Resonant-Mass Detectors of Gravitational Radiation

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A network of second-generation low-temperature gravitational radiation detectors is nearing completion. These detectors, sensitive to mechanical strains of order 10^{-18}, are possible because of a variety of technical innovations hat have been made in cryogenics, low-noise superconducting instrumentation, and vibration isolation techniques. Another five orders of magnitude improvement in energy sensitivity of resonant-mass detectors is possible before the linear amplifier quantum limit is encountered.

GRAVITATIONAL WAVES ARE RIPPLES IN THE CURVATURE OF space-time that, according to Einstein's theory, carry energy and momentum and propagate at the speed of light. The oscillating curvature of a gravitational wave, generated by supernova explosions, coalescing binary stars, gravitational collapse, exploding galactic nuclei, and so forth, acts like a tidal force that produces oscillations in the separation between two neighboring test particles. All mechanical detectors of gravitational radiation rely on detection of this time-varying separation between massive bodies.

In the 1960s Joseph Weber established most of the experimental techniques for detecting gravitational radiation that are still being developed in his laboratory and in other laboratories throughout the world (see Table 1). In particular, Weber realized that a dynamic strain could be induced in a suitable resonant mode of an extended massive object by interaction with gravitational radiation (*1*). The massive object or "Weber bar" usually takes the form of a solid right cylinder (see Fig. 1), made from a material such as aluminum, with a fundamental longitudinal resonance frequency near 1 kHz. Gravitational radiation from astrophysical sources such as the gravitational collapse or coalescence of solar-mass size objects is expected to be largest in this spectral region. For example, a supernova event at the center of our galaxy that converts 1% of a solar mass into a gravitational radiation pulse of 1 msec duration would produce a strain of 3×10^{-18} at the earth (*2*).

Since Weber began the effort there have been technical breakthroughs leading to an improvement in energy sensitivity of gravitational radiation detectors by more than five orders of magnitude, but the ultimate objective of unequivocally detecting gravitational radiation has not yet been reached. Coincidence searches with two or more second-generation low-temperature detectors are just beginning, however, and various technical improvements not yet incorporated in working detectors should improve energy sensitivity by another three to four orders of magnitude. Together with laser interferometric gravity wave detectors (*3*) and relatively recent discoveries in astronomy of phenomena (quasars, pulsars, cosmic background radiation, black holes, exploding galaxies, for example) that point to a far more violent universe than we had previously believed existed, these developments give us reason to be optimistic that in the next decade experimentalists will succeed not only in detecting gravitational radiation but also in exploiting it as a tool for observational astronomy.

One focus of the technical improvements in resonant-mass detectors has been on the motion or strain transducer that monitors the dynamic strain of the antenna. On most first-generation room-temperature detectors this transducer is a block of piezoelectric crystal. A strain in the crystal induces a voltage across it, which is measured with a sensitive amplifier. The antenna is suspended from a vibration isolation structure and housed in a vacuum tank to reduce disturbances from laboratory acoustic and seismic noise. Unavoidably, Brownian motion noise associated with dissipation in the antenna and the transducer, and electronic noise from the amplifier, limit the sensitivity of the detector. Second-generation low-temperature detectors, equipped with more advanced transducers coupled to antennas made from high mechanical quality factor (Q) materials, have been constructed to reduce these noise sources. These new transducers include variable inductors and capacitors and modulated microwave cavities. They take advantage of the low mechanical and electrical losses exhibited in certain materials at low temperature. The technology developed has already achieved a sensitivity equivalent to a displacement measurement of $\Delta x \sim 10^{-18}$ m, which is much less than the diameter of an atomic nucleus (*4*).

It is still possible to improve the energy sensitivity of resonant-mass detectors by another five orders of magnitude before being limited by the Heisenberg uncertainty principle. In theory, the linear amplifier quantum limit can then be evaded through the use of nonlinear "back-action evasion" (BAE) measurement techniques or so-called "quantum nondemolition" (QND) techniques first proposed by Braginsky *et al.* (*5*). Demonstrations of these methods are being pursued in several laboratories. None of the proposed BAE techniques mitigate any of the problems inherent in the more conventional linear readout schemes, however.

