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ROCHUS E. VOGT

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Alex Abramovici

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Richard Benford

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"Measurements of the Anisotropy of the Cosmic Background Radiation and Diffuse Galactic Emission at Millimeter and Submillimeter Wavelengths," with M. Halpern, R. Benford, S. Meyer, D. Muehlner

E. Michael Burka

List of Publications

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APPENDICES

APPENDIX A

THE PHYSICS OF GRAVITATIONAL WAVES, AND COMPARISON OF SOURCE STRENGTHS WITH DETECTOR SENSITIVITIES

This appendix presents a detailed discussion of the issues raised in Sections II.A, II.B, and II.C of the proposal. For still greater detail see Reference [A-1].

A.1 The Physics of Gravitational Waves

Gravitational waves are predicted by general relativity theory and by all other relativistic theories of gravity, and all the theories agree, in rough order of magnitude, on the strengths of the waves to be expected from astrophysical sources. Although gravitational waves have not yet been observed directly, the effect of the back-action of gravitational-wave emission on one source (the orbital decay of the binary pulsar PSR 1913+16) has been has been measured and agrees with general relativity's predictions to within the experimental error of several per cent [A-2]. The primary goal of the LIGO Project is to detect gravitational waves directly and use them to test the fundamental laws of physics and to open a new window onto the astrophysical universe.

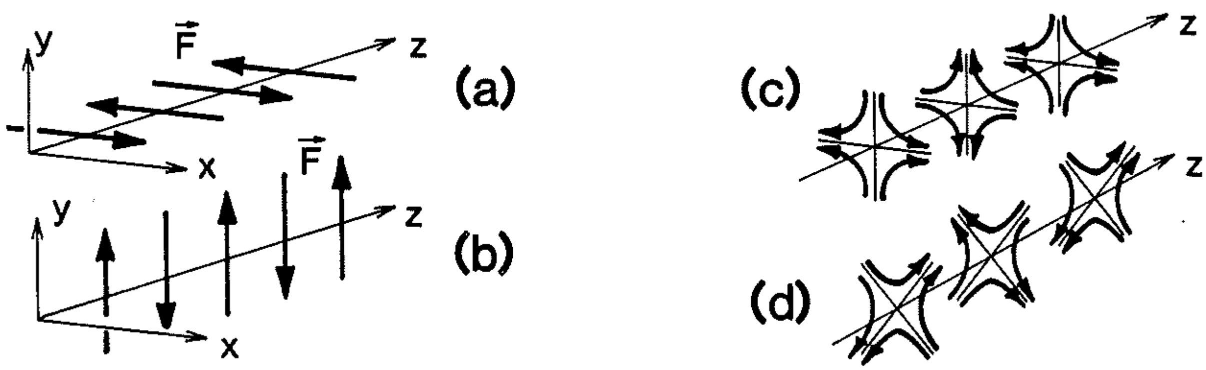

Figure A-1 Left half: The Forces produced on charged particles by an electromagnetic wave propagating in the z direction: (a) for x-polarization, and (b) for y-polarization. Right half: The forces on massive particles produced by a gravitational wave propagating in the z direction: (a) for + polarization, and (b) for × polarization.

The forces produced by gravitational waves. Just as an electromagnetic wave pushes a charged particle that initially is at rest back and forth in a direction transverse to the wave's propagation (figures A-1a and A-1b), so also a gravitational wave pushes a massive particle, initially at rest, back and forth transversely (figures A-1c and A-1d). The figures show the lines of force as measured in a local "proper reference frame", whose time coordinate t is equal to the proper time ticked by physical clocks and whose orthogonal spatial coordinates (x, y, z) measure proper (physical) distance. For a gravitational wave the force on a particle of mass m at location (x, y, z) is the sum of contributions from two polarizations: the + ("plus") polarization (Figure A-1c) with force

$$\vec{F} = \tfrac{1}{2} m \ddot{h}_+ (x\vec{e}_x - y\vec{e}_y) \qquad (A.1a)$$

and the $\times$ ("cross") polarization (Figure A-1d) with force

$$\vec{F} = \tfrac{1}{2} m \ddot{h}_{\times} (y\vec{e}_x + x\vec{e}_y). \tag{A.1b}$$

Here dots denote time derivatives, $\vec{e}_x$ and $\vec{e}_y$ are unit basis vectors in the x and y directions, and h_+ and $h_\times$ are dimensionless *gravitational-wave fields*, which propagate in the z-direction at the speed of light

$$h_+ = h_+(t - z/c), \quad h_\times = h_\times(t - z/c). \tag{A.2}$$

Notice that the gravitational force fields (A.1c,d) are quadrupolar and are transverse to the waves' propagation direction.

If a test particle at (x, y, z) is unconstrained by other forces, then it will accelerate by an amount $\delta\ddot{\vec{x}} = \vec{F}/m$ in response to the gravitational wave, and its resulting displacement will be

$$\delta x = \tfrac{1}{2} h_+ x, \quad \delta y = -\tfrac{1}{2} h_+ y, \quad \delta z = 0 \tag{A.3a}$$

for the + polarization and

$$\delta x = \tfrac{1}{2} h_\times y, \quad \delta y = \tfrac{1}{2} h_\times x, \quad \delta z = 0 \tag{A.3b}$$

for the $\times$ polarization. Since the displacement is proportional to the separation of the particle from the origin of the local proper reference frame, with proportionality factor h_+ or $h_\times$, one can regard h_+ and $h_\times$ as dimensionless "strains of space".

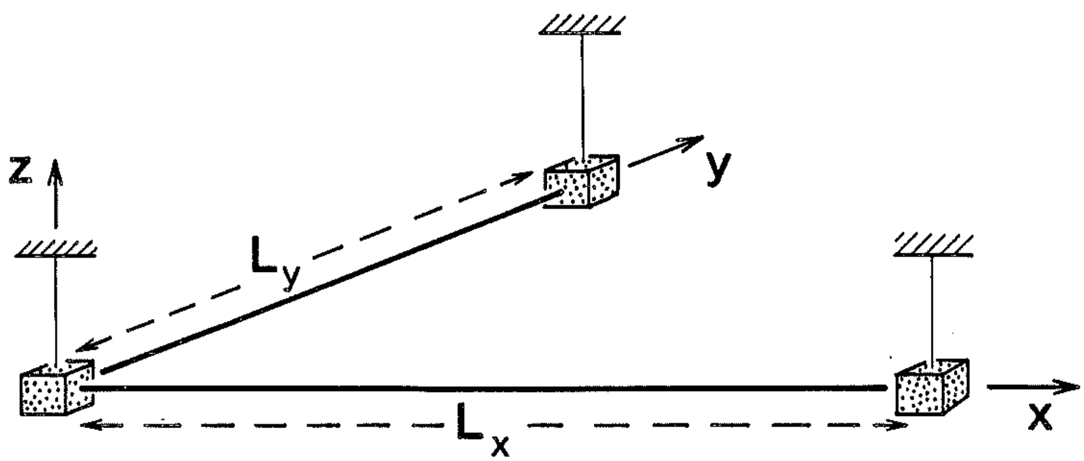

Figure A-2 Schematic diagram of a laser interferometer gravitational wave detector.

Effect of the wave on an Interferometric Detector. Figure A-2 is a schematic diagram of an interferometric detector of the type to be operated in the LIGO. Three masses hang by wires from overhead supports at the corner and ends of an "L". We shall denote by L the lengths of the arms of the "L" and shall place the origin of a proper reference frame at the corner mass as shown. If a gravitational wave propagates vertically (z-direction), and has its + polarization axes parallel to the detector's arms, and has a frequency f high compared to the one-Hertz swinging frequency of the masses, then the wave will move the end masses back and forth relative to the corner mass in just the same manner as if the end masses were free (the pendulum restoring force does not have time to act). The resulting wave-induced changes in the x-arm and y-arm lengths [equation (A.3a)] will be $\delta L_x = \frac{1}{2}h_+ L$ and $\delta L_y = -\frac{1}{2}h_+ L$; i.e. they will be equal and opposite. These changes are monitored by laser interferometry: Laser beams, sent from the center mass down the two arms and reflected off mirrors on the end masses, will return to the corner with a relative phase change $\Delta\Phi$ that is proportional to the difference in arm lengths,

$$\Delta\Phi = 2\pi\Delta L/\lambda_l, \quad \text{where } \Delta L \equiv \delta L_x - \delta L_y = h_+(t)L. \qquad (A.4)$$

Here λ_l is the light's wavelength. By interfering the beams one can monitor this phase change and thence monitor the gravitational wave field $h_+(t)$. A variety of interferometric optical systems have been proposed and developed for performing the monitoring. The most promising ones are discussed in Parts V and VI and Appendices F, G, and H. [*Side remark*: One might worry that the gravitational wave will interact with the laser beams and thereby alter the standard phase-change relation $\Delta\Phi = 2\pi\Delta L/\lambda_l$. Not so if one uses, as we have, a rigid, Cartesian coordinate system whose coordinate lengths are unaffected by the wave. Only if one uses "rubbery coordinates" (e.g. the "transverse-traceless coordinates" introduced in many textbooks) need one worry about interaction of the gravitational wave with the light.]

If the wave, instead of coming in vertically, comes in from a direction with polar angles (θ, ϕ) relative to the Cartesian coordinates of Figure A-2 (cf. Figure II-1 in Section II.A), and if we take one of the + state's polarization axes to be horizontal, then straightforward algebra shows that the forces (A.1) produce the relative arm-length change

$$\Delta L/L = F_+(\theta,\phi)h_+(t) + F_\times(\theta,\phi)h_\times(t), \qquad (A.5a)$$

where F_+ and $F_\times$ are the detector's quadrupolar beam pattern functions

$$F_+ = \tfrac{1}{2}(1+\cos^2\theta)\cos 2\phi, \quad F_\times = \cos\theta\sin 2\phi. \qquad (A.5b)$$

Note that the beam patterns are very broad. This means that the relative responses of different detectors, with different orientations, will give rather poorer information about source directions than the time-of-flight between widely separated detectors.

