Gravitational radiation

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I. INTRODUCTION

There is an excellent prospect that early in the next century gravitational radiation emitted by astrophysical sources will be detected and that gravitational-wave astrophysics will become another method of observing the universe. The expectation is that it will uncover new phenomena as well as add new insights into phenomena now observed in electromagnetic astrophysics. Gravitational radiation will come from the accelerated motions of mass in the interior of objects, those regions obscured in electromagnetic, and possibly, even neutrino astronomy. It arises from the motion of large bodies and represents the coherent effects of masses moving together rather than individual motions of smaller constituents such as atoms or charged particles that create the electromagnetic astrophysical emissions. Over the past 20 years relativistic gravitation has been tested with high precision in the weak field, characterized by the dimensionless gravitational potential $Gm/rc^2 = \varphi_{\mathrm{Newton}}/c^2 \ll 1$ in solar system and Earth orbital tests, and in the past decade, most spectacularly, in the Hulse-Taylor binary neutron star system (PSR 1913+16). Gravitational radiation will provide an opportunity to observe the dynamics in the regions of the strong field and thereby test the general relativity theory where Newtonian gravitation is a poor approximation—in the domain of black holes, the surfaces of neutron stars, and possibly, in the highly dense epochs of the primeval universe.

The basis for the optimism is the development and construction of sensitive gravitational-wave detectors on the ground, and eventually in space, with sufficient sensitivity and bandwidth at astrophysically interesting frequencies to intersect reasonable estimates for sources.

This short article shall provide the nonspecialist an entry to the new science including a cursory description of the technology (as well as its limits), a brief overview of the sources, and some understanding of the techniques used to establish confidence in the observations.

II. BRIEF HISTORY

(See the article by I. Shapiro in this issue for a comprehensive review of the history of relativity.) Newtonian gravitation does not have the provision for gravitational radiation although Newton did ponder in a letter to Lord Berkeley how the "palpable effects of gravity manage to maintain their influence." When the theory of special relativity was put forth in 1905 it was clearly necessary to determine the news function for gravitation and several Lorentz covariant gravitational theories were developed (scalar, vector, tensor theories), all with gravitational radiation.

The basis of most current thinking is the Einstein theory of general relativity, which was proposed in the teens of our century and whose subtlety and depth has been the subject of gravitation theories ever since. Gravitational radiation, the spreading out of gravitational influence, was first discussed in the theory by Einstein in 1916 in a paper given in the Proceedings of the Royal Prussian Academy of Knowledge (Sitzungsberichte der Königlich Preussichen Akademie der Wissenschaften). This paper deals with small field approximations to the general theory and is nestled between a paper describing the perception of light by plants and another that analyzes the authenticity of some writings attributed to Epiphanius as well as a commentary on the use of the first person in Turkish grammar. Einstein was still new at the development of the theory and made an algebra mistake, which resulted in the prediction of gravitational radiation from accelerating spherical mass distributions. In a later paper in 1918, in the proceedings of the same academy, this time preceded by a paper on the Icelandic *Eddas* and followed by one on the middle-age history of a cloister in Sinai, he corrected his mistake and showed that the first-order term was quadrupolar. He was troubled by the fact that he could only make a sensible formulation of the energy carried by the waves in a particular coordinate system (the theory is supposed to be covariant, able to be represented in a coordinate-independent manner) and that he had to be satisfied with a pseudotensor to describe the energy and momentum flow in the waves. He found solutions to the field equations for gravitational waves that carry energy but also ones that seemed not to, the so-called coordinate waves. This problem of deciding what is real (i.e., measurable) and what is an artifact of the coordinates has been an endless source of difficulty for many (especially the experimenters) ever since.

It was recognized early on that the emission of gravitational radiation is so weak and its interaction with matter so small, that there was no hope for a laboratory confirmation with a source and a neighboring receiver in the radiation zone, as was the case for electricity and magnetism in the famous Hertz experiment. If there was any chance to observe the effects of the radiation it would require the acceleration of astrophysical size masses at relativistic speeds, and even then, the detec-

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tion would require the measurement of infinitesimal motions. This was going to be a field that would require the development of new technology and methods to observe the universe.

The weakness of the radiation, however, also leads to some profound benefits for astrophysics. The waves will not scatter, so they emanate undisturbed from the densest regions of the universe, from the inner cores of imploding stars, the earliest instants of the primeval universe, and from the formation of black holes, and even singularities of the classical theory (unmodified by quantum theory). They will provide information on the dynamics in these regions, which are impossible to reach by any other means. Furthermore, the gravitational waves, to be detectable, would have to come from regions of strong gravity and large velocity, just those regions where Newtonian gravitation is a poor approximation and relativistic gravitation has not been tested.

III. STRONG INDIRECT EVIDENCE FOR GRAVITATIONAL RADIATION

A radio survey for pulsars in our galaxy made by R. Hulse and J. Taylor (1974, 1975) uncovered the unusual system PSR 1913+16. During the past two decades the information inscribed in the small variations of the arrival times of the pulses from this system have revealed it to be a binary neutron star system, one star being a pulsar with a regular pulse period in its rest frame. The stars are hard, dense nuggets about the mass of the sun, but only 10 km in size. It takes so much energy to excite the internal motions of the stars that in their orbital motion around each other they can be considered rigid pointlike objects. Luckily, the system is also isolated from other objects. The separation of the neutron stars is small enough that the dimensionless gravitational potential of one star on the other is 10^{-6}, compared with 10^{-1} on the stellar surfaces. The system is made to order as a relativity laboratory; the proverbial moving proper clock in a system with "point" test masses [Taylor and Weisberg (1982, 1989)].

