3 important frequencies: 10^{-4} Hz, the lowest frequency accessible to planned space-based detectors; 1 Hz, roughly the boundary between what can be detected from the ground and from space; and 10^4 Hz, the upper limit to what can in practice be observed from the ground. The upper part of the diagram is therefore the space-accessible region; the lower part, the domain of ground-based detectors.

In the diagram we place a number of interesting possible gravitational-wave sources. At the low-mass end, the natural vibrations of a typical neutron star and stellar-mass black hole radiate in the ground-based band; these should be excited when the objects are formed. The Sun lies in the space band, and indeed its natural vibrations could be detected by a space detector, through the near-zone Newtonian gravitational oscillations they produce rather than through their gravitational waves. Binaries in this mass range are discussed below. At the high-mass end, a $10^6 M_\odot$ black hole would radiate in the space band. These vibrations could be excited by the formation of the hole or by a neutron star falling into such a hole.

There are other useful lines in this diagram, as described in the next sections.

2.4.1. The black-hole line The most important is the black-hole line, drawn for

$$R = \frac{2GM}{c^2} = 3 \times 10^9 \left[\frac{M}{10^6 M_\odot}\right] \text{ m}. \tag{20}$$

(Compare this with Equation (4)). The region of the diagram below this line does not contain any physically realisable systems: a system forms a black hole when it reaches this line from above. The space-accessible

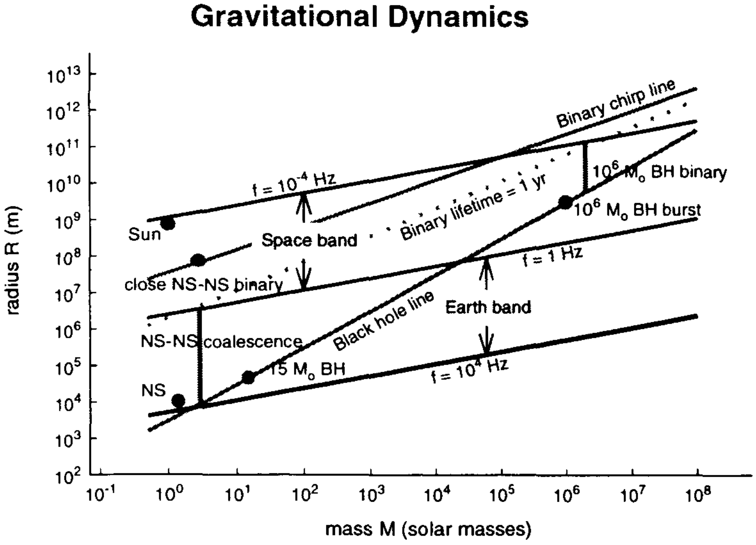

Figure 2. *This diagram shows the wide range of masses and radii of sources whose natural dynamical frequency is in the band detectable from space or the ground. The three heavy lines delineate the outer limits of the space band at gravitational wave frequencies of 0.1 mHz, 1 Hz, and 10 kHz. The "black hole line" limits possible systems: there are none below it if general relativity is correct. The "chirp line" shows the upper limit on binary systems whose orbital frequencies change (due to gravitational-wave energy emission) by a measurable amount (30 pHz) in one year: any circular binary of total mass M and orbital separation R that lies below this line will "chirp" in a 1-year observation, allowing its distance to be determined. The curve labelled "binary lifetime = 1 yr" is the upper limit on binaries that chirp so strongly that they coalesce during a 1-year observation. These lines and the indicated sources are discussed more fully in the text.*

frequency region contains black holes above about $10^4 M_\odot$ up to $10^8 M_\odot$, which means that space detectors can in principle confirm the present astrophysical consensus that most galaxies contain one or more giant black holes. Conversely, ground-based detectors cannot see massive black holes, being limited to observing the kind we expect to form from normal massive stars.