Measurement of the graviton's rest mass and spin. Quantum field theory tells us that classical waves are carried by quanta (photons for electromagnetic waves and gravitons for gravitational waves), and that the rest masses and spins of the quanta can be inferred from the propagation speeds and polarization properties of their waves:

The propagation speed will be precisely the speed of light if and only if the quanta have zero rest mass; otherwise it will be slower. Thus, one goal of the LIGO Project is to detect gravitational waves from a supernova outburst in the nearest large cluster of galaxies, the Virgo Cluster, and compare the waves' arrival time with the beginning of the optical outburst. Since the distance to Virgo is about 30 million light years, even with an optical time resolution of only one day, one could infer that the light and gravitational waves propagated with the same speed to within a fractional error of (one day)/(30 million light years) $\sim 10^{-10}$, and one thereby could place on the graviton rest mass a limit of $\sim 10^{-6}\times$ (the energy of a 1000 Hz graviton)$\sim 10^{-16}$ eV. If neutrinos could also be detected, the time resolution for both neutrinos and gravitational waves could be about one millisecond; and if their onsets were that close together, one would infer equal speeds to within $\sim 10^{-18}$ and corresponding rest mass limits of $\sim 10^{-20}$ eV for the graviton, and $\sim 10^{-2}$ eV for the neutrino.

The spin S of the quantum that carries a classical wave determines the "return angle" of the wave's force field: Rotate the force field (Figure A-1) about the wave's propagation direction. The minimum angle of rotation that brings the field back to its original orientation is its return angle $\theta_{\rm ret}$ and is equal to (360 degrees)/S. For the electromagnetic wave of Figures A-1a and A-1b, $\theta_{\rm ret}$ is 360 degrees, so the photon must have spin one; for the gravitational wave of Figures A-1c and A-1d, $\theta_{\rm ret}$ is 180 degrees, so the graviton must have spin two. Correspondingly, one goal of the LIGO project is to determine the return angle for gravitational waves by simultaneous measurements with several different detectors (in a world-wide network) that have several different orientations. Since most other relativistic theories of gravity predict a mixture of spin-two, spin-one, and/or spin-zero gravitons [A-3], such a measurement would be a powerful test of whether general relativity is correct.

The strengths of cosmic gravitational waves. Energy conservation dictates that the wave fields h_+ and $h_\times$ die out as 1/(distance to the source)$= 1/r$. Just as an electromagnetic wave is produced by oscillating multipole moments of a charge distribution, so also a gravitational wave is produced by oscillating multipole moments of a mass distribution. In the electromagnetic case the monopole moment cannot oscillate because it is the source's total charge and charge is conserved; and, consequently, the radiation is typically dipolar. Similarly, in the gravitational case the monopole moment cannot oscillate because it is the source's total mass and mass is conserved; moreover, the mass dipole moment cannot oscillate because its time derivative is the source's total momentum and momentum is conserved; and, consequently, gravitational radiation is typically quadrupolar. Dimensional considerations then dictate that $h_+ \sim h_\times \sim (G/c^4)\ddot{Q}/r$ where G is Newton's gravitation constant, c is the speed of light, Q is the quadrupole moment, and dots denote time derivatives. Since the quadrupole moment is of order the mass of the source times the square of its size, $\ddot{Q}$ is of order the mass times the square of the source's internal velocities, i.e. of order the source's internal kinetic energy—or, more precisely, that part of the kinetic energy associated with oscillatory, nonspherical motions, $E^{\rm ns}_{\rm kin}$:

$$h_+ \sim h_\times \sim \frac{G}{c^4}\frac{E^{\rm ns}_{\rm kin}}{r} \sim 10^{-20}\left[\frac{E^{\rm ns}_{\rm kin}}{M_\odot c^2}\right]\left[\frac{30 \text{ million light years}}{r}\right] . \qquad (A.6)$$

Here $M_\odot$ is the mass of the sun and 30 million light years is the distance to the Virgo Cluster. Equation (A.6) is a correct order-of-magnitude estimate not only for general relativity, but also for other theories of gravity; and it suggests that the strongest extragalactic waves bathing the earth are not likely to exceed 10^{-20}.

Characteristics of the strongest sources. The strongest sources are those for which the nonspherical, internal kinetic energy is largest, which means those with large masses and large internal velocities. Since the internal velocities are generated by internal gravity, large internal velocities means large internal gravity, which means compact size. Thus it is that the strongest sources are likely to be black holes and neutron stars—e.g. the violent births of black holes and neutron stars in stellar implosions, the inspiral and coalescence of binary neutron stars and black holes in distant galaxies, and the rotation of nonaxisymmetric neutron stars (pulsars) in our own galaxy.

The frequencies of cosmic gravitational waves. The characteristic frequencies of vibration and rotation for neutron stars are less than or of order a few kilohertz; and those for a black hole of mass M are

$$f \sim \frac{10 \text{ kHz}}{M/2M_{\odot}} \qquad (A.7)$$

(where $2M_{\odot}$ is the smallest possible mass for a black hole that forms by stellar collapse). Thus, the strongest waves are likely to lie at frequencies of 10 kHz and below. The LIGO is designed to work from 10 kHz down to the lowest frequencies at which one can isolate the detectors from earth vibrations, ~10 Hz—a range in which a rich variety of sources should exist. At yet lower frequencies, where there should also be interesting sources, one must use space-based detectors—the most promising of which will be LIGO-type detectors that might fly in space in the early 21st century [A-4]. The LIGO Project will provide an important base of technology and experience for those future detectors.

Penetrating power of gravitational waves. Because the strongest sources of gravitational waves are compact concentrations of highly dynamical mass, they typically will lie in regions obscured by surrounding matter (e.g. in the core of a supernova explosion or at the center of a galaxy or in the big-bang origin of the universe). Fortunately, gravitational waves are highly penetrating. For example, whereas neutrinos scatter many times in emerging from the center of a supernova and photons cannot get out at all, gravitational waves should emerge with impunity. Similarly, whereas photons from the big bang (the cosmic microwave radiation) last scattered off matter when the universe was about one million years old and neutrinos last scattered when it was a few seconds old, primordial gravitational waves should have last scattered near the Planck time, $\sqrt{G\hbar/c^5} \sim 10^{-43}$ seconds, when the initial conditions of the universe were being set by the (little understood) laws of quantum gravity [A-5].

Electromagnetic information as a poor predictor of cosmic gravitational waves. Electromagnetic waves studied by astronomers are almost always incoherent superpositions of the emissions from a huge number of molecules, atoms, or charged particles. In contrast, cosmic gravitational waves are produced by the coherent, bulk motions of huge amounts of mass-energy (either in the form of matter as in neutron stars, or in the form of vibrating, nonlinear spacetime curvature as in colliding black holes). This difference of emission mechanism, together with the fact that the strongest gravitational wave sources are probably opaque to photons, serves as a warning that our present photon-based knowledge of the universe may be a rather poor guide as to what gravitational-wave astronomy will bring. On one hand, we cannot estimate with confidence how sensitive must be the LIGO's detectors in order to discover waves. On the other hand, when waves are discovered, they are likely to bring surprises. Indeed, it seems likely that gravitational radiation will produce a revolution in our understanding of the universe comparable to that which came from radio waves in the 1950s and 1960s [A-6].

The information carried by gravitational waves. Gravitational waves carry substantial information about their sources. The total information carried to earth is embodied in the celestial coordinates (α, δ) of the source on the sky, plus the two "gravitational wave forms" $h_+(t)$ and $h_\times(t)$ evaluated at the location of a detector. The LIGO detectors are broad-band instruments, designed to measure the wave forms in the time domain with a high-frequency cutoff around 10 kHz and a seismic-noise-induced low-frequency cutoff, which in present prototypes is around 400 Hz and will be pushed continually downward toward 10 Hz over the coming years. A goal of the LIGO project, in cooperation with other detectors in a world-wide network, is to extract the full information, α, δ, $h_+(t)$, and $h_\times(t)$ from the waves; and, where possible, to cross-correlate that information with data from other kinds of radiation.

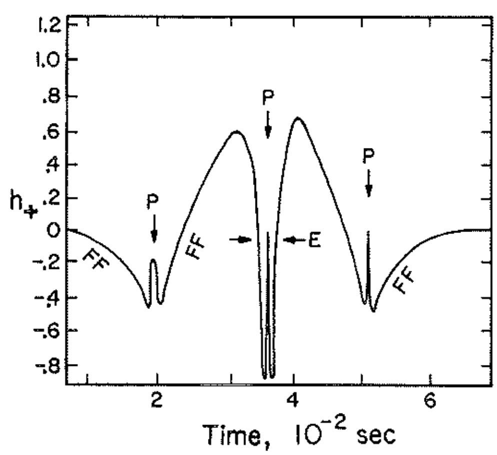

Figure A-3 The gravitational waveform produced by one scenario for the collapse of a star to form a neutron core, as computed in a numerical simulation by Richard A. Saenz and Stuart L. Shapiro [A-7].

Extraction of information from a wave form. Figure A-3 shows a wave form $h_+(t)$ computed several years ago by numerical simulation of a specific kind of source [A-7]. Without knowing the details of the simulation one can infer the following: (i) Because the shortest time scales present in the wave form are ~ 0.5 msec, the source must be either a neutron star or a several-solar-mass black hole. Assuming, as usually will be the case, that the radiation is predominantly quadrupolar, one can double-time-integrate the waveform to get the time evolution of the source's quadrupole moment. One then notices that the segments of the waveform marked *FF* have the shapes, $h_+ \propto (t - \text{const})^{-2/3}$ that one expects from nonspherical, free-fall motion; and the sharply reversed peaks marked $\dot{P}$ are what one expects from a sharp acceleration in the direction opposite to the free fall. The natural and correct interpretation is that these waves are from a stellar collapse that formed a neutron core which bounced three times. The fact that the three sharp peaks are all in the same direction (up, not down) indicates that the sharp bounces were all along the same axis. Surely the other axis or axes should have bounced as well, or at least stopped their collapse; so there should be at least one sharp peak in the down direction. Indeed there is; it is superposed on the central up peak (region labeled E). The natural and correct interpretation is that the collapsing star was centrifugally flattened by rotation; its pole collapsed fast and bounced three times (up peaks P) while its equator collapsed more slowly and bounced once (down peak E).