One has to marvel at how much is learned from so sparse a signal. The small changes in the arrival time of the pulses encode most of the dynamics of the two-body system. By modeling the orbital dynamics and expressing it in terms of the arrival time of the pulses, it is possible to separate and solve for terms that are dependent on the different physical phenomena involved in the motion. The motion of the pulsar radio waves in the field of the companion star experiences both the relativistic retardation (the Shapiro effect) and angular modulation (bending of light). The aphelion advance of the orbit, the analog to the perihelion advance of Mercury around the Sun, is 4 degrees per year rather than the paltry 40 seconds of arc per century. Finally, the unrelenting acceleration of the orbit as the two stars approach each other is due to the loss of energy to gravitational waves, explained by the Einstein quadrupole formula

$$\langle P\rangle = \frac{G}{45c^5}\left(\frac{d^3Q}{dt^3}\right)^2, \tag{1}$$

to a precision of a few parts in 1000; where $\langle P\rangle$ is the average power radiated, and Q is the gravitational quadrupole moment of the system characterized by the product of the mass and the square of the orbit size. As an additional bonus the various relativistic effects permit the solution for the masses of the individual stars (a pure Newtonian description could only provide the sum of the masses) and shows, remarkably, that the two stars are each at the anticipated value for a neutron star of 1.4 solar masses. One of the most elegant graphs in recent astrophysics shows the locus of points for the various relativistic effects as a function of m_1 and m_2 (Taylor and Weisberg, 1989).

The measurements of the binary neutron star system have laid to rest uncertainties about the existence of gravitational waves. Furthermore, the possibility of directly detecting the gravitational waves from the coalescence of such systems throughout the universe has had the effect of setting design criteria for some of the instruments coming into operation in the next few years.

IV. WAVE KINEMATICS AND DESCRIPTION OF THE INTERACTION

Gravitational waves can be thought of as a tidal force field transverse to the wave propagation in a flat space (flat-space representation with a complex force field) or as a distortion of the spatial geometry transverse to the propagation direction (curved space with no forces). The former approach works best for bar detectors where one needs to consider other phenomena than gravitational forces. This is the approach taken by J. Weber (1961), who was the first to attempt the direct detection of gravitational radiation. The interferometric detectors both on the ground and in space are more easily understood in the latter approach. It is a matter of taste which representation is used, the only proviso being not to mix them, as that leads to utter confusion. Here, a heuristic application of the curved-space approach is taken.

Far from the sources the waves will be a small perturbation h on the Minkowski metric η of inertial space

$$g_{ij} = \eta_{ij} + h_{ij}.$$

The gravitational-wave perturbation is transverse to the propagation direction and comes in two polarizations, h_+ and h_X. For a wave propagating in the x_1 direction, the metric perturbations have components in the x_2 and x_3 directions. The + polarization is distinguished by $h_{22} = -h_{33}$; a stretch in one direction and a compression in the other. The X polarization is rotated around x_1 by 45 degrees.

The gravitational wave can be most easily understood from a "gendanken" experiment to measure the travel time of a pulse of light through the gravitational wave. Suppose we lay out the usual special-relativistic assembly of synchronized clocks at all coordinate points and use the + polarization. The first event is the emission of the pulse, $E_1(x_2,t)$, and the second, $E_2(x_2+\Delta x_2,t+\Delta t)$, is the receipt. Since the events are connected by the propagation of light, the interval between the events is zero. So writing the interval in terms of the coordinates of the events one gets

$$\Delta s^2=0=g_{ij}dx_i dx_j=[1+h_{22}(t)](\Delta x_2)^2-c^2(\Delta t)^2.$$

The coordinate time and the proper time kept by the synchronized clocks are the same and not affected by the gravitational wave. The "real" distance between the end points of the events is determined by the travel time of the light as inferred by the clocks. There are two pieces to the inferred spatial distance between the events given by

$$c\Delta t=\left(1+\frac{h_{22}(t)}{2}\right)\Delta x_2, \quad \text{where } h_{22}\ll 1.$$

The larger part is simply the spatial separation of the events Δx_2, while the smaller is the spatial distortion due to the gravitational wave $[h_{22}(t)/2]=(\delta x_2/\Delta x_2)$, the gravitational-wave strain. (A more formal calculation would take the integral over time; the result here is valid if h changes little during the transit time of the pulse.) The strain h is the wave amplitude analogous to the electric field in an electromagnetic wave and varies as the reciprocal of the distance from the source. The intensity in the wave is related to the time derivative of the strain by

$$I=\frac{c^3}{16\pi G}\left(\frac{dh_{22}}{dt}\right)^2. \tag{2}$$

The enormous coefficient in this equation is another way of understanding why gravitational waves are difficult to detect (space is very stiff, it takes a large amount of energy to create a small distortion). For example, a gravitational wave exerting a strain of 10^{-21} with a 10 millisec duration, typical parameters for the detectors operating in the next few years, carries 80 μ watts/meter^2 (about 10^{20} Jansky) past the detector.