2.4.2. Binary lifetime line Two other lines in the diagram refer to the chirping of a binary system, as discussed above. The line called "binary lifetime = 1 yr" is the line along which the characteristic timescale for the frequency to change, as inferred from Equation (17), is one year. Binary systems below this line are systems which can be followed right to coalescence during a reasonable observation period, and whose detectability is therefore not strongly dependent on how compact they are when they are first observed. From Equation (18), we see that this is a line on which R^4/M^3 is constant. Notice that *all* solar-mass binary systems observable from the ground will coalesce within a year. A typical coalescing neutron-star binary is illustrated in the diagram. A compact binary that is observed from the time it reaches about 1 Hz will coalesce within a year. At present, no detectors are planned which can operate well at this frequency. If one were available, it could give advance warning to existing detectors about coalescence events. From space, we can expect only binaries of massive black holes, above $M \sim 10^6 M_\odot$, to coalesce during an observation, as shown.

2.4.3. Binary chirp line Just as important, but less dramatic, is just seeing a binary system "chirp", i.e. change its orbital frequency. Here the criterion is not that its coalescence time-scale be the observation time, but rather that its frequency should change by an observable amount during the same one-year observation $T_{\rm obs}$. This means that its frequency change need only be as large as the frequency resolution of a 1-year observation, $\Delta f_{\rm gw} = 1/T_{\rm obs} = 3 \times 10^{-8}$ Hz. If we take the frequency change to be the same Δf, and assume that this occurs because of gravitational radiation, then we have

$$\Delta f_{\rm gw} = \frac{f_{\rm gw}}{T_{\rm gw}} T_{\rm obs}.$$

The formulas above can be used to show that the resulting "chirp line" is a line of constant R^{11}/M^7. For a separation and mass appropriate to a compact binary with a 1000 s period, we have

$$\left[\frac{R}{2 \times 10^8 \text{ m}}\right]^{11} \left[\frac{M}{2.8 M_\odot}\right]^{-7} = \left[\frac{T_{\rm obs}}{3.7 \text{ yr}}\right]^4 . \qquad (21)$$

The diagram shows the chirp line appropriate to a 1-year observation, essentially the same as Equation (21).. It shows that chirping without coalescence is important for space-based detectors; ground-based detectors will be able to follow any chirping system right to coalescence. As we show below, this allows a detector to determine the distance to the binary. A space detector should also detect chirping in binaries consisting of massive black holes. The resulting distances will be particularly interesting, as we describe below.

2.4.4. Distance to a chirping binary The key to determining the distance is to show that there are enough observables in the signal from a binary system to make the measurement. The mass and radius of the system, which are convenient axes for the diagram in Figure 2, are not directly observable. What we can determine from the response of the detector are the frequency f_{gw}, rate of change of frequency $\dot{f}_{gw} = f_{gw}/T_{gw}$ (if the system chirps) and amplitude h of the signal. Equations 11, 17, and 10 (taken as an equality, which is okay for a binary system) together allow us to eliminate all the unknowns and solve for the distance r to the binary. This gives the remarkably simple formula

$$r = \frac{c}{2\pi^2} \dot{f}_{gw} f_{gw}^{-3} h^{-1}. \tag{22}$$

This equation, first derived in a somewhat different form by [8], is actually more robust than our simple derivation might suggest. We have used a single mass M to characterise the system, but of course a binary has two masses. Which combination of them is appropriate here? More importantly, can we really eliminate the mass at all from these equations: maybe we have to eliminate two masses, and we don't have enough equations.

The answer is that there is only one mass that matters, which is the combination

$$\mathcal{M} = \mu^{3/5} M^{2/5}, \tag{23}$$

where μ is the reduced mass of the binary and M its total mass. Our analysis here was not detailed enough to distinguish these two masses, but if we had done so then we would have found that this is the way the masses of the individual stars enter the radiation timescale equation, Eqrefeqn:timescale, if we eliminate the unknown radius R in favour of the measurable frequency f_{dyn}. This gives a relation between the measured timescale and frequency and the mass of the system, which then can be used to determine the chirp mass $\mathcal{M}$.