The interaction of a gravitational wave with a resonant-mass detector and the signal-to-noise analysis and detector optimization for linear transducer readouts are all now well understood. Such an analysis shows that even a relatively large energy flux of gravitational radiation expected from some astrophysical sources couples very weakly to a detector. By considering the signal and all the relevant detector noise sources, we can understand the fundamental sensitivity and bandwidth limitations of resonant-mass detectors. For example, we will show that a high-Q antenna resonance does not lead to a narrow detection bandwidth.

Interaction of Gravitational Radiation with a Resonant-Mass Detector

Any mode of a resonant-mass antenna that has a mass quadrupole moment, particularly the fundamental longitudinal mode of a

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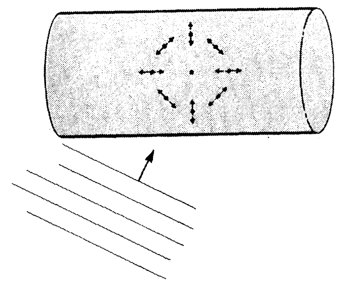


Fig. 1. An incident gravitational wave pulse induces a dynamic strain in the fundamental longitudinal mode of a solid right-cylindrical antenna or "Weber bar." The antenna has maximum sensitivity to waves that are incident at 90° from the cylinder's axis.

cylindrical antenna, can be excited by a gravitational wave pulse with nonzero energy spectral density at the mode eigenfrequency. Figure 1 shows the motion pattern induced in such an antenna by an incident wave.

The size of a resonant antenna is determined by the frequency and the velocity of sound v_s in the material used. Since v_s is always orders of magnitude less than the speed of propagation of gravitational radiation (presumed to be equal to the speed of light), resonant-mass antennas are always much smaller than the wavelength of the radiation. This fact is the primary reason why resonant-mass gravitational radiation detectors are relatively insensitive when compared with quadrupole electromagnetic antennas.

For a detector that is small compared to the wavelength of the gravitational wave, the effective tidal force dF, at time t, due to the wave acting on a mass element dm at position r from the center of mass is given by

$$dF_j = -\sum_k R_{j0k0}(t)\, r_k\, dm \qquad (1)$$

where R_{j0k0} are the components of the Riemann curvature tensor (*6*). The Riemann tensor has 20 independent components that contain all of the geometrical information about how space-time is curved in different directions. For a weak plane wave traveling in the x direction with optimum polarization for exciting an antenna with axis oriented along the z direction, the nonzero components of the Riemann tensor are related to the dimensionless wave strain $h(t)$ by

$$R_{z0z0} = -R_{y0y0} = -\frac{1}{2}\frac{\partial^2 h}{\partial t^2} \qquad (2)$$

It is conventional to characterize the response of the antenna in the frequency domain in terms of a cross section $\sigma(\omega)$, where ω is the frequency. The energy deposited by a pulse of gravitational radiation in an antenna originally at rest is

$$E = \int E(\omega)\sigma(\omega)d\omega \approx E(\omega_0)\int \sigma(\omega)d\omega \qquad (3)$$

where $E(\omega)$ is the energy spectral density of the signal pulse and ω_0 is the antenna mode frequency. The approximate equality holds if the pulse duration is less than Q times the antenna oscillation period so that σ is sharply peaked at $\omega = \omega_0$. For a cylindrical antenna excited by a source of random polarization, the resonance integral of the cross section, averaged over all source directions, is given by

$$\int \sigma(\omega)d\omega = \frac{32\ GM}{15\pi\ cn^2}\left(\frac{v_s}{c}\right)^2 \qquad (4)$$

where M is the antenna mass, G is the gravitational constant, and n = 1, 3, 5, 7, . . . is the mode number. For the Stanford detector, shown in Fig. 2, this integral is 4×10^{-21} cm^2 Hz. Note that gravitational radiation only couples to the odd modes.

Near a given mode, the cross section $\sigma(\omega)$ is a narrow-band resonant function centered at the mode eigenfrequency ω_0 with a full width at half maximum of $(2\omega_0/Q)$, where Q is the mechanical quality factor of the antenna. This behavior of the cross section seems to imply that a high-Q antenna will have a very narrow bandwidth, but this is not the case. Both the strain signal spectrum and the thermal Brownian motion noise in the antenna exhibit the same resonant response near the mode eigenfrequency. Thus the signal-to-noise ratio is not bandwidth limited by the antenna thermal noise. A more significant sensitivity and bandwidth restriction comes from the transducer-amplifier readout (*7*).