A relation that is useful for estimating the gravitational-wave strain h from astrophysical sources, consistent with a combination of Eqs. (1) and (2), is

$$h\approx\frac{GM}{Rc^2}\left(\frac{v^2}{c^2}\right)=\frac{\varphi_{\text{Newton}}}{c^2}\beta^2. \tag{3}$$

v^2 is a measure of the nonspherical kinetic energy; for example, the tangential kinetic energy in a simple orbiting source. Now, to finally set the scale, the very best one could expect is a highly relativistic motion $\beta\sim 1$ of a solar mass placed at the center of our galaxy. Even with these extreme values, $h\sim 10^{-17}$. With this as "opener" it is easy to understand why this line of research is going to be a tough business. The initial goal for the new generation of detectors is $h\sim 10^{-21}$ for averaging times of 10 msec.

V. TECHNIQUES FOR DETECTION AND THEIR LIMITS

All the current detection techniques, as well as those planned, measure the distortions in the strain field directly, the "electric" interactions. One can conceive of dynamic detectors (high-energy particle beams) that interact with the "magnetic" terms in the gravitational wave, although there seems to be no compelling argument, at the moment, to develop them.

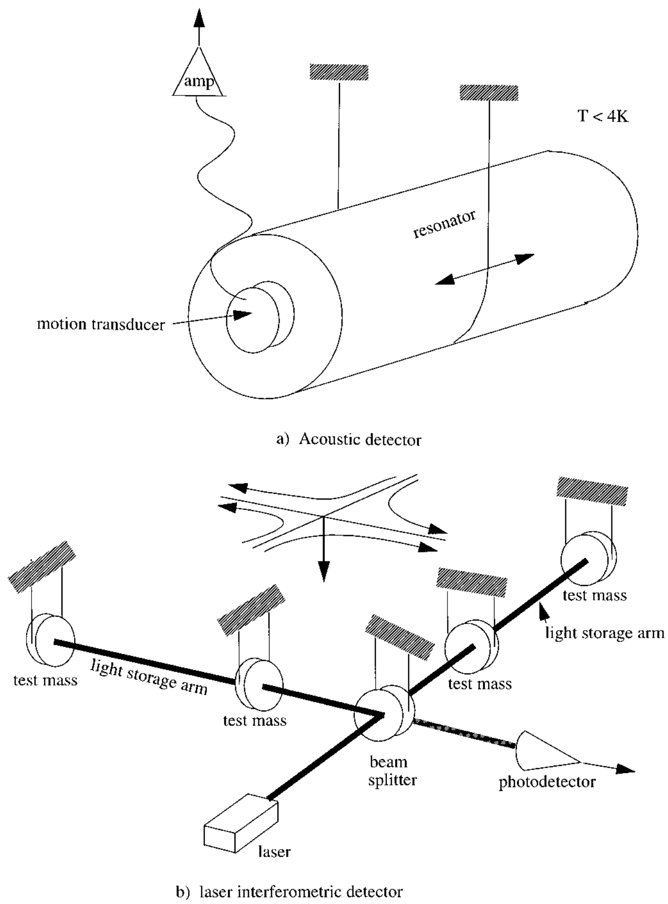

FIG. 1. Schematic diagrams: (a) an acoustic bar detector, (b) a laser interferometer detector.

Most of the initial gravitational-wave searches have been carried out with acoustic detectors of the type initially developed by J. Weber (1961) and subsequently improved by six orders of magnitude in strain sensitivity in the hands of a dedicated international community of scientists. The detection concept, depicted in Fig. 1(a), is to monitor the amplitude of the longitudinal normal-mode oscillations of a cylinder excited by the passage of a gravitational wave. The detector is maximally sensitive to waves propagating in the plane perpendicular to the longitudinal axis. The frequency response of the detector is concentrated in a narrow band around the normal-mode resonance, although it is possible, by designing the motion transducer together with the resonator as a coupled system, to increase the bandwidth. Typical resonance frequencies have ranged from 800 to 1000 Hz with detection bandwidths ranging from 1 to 10 Hz.

The resonator is isolated from perturbations in the environment by being suspended in a vacuum, and if this is done successfully, the measurement will be limited only by fundamental noise terms. The fundamental limits come from thermal noise (thermal phonon excitations in the resonator and transducer), which can be reduced significantly by operating at cryogenic temperatures, and from the amplifier noise, which has both a broadband component that helps to mask the displacement measurement as well as a component that randomly drives the resonator through the transducer (back-action force). This combination of sensing noise and back-action-force noise is characteristic of all linear systems and ultimately results in the ''naive'' quantum limit of the measurement. (''Naive'' since ideas have been proposed to circumvent the limit though these do not seem trivial to execute.) Current performance limits for the acoustic detectors is an rms strain sensitivity of approximately 5×10^{-19} near 1 kHz (see Fig. 4). The ''naive'' quantum limit is still a factor of 50 to 100 times smaller, so there is room for improvement in these systems.

Acoustic detectors have operated at lower frequencies ranging from 50–300 Hz in other resonator configurations such as tuning forks and disks but with a reduced overall sensitivity due to their limited size. Upper limits for a gravitational-wave background have been set in various narrow low-frequency bands by measuring the excitation of the normal modes of the Sun and the Earth. The Earth's prolate-to-oblate spheroidal mode at a period of 53 minutes was used to set an upper limit on a gravitational-wave background at about 10^{-14} strain. Laboratory spherical detectors with a higher sensitivity are currently being considered.

The high-sensitivity detectors being constructed now and planned for space are based on electromagnetic coupling. The underlying reason for their sensitivity comes from the fact that most of the perturbative noise forces affecting the relative displacement measurement used to determine the strain are independent of the detector baseline, while the gravitational-wave displacement grows with the baseline.