This wave form is not a firm prediction; it is merely one of many different wave forms that have been computed based on many different scenarios for stellar collapse. Neutron-star physics is so complicated—especially in the highly dynamical, shock-wave-endowed situations that produce strong gravitational waves—that theorists in the early years of gravitational wave astronomy are likely to be relegated to the task of interpreting the observed waveforms, as above, rather than predicting them with confidence. From those interpretations we should learn much about the uncertain physics that governs dynamical neutron stars.

Wave-form tests of black-hole physics. Because black holes are made of pure vacuum gravity, their dynamics can be computed with far greater confidence (if one believes in general relativity) than the dynamics of neutron stars. For example, numerical relativity experts expect, by the early 1990s, to compute in detail the waveforms produced when two black holes orbiting each other spiral together and coalesce [A-8]—a type of source that the LIGO may ultimately be able to see throughout the universe (Figure A-4a below). A detailed agreement between the computed and observed wave forms would simultaneously confirm the existence of black holes in the real universe and test general relativity's predictions for the behavior of gravity in highly nonlinear, dynamical situations.

The signal-to-noise ratio required for wave-form studies. One might worry that the LIGO detectors will never have good enough signal-to-noise ratio to see the details of the wave forms. On the contrary, if the LIGO is sensitive enough to make detections at all, it will be sensitive enough for wave-form studies. This is because to detect so rare an event as a stellar collapse or binary coalescence in the midst of the detector's Gaussian noise will require an amplitude signal-to-noise ratio of 5 or more; and if the signal-to-noise is high enough to be confident the event was real, that full ≥ 5 signal-to-noise can be used for wave-form extraction.

The use of waves to probe the large-scale structure of the universe. As we shall see, the coalescence of neutron-star and black-hole binaries is a promising source for detectors of the second or third generation in the LIGO. For such coalescences the wave-form signatures (a sinusoid with frequency sweep from low to high) are so clean and the wave strength is so firmly predictable, that they could act as a "standard candle" with which to measure the large-scale structure of the universe (the Hubble expansion rate and deceleration parameter) [A-9]; cf. the paragraph preceding Eq. (A.10) below.

A.2 Scientific Payoff from the LIGO Project

From the above discussion we can cull a list of scientific payoffs that might come from the LIGO Project. That list was presented in Part II; and we reproduce it here for ease of reading. The LIGO Project is being designed and managed, so far as possible, in such a way as to maximize the likelihood that some or most of these payoffs will be achieved.

Possible Payoffs for Physics

- The observational discovery of gravitational waves.
- Measurement of the rest mass and spin of the graviton: do they agree with general relativity's predictions, $m = 0$ and $S = 2$?
- Verification (by comparing theoretical and observed wave forms) that black holes exist and that their dynamics are as predicted by general relativity. Thereby test general relativity for the first time in the domain of highly nonlinear, dynamic gravity.

Some Possible Payoffs for Astronomy and Astrophysics

- Open up a new window onto the universe, a window that is almost certain to bring surprises and that may bring a revolution comparable to that which came from the radio window in the 1950s and 60s.
- Study the behaviors of neutron stars in highly dynamical situations. Thereby extract information about the uncertain physics that governs neutron stars.
- Use the waves from binary coalescences as "standard candles" for the determination of the Hubble expansion rate and deceleration parameter of the universe.
- Detect primordial gravitational waves from the big bang, and from them extract information about the initial conditions and earliest stages of evolution of the universe.

A.3 Estimates of the Strengths of the Waves at Earth and Comparison with Anticipated LIGO Sensitivities

Whether these payoffs can be achieved will depend, primarily, on whether detectors in the LIGO can reach the required sensitivities. The best estimates of the required sensitivities come from astrophysical source-strength calculations. Unfortunately, those calculations, being based on our electromagnetic understanding of the universe, are very uncertain: With the single exception of binary-neutron-star coalescences (see below), for each type of source either (i) the strength of the source's waves for a given distance from earth is uncertain by several orders of magnitude, or (ii) the rate of occurrence of that type of source, and thus the distance to the nearest one, is uncertain by several orders, or (iii) the very existence of that type of source is uncertain.

The source strength calculations are summarized by the thin curves and lines in Figures A-4a (short bursts), A-4b (periodic waves), and A-4c (stochastic background). For full details of the assumptions and calculations that underlie these figures and for extensive references to the literature see section 9.4 of Reference [A-1]. Here we shall give only a brief overview.

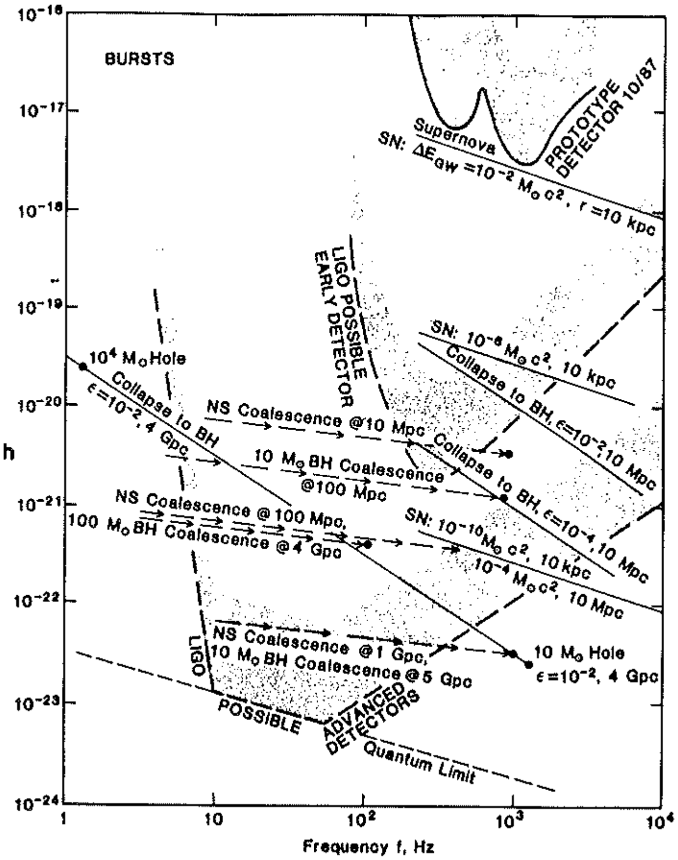

Figure A-4a The estimated wave strengths for various gravitational-wave bursts [thin curves and arrows]; and benchmark sensitivities [thick curves and stippled strips atop them] for interferometric detectors today and in the proposed LIGO.

Gravitational wave bursts (Figure A-4a)

Gravitational wave bursts that have been modeled by theorists last for no more than a few thousand cycles, and usually no more than three cycles. We shall describe such a burst by a characteristic frequency f (horizontal axis of Figure A-4a) and by a characteristic dimensionless amplitude h_c, which is defined in Reference [A-1, Equation (31)], in terms of optimal signal processing of a gravitational-wave detector's output and an average over source orientations, and which is approximately equal to the amplitude of the wave-form oscillations $h_+(t)$ and/or $h_\times(t)$ multiplied by the square root of the the number n of cycles that the burst spends near frequency f. (The factor $\sqrt{n}$ accounts for the ability of the detector to amplify the signal by integrating up the cycles.)

Coalescing neutron-star binaries. Our one moderately (but not highly) certain source is the coalescence of a neutron-star binary system. That coalescence should produce, during the inspiral phase, a "chirp", with characteristic frequency sweeping upward through the LIGO's band from a few tens of Hertz to 1000 Hz in a time of a few minutes. The characteristic amplitude of the inspiral waves for a binary at a given distance is predicted with confidence and accuracy by general relativity [equation (46b) of Reference A-1]:

$$
\begin{aligned}
h_c &= 0.287 \frac{G(\mu M)^{1/2}}{c^2 r} \left(\frac{\pi G M f}{c^3}\right)^{-1/6} \\
&= 4.1 \times 10^{-22} \left(\frac{\mu}{M_\odot}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{1/3} \left(\frac{100 \text{ Mpc}}{r}\right) \left(\frac{100 \text{ Hz}}{f}\right)^{1/6}
\end{aligned}
\tag{A.8}
$$

Here μ is the binary system's reduced mass, M is its total mass, r is its distance from earth, and G and c are Newton's gravitation constant and the speed of light. The number of cycles spent near frequency f is

$$
\begin{aligned}
n \equiv \frac{f^2}{\dot{f}} &= \frac{5}{96\pi} \frac{M}{\mu} \left(\frac{c^3}{\pi G M f}\right)^{5/3} \\
&= 3200 \frac{M/4}{\mu} \left(\frac{M_\odot}{M}\right)^{5/3} \left(\frac{100 \text{ Hz}}{f}\right)^{5/3}
\end{aligned}
\tag{A.9}
$$

The arrows at $h\sqrt{n} \sim 10^{-20}$ to 10^{-23} in Figure A-4a show the sweep of such binaries from low frequency to high, for neutron stars (abbreviated NS in the figure) with individual masses $1.4M_\odot$ (so $M = 2.8M_\odot$ and $\mu = 0.7M_\odot$). The distance to which one must look in order to see three such coalescences per year can be estimated from the observed statistics of pulsars in our own galaxy: Clark, Van den Heuvel and Sutantyo [A-10] compute for the 3/year distance 100^{+100}_{-40} Megaparsecs with 90 per cent confidence. Schutz [A-11] computes, with "very high confidence", 10 Megaparsecs to 1 Gigaparsec. The arrows in Figure A-3 are for 100 Mpc (best estimate), 1Gpc (most pessimistic estimate) and 10 Megaparsec (most optimistic). [Recall: one parsec is three light years; the center of our galaxy is at 10 kpc, the Virgo cluster is 10 Mpc, and the Hubble distance is 4 Gpc.]