Mechanical Nyquist Noise and Amplifier Noise

The design of resonant-mass gravity wave antennas is based on a noise model that relates the detection sensitivity to a number of basic system parameters, such as the antenna mass, geometry, resonant quality factor, and the amplifier noise properties. The first step in constructing a noise model is to reduce the distributed detection system to a lumped element model with only a few degrees of freedom. To be definite, we suppose that the antenna is a cylindrical bar and that its lowest longitudinal normal mode is monitored by a linear mechanical amplifier that includes the electromechanical transducer and the electronic amplifier. The resulting lumped mass-spring-dashpot circuit with signal and noise generators is shown in Fig. 3.

Table 1. Research groups developing resonant-mass gravitational radiation detectors. Selected references are given which describe each group's research program in more detail. The cryogenic detectors at Stanford, Rome (CERN), and Louisiana State University were recently operated in coincidence for the first time.

Group	Current program	References
Institute of Physics, Academia Sinica, Beijing	Aluminum bar and low-frequency tuning fork at room temperature. Piezoelectric transducers with field-effect transistor amplifiers.	(*33, 34*)
Louisiana State University	Aluminum bar at 4 K. Inductive superconducting transducer with SQUID amplifier and parametric transducer.	(*35*)
Moscow State University	Ultrahigh-O sapphire bars and quantum nondemolition methods.	(*36*)
Stanford University	Aluminum bars at 4 K. Inductive superconducting transducer and SQUID amplifier.	(*4, 23*)
University of Maryland	Aluminum bars at 4 K and 300 K. Inductive superconducting transducer and SQUID amplifier.	(*37*)
University of Rome	Aluminum bars at 4 K. Electrostatic transducer.	(*12*)
University of Tokyo	Disk antenna for low-frequency monochromatic waves. Microwave parametric transducer.	(*25, 38*)
University of Western Australia	Niobium bars at 4 K. Microwave parametric transducer.	(*39*)
Zhongshan University, Guangzhou	Aluminum bar and low-frequency tuning fork at room temperature. Piezoelectric transducers with junction field-effect transistor amplifiers.	(*33, 34*)

In this model, the Fourier transform of the gravity wave force is given by

$$f_{gw}(\omega) = \int_{-\infty}^{+\infty} e^{-j\omega t} f_{gw}(t)dt = \frac{2}{\pi^2} ML\omega^2 h(\omega) \quad (5)$$

where M is the effective mass of the bar's lowest longitudinal mode, L is the bar's length, and $h(\omega)$ is the Fourier transform of the dimensionless strain of a favorably directed and polarized wave. The numerical factor takes into account the mode shape of the bar's elastic deformation. The spring constant k is fixed so that $(k/M)^{1/2}$ is equal to the bar's resonant frequency ω_0, and the dissipation D is fixed so that the model's quality factor $Q = \omega_0 M/D$ is equal to the bar's Q. For an impulse of short duration ($\tau << 1/\omega_0$), $f_{gw}(\omega)$ varies slowly near ω_0 and can be approximated by $f_{gw}(\omega_0)$. The spectral density, or mean square fluctuations per unit bandwidth, of the thermal force is given by the mechanical Nyquist formula

$$S_{f_{th}} = 2k_B TD \quad (6)$$

where k_B is Boltzmann's constant and T is the ambient temperature. This relation is an example of the fluctuation-dissipation theorem.