Figure 1(b) shows a schematic diagram of a laser gravitational-wave interferometer in a Michelson interferometer configuration with the Fabry-Perot cavity optical storage elements in the arms (Saulson, 1994). The test masses are mirrors, suspended to isolate them from external perturbative forces. Light from the laser is divided equally between the two arms by the symmetric port of the beam splitter; transmission is to the right arm and reflection is toward the left arm. The light entering the cavities in a storage arm can be thought of as bouncing back and forth b times before returning to the beam splitter. The storage time in the arms is $\tau_{st}=b(L/c)$. Light directed to the photodetector is a combination of the light from the right arm reflected by the splitter and transmitted light from the left arm. By choosing the path lengths properly and taking note of the sign change of the optical electric field on reflection from the detector side of the splitter (the antisymmetric port), it is possible to make the field vanish at the photodetector (destructive interference). At this setting, a stretch in one arm and a compression in the other, the motion induced by the polarization of the gravitational wave, will change the optical field at the photodetector in proportion to the product of the field at the symmetric port times h. The optical phase associated with this field becomes the gravitational-wave detector output. The interferometer is uniformly sensitive to gravitational-wave frequencies $<(1/4\tau_{st})$ and loses sensitivity in proportion to the frequency at higher values.

With little intensity at the photodetector, almost all the light entering the interferometer is reflected back to the laser. One can increase the light power circulating in the interferometer by placing a partially transmitting mirror between the laser and the beam splitter (the mirror is not shown in the figure). If the mirror is placed correctly and the transmission set to equal the losses in the interferometer, no light will be reflected toward the laser. The circulating power in the interferometer will be increased by the reciprocal of the losses. This technique, called power recycling, matches the laser to the interferometer without changing the spectral response of the instrument and is equivalent to using a higher power laser. The initial interferometer in LIGO (see Fig. 2) and the VIRGO projects will use this configuration.

To bring such an instrument into operation so that fundamental noise dominates the performance, several experimental techniques, first introduced into precision experiments by R. H. Dicke, are employed. In particular, the laser frequency, amplitude, and beam position, and the mirror positions and orientations are controlled and damped by low-noise servo systems to maintain the system at the proper operating point. An associated strategy is to impress high-frequency modulation on the important experimental variables to bring them into a spectral region above the ubiquitous $1/f$ noise.

The remaining noise can be classified into sensing noise—fluctuations in the optical phase independent of the motions of the mirrors—and stochastic-force noise—random forces on the mirrors that are not due to gravitational waves. Sensing noise has nonfundamental contributions from such phenomena as scattered optical fields derived from moving walls and gas molecules or excess amplitude noise in the light, which are controlled by good design, and in the case of the gas, by a vacuum system. The fundamental component is the intrinsic uncertainty of the optical phase and number of photons in the same quantum state of the laser light—referred to as shot noise in the literature. The phase noise varies as $1/\sqrt{P_{\text{splitter}}}$, the optical power at the symmetric port of the beam splitter. The increase in the noise at frequencies above the minima of all the detectors shown in Fig. 4 is due to the sensing-noise contribution.

The stochastic-force noise has both fundamental and nonfundamental components as well. A key feature seen in the low-frequency performance of the terrestrial interferometers in Fig. 4 is the sharp rise at the lowest frequencies below the minima. The noise is due to seismic accelerations not completely removed by the isolation stages and suspension systems. Seismic noise will yield to better engineering since it is a motion relative to the inertial frame and can be reduced by reference to this frame; it is not a fundamental noise. The Newtonian-gravitational gradients associated with den-

FIG. 2. Photograph of the Laser Interferometer Gravitational-wave Observatory (LIGO) site at the Hanford Reservation site in central Washington state. The LIGO is comprised of two sites, the other is in Livingston Parish, Louisiana, which are run in coincidence. The figure shows the central building housing offices and the vacuum and laser equipment area at the intersection of the two 4-km arms extending toward the top and left. The arms are 120-cm-diameter evacuated tubes fit with baffles to reduce the influence of scattered light. The tubes are enclosed in concrete arched covers to reduce the wind and acoustic forces on the tube as well as to avoid corrosion. At the Hanford site the initial interferometer configuration includes a 4-km- and a 2-km-long interferometer operating in the same evacuated tube. At Livingston there will initially be a single 4-km interferometer. The three interferometers will be operated in coincidence and the detection of a gravitational wave will require consistency in the data from the three. The first data runs are planned in November of 2001 at a sensitivity $h_{\rm rms}\approx 10^{-21}$ around 100 Hz. The expectation is that the French/Italian VIRGO project, the German/Scotch GEO project, and the Japanese TAMA project will be operating at the same time.

sity fluctuations of the ground that accompany the seismic waves (as well as density fluctuations of the atmosphere) cannot be shielded from the test masses and constitute a ''fundamental'' noise at low frequencies for terrestrial detectors; the extension of gravitational-wave observations to frequencies below a few Hz will require the operation of interferometers in space.

The most troublesome stochastic force in the current systems is thermal noise [Brownian motion; again Einstein, as it also is with the photon (Pais, 1982)] coming both from the center of mass motion of the test mass on the pendulum and through the thermal excitation of acoustic waves in the test mass causing random motions of the reflecting surface of the mirrors. The normal modes of the suspension as well as the internal modes of the test mass are chosen to lie outside the sensitive gravitational-wave frequency band. The off-resonance spectrum of the noise that falls in band depends on the dissipation mechanisms in the solid that couple to the thermal disorder (the fluctuation-dissipation theorem of statistical mechanics). The noise at the minima of the room-temperature, large-baseline terrestrial detectors in Fig. 4 is due to thermal excitation. Current strategies to deal with thermal noise use low-loss materials; future development may require selective refrigeration of normal modes by feedback or cryogenic operation of the test masses and flexures.