What is remarkable about binaries is that the same chirp mass also enters the equation for the amplitude of the radiation, again obtained by eliminating R in favour of f_{dyn} in Equation (10). Then one can go through the same procedure, only using $\mathcal{M}$ in place of M in all our equations, and arriving finally at the distance r to the binary given by Equation (22), with M replaced by $\mathcal{M}$.

For cosmological sources, this distance turns out to be what cosmologists call the luminosity distance. The ability to treat chirping binaries as standard candles is one of the most interesting aspects of gravitational wave observations. It opens the possibility of using observations of chirping systems to measure the Hubble parameter H_0 ([8]) and even the deceleration parameter of the universe q_0.

3. Detectors and sources: seeing waves

3.1. Ground-based detectors and what they may see

Right now there are three promising detector projects with instruments under construction. I call these three projects the *first generation interferometers.* They are called GEO600 [9], LIGO [10], and VIRGO [11]. They are of course not the first interferometers to be built: prototypes operate at Glasgow [12], Garching [13], Caltech [14], and MIT [15]. There is a large 300 m interferometer under construction in Japan, called TAMA300 [16]. In addition, the original bar detector design of Weber has been improved dramatically, and there are many bar detectors in regular operation, in Italy [17], the USA [18], and Australia [19]. These have similar sensitivity to the prototype interferometers, and will be orders of magnitude less sensitive than the first-generation interferometers for certain kinds of sources. But bars, too, will get better. There are plans for sensitive spherical solid-mass detectors [20] and for arrays of smaller bars to get to very high frequencies [21].

However, the GEO600, LIGO, and VIRGO interferometers are the first that should reach the target strain sensitivity of 10^{-21}, which has always been the theorists' threshold, because at this sensitivity there are grounds to believe that gravitational wave events could be detected a few times per year. And interferometers have the most straightforward path to improvement

An enlarged TAMA and improvements in the optical systems of the LIGO and VIRGO detectors could, after a few more years, lead to detectors that are a factor of 10 more sensitive. I would call such detectors *second generation interferometers.* On the same timescale we may see spherical detectors or large arrays of smaller bars [21] that would have astrophysical interesting sensitivity at higher frequencies, above 1 kHz.

In this frequency range, as we can see in Figure 2, the sources of gravitational waves are all on the stellar scale. We expect to see large numbers of coalescences of binary neutron star systems (as the Hulse-Taylor pulsar will so in 10^8 years), and of stellar-mass black holes, which are rarer but stronger and can be seen further away. We expect to be able to see supernova explosions, leading to the emission of gravitational radiation if the collapse is highly asymmetric. We may see isolated neutron stars, radiating as they spin because of some asymmetry in their crust or because they are in free precession. We may see the vibrations of neutron stars, especially with bar detectors. And we may see a background of gravitational waves left over from processes in the very early universe. We will come back to some of these below.

3.2. A space-based detector and what it may see

The most spectacular and ambitious detector project is called LISA, a plan to put a low-frequency detector into space. LISA is currently identified as a future European Space Agency Cornerstone mission in the next century. The fascinating and challenging technology to do has been reviewed in the literature ([22, 23]).

LISA will operate in what we call the low-frequency band of gravitational waves, between 1×10^{-4} Hz and 1 Hz. We have seen that this is an interesting band, where we expect radiation from binary stars, massive black holes, and possibly the Big Bang. The sources that radiate strongly in this band are very different from those that radiate in the higher-frequency band from about 1 Hz to 10^4 Hz. Most of them do not radiate at the higher frequencies, and so much of the physics and astrophysics that LISA can explore will be totally new, even if (as we hope) ground-based instruments are successful soon in making the first detections of gravitational waves.

The most impressive source for LISA is the coalescence of two massive black holes in the centre of a distant galaxy. This is certainly a rare event, but with LISA's sensitivity it can be seen everywhere in the Universe, so it may be observed relatively frequently. More certain, and almost as spectacular, will be the radiation from compact objects (neutron stars and black holes of stellar size) as they spiral into the giant central black holes in galaxies. It is believed that quasars are powered by the gas that results from the break-up of an ordinary star falling into the hole. Compact stars will not break up. Instead they will give a characteristic gravitational wave signature. This will be one of the most important LISA sources.