Coalescing black-hole binaries, during their inspiral phase, are described by the same formulas (A.8) and (A.9) as for neutron stars, but their final gravitational-wave burst, as their horizons coalesce and the combined hole then vibrates, will be very different. It is this final burst that will be computed with confidence using supercomputers in the next few years and that, by comparison of theory and experiment, should constitute both a firm proof of the existence of black holes and a powerful test of general relativity. Coalescing black-hole binaries should be more rare than coalescing neutron-star binaries. Most likely their event rate is somewhat larger than one per year out to the Hubble distance of ~ 4 Gpc; but they might not exist at all, and they might be as common as several per year at 100 Mpc. The characteristic amplitudes during the inspiral phase are shown in Figure A-4a for distances of 4 Gpc and 100 Mpc and for several masses.

Coalescing binaries as standard candles. Notice that during the inspiral phase of any compact binary the number of cycles spent near a given frequency [equation (A.9)] and the characteristic amplitude [equation (A.8)] depend on the same combination of masses, $\mu M^{2/3}$. Correspondingly, as Schutz [A-9] has pointed out, one can solve directly from the observational data for the distance r to the source. If one can also identify the galaxy or cluster of galaxies in which the source lies and get a redshift from its electromagnetic radiation, one therefrom can determine the Hubble expansion rate of the universe and perhaps get a handle on its deceleration parameter.

Supernovae and other stellar collapses that form neutron stars. The rate of occurrence of supernovae is fairly well determined (about one every 30 years per galaxy as large as our own; several per year in the Virgo cluster). Stellar collapses that produce no bright optical display could be up to ten times more numerous, or might not occur at all. Unfortunately, the strengths of the waves from a stellar collapse at a given distance are highly uncertain. If the collapse is spherical, no waves are produced at all; if it is highly nonspherical, as much as one per cent of the rest mass of the collapsing stellar core could come off in gravitational waves. Even the characteristic frequency of the waves is uncertain; various plausible models have given frequencies anywhere from a few hundred Hertz to 10 kHz. The characteristic amplitude h, as a function of the characteristic frequency f, the total energy ΔE_{GW} carried off in gravitational waves, and the distance r to the source is (equation (37) of Reference [A-1]):

$$h \simeq \left(\frac{3}{2\pi^2}\frac{G\Delta E_{GW}/f}{c^3r^2}\right)^{1/2} = 2.7\times10^{-20}\left(\frac{\Delta E_{GW}}{M_\odot c^2}\right)^{1/2}\left(\frac{1\ \mathrm{kHz}}{f}\right)^{1/2}\left(\frac{10\ \mathrm{Mpc}}{r}\right)\ . \tag{A.10}$$

Figure A-4a shows this characteristic amplitude for collapses that produce neutron stars (labeled "SN" with gravitational-wave outputs of 10^{-2} to 10^{-10} solar masses and distances of our galactic center (10 kpc) and the Virgo Cluster (10 Mpc). Note that the recent supernova in the Large Magellanic Cloud, being 5 times more distant than our galactic center, would have produced

$$h \simeq \tfrac{1}{2}\times10^{-18}\left(\tfrac{\Delta E_{GW}}{10^{-2}M_\odot c^2}\right)^{1/2}\left(\tfrac{1\ \mathrm{kHz}}{f}\right)^{1/2}\ . \tag{A.11}$$

Stellar collapses that form black holes produce short wave bursts with characteristic amplitude given by (A.10) and with characteristic frequency $f \sim c^3/5\pi GM \simeq (1.3\ \mathrm{kHz})(10M_\odot/M)$. The energy carried off can vary from $\Delta E_{GW} \sim 0.1Mc^2$ down to zero, depending on the degree of nonsphericity of the collapse. The wave strengths and frequencies shown in Figure A-4a are for efficiencies $\epsilon \equiv \Delta E_{GW}/Mc^2$ of 10^{-2} and 10^{-4} and distances of 10 Mpc (Virgo) and 4 Gpc (Hubble).

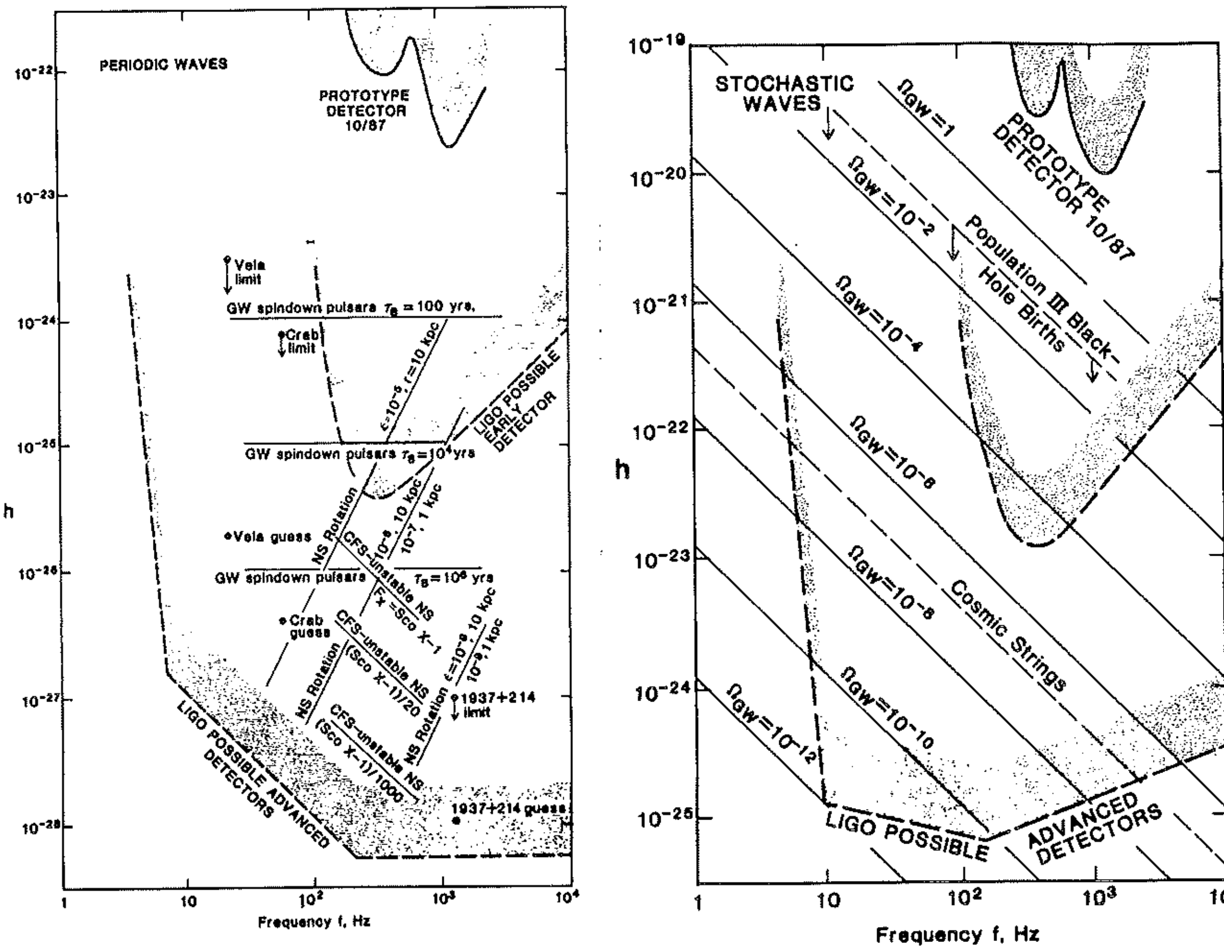

Figure A-4b,c Same as Figure A-4a, but for periodic waves (b), and for stochastic background waves (c). In both figures the detectors are assumed to use an integration time of 10^7 seconds.

Periodic Gravitational Waves (Figure A-4b)

Periodic Gravitational Waves are characterized by the amplitude h of the wave forms' sinusoidal oscillations (vertical axis) and their frequency (horizontal axis). The sources shown in Figure A-4b are all ***non-axisymmetric, rotating neutron stars*** in our own galaxy. The number of neutron stars in our galaxy is $\gtrsim 10^8$; but most may rotate so slowly and/or be so axisymmetric as to be poor gravitational-wave sources. The dependence of the gravitational-wave amplitude on the neutron star's moment of inertia $I_{\hat{z}\hat{z}}$ about the rotation axis, its distance r from earth, its frequency f, and its ellipticity in the equatorial plane $\epsilon = (Q_{\hat{x}\hat{x}} - Q_{\hat{y}\hat{y}})/I_{\hat{z}\hat{z}}$ (where $Q_{\hat{j}\hat{k}}$ is its quadrupole moment) is [equation (55) of Reference A-1]

$$h = 8\pi^2\sqrt{2/15}\frac{\epsilon I_{\hat{z}\hat{z}} f^2}{r} = 7.7\times 10^{-20}\epsilon\left(\frac{I_{\hat{z}\hat{z}}}{10^{45}\mathrm{g\ cm}^2}\right)\left(\frac{f}{1\ \mathrm{kHz}}\right)^2\left(\frac{10\mathrm{kpc}}{r}\right). \qquad (A.12)$$

This amplitude is shown in Figure A-4b for a distance of 10 kpc (the center of our galaxy), a moment of inertia of 10^{45} (all neutron stars should be within a factor ~ 3 of this), and a range of plausible ellipticities, $\epsilon \lesssim 10^{-5}$.

Known pulsars. The large dots in Figure A-4b are known pulsars, for which the amplitudes are uncertain by ~ 5 orders of magnitude because we do not know the stars' ellipticities. For each pulsar are shown (i) a best guess of h based on all present knowledge; and (ii) an upper limit, based on the observed slow down rate of the star's rotation and the (somewhat unlikely) assumption that the slow down is due to gravitational wave emission rather than electromagnetic emission; see section 9.4.2b of Ref. [A-1].