As with the acoustic detector but at a much lower level in the long-baseline systems, the combination of the sensing noise, varying as $1/\sqrt{P}$, and the stochastic forces associated with sensing, the fluctuating radiation pressure, varying as $\sqrt{P}$ on the test masses leads to the ''naive'' quantum limit. The physics is the same as the Heisenberg microscope we use to teach about the uncertainty relation. The electron has become the test mass, while the random recoil from the photon has been replaced by the beat between the zero-point vacuum fluctuations and the coherent laser light. The naive quantum limit for broadband detection, assuming a bandwidth equal to the frequency, is given by

$$h_{\rm rms}=\frac{1}{2\pi L}\sqrt{\frac{4h_{\rm Planck}}{\pi m f}},$$

for example, $h_{\rm rms}=1\times 10^{-23}$ at $f=100\,{\rm Hz}$ for a 100 kg mass placed in the 4-km arms of the LIGO.

Figure 4 shows several curves for the long-baseline detector. Enabling research is being carried out in many collaborating laboratories throughout the world to reduce the limiting noise sources to gain performance at the advanced detector level and ultimately to the gravity gradient and quantum limits.

Observations of low-frequency gravitational waves need the large baselines and low environmental pertur-

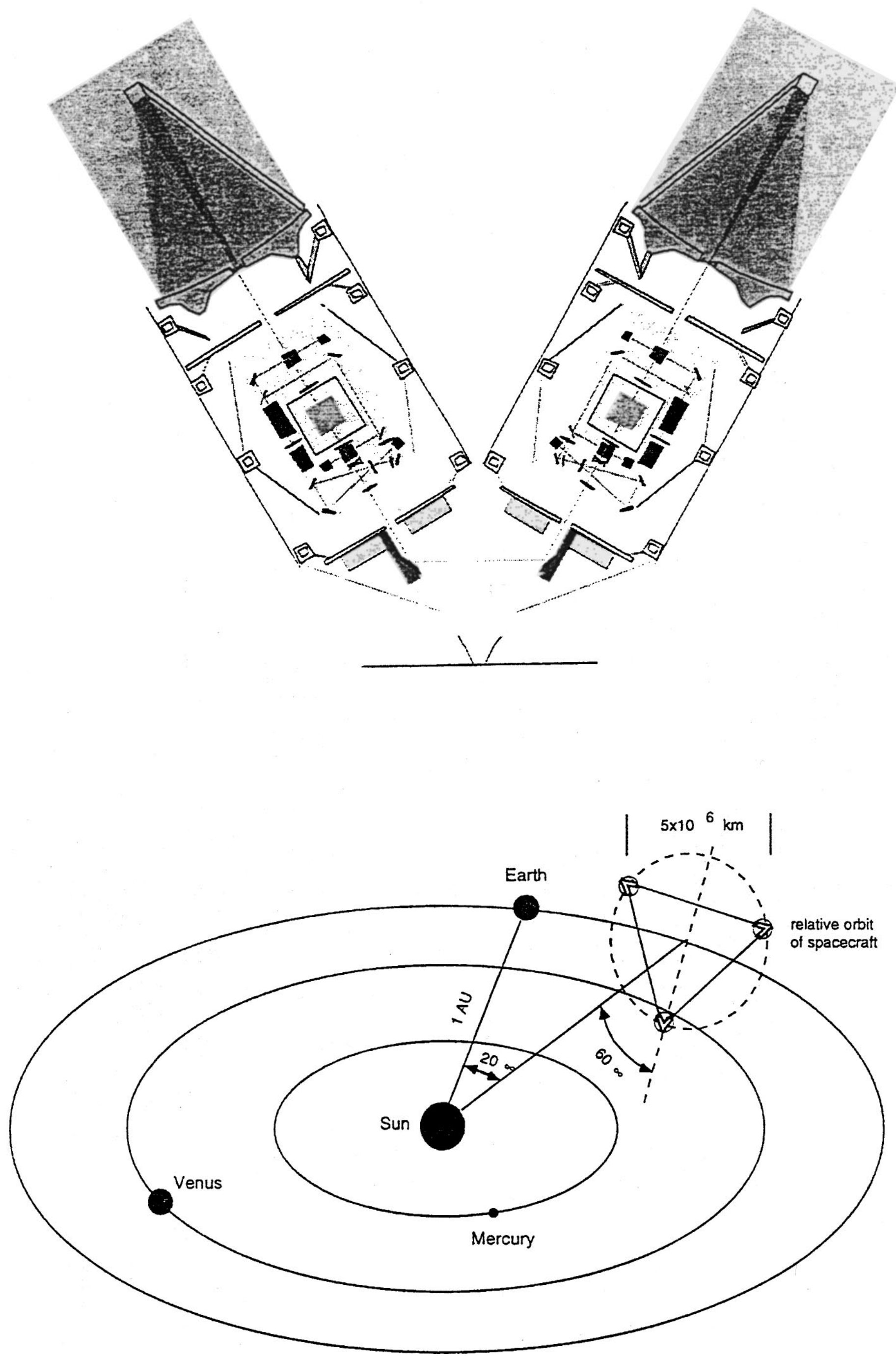

FIG. 3. A schematic of the Laser Interferometer Space Antenna (LISA) being considered by ESA and NASA as a possible joint mission to observe gravitational waves at low frequencies between 10^{-5} and 1 Hz. This region of the gravitational wave spectrum includes several promising types of sources involving massive black holes at cosmological distances. It also includes the orbital frequencies of white dwarf and other types of binaries in our own Galaxy. The spectral region is precluded from terrestrial observations by gravity gradient fluctuations due to atmospheric and seismic density changes. The interferometric sensing is carried out by optical heterodyne using 1 micron, 1-watt lasers, and 30-cm-diameter optics. Current hopes are to launch LISA by about 2008.