In addition, LISA will see hundreds, perhaps thousands of binary systems in our Galaxy. There will be so many that they will probably blend into a confused background at low frequencies, and only the nearest will be studied individually. Many known binary systems should be detectable.

Finally, LISA will search for the cosmic background of gravitational radiation. If it is stronger than the confusion limit of binaries, it will be seen by LISA.

3.3. Ground-based and space-based frequency ranges

Importantly, the low-frequency band cannot be observed from the ground. Any gravitational wave detector is a sensitive recorder of time-dependent changes in the gravitational field, and it will respond as well to changes in the local Newtonian gravitational field induced by the motion of a terrestrial mass (a person or a truck) as to a gravitational wave. Because gravitational fields cannot be screened out, it is impossible to avoid terrestrial interference.

In the higher-frequency band from about 1 Hz to 10^4 Hz, terrestrial gravitational noise is smaller than the signals from astronomical sources, and detectors can be built on the ground. In the LISA band, the reverse is true: gravitational interference from local mass movements, from density perturbations carried by seismic activity, and even from the passage of atmospheric masses is much stronger than extraterrestrial waves, and Earth-based detection is hopeless. By putting a detector in space, far enough from Earth, one escapes this interference: terrestrial noise falls off in strength moving away from Earth, while the amplitude of the incoming gravitational waves is essentially the same everywhere in the solar system, since they come from so far away.

Ground-based interferometers are limited in size to a few kilometres simply by the cost of building a vacuum system of that size; ideally they should be several hundred kilometres in length. In space one can make as large a detector as one likes, within technological constraints. The result is that detectors need not be designed to have only barely enough sensitivity to detect something: LISA will be so sensitive that its signal-to-noise ratio when it detects the collision of two massive black holes in a distant galaxy could well be better than that of an optical observation of the same galaxy. It will have enough signal to pin down directions to sources, to measure their masses and other properties, and especially to look for the small details in the signal that will test our understanding of aspects of fundamental physics. When thinking about LISA, one must forget the impression that one has from ground-based gravitational wave projects, that gravitational wave detectors operate at the margins of detection. LISA will be a robust observatory.

This is illustrated in Figure 3, where I compare the sensitivity of LISA to that of the first and second-generation ground-based interferometers when looking at "bursts" of radiation, which are defined as signals that have broad bandwidth. Interesting sources in the high-frequency band are just barely detectable, while those in the space-based band will be so strong that they can be studied in great detail.

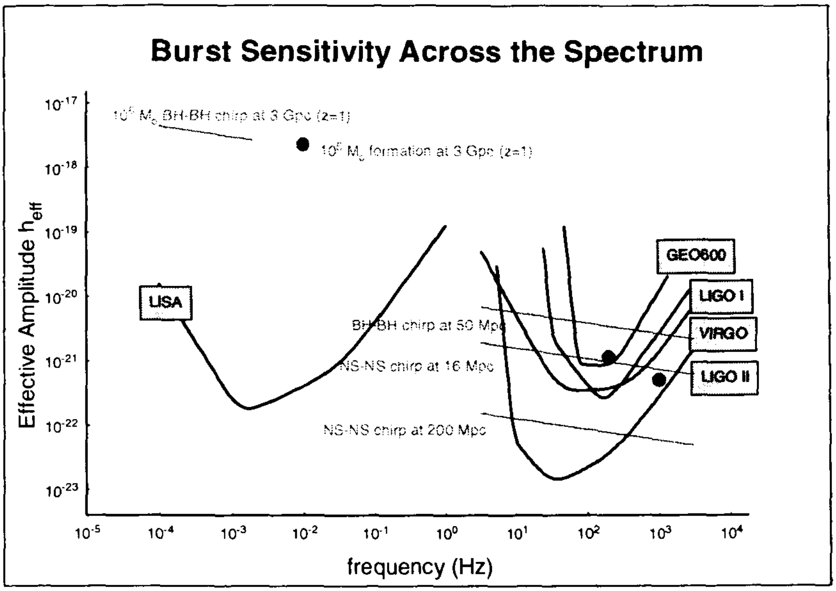

Figure 3. Sensitivity to bursts (signals of short duration and wide bandwidth) in the space and ground-based bands. Ground-based detectors at high frequencies will see coalescences (chirps) of black holes and neutron stars with low signal-to-noise ratios, but LISA will see coalescences of massive black holes with signal-to-noise ratios of several thousand.