If, for the moment, we ignore the problem of amplifier noise, we can evaluate the limit that thermal noise sets on the system sensitivity. We assume that, because of the presence of other noise sources, the bandwidth is restricted to a region $\delta\omega$ about the resonant frequency ω_0. We can then compute a signal-to-noise ratio (SNR), which is defined as the square of the peak signal at the output divided by the mean square fluctuations. A standard result in signal detection theory (*8*) states that the SNR is optimized by a filter which has a transfer function proportional to the complex conjugate of the signal Fourier transform divided by the total noise spectral density. If such an optimal filter is applied, then the SNR is given by

$$\text{SNR} = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{|u(\omega)|^2}{S(\omega)} d\omega \quad (7)$$

where $S(\omega)$ is the spectral density of the total noise and $u(\omega)$ is the Fourier transform of the signal velocity. Both quantities are evaluated at the input terminals of the ideal mechanical amplifier. Given the sophistication of modern digital filtering hardware and software, it is safe to assume that a sufficient approximation to the optimal filter can always be applied, so that the SNR that is actually realized will equal the optimal SNR. The detector sensitivity can be expressed as the SNR for some standard pulse, but a more common figure of merit is the pulse detection noise temperature T_p, which specifies the energy that must be deposited by a brief pulse to achieve SNR = 1. If the force pulse is brief ($\tau << 1/\omega_0$), unipolar, and the antenna is initially at rest, then the deposited energy ϵ is related to $f_{gw}(\omega_0)$ by

$$\epsilon = \frac{|f_{gw}(\omega_0)|^2}{2M} \quad (8)$$

If for this value of $f_{gw}(\omega_0)$ we have SNR = 1, then $T_p \equiv \epsilon/k_B$. For the case that includes only the antenna thermal noise, we find the simple result

$$T_p = \frac{T}{Q} \frac{\omega_0}{\delta\omega} \quad (9)$$

Thus there is a relation between the bandwidth and the sensitivity limit due to thermal noise; for a given value of T/Q, the detector can be more sensitive if it has a large bandwidth. As noted earlier, the thermal noise spectral density appears at the input and is independent of frequency; it does not by itself limit the detection bandwidth. The electromechanical transducer and the electronic amplifier do impose a bandwidth limitation, however. For our analysis, these are lumped together and identified as a linear mechanical amplifier.

A general model of a linear mechanical amplifier consists of an ideal zero input-impedance amplifier with uncorrelated force and velocity noise generators, preceded by a noiseless mechanical impedance. In most cases this impedance disappears from the analysis because it can be included in the source network. The amplifier noise properties can be summarized by the noise temperature T_n and the noise resistance r_n, which are defined in terms of the amplifier noise generator spectral densities:

$$T_n \equiv \frac{(S_{f_{amp}} S_{u_{amp}})^{1/2}}{k_B}$$
$$r_n \equiv (S_{f_{amp}}/S_{u_{amp}})^{1/2} \quad (10)$$

For present detectors, these quantities are approximately frequency independent within the detection bandwidth. The noise tempera-