bations afforded by operation in space. Searches for gravitational waves with periods of minutes to several hours have been executed using microwave Doppler ranging to interplanetary spacecraft. The strain levels shown in Fig. 4 are limited by the propagation fluctuations in the interplanetary solar plasma and can be reduced by operating at shorter wavelengths.

Currently there are efforts underway by both the European Space Agency (ESA) and NASA to study the Laser Interferometer Space Antenna (LISA). A concept for the project is shown in Fig. 3. Three spacecraft are placed in solar orbit at 1 a.u. trailing the Earth by 20 degrees. The spacecraft are located at the corners of an equilateral triangle with 5×10^6-km-long sides. Two arms of the triangle comprise a Michelson interferometer with vertices at the corners. The third arm permits another interferometric observable to be measured, which can determine a second polarization. The interferometers use the same 1 micron light as the terrestrial detectors but need only a single pass in the arms to gain the desired sensitivity. The end points of the interferometers are referenced to proof masses free-floating within and shielded by the spacecraft. The spacecraft is incorporated in a feedback loop with precision thrust control to follow the proof masses. This drag-free technology has a heritage in the military space program and will be further developed by the GPB program.

Figure 4 shows projections for LISA as a broadband burst detector. At frequencies below the minimum noise, the system is limited by a combination of stochastic forces acting on the proof masses. An important effect is from the fluctuating thermal radiation pressure on the proof mass. At frequencies above the minimum, the noise is mainly due to the sensing noise from the limited-light power. The limits follow from design choices and are far from the ultimate limits imposed by cosmic rays at low frequencies or by laser and optical technology at high frequencies.

VI. ASTROPHYSICAL SOURCES

Gravitational dynamics of self-gravitating objects has time scales derived from Newtonian arguments:

$$\tau \approx \frac{1}{\sqrt{G\rho}} \approx \sqrt{\left(\frac{R^3}{GM}\right)} \quad \text{(for black holes)} \rightarrow \frac{GM}{c^3}.$$

Spheroidal oscillations or orbits close to the surface of a neutron star (solar mass, 10 km radius, nuclear density) have periods around 1 msec. For black holes, the geometric relation between the mass and the radius of the horizon constrains the dynamics and the natural time scale becomes the light travel time around the horizon, about 0.1 msec for a solar mass black hole. Broadly, the terrestrial detectors will observe events at black holes in the range of $1-10^3$ solar masses, while space detectors can detect signals long before coalescence and observe black holes up to 10^8 solar masses.

Astrophysical sources have been classified by the gravitational-wave time series they generate as burst, chirp, periodic, and stochastic background sources. A comprehensive summary is presented by Thorne (1987). The new detectors will be able to detect all classes. The brief summary below begins with sources in the band of the terrestrial detectors.

The classical burst source with frequency components in the band of terrestrial detectors has been the supernova explosion for which the event rate per typical galaxy is once in 30 to 40 years. Although the rate is known, the energy radiated into gravitational waves is poorly estimated since the degree of nonsphericity in the stellar collapse is difficult to model. Systems with large specific angular momentum are expected to be strong radiators as are those which pass through a highly ex-