Gravitational-spindown neutron stars. Each horizontal line in Figure A-4b shows the h of the brightest member of a hypothesized population of rotating neutron stars that are spinning down due to gravitational radiation reaction rather than due to electromagnetic emission [A-12]. Each line is for a fixed mean time τ_B between births of those neutron stars; and the frequency-independent amplitude is [equation (57) of Ref. A-1]

$$h \simeq \left[\frac{4}{3}\frac{GI_{zz}}{c^3 R_G^2 \tau_B}\right]^{1/2} \sim 1 \times 10^{-25} \left(\frac{10^4 \text{ years}}{\tau_B}\right)^{1/2} . \qquad (A.13)$$

where $I_{zz} \sim 10^{45}\text{g cm}^2$ is the star's moment of inertia and R_G is the radius of our Galaxy's disk.

Chandrasekhar-Friedman-Schutz Instability. The rightward slanted lines in Figure A-4a are neutron stars that have been spun up by accretion from a companion, until they became unstable against nonaxisymmetric perturbations (the "Chandrasekhar-Friedmann-Schutz" [A-13] or CFS instability). These neutron stars would now be sources of X-rays due to the accretion and gravitational waves due to their nonaxisymmetry, and their gravitational wave amplitudes would be proportional to the square root of their X-ray luminosities, F_X ([A-14], equation (53) of Reference A-1):

$$h \simeq 2 \times 10^{-27} \left(\frac{300 \text{ Hz}}{f}\right)^{1/2} \left(\frac{F_X}{10^{-8} \text{ erg/cm}^2\text{sec}}\right)^{1/2} . \qquad (A.14)$$

This amplitude is shown in Figure A-4a for X-ray luminosities as fractions of that of the brightest candidate for such an object, *Sco X-1*. NASA is presently considering a proposal [A-15] for an X-ray satellite, the X-ray Timing Explorer (XTE), which, among other things, would search for X-ray modulations that might be due to the CFS instability. Any observed modulations would be cross-correlated with the outputs of gravitational wave detectors.

Stochastic Waves (Figure A-4c)

Stochastic gravitational waves are characterized in Figure A-4c by the amplitude h of the fluctuations of h_+ and $h_\times$ in a bandwidth Δf equal to the frequency f at which one searches; cf. section 9.4.3a of Reference [A-1].

Primordial gravitational waves. The most interesting stochastic background would be that from the *big bang*. Its strength is often described in terms of the gravitational-wave energy density $\rho_{GW}(f)$ in a band $\Delta f = f$ divided by the energy density required to close the universe,

$$\Omega_{GW}(f) \equiv \frac{\rho_{GW}(f)}{\rho_{\text{closure}}} , \qquad (A.15)$$

which is related to h by [equation (65) of Reference A-1]

$$\begin{aligned} h(f) &= \left[\frac{4G}{\pi f^2}\Omega_{GW}(f)\rho_{\text{closure}}\right]^{1/2} . \\ &= 1.3 \times 10^{-18}\left(\frac{\rho_{\text{closure}}}{1.7 \times 10^{-8}\ \text{erg cm}^{-3}}\right)^{1/2}\left(\frac{1\ \text{Hz}}{f}\right)[\Omega_{GW}(f)]^{1/2} \end{aligned} \qquad (A.16)$$

Lines of constant Ω_{GW} are shown in Figure A-4c. Current speculations about gravitational waves from the very early universe would place Ω_{GW} in the range 10^{-4} on downward. These waves almost certainly are not thermalized at $\sim 3K$ like primordial photons because they decoupled from matter at the Planck time, and because their interaction with background spacetime curvature is likely to have produced significant nonadiabatic, frequency-dependent amplification soon after the Planck time (e.g. during the inflationary era). See section 9.4.3d of Reference A-1 for details and references. Pulsar timing [A-16] has produced an observational limit $\Omega_{GW} \lesssim 10^{-6}$ at the exceedingly low frequency $f \sim 10^{-8}$ Hz, 10 orders of magnitude away from the LIGO frequency band.

Cosmic Strings. Another possible source of stochastic background is the decay of nonsuperconducting, cosmic strings. If such strings, created in a GUT phase transition in the very early universe, actually exist, they are estimated [A-17] to produce

$$\Omega_{GW} \sim 10^{-7}\left(\frac{\mu}{10^{-6}}\right)^{1/2} \qquad (A.17)$$

throughout the LIGO frequency band [equation (68) of Reference A-1]. Here μ is G/c^2 times the string's mass per unit length, and a value $\mu \sim 10^{-6}$ is suggested both by fundamental theory and by that value's success in producing from strings possible seeds for galaxy formation [A-17].

Population III Black-Hole Births. Stochastic waves could also result from a superposition of emissions from the deaths, long ago, by stellar collapse to form black holes, of a pre-galactic population of massive stars ("Population III stars") [A-18]. Such a population has been hypothesized to help explain the observed abundances of the elements in very old stars. Figure A-4c shows an upper limit [A-18] on the plausible strengths of such Population III waves—which, of course, might not exist at all.

Sensitivities of Detectors in the LIGO

Characterization of detector sensitivities. Internal noise in an interferometric detector (discussed in detail in Part V) causes the fractional arm length difference, $\Delta L/L$, as inferred from the detector's readout, to fluctuate stochastically in time. Those fluctuations are characterized statistically by their spectral density $S_{\Delta L/L}(f)$ as a function of frequency f. It is conventional in this field to denote the square root of that spectral density by

$$\tilde{h}(f) \equiv \sqrt{S_{\Delta L/L}(f)}\ , \tag{A.18}$$

and call it the detector's ***strain per root hertz.*** The root-mean-square fluctuations of $\Delta L/L$ at frequency f and in a bandwidth Δf are

$$(\Delta L/L)_{\rm rms} = \tilde{h}(f)\sqrt{\Delta f}\ . \tag{A.19}$$

It is these rms fluctuations that compete with the gravitational wave (A.5a) in the output data.

When searching for gravitational wave bursts the relevant bandwidth is $\Delta f \sim f$; and, correspondingly, we plot $h \equiv \tilde{h}(f)\sqrt{f}$ in Figure A-4a (curves at the bottom of the stippled strips) as a measure of detector sensitivity. When searching for periodic sources the relevant bandwidth is $\Delta f \sim 1/\hat{\tau}$, where $\hat{\tau}$ is the integration time; and correspondingly, we plot $h \equiv \tilde{h}(f)\sqrt{1/\hat{\tau}}$ in Figure A-4b (curves at the bottom of the stippled strips) as our measure of detector sensitivity, with $\hat{\tau}$ set equal to 10^7 seconds. When searching for stochastic background one cross correlates two detectors and thereby, if one cross correlates over a band Δf, one achieves an effective bandwidth of order $f/\sqrt{\frac{1}{2}\hat{\tau}\Delta f}$; correspondingly, we plot in Figure A-4c (bottom of stippled curves) $h \equiv \tilde{h}(f)[f/\sqrt{\frac{1}{2}\hat{\tau}\Delta f}]$ with $\Delta f = f$ for the upper two curves, but $\Delta f \ll f$ (see below) for the bottom curve. [To a great extent the choice of bandwidth and the details of the search are fixed in the data analysis. Thus, general purpose data can be collected and then analyzed in a variety of ways for a variety of sources. However, this is not entirely true: some special choices of the interferometric optics produce in the "hardware" special narrow banding of the output, with significant gains of sensitivity at the price of a loss of frequency coverage. These issues are discussed in Part VI and in greater detail in section 9.5.3e of Reference [A-1] (especially Figure 9.13).]

The above measures of detector sensitivity give unity signal to noise ratio when the source direction and polarization are optimal, and when compared to the measures of source strength used in Figures A-4. When one assumes random source direction and polarization the h sensitivity gets degraded by a factor $\sqrt{5}$. If one asks for 90 per cent confidence that the signals are due to waves rather than detector noise, one must demand an amplitude signal-to-noise ratio S/N larger than unity. In the case of stochastic and periodic waves, which are on at all times, and assuming that cross-correlation of two or more detectors has been used to remove all non-Gaussian noise, then that 90%-confidence S/N is 1.7. For bursts which occur on average 3 times per year the 90%-confidence S/N is way out on the tail of the gaussian noise: $S/N \simeq$

$[\ln(2\pi f 10^7 \mathrm{sec})]^{1/2} \simeq 5$. In Figures A-4 the tops of the stippled regions are the 90%-confidence sensitivities for randomly directed and polarized waves:

$$\frac{h_{\text{top of stipple}}}{h_{\text{bottom of stipple}}} = [5\ln(2\pi f \times 10^7 \text{ sec})] \simeq 5\sqrt{5} = 11 \text{ for bursts, Figure A}-4\text{a}$$
$$= 1.7\sqrt{5} = 3.8 \text{ for periodic and stochastic, Figures} - \text{A.4a, b.} \qquad (A.20)$$

In Figures A-4 we show three detector sensitivity curves:

Prototype detector. The upper curve-with-stippled-strip is the sensitivity, as defined above, for our prototype detector with 40-meter arms as of October 1987; see Part V for further detail.

Possible early detector in the LIGO. The middle curve-with-stippled-strip in each figure is the sensitivity of a possible detector that might operate soon after the LIGO is completed. The rms-noise curve at the bottom of the stippled region describes, at frequencies above ~500 Hz, receivers that are shot-noise-limited, without recycling or resonating or squeezing, with argon ion laser light (reduced wavelength $\lambda\!\!\!^{-}_l \equiv \lambda_l/2\pi = 0.0818\mu\mathrm{m}$), with (laser power)×(photodetector efficiency) $= I_o\eta = 10$ Watts, and with light storage times in each arm of a half gravity-wave period or longer. For two such detectors operating in coincidence, (cf. Equation (123a) of Reference [A-1]):

$$\tilde{h}(f) = \left[\frac{2\hbar c \lambda\!\!\!^{-}_l}{I_o\eta}\left(\frac{\pi f}{c}\right)^2\right]^{1/2} = (2.4 \times 10^{-22}\ \mathrm{Hz}^{-1/2})\left(\frac{f}{1000\ \mathrm{Hz}}\right); \qquad (A.21)$$

and correspondingly, Equations (123b,c,d) of [A.1]

$$h = \tilde{h}\sqrt{f} = 7 \times 10^{-21}\left(\frac{f}{1000\ \mathrm{Hz}}\right)^{3/2} \quad \text{for bursts,} \qquad (A.22a)$$

$$h = \tilde{h}\sqrt{10^{-7}\mathrm{Hz}} = 8 \times 10^{-26}\left(\frac{f}{1000\ \mathrm{Hz}}\right) \quad \text{for periodic sources,} \qquad (A.22b)$$

$$h = \left(\frac{2f}{10^{-7}\ \mathrm{Hz}}\right)^{-1/4}\tilde{h}\sqrt{f}$$
$$= 2.9 \times 10^{-23}\left(\frac{f}{1000\ \mathrm{Hz}}\right)^{5/4} \quad \text{for stochastic sources.} \qquad (A.22c)$$

Below ~500Hz it is presumed that seismic noise debilitates the performance of these early LIGO detectors. The debilitation shown is a guess, but is quite plausible based on that in the present prototype (upper curve in these figures).