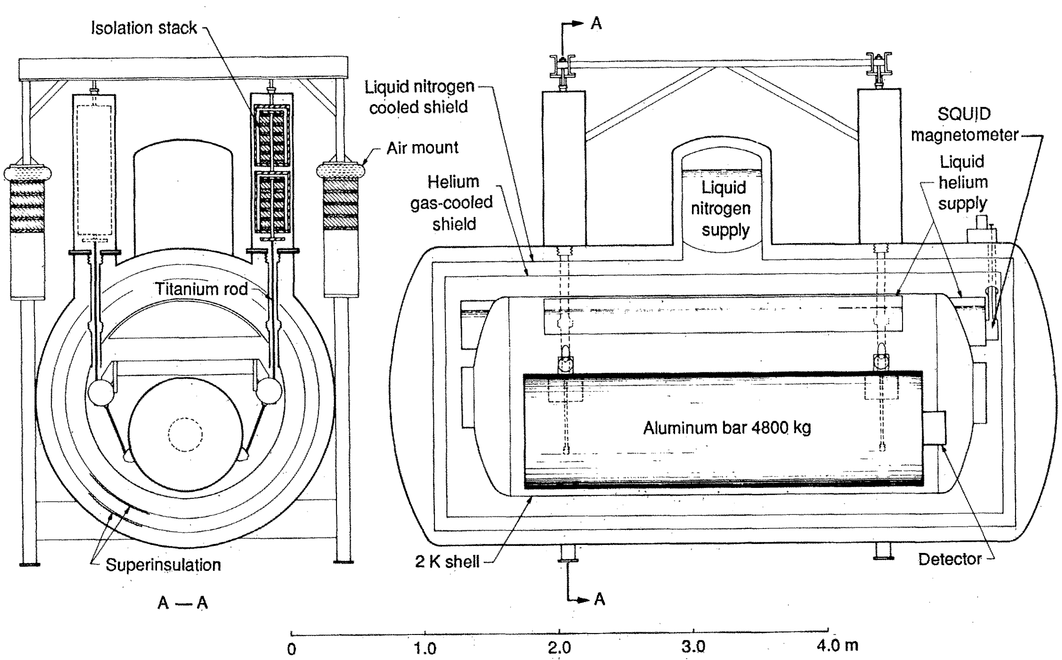


Fig. 2. Schematic diagram of the 4800-kg cryogenic detector at Stanford University.

ture gives a measure, independent of impedance matching, of an amplifier's sensitivity. The noise resistance is the optimal source impedance for the amplifier, which is the source impedance for which the force and velocity noise generators make equal contributions to the total noise. Because comparison of r_n with the antenna mass impedance $M\omega_0$ gives a measure of the intrinsic mismatch in the system, it is useful to define the dimensionless noise resistance

$$R_n \equiv \frac{r_n}{\omega_0 M} \tag{11}$$

To give some examples, for the Stanford University detector, and approximately also for the University of Maryland and Louisiana State University detectors, $T_n \approx 10$ mK and $R_n \approx 10^{-5}$. The University of Rome detector has $T_n \approx 3$ mK but $R_n \approx 10^{-7}$.

The parameters T_n and r_n summarize the behavior of the electromechanical transducer and the electronic amplifier and a large fraction of the technological complexity of a resonant-mass gravity wave detector results from optimizing these quantities. If the antenna thermal noise is negligible (Q is very large), then it can be shown from the SNR integral (Eq. 7) that the pulse detection noise temperature T_p becomes equal to the amplifier noise temperature T_n. This amplifier limit cannot be improved upon. For a mechanical amplifier connected directly to a high-Q antenna, the detector bandwidth is given by

$$\delta\omega = \omega_0 R_n \tag{12}$$

which when used in Eq. 9 implies that the Q must satisfy

$$Q >> \frac{T}{T_n}\frac{1}{R_n} \tag{13}$$

for the amplifier limit to be achieved.

Because R_n is always small, this Q requirement can be very stringent. For example, $R_n = 10^{-5}$, $T = 4.2$ K, and $T_n = 10$ mK would require $Q > 4 \times 10^7$. The very high Q is required because of the limited detection bandwidth. A means of very substantially increasing the detection bandwidth was identified by Paik (*9*), who introduced a mechanical resonator as a matching device. The resonator with mass $m << M$ is tuned to the antenna frequency and attached to the end of the antenna, as shown in Fig. 4. The lowest longitudinal normal mode of the bar is now split into two normal modes separated by $\omega_0 (m/M)^{1/2}$. Richard (*10*) has pointed out that additional stages of resonant coupling can be used to further improve the matching, and Blair *et al.* (*11*) have proposed the use of a tapered mechanical transmission line as the limit of this family of devices. A full analysis of multimode systems can be made by adding elements to the one-mode model of Fig. 3. An important result is that for a given value of R_n and a given number of modes, there is an optimum mass for each resonator that makes the system most tolerant to mechanical losses.

In principle, if many modes are used, the deleterious effects of small values of R_n can be completely eliminated. The fractional bandwidth $\delta\omega/\omega_0$ can approach unity, and the requirement on the antenna Q (and the Q's of the matching resonators) becomes relatively mild:

$$Q >> \frac{T}{T_n} \tag{14}$$

In practice, sufficient matching has been obtained with a small number of modes. The Stanford detector, with a mechanical Q of about 4×10^6 and a detection bandwidth of 10 Hz, is mechanical amplifier–limited with only two modes. Most other detectors are either two- or three-mode designs.

For some mechanical amplifiers with small values of r_n design constraints make it impossible to achieve the optimal mass for the final resonator. This is the case for the electrostatic transducer used by the University of Rome group (*12*). Such transducers are useful, but they impose a requirement for a higher antenna Q than would otherwise be needed. Although the Rome group's antenna has a Q of 5×10^6, the system is not mechanical amplifier–limited since $T_p = 10$ mK, which is greater than T_n.