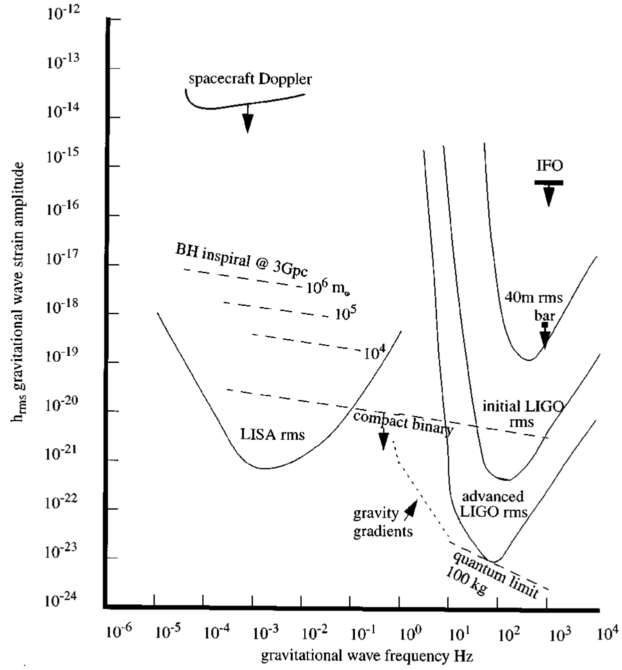

FIG. 4. The rms gravitational-wave spectrum for impulsive (burst) sources using a bandwidth equal to the frequency. The figure shows currently established upper limits indicated by heavy lines associated with an arrow downward: "bars" is the rms limit of the LSU bar detector run in coincidence with the Rome group; "ifo" refers to the "100 hour" coincidence run made by the Glasgow and Max Planck groups; spacecraft Doppler ranging designates the limits achieved by the JPL group on the Galileo and other deep space missions. The curve labeled by "40 m" is the best spectrum attained in the LIGO 40-meter prototype at Caltech. The spectrum is not a measurement of an astrophysical limit. The curves labeled "initial LIGO" and "advanced LIGO" are projections for the rms sensitivity of the initial LIGO detector and a detector with improved seismic isolation, suspensions and optics to be placed in the LIGO facilities within a decade of the initial runs. A goal for the ultimate sensitivity of the terrestrial long-baseline detectors are the dotted lines labeled "gravity gradients" and "quantum limit." The curve designated by LISA is the rms noise projected for the space based LISA mission. The dashed lines are projections for a few burst sources. For chirp sources, to account for optimal filters in the detection, the strain amplitude is multiplied by the $\sqrt{n}$, where n is the number of cycles in the time series. The upper estimate curve labeled "compact binaries" is an optimistic one assuming $3NS/NS$ coalescences a year coming from all galaxies within 23 Mpc. The strength of the wave varies linearly as the reciprocal of the distance. In comparing the sources with the rms spectra of the detectors one needs to include a factor for the desired signal to noise and to take an average over all polarizations and directions of incidence. To gain a signal to noise of 5/1 and to take account of the possibility of nonideal orientation of the detector, it has become a standard practice to multiply the rms detector noise by about 11. The dashed lines at low frequencies "BH inspiral" are drawn for the chirp from BH/BH coalescence.

cited dense fluid state before becoming quiescent. A supernova losing 10^{-3} of its rest energy to gravitational waves in our own galaxy would produce an rms strain around 10^{-18} in the 100 Hz–1 kHz band. The sequence of events would be the detection of the gravitational-wave pulse followed shortly by the neutrinos and then hours later by the optical display. A high signal-to-noise detection with enough bandwidth to follow the motion of a close supernova could be one of the most interesting contributions of gravitational-wave observations to the knowledge of stellar dynamics. Even though such an event has a low probability, the long-baseline detectors are targeting almost continuous operation of at least a single interferometer for this eventuality.

The event rate of all classes of sources is increased by improving the sensitivity. For a given intrinsic source strength, the rate of events (once the sensitivity is enough not to be dominated by the local group of galaxies) will grow with the volume of space opened to the search, as the cube of the strain sensitivity. A benchmark for the field has been to bring the initial sensitivity to a level to include plausible sources at the distance of the Virgo cluster of galaxies, about 10^3 galaxies at a distance 10^3 times our galactic radius (10 Mpc). The supernova rate would then be about 3/year and the hypothetical supernova of the prior paragraph would provide a strain of 10^{-21}.

Black holes are sources with converse uncertainty, the event rate is uncertain but there is a reasonable estimate for the amplitude. The mass spectrum of black holes is not known although there is increasing evidence that most galaxies contain massive black holes in their cores; this, in part, has given impetus to place an interferometer in space. Even though the most energetic formations have not yet been successfully computer modeled, a reasonable estimate of the amplitude and time scales has been established from perturbation theory of black-hole normal modes. The radiating mechanism is the time dependence in the geometry of the event horizon as the hole changes mass; when matter falls into the hole, or when the hole forms initially. The horizon cannot readjust instantaneously to reflect the change, and a gravitational wave with periods determined by the local travel time of light around the event horizon is emitted. The radiation has a characteristic decaying exponential wave form of several cycles damped by the radiation itself.

Currently, the only source for which a reasonably reliable rate and amplitude can be estimated is the neutron star/neutron star coalescence; the end point of a system like the Hulse-Taylor neutron star binary. In the final hours the stars orbit each other more and more rapidly until at an orbital frequency close to 1 kHz, the neutron stars collide. The collisions are possible candidate sources for the cosmological γ-ray bursts that have been observed since the mid-1970s. In the last $\frac{1}{4}$ hour before the collision, the system executes about 10^4 oscillations in a chirp extending over the sensitive band of the interferometric detectors. The wave form of the chirp can be modeled within a few milliseconds of the moment of contact and then new information concerning the equation of the state of the nuclear matter and conditions on the neutron star surface may become inscribed on the gravitational wave form.

The rate of coalescence is calculated from a number of such systems discovered in our own galaxy and from estimates of pulsar detection efficiencies. The expectation is that one needs to be able to look into the universe with a depth of 200 to 400 million light years to observe three coalescence chirps per year, at a strain integrated over the chirp of $h=10^{-22}$. The chance of detecting these sources in the initial interferometer system is small but not vanishing. With improvements in the low-frequency performance, in particular, the thermal noise, the probability of detection improves significantly.

The neutron star/neutron star compact binary system is but one of several compact binary candidates; there should also be black hole/neutron star and black hole/black hole binaries. The stars in these systems will be more massive and stronger radiators. They may well be more interesting radiators since there will be new relativistic physics that can be studied in these systems. The Lense-Thirring, or "frame dragging" effect, should one of the compact objects be spinning, will cause new equations of motion and subtle modulations in the chirps. The detailed wave forms of the black-hole mergers are still not known and are the subject of extensive theoretical work. A major effort by the theoretical community in relativity is involved in calculating wave shapes to guide in the detection and to engender a comparison of theory with experiment as the field makes the transition into a real science.