4. Fundamental physics from gravitational wave detection

In this section I will run through a list of possible observations that will, if successful, have a direct and important impact on our understanding of fundamental physics.

- *Existence of gravitational waves.* The most direct conclusion from the first detection of gravitational waves is that they exist! The Hulse-Taylor pulsar has given us very strong indirect evidence that gravitational radiation behaves just as Einstein predicted, but it would be reassuring to have a direct detection that confirmed this. In addition, a detection with reasonable signal-to-noise ratio in several detectors (say, four interferometers) could study the polarisation properties of the waves. If there are hidden gravity-like fields, they could show up this way. It would probably take the signal-to-noise ratios anticipated from LISA to be able to make any serious constraints on this possibility.

- *Black hole studies.* Black holes are the most fundamental way in which general relativity differs from our pre-Einsteinian notions of space and time. In relativity there are many theorems about black hole uniqueness (all stationary uncharged holes are Kerr black holes) and dynamics (the area of a hole must always increase); and there are reasonably but unproved conjectures (space-time singularities can only occur inside black holes, where they cannot affect the outside world). Observations with ground-based interferometers, and especially LISA observations of massive mergers and of compact objects falling into massive holes, have the potential to verify observationally for the first time the validity of these theorems. And it is always possible that we will see naked singularities (not inside black holes). In addition, the merger of black holes is the ideal laboratory for observing stong-field, nonlinear dynamical gravity, something that is very poorly understood theoretically. By comparing observations of black-hole mergers with numerical simulations, we can begin to develop our intuition about strong-field gravity.

- *Cosmological parameters.* As emphasised earlier, coalescing binaries are standard candles: one can tell the distance to them from gravitational wave observations alone. Coupled with some information that can be used to identify an optical counterpart that would give a redshift, gravitational wave observations could establish a cosmic distance scale. Ground-based detectors have a chance through this method to measure the Hubble constant H_0 and put bounds on the deceleration of the Universe, q_0. LISA can do much better, and may indeed reveal how close to closure the Universe really is. This has, of course, enormous implications for fundamental physics.

- *Early universe.* The Big Bang should have produced a background of gravitational waves, but the size of it and its spectrum depend in detail on the physics at high energies [24]. Measurements by either ground-based or space-based detectors (which in this respect have similar sensitivities) could confirm the existence of the radiation, constrain physics at the GUTs scale, and even go a long way to establishing the reality of inflation.

- *Neutron matter equation of state.* The equation of state at nuclear densities is poorly known, since nuclei are not large enough. There are many guesses at how matter behaves inside neutron stars, but experimental data is very limited. Direct observations of the normal mode frequencies of neutron stars, or of the dynamics of the merger of two neutron stars, would help to pin down some of the uncertainties. These observations will probably be made by bar detectors, since they require good high-frequency sensitivity. There are proposals that there could be more exotic stars, quark stars or boson stars. If these exits, their binaries will be very different and readily identifiable. If binary coalescences are associated with the puzzling gamma-ray bursts, the association could greatly narrow down the list of viable models.

- *Miscellaneous tests.* One can look for secondary gravitational fields by detecting the differences in polarisation. One can try to set a limit on the mass of the graviton by comparing travel time differences between gravitational waves and light from distant events, or even by looking for dispersion inside the gravitational signal.

Any of these observations could bring about major changes in our understanding of physics. Which ones, if any, will come about is what we are all eagerly waiting to see. Answers could come within a few years, and should be there before the next two decades are finished.

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