The notion of an amplifier limit on the pulse detection noise temperature is very important and much more general than may be evident from the discussion so far. The noise temperature of the mechanical amplifier T_n is itself limited by the noise temperature T_n' of the electronic amplifier that follows the electromechanical transducer. This is given in terms of the spectral densities of the current and voltage noise generators of the electronic amplifier by

$$T_n' = \frac{(S_v S_i)^{1/2}}{k_B} \tag{15}$$

where S_v and S_i are the amplifier voltage and current noise spectral densities, respectively. As first discussed by Giffard (*13*) in the context of gravity wave detectors, any linear amplifier is limited by the quantum mechanical uncertainty principle to a noise temperature greater than $\approx \hbar\omega_0/k_B$, leading to a fundamental sensitivity limit on resonant-mass gravity wave antennas given by $T_P > \hbar\omega_0$, which is equal to 40 nK at 850 Hz. There is now an extensive literature on ways in which this limit might be circumvented (*3*), but just how far these considerations are from current practice can be appreciated by considering the hierarchy of limits

$$T_P > T_n > T_n' > \hbar\omega_0 \tag{16}$$

T_n' for the lowest noise kilohertz-band electrical amplifiers [dc superconducting quantum interference devices (SQUIDs) (*14*)] is about 1000 times $\hbar\omega$ for frequencies around 1 kHz, while T_n for the best mechanical amplifiers is about 10 mK or 200,000 times $\hbar\omega$. Much progress must be made in improving electromechanical transducers before the quantum limit must be faced.

The Vibration Isolation Problem

Brownian motion noise and amplifier noise are unavoidable. There are a number of other noise sources that are also important to the designer but are, in principle, completely avoidable. Efforts to control two of these have been nearly as extensive as the effort to control Brownian motion noise and amplifier noise. These noise sources are (i) vibrational noise coupled from the exterior of the detector and (ii) acoustic emission occurring within the detector assembly. In a sense these two sources are the linear and the nonlinear parts of the vibration isolation problem, respectively.

The current generation of cryogenic detectors demonstrate root-

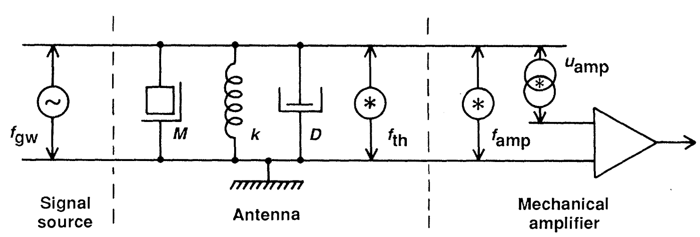
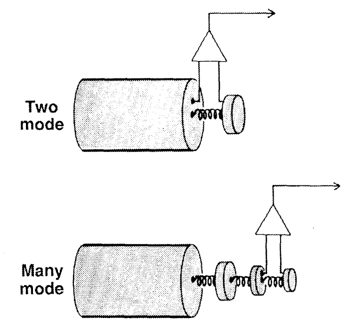


Fig. 3. Lumped element model of a resonant-mass gravitational radiation detector. The continuous system is reduced to a noise model with only a few degrees of freedom. M is the mode effective mass, f_{gw} is the gravity wave force, k is the spring constant, D is the dissipation, and f_{th} is the stochastic thermal noise force. The mechanical amplifier contains a force noise f_{amp}, a velocity noise u_{amp}, and an ideal noiseless mechanical amplifier with mechanical input terminals and electrical output terminals.

Fig. 4. Mechanically resonant matching between the antenna and a mechanical amplifier. Two-mode detectors using superconducting inductive transducers have been operated at Stanford University and Louisiana State University. A similar system with an electrostatic transducer has been developed at the University of Rome. A three-mode detector is being developed at the University of Maryland.



mean-square displacement noise levels of approximately 10^{-18} m, roughly 1/1000 of the diameter of a typical nucleus. For comparison, the recent revolutionary development of scanning tunneling microscopes (*15*) was made possible, in part, by the development of vibration isolation techniques that resulted in vibration levels on the order of 10^{-10} m—approximately the diameter of an entire atom.