A different class of sources are periodic or almost periodic systems in our galaxy that radiate extended wave trains. An example is a spinning neutron star with a time-dependent quadrupole moment due to a bump on its surface or an accretion-driven normal mode of oscillation. Such stars will radiate at twice the spin or oscillation frequency and at higher harmonics. They may show a small period derivative due to energy loss (possibly into gravitational waves) or spectral broadening from inhomogeneous excitation. The detection can take advantage of long integration times providing proper account is made of the frequency changes due to the motion of the detector relative to the source. The techniques required are similar to pulsar searches in radio astronomy. For a source at a specific location in the sky, it is possible to remove the Doppler shifts due to the Earth's rotation and orbit at all gravitational frequencies. The Fourier transform of the Doppler-corrected data is used as the narrow-band filter to search for periodicities. The concept is straightforward but the actual execution of a full-frequency/full-sky search poses a formidable computational challenge for extended integration times.

Periodic sources afford particularly attractive possibilities to test gravitational-wave kinematics from the amplitude modulation due to the rotation of the detector relative to the source. Such measurements would give information on the polarization state and propagation speed of the gravitational wave. The detection of the same periodicities in widely separated terrestrial detectors would provide strong confirmation, and would help in separating periodic signals with modulation at solar and sidereal days as well as to discriminate the artifacts from wandering local oscillators.

A stochastic background of gravitational waves may exist and is computationally one of the easier sources to search for. Such backgrounds could arise from the overlap of unresolved impulsive sources or the incomplete spectral resolution of many periodic sources. The most interesting source would be the random metric fluctuations associated with the primeval universe. These would constitute a gravitational equivalent to the cosmic microwave background radiation but come from a time much closer to the origin of the explosion, at an epoch inaccessible electromagnetically. The internal noise of the terrestrial detectors cannot be modeled well enough to establish a small excess due to a gravitational-wave noise. The detection of such a background requires the measurement of a small common noise in several detectors against a much larger uncorrelated component. The cross correlation depends on the gravitational-wave frequency and the separation of the detectors. For an isotropic background the correlation washes out at $f > (c/L_{\mathrm{separation}})$. The detected correlation amplitude signal to noise grows slowly, only as $\frac{1}{4}$ power of the correlation time. The measurement of a stochastic background would benefit from the multiple correlations afforded by a network of detectors.

The sources to be studied by the LISA detector are quite different. There are binaries throughout our galaxy nearly certain to be observable at frequencies above 0.003 Hz. At lower frequencies, the spectrally unresolved high density of a white dwarf and other binary systems is anticipated to cause a background noise of gravitational radiation. The "gravitational confusion" will not compromise the main objective of the LISA to detect and study signals from massive black holes at cosmological distances.

The mass spectrum of black holes is not known, although there is increasing evidence that many galaxies contain massive black holes in their cores. One promising source for LISA is five to ten solar mass black holes orbiting and ultimately coalescing with the massive hole at the galactic center. The coalescence of massive galactic black holes during the merger of galaxies is another candidate as could be the metric perturbations during the initial formation of the massive holes themselves.

VII. DETECTION CRITERIA

A signal needs to be above the noise experienced in the instrument and environment, however, this alone is insufficient to establish it as a gravitational wave in the terrestrial detectors. The most satisfying circumstance is that a gravitational-wave observation be made in a set of widely distributed detectors [the Gravitational-Wave Network (GWN)] and the recorded wave forms allow the solution for the polarization of the wave and the position of the source. Armed with this information, an electromagnetic (or neutrino) search could be attempted in the error circle of the gravitational wave detection; a time-honored approach bringing gravitational-wave observations into the main stream of astrophysics. The strategy would apply to all classes of sources: impulsive, chirps, quasiperiodic, and periodic.

The confident detection of impulsive sources is more difficult. While the periodic and quasiperiodic detections will have confidence limits based on quasi-stationary system noise (the signals last long enough to take a meaningful sample of the noise spectrum), the impulsive signals, especially if rare, will be particularly dependent on the non-Gaussian component of the noise; the noise most difficult to reduce and control in a single detector. The technique of multiple coincidence of several detectors is one of the best means to gain confidence. The coincidences must occur within a time window to permit a consistent solution for a location in the sky. If the general character of the source can be guessed in advance (for example, a binary coalescence chirp, or a black-hole normal-mode oscillation), the signal is filtered prior to the coincidence measurement to improve the sensitivity. The more detectors involved, the greater the confidence assigned to the detection.

There is still the possibility of coincidence due to environmental or anthropogenic causes. The various sites throughout the world are far enough apart that most environmental perturbations should not correlate between them. The acoustic noise, the seismic noise, and the power line (especially if the network includes detectors in different power grids and significantly different time zones) will be uncorrelated. There are correlations in the magnetic-field fluctuations (thunderstorms) and in radio frequency emissions. As part of the detection strategy a large number of environmental parameters will be measured along with the gravitational-wave signals at each site. One of the requirements for the authenticity of impulsive sources will be the lack of correlation with environmental perturbations and other ancillary internal signals developed to monitor the performance of the instruments.

VIII. THE FUTURE

As has been the rule rather than the exception in astrophysical observations, when new instrumentation offering a factor of 1000th improvement in sensitivity or bandwidth is applied to observing the universe; new phenomena are discovered. There is no reason to expect less for gravitation which involves looking at the universe in a new channel, going deep into the astrophysical processes to observe with no obscuration or scattering. The research has the two ingredients that make physics and astrophysics such a rewarding experience. There are the sharpshooter questions: the tests of the strong field, the confirmation of the wave kinematics, and the tests of astrophysical models; and there is also the buckshot part of the research with the high probability of discovering new and so far unthought-of processes—this gives an added romance to the new field.

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