Once the first detector has been operated successfully in the LIGO at something like the sensitivities (A.22), there will follow a succession of generations of ever improving detectors, with the sensitivity levels being pushed continually downward (to smaller h) and leftward (to lower frequencies f) in Figures A-4a,b,c. As a rough measure of where this might lead after a few years, we have drawn in the figures a lower sensitivity curve which corresponds to the following "Advanced Detector" parameters:

$$
\begin{aligned}
L &= (\text{arm length}) = 4\text{km}, \\
\lambda_l &= 0.0818\mu\text{m (argon ion laser light)}, \\
I_o\eta &= (\text{laser power}) \times (\text{photodetector sensitivity}) = 100 \text{ Watts}, \\
\mathcal{R} &= (\text{maximum mirror reflectivity}) = 0.9999. \\
m &= (\text{mirror mass}) = 1000 \text{ kg when working at } f \lesssim 100 \text{ Hz}, \\
&\quad \text{photon shot noise dominant at } 100 \text{ Hz} \lesssim f \lesssim 10^4\text{Hz}, \\
&\quad \text{quantum limit noise dominant at } 10\text{Hz} \lesssim f \lesssim 100 \text{ Hz}, \\
&\quad \text{seismic noise dominant at } f \lesssim 10\text{Hz}.
\end{aligned}
\tag{A.23}
$$

It is presumed that light recycling is used for burst searches, with a resulting modest narrow-banding, $\Delta f \simeq f$ of the detector (figure 9.13 of Reference [A-1]). If the optics are adjusted to give optimal sensitivity at frequency f, the resulting rms shot noise there is [equation (125a) of Reference A-1]

$$h = \tilde{h}\sqrt{f} = \left[\frac{2\pi\hbar\lambda_l}{I_o\eta}\frac{(1-\mathcal{R})}{L}f^2\right]^{1/2} = 1.2 \times 10^{-22}\left(\frac{f}{1 \text{ kHz}}\right) \quad \text{for bursts.} \tag{A.24a}$$

This is the sensitivity shown on the upward sloping line in Figure A-4a. It is presumed that light resonating is used for periodic and stochastic searches, with a resultant narrow banding of the detector to $\Delta f = (1-\mathcal{R})c/(4\pi L) = 0.6$ Hz; figure 9.13 of Reference A-1. (If squeezed light is used, the same sensitivity can be obtained with a broader bandwidth—in fact, recycling plus squeezing in principle can achieve this same sensitivity as narrow-band resonating, but with $\Delta f \sim f$; cf. section 9.5.3f of Reference [A-1].) If the optics are adjusted to put the optimal sensitivity at frequency f, then the photon shot noise is [equations (125b,c) of Reference A-1]

$$h = \left[\frac{2\hbar c\lambda_l}{I_o\eta} \times 10^{-7}\text{Hz}\right]^{1/2}\left(\frac{1-\mathcal{R}}{L}\right) = 6 \times 10^{-29} \text{ for periodic waves,} \tag{A.24b}$$

$$
\begin{aligned}
h &= \left[\frac{2\hbar c\lambda_l}{I_o\eta}f\right]^{1/2}\left[\frac{4\pi}{c}\left(\frac{1-\mathcal{R}}{L}\right)^3 \times 2 \times 10^{-7}\text{Hz}\right]^{1/4} \\
&= 1.4 \times 10^{-25}\left(\frac{f}{1 \text{ kHz}}\right)^{1/2} \quad \text{for stochastic waves.}
\end{aligned}
\tag{A.24c}
$$

Here it is assumed that the stochastic search is restricted to the bandwidth over which the narrow-banded detector has good performance.

At frequencies below about 100 Hz these shot-noise limited sensitivities are so good that light-pressure fluctuations on the mirrors produce stochastic mirror motions that become a more serious problem than shot noise. The result, after adjustment of laser power to produce an equal balance of light-pressure noise and shot noise, is the so-called "standard quantum limit" for the detector's sensitivity [equations (126) of Reference A-1]:

$$h = \left[\frac{2}{\pi^2}\frac{\hbar}{mL^2}\frac{1}{f}\right]^{1/2} = 1.2 \times 10^{-24}\left(\frac{1000\text{Hz}}{f}\right)^{1/2} \quad \text{for bursts,} \qquad (A.25a)$$

$$h = \left[\frac{2}{\pi^2}\frac{\hbar}{mL^2}\frac{10^{-7}\text{Hz}}{f^2}\right]^{1/2}$$
$$= 1.2 \times 10^{-29}\left(\frac{1000\text{Hz}}{f}\right) \quad \text{for periodic waves,} \qquad (A.25b)$$

$$h = \left(\frac{4}{3\pi}\right)^{1/2}\left(\frac{4\hbar}{mL^2}\right)^{3/8}\left[\frac{\hbar\lambda_l}{I_o\eta c}\left(\frac{2\times 10^{-7}\text{Hz}}{f}\right)^2\right]^{1/8}$$
$$= 4 \times 10^{-26}\left(\frac{1000\text{Hz}}{f}\right)^{1/4} \quad \text{for stochastic waves.} \qquad (A.25c)$$

Here $\hbar$ is $\frac{1}{2}\pi$ times Planck's constant. There are known techniques, at least in principle, for circumventing this quantum limit in the periodic and stochastic cases [section 9.5.3f of Reference [A-1], but nobody yet has found a way around this limit when searching for broad-band bursts.

The Advanced Detector sensitivities of figures A.4 presume that seismic noise is strongly debilitating at frequencies $f \lesssim 10\text{Hz}$. The indicated location and form of the seismic-noise cutoff is a very crude guess. The sensitivities also assume vastly improved suspension systems so that thermal noise does not enter the noise budget.

Conclusions

By comparing the source strengths and benchmark sensitivities in figures A.4a,b,c one sees that *(i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is very probable at the sensitivity level of the Advanced Detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in the second or third, as the sensitivity and frequency are being pushed downward from the middle curves toward the bottom curves of figures A.4a,b,c.*

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APPENDIX B

LIGO CONCEPT

In this appendix we present more detailed justifications and discussions of issues raised in Part IV.

A. Essential Features of the LIGO

The design goals of optimizing the probability of discovering gravitational waves and optimizing the information extracted from the waves dictate the following essential features of the LIGO:

1. Two widely separated sites under common management.
2. Arm lengths of order 4 kilometers at each site.
3. The capability to operate simultaneously several receiver systems at each site.
4. The capability for receivers of two different arm lengths.
5. A vacuum tube diameter of order 48 inches.
6. The capability of a vacuum level of 10^{-8} torr.
7. A minimum lifetime of the facilities of 20 years.
8. Adequate support instrumentation.

Discussion of these essential features follows:

1. Two antennas at widely separated sites. At least two receivers located at widely separated sites are essential for unequivocal detection of gravitational wave bursts. The best means to eliminate the large set of external noise sources (seismic noise, acoustic noise, ...), as well as internal impulsive phenomena (sudden strain release in wire suspensions, fluctuations in index of refraction of residual gas, ...), is to operate the two receivers with comparable sensitivities at separations sufficiently large so that the noise at the two locations is uncorrelated over the relevant observation times. Gravity wave signals, by contrast, would be correlated.

2. Arm lengths of order 4 kilometers. The choice of antenna arm length is a complex tradeoff between achievable sensitivity and cost. A "first-order" version of the tradeoff is this (see below for details): In the regime where gravitational waves are most likely to be found (at $f \leq 100$ Hz and $h \leq 10^{-21}$), the dominant noise is likely to be local stochastic disturbances (seismic, acoustic, thermal, local gravity gradients). In this regime the gravity-wave event rate (number of detectable sources) scales with detector sensitivity as h^{-3}, and h scales with arm length as L^{-1}, so (event rate) $\propto L^3$. By contrast, at arm lengths $L \lesssim 1$ km fixed costs dominate, so the cost is roughly independent of L while at $L \gtrsim 4$ km cost is roughly proportional to L so a doubling of L (and cost) increases the event rate by ~ 8.

A more careful discussion reveals the justification of and second-order caveats in this analysis: For arm lengths short compared to half the gravitational wavelength ($1/2 \times 300$ kilometers for 1 kHz waves), the signal $\Delta L = hL$ increases linearly with length, L (Equation II.1). By contrast, many, indeed most, noise sources are unaffected by the separation L of the test masses. Holding constant all other variables except the arm length, L, the scaling of the strain amplitude noise, h (i.e. $\tilde{h}\sqrt{\Delta f}$ in notation of Part II and Appendix A), with L is:

$1/L$ for

- most stochastic disturbances (seismic, acoustic, thermal, local gravity gradients, ...), noise produced by objects at distances much less than L from the test masses;
- the quantum limit (Figure II-2; Equation A.25 of Appendix A);
- photon shot noise if the light storage time in the antenna arm is limited to much less than 1/2 the gravitational wave period for burst sources;
- photon shot noise in a search for periodic sources with an optical resonating recycling system (Section VI.A.2(b); Equation A.24a);

$1/L^{3/4}$ for

- statistical fluctuations in the index of refraction of the residual gas for fixed pressure and minimum optical beam size;
- photon shot noise in a search for stochastic waves using optical resonating recycling (Section VI.A.2(b); Equation A.24b);

$1/L^{1/2}$ for

- photon shot noise using light recycling on burst sources with optimum storage times in the arms (Section VI.A.2(b); Equation A.24a);

Independent of L for

- photon shot noise for storage times $\gtrsim$ half the gravitational wave period, but without recycling or resonating (Equations A.21, A.22).
- gravity gradient noise from objects at distances large compared to L.