A comparison of the mechanical Nyquist force that drives the antenna mode with an estimate of the acceleration level at the exterior of the apparatus establishes a minimum mechanical force isolation requirement of 10^{-10}. This goal is accessible because the isolation is required only in a limited frequency range. For the Stanford gravity wave detector the isolation system performance exceeds 10^{-15} in a frequency band approximately 200 Hz wide centered at 850 Hz.

Gravity wave detector isolation systems consist of a cascade of N mechanical low-pass filters. At a frequency well above the characteristic cutoff frequency of each filter ω_c, the attenuation is proportional to $(\omega/\omega_c)^{2N}$. The simplest implementation of such a composite filter is a stack of steel plates with rubber spacers between the plates. The spacers provide a spring constant, and the steel plates act as lumped masses. Together, a plate and its adjacent spacer have a resonant frequency which determines the value of ω_c. For longitudinal vibration, the entire structure contains N modes confined to a frequency range below $2\omega_c$. In addition to these longitudinal modes, such a structure has other modes associated with the other five degrees of freedom. These modes appear as, for instance, twisting or bending motion of the entire structure. In order for the isolator to function properly, all of these modes must be confined to the same frequency range as the longitudinal modes.

It is a common misconception that vibration isolation somehow requires damping in order to dissipate the vibrations. These structures do not dissipate the vibrational energy, they simply do not convey it to the supported components. Another misconception holds that a good isolator is necessarily massive when, in fact, the resonant frequencies are more important than the masses of the components.

In practice, these multipole low-pass filters typically display some upper cutoff frequency above which the isolation is not particularly strong. This is because the components possess internal resonant modes. For instance, the steel plates in the Stanford detector have bending resonances near 2 kHz. As a result the isolation falls off at frequencies above about 1 kHz.

The isolation provided by the mechanical filters is intended to be linear. Unfortunately, linearity is not usually obtained to the desired degree. The most important result of this defect is that low-frequency input signals can be converted to high-frequency responses. It has not been possible to accurately catalog all of the circumstances that lead to this result but a few of them have been guessed at. Perhaps the most obvious case is creaking. If the upper portion of the suspension system is driven at some frequency that is below the cutoff frequency of the isolation, the entire antenna will undergo substantial displacement. If there are cracks in the joints where the attachments to the antenna are made, they can creak because of this excitation and the result is that the incoming low-frequency force is converted to a broadband high-frequency response. Cracks can serve as stress concentration points for any fluctuations in the forces that support the antenna. The concentration of the stress results in localized hysteretic deformation of the material, which, in turn, results in the dissipation of broadband acoustic energy. This process of acoustic emission in highly stressed materials has been widely studied by the mechanical engineering community (*16*). The significance of these studies to gravity wave detector design is that all components should be kept as far from their elastic yield points as possible—an objective that is fully at odds with the desire to keep the elastic components of the isolation system as compact as possible and is somewhat at odds with the desire to establish large mating forces between components in order to minimize the potential for creaking.

One obvious strategy for controlling these problems is to provide some isolation down to the lowest possible frequency, far below the antenna resonance itself. This is usually accomplished by including an air cushion suspension similar to those used for optical tables. Another approach is to design the details of the support attachment such that creaking is minimized. The Stanford detector utilizes welded aluminum support fixtures with some success, but it has not been verified whether this approach is more successful than other configurations in use elsewhere.

There are a number of other noise sources that have not so far proven to be important to the problem of gravity wave detection. As the detector sensitivities are improved, some of these may become significant. For example, it is expected that after another two orders of magnitude improvement in energy sensitivity it will be necessary to monitor cosmic-ray activity at the detector site and veto any detector responses that are coincident with energetic showers.

Future Developments: Can the Quantum Limit Be Reached?

It follows from the complexity of the components of the noise model that there can be a variety of strategies for improving detector sensitivity. For example, in detectors using mechanical amplifiers with small values of r_n, extremely high values of antenna Q are necessary, whereas for larger values of r_n more moderate values of antenna Q are satisfactory. As a means of gauging progress and comparing the status of rather disparate approaches, it has become common to express detector performance in relation to the quantum limit. Note that two quantum-limited detectors will have the same sensitivity to gravity waves only if they have the same geometry and mass. Nevertheless, the quantum limit is an important target in gravity wave detector development.