With these differing dependencies on arm length of the various noise sources, the expected variation of interferometer sensitivity with length depends on the dominant noise source and the instrument configuration. For example, for a wideband receiver using light recycling, photon shot noise will vary as $1/L^{1/2}$ while most stochastic noise will vary as $1/L$.

A major consideration related to length of the arms is the rate of detectable burst events. Once the interferometer sensitivities have reached a level where it is possible to detect sources at the distance of the Virgo cluster of galaxies (e.g., for the supernovae, binary neutron stars, and binary black holes discussed in Part II, Appendix A, and Figures II-2 and A-4), the detectable event rate is expected to grow inversely with the cube of the amplitude sensitivity, h^{-3}. This is because the number of galaxies that can be monitored is proportional to the volume of the universe that can be observed, and the distance at which a specific kind of source can be detected is inversely proportional to the amplitude sensitivity. Under these circumstances the event rate varies as the inverse cube of the length-dependent factors listed above. For example, in the case of sensitivities limited by $1/L$-varying noise, *a factor 2 increase in arm length L produces a factor 8 increase in event rate.*

The expected sensitivity of advanced detectors, as given in Figure II-2, corresponds to an arm length of 4 kilometers. This limiting sensitivity just reaches that required to detect with high confidence the coalescence of neutron star binaries in distant galaxies. It is extremely important to build a system of sufficient length to have a high probability of successful detection, and this source is the only one for which both signal amplitude and frequency of occurrence can be predicted with considerable confidence. Because the dominant noise in the very best searches for this source's waves will almost certainly be the quantum limit and low- frequency stochastic forces (seismic and thermal), and because these scale as $1/L$, the event rate will almost certainly be $\propto L^3$, and an arm length substantially less than 4 km would move us out of the high-confidence regime for this, our only "semi-guaranteed" source.

3. Capability for several simultaneous receiver systems at each site. The facilities will be designed so that, even in the early stages of operation, they will support work on a developmental receiver system while another operational receiver system carries out a search for gravitational waves. A high live-time of the observatory will be achieved by restricting development to specified, simultaneous hours at both sites and by designing the facilities so that the vacuum is maintained for the operating receiver at all times.

As receiver technology matures, additional receivers will be accommodated with minimum interference to measurements in progress. These additional, simultaneous investigations will permit gravitational astronomy to become a research field like other branches of astrophysics with many independent and interesting research programs involving experimenters from a number of institutions.

4. Receivers of different arm lengths. The LIGO will be able to accommodate interferometers with both two and four kilometer arm lengths acting together as a single receiver system. The fact that gravity wave signals in interferometers are proportional to arm length can be exploited to aid in discriminating between gravity waves and local disturbances at one site, thereby reducing the spurious coincidence rate between the two sites. Such reduction may be essential to unequivocal identification of gravitational wave bursts. Two receiver beams sharing the same vacuum will also be very useful in diagnostic studies of local noise sources.

5. Vacuum tube of order 48 inches in diameter. The long vacuum tubes must be able to pass Gaussian optical beams without causing diffraction loss of the beams or being a serious source of scattered light. In particular, the tubes must be large enough so that motion of the tube walls, when driven by seismic noise or thermal-expansion-induced creep, do not add to the noise in the receivers through diffraction of the beams at the walls. This condition must be met with some margin for misalignment and settling of the tube supports.

The single Fabry-Perot interferometer planned at each site for the initial search will not require the full vacuum tube diameter. Longer range goals for the facilities, however, require that multiple investigations can be carried out simultaneously. Also, some of the single Fabry-Perot receiver designs will be using multiple beams for seismic noise reduction (Section 6 and Appendix F) as well as full and half length interferometers for diagnostic studies. A single delay-line interferometer using light of 1 micron wavelength would require, because of its many discrete beams, a minimum diameter of 43 inches. The smallest standard tube diameter which satisfies these requirements is 48 inches.

6. Vacuum level of 10^{-8} *torr.* The vacuum system will be designed so that fluctuations in the index of refraction of the residual gas in the interferometer arms will not become a limiting noise source. Noise from such fluctuations depends on the ratio of the molecular polarizability, χ of the gas at the laser wavelength to the square root of the molecular thermal velocity, v_{th}. The major constituent (95 to 99%) of the residual gas in a clean stainless steel system is molecular hydrogen which diffuses out of the metal; fortunately, this gas has a small value of $\chi/\sqrt{v_{th}}$. The ultimate sensitivity goals require residual gas pressures of less than 2×10^{-8} torr for hydrogen and 1×10^{-9} torr for nitrogen. These pressures can ultimately be achieved through a combination of selection and preparation of materials, outgassing methods, and pumping strategy. The sensitivity of the first LIGO receiver (Figure II-2) is compatible with higher pressures, but the attainable vacuum cannot be allowed to limit ultimate sensitivities.

7. Minimum lifetime of the facilities of 20 years. The LIGO facilities are expected to be used with a succession of gravitational wave detectors of continually improving sensitivity as the receiver technology advances. Specialized receiver systems will be developed with enhanced sensitivities for specific frequency bands or temporal characteristics. As with other kinds of astronomical observatories, scientific productivity in large measure will be dependent on improvements in instrumentation over a period of many years as the technology advances.

The 20-year lifetime requirement is intended as a guide in design tradeoffs which exchange capital costs for operating costs. Such design decisions will be made so as to minimize total life cycle costs, while maintaining flexibility to deal with a variety of possible situations downstream (e.g., quick discovery of waves at large h's versus a long struggle to find them at small h's).

8. Support instrumentation. The LIGO facilities must be designed with instrumentation to monitor environmental disturbances (acoustic, seismic, residual gas fluctuations, electromagnetic interference, cosmic rays, etc.) for cross correlation with receiver signals.

B. Sites

Two sites are essential for the unambiguous detection of gravitational waves.

In the early phase of the search for gravitational waves it will be extremely important to have two sites in operation with overlapping sensitivities, frequency coverage, and observation times. Close coordination of development and operation of the two receivers is vital; this can be achieved only through common management of the two facilities. Site selection and development depends on considerations which are discussed in the following paragraphs.

Scientific considerations.

The LIGO configuration, including sites, will be chosen so that (i) most importantly, it comes close to optimizing the probability of successfully discovering gravitational waves; and (ii) secondarily (and to the extent of noninterference with (i)), it optimizes the information extracted from the waves. The implications of these criteria have been studied by a LIGO site selection working group formed from a subset of the Caltech and MIT scientists. The implications include the following:

Receiver alignment: If the two receivers at the two sites are "co-aligned" (coincident projections of their arms on the plane that bisects their two planes), then they are optimally sensitive to the same polarization state and the probability of wave detection is optimized. If one of the receivers, instead, is rotated 45 degrees relative to co-alignment, the two are most sensitive to orthogonal polarizations and together extract the most information from the waves. The Working Group has recommended co-alignment (and thus that the two sites be capable of co-alignment) in order to optimize discovery, and it strongly recommends that one of the two sites be capable of supporting (in a future upgrade) a second receiver rotated 45 degrees to the first, for maximal information extraction.

Distance between sites: Optimization of discovery dictates that the sites be much farther apart than the correlation lengths of the various noise sources that can affect the receivers; for this, 300 km is probably adequate. Optimal determination of source directions, via time-of-flight between sites (which is much more accurate than via antenna beam patterns), dictates a separation between sites as large as possible. However, at separations larger than $\approx$4500 km the detectors' planes disagree sufficiently to drive their beam patterns (the angular factors in equation (1)), even with co-alignment, far enough away from each other to noticeably reduce the probability of discovery. These considerations suggest a site separation in the range 2500 to 4500 km.

Direction between sites: The probability of detection is not significantly sensitive to the direction between sites; but the accuracy of position determination via time-of-flight between sites will be direction-sensitive when there is a network of detectors. Optimal directionality requires a minimum of four detectors at the corners of a tetrahedron of maximum volume; or, failing that, at least three detectors at the corners of a triangle of maximum area. The first likely sites are two in America and one to three in Europe. The shorter baselines within Europe give poorer angular resolution for most source directions than the transatlantic or trans-American baselines, but they will be able at the very least to resolve the two-fold ambiguity left by data from the three longer baselines alone. In general every operating site will contribute significantly to the final gravity-wave map of the sky. In the more distant future, sites in Japan and/or Australia are likely to come into operation, and their geographical position will make them a particularly useful component of a world network. The American sites should be chosen so as to contribute significantly to the area of an America-America-Europe triangle and the volume of a tetrahedron.

In terms of these scientific criteria for site selection, the preliminarily chosen site pair, Edwards, CA and Columbia, ME, is satisfactory.

Other Considerations. Site accessibility, availability, topography and geophysical nature, and expandability are additional variables that must be considered in the site selection process. Because not all of these can be quantified until further studies (such as detailed geophysical surveys) are completed, alternate sites are continuing to be explored.

C. Vacuum System and Architectural Facilities

In the past several years, substantial progress has been made toward defining the conceptual design of the LIGO facilities, leading to the list of essential features discussed in section A, above. Since the completion of the A. D. Little/Stone & Webster design study, a continuing examination has been made of ways to build a facility which meets the requirements with particular attention to finding the most economical and reliable method. Caltech's Jet Propulsion Laboratory has been principal consultant in this activity. The effort has resulted in iteration of the cost estimates of many elements of the LIGO facility such as the buildings, vacuum system, enclosure for the vacuum system, electric power system, laser cooling system, and civil engineering work. The estimates have been used in evolving and guiding the conceptual design of the LIGO.

Details of the vacuum system and supporting facilities will be defined during the engineering design phases. The conceptual design of the system will be completed during the coming 6 months before contracting for the Preliminary Engineering Design and Cost Definition. Some of our present, preliminary concepts for the vacuum system and architectural design are profiled here.

Key features of the vacuum system. The vacuum system, representing a major cost item, is that component of the LIGO, apart from the receivers, which requires the most careful planning and design. The function of the vacuum system is twofold:

1. to reduce refractive index fluctuations in the light paths along the 4 kilometer arms; and,
2. to reduce the stochastic forces on the test masses and mirrors in the instrumentation chambers.

It is expected that the vacuum enclosure will be made entirely of stainless steel tubing and bellows. This plan is consistent with our philosophy that the LIGO should be designed using established engineering practices familiar to contractors to minimize risk. The instrumentation chambers will be stainless steel vessels designed to allow easy access to receiver components. The chambers, gate valves, and support structures for the test masses and other receiver components will be arranged so that development work can proceed while maintaining vacuum where the gravity wave investigations are being conducted.

Architectural facilities. It is expected that the long vacuum tubes will be enclosed in a housing and insulated with an earthen berm in order to:

1. provide general protection from the weather;
2. reduce wind-driven vibrations;

3. improve thermal stability so as to avoid
   a) daily fluctuations in outgassing,
   b) mechanical thermal distortions of the tubing,
   c) acoustic and mechanical noise that might be transmitted to the instrumentation chambers due to the possible stick/slip at tube supports;
4. protect the tubes from vandalism.

The instrumentation stations will be located in buildings and structures within the vacuum chambers will be seismically isolated. Acoustic and vibrational noise in excess of naturally occurring background will be minimized through appropriate construction specifications. It is not expected that the instrumentation stations will be used as general laboratory or operations buildings; these will be provided elsewhere at the sites.

Detailed requirements for power, cooling, and facility instrumentation will be defined during the engineering design phases. The data analysis system will include provisions for merging housekeeping and environmental information with the receiver data streams for correlation and veto analysis. The two sites are expected to include data links to the home institutions and to each other.

D. Science Strategy for the LIGO

The LIGO is being designed to give a high probability of detecting gravitational wave signals and thereby to open the field of gravitational wave astronomy. A less ambitious goal would be incommensurate with the costs and scientific effort being expended. It is clearly not sufficient to plan the LIGO as only an extension of the technology development and demonstration now being carried out in the prototype research.

The first goal of a science strategy for the LIGO is the unambiguous detection of gravitational wave signals at a sufficiently high signal to noise and event rate to establish gravitational astronomy as a means of studying astrophysical phenomena. This goal requires more than the observation of a few events per decade. It also demands a different style of research than has been the custom in the development phase of the prototype detectors; engineering and careful design must be applied to facilities and receivers so that they will operate for long periods trouble-free and without substantial attention.

A successful initial science strategy for the LIGO has to cope with the present uncertainty in the knowledge of the amplitude, rate and frequency spectra of the waves bathing the earth. Conventional wisdom holds that the initial sensitivities projected for the LIGO (middle stippled region of Figure II-2) will be needed, at the minimum, to discover waves, and that sensitivities near those of the "possible advanced detectors" (Figure II-2) may be required, and that the uncertainties in the source strengths are unlikely to be reduced before the LIGO is constructed. Even if we are lucky enough to have a nearby event, such as the supernova of 1987, register in improved bar or interferometric detectors, the event though a newsworthy singularity, could not become the basis for formulating a longer term scientific strategy for gravitational wave astronomy.

In order to deal with the uncertainty, the LIGO facilities and research program are designed to support both an observing and a development program concurrently. For the observing program we have chosen early in the program to fix an initial receiver design, common to both sites of the LIGO. This will allow time for the engineering of the receivers and the receiver/facility interfaces. A common receiver is dictated by the fact that in cross-correlation measurements the overall sensitivity is effectively determined by the receiver with the poorer sensitivity. Furthermore, given the intellectual and financial resources available to the LIGO, a common receiver is the most sensible way to guarantee that two sites together will be able to carry out a meaningful observation in a timely manner.

The observing program requires the development of more than just the receivers. A facility instrumentation system is required to monitor environmental disturbances such as ground and acoustic noise, electromagnetic field fluctuations, and residual gas fluctuations. Such monitoring is needed to diagnose intermittent problems in the receivers and ultimately become part of the overall experiment design, and to veto the events in the non-Gaussian tail of the receiver noise which in turn affect the accidental coincidence rate between the sites.

The initial receivers as currently envisaged will probably be designed for broadband coverage of a wide range of frequency, from a few hundred Hertz to several kilohertz. The sensitivity will be the highest that we can reliably achieve at the time the design has to be frozen; it may be somewhere near that suggested by the "LIGO Possible Early Detector" curves in Figures A-4a,b,c. The data analysis of the cross-correlated output from these first receivers can be tailored to search for bursts, periodic sources and a stochastic background. (This present concept for the initial receiver may change if developments in the prototype research or in source expectations make some other variant of receiver preferable). The initial receivers will be designed and built by members of the LIGO project and components will be constructed in the research laboratories, in industry and by affiliates of the project at other research centers. The engineering, management and documentation of the receiver design and construction will be the responsibility of the LIGO engineering staff.

A continuing development program is needed irrespective of whether the initial observations are successful or not. In the case that no detections are made with the first receivers, it will be urgent to have prepared and begun to test new receiver designs with increased sensitivity and spectral coverage. This will be carried out in part in facilities on the Caltech and MIT campuses that are able to handle full scale receiver components, and in part within the long baseline facilities themselves. The scaling from short to long baselines is an important factor in the receiver development especially as some of the proposed methods to enhance the sensitivity in second generation receivers cannot be adequately tested on small baselines. We therefore envisage that the LIGO will be constructed in such a manner as to enable development and observation with a minimum of interference. The expectation is that smooth transitions will be possible from one observing receiver system to the next iteration of an enhanced receiver system that has been technically qualified in the LIGO.

In the event of detections in the initial observing program, the dual capability for observation and development is also important; but in this case the optimization of the enhanced receiver designs will be guided by the observed signals. The scientific program, once detections have been made, is expected to change substantially. There will be multiple demands on the facilities as the field moves from a discovery phase to a diagnostic one. One could expect good scientific reasons to carry out continuous observations for improved statistics and comparative studies, but equally good reasons to develop specialized receivers tailored to studying specific sources, and most likely pressures to look deeper and with more sensitivity. The success of the field will doubtless engender enough interest so that a much larger part of the scientific community, both observers and instrument developers, will want to join the new science. At this point in the LIGO project it would be most useful to multiplex the facilities and enable the use of the LIGO for many different and concurrent observing programs. The necessary manpower and the resources should then be readily available.

Once waves have been detected, the gravitational sky will have to be connected to the electromagnetic one, which means that source location will become an important part of the science. A single gravitational wave receiver has such little directivity (cf. the angular factors in equation II.1), that the best means for determining source position is by measuring time of flight between several receiver sites. The initial two LIGO sites are not sufficient to uniquely specify the source position; four sites at the corners of a large-volume tetrahedron will be required to make an unambiguous identifications of source positions over the whole sky. At the present point in the development of gravitational wave research, it is unrealistic for the LIGO project to propose any more than the minimum configuration of two sites to establish the field. It is possible, though not guaranteed, that European, Asian and/or Australian research groups will build large baseline gravitational wave systems and thereby will help develop the network required (cf. Section B above on Sites).

If, unexpectedly, not only does the rest of the world fail to contribute to a network of receivers on the same timescale as the LIGO but even fails to build receivers after waves are discovered, it may be appropriate for a third site to be added to the LIGO.

Once waves have been detected, the extraction of their full information will require measuring the two wave forms $h_+(t)$ and $h_\times(t)$; and the determination of the graviton spin will require a network measurement of h_+ and $h_\times$ in two or more independent ways. For these purposes unless several receivers with proper orientations are being built elsewhere in the world, it will be important to construct at one of the LIGO sites additional arms, rotated 45 degrees to the first (see Section B above on Sites).

The optimum strategy for facility upgrades, once sources have been observed, is not easy to anticipate; it depends critically on what has been discovered.

APPENDIX C

NATIONAL AND INTERNATIONAL COOPERATION

Caltech and MIT are committed ultimately to operate the proposed LIGO as an open facility for the benefit of the U.S. science community. In addition, international collaboration will be pursued vigorously in order to enhance the LIGO's observing capabilities and science output, while reducing the cost to any one country for a full program in gravity wave astronomy. The final design and construction proposal, to be submitted for NSF approval during this proposal's grant period, will address these items in full, on the basis of serious contacts with the national and international communities.

We intend to convene in the near future a workshop for the national and international communities. At this meeting current plans and concepts for the Caltech-MIT LIGO will be presented and discussed. This will allow others to critique and influence the design activities in a timely fashion, it will provide a basis for others to perform technical tasks in affiliation with the LIGO team, and it will provide data for others to do planning for their eventual use of LIGO, once it has reached its steady state operational phase.

As discussed below, a two-site U.S. observatory under single management will provide the indispensable nucleus of a worldwide effort in gravity wave astronomy. Significant science can be done with the proposed LIGO alone. However, a full operation that maximizes science results and allows their correlation with electromagnetic data (position resolution, in particular) will ultimately require an expanded interferometer network, consisting to first order of four interferometers, ideally at the corners of a large volume tetrahedron. It is our intention to engage in serious negotiations with potential partners in this enterprise outside the U.S., particularly in Europe, where France, Germany, Great Britain, and Italy have development programs relevant to the LIGO project. We intend to seek agreements on protocols for technical compatibility of facilities, exchange of data, and operational planning, and to institute mutual exchange of technical data. We are hoping for support in these endeavors from the International Office of NSF. We believe a favorable climate for such international collaboration exists with the existing science teams. In fact, (I. Corbett, G.B., private communication) the European planning efforts are proceeding with the assumption that a two-site U.S. LIGO will exist in time to provide the European effort with the necessary long-baseline complement to its system.

The initial U.S. effort must involve two sites at the minimum, because cross-correlated measurements between two widely separated sites are mandatory for identification of gravity waves amidst a background of local, non-Gaussian noise. Since the LIGO project entails a totally new technology, a single management for the two-site core facility is essential to assure timely optimization for design tradeoffs, comparable sensitivity, operational compatibility, simultaneous availability, and scheduling.