The uncertainties in attaining this goal arise more from mundane technological issues than from the quantum limit itself. As one example of a system that nearly reaches the quantum limit, consider a detector that includes a magnetically coupled transducer followed by a dc SQUID. The system must satisfy the following criteria: First, the SQUID itself must be quantum limited. So far, SQUIDs have performed within a factor of 10 of the quantum limit, but only under specialized conditions (*17*). For strongly coupled SQUIDs operating near 1 kHz there is a remaining factor of 1000 (*18*). Second, a quantum-limited transducer operated at 4 K would require an input circuit electrical Q of 10^8, which would be an improvement by a factor of 4000 beyond present performance. If the antenna and transducer are operated at 100 mK, the electrical Q requirement relaxes to 2.5×10^6. This electrical Q has been demonstrated in a prototype transducer. Third, Eq. 9 shows that for an antenna operating at 100 mK with a Q of 5×10^7, a bandwidth of slightly more than 40 Hz will be needed. A three-mode detector with an intermediate mass of 6 kg and a transducer mass of 15 g can provide this bandwidth. None of these requirements is prohibitive, but the operation of a system that satisfies all of them presents a substantial challenge. In fact, the operation of a single quantum-limited system is not enough; two or more are needed in order to provide coincident observation of events.

Future Developments: Vibration Isolation

For detectors functioning near 1 kHz, a straightforward extension of the present vibration isolation technology should prove adequate even for detectors approaching the quantum limit. However, there is considerable interest in extending the search for gravitational radiation with Earth-based detectors to frequencies as low as 10 Hz (*19*), but present state-of-the-art vibration isolation techniques are inadequate at these frequencies.

The key obstacle to improving low-frequency isolation is the difficulty of developing suitably soft springs to provide the required low-frequency isolation. For a given antenna weight, the gravitational energy stored in a suspension spring is inversely proportional to the stiffness of the spring. Since the maximum permissible energy storage density is limited by materials properties, the spring size tends to become prohibitively large as the resonant frequency is reduced. Also, proper control of the resonant frequencies of modes internal to the support springs is important because these modes will tend to defeat the isolation provided by the spring. Selection of materials with a high sound speed will help keep these resonances at high frequencies. In this respect it would be ideal to support the antenna on a magnetic field, which would result in a suspension with internal resonances in the gigahertz range. In fact, superconducting magnetic levitation has been used by several of the gravity wave research groups in prototypes, but it has been eliminated from the current designs because, for systems operating near 1 kHz, magnetic levitation has been proven to be unnecessary. However, for systems operating at much lower frequencies, a hybrid design incorporating magnetic levitation with other isolation components may yet prove attractive.

Isolation systems incorporating active feedback are expected to play an important role in low-frequency detectors. Because a high degree of isolation is required for all six mechanical degrees of freedom, an active feedback isolation system is potentially very complex (*20*). The optimal design of such a system presents an interesting interdisciplinary engineering challenge.

Future Developments: Brownian Noise Reduction

Recent improvements in the sensitivities of gravity wave detectors have resulted both from improvements in the amplifier-transducer systems and from improvements in the factors T and Q. The present generation of detectors operate at 4 K, a factor of 75 lower than the original room-temperature detectors. So far, the highest mechanical Q achieved in a functioning detector is 5×10^6, obtained by the University of Rome group (*12*). This is a factor of 25 better than first-generation detectors. In the near future, antennas constructed from the aluminum alloy 5056 are expected to provide Q's near 5×10^7. This estimate allows for an appreciable Q degradation resulting from the antenna suspension and the transducer mounting. Quality factors as high as 2×10^8 have been measured in small samples of this alloy (*21*). A niobium antenna at the University of Western Australia has a Q of 2×10^8 (*22*).

Within the next few years at least four groups (Maryland, Rome, Louisiana State University, and Stanford) intend to operate detectors at a temperature near 50 mK, an additional factor of 80 lower than present detectors. This will be accomplished with relatively conventional dilution refrigerator technology. Commercially available dilution refrigerators are capable of providing sufficient cooling capacity at temperatures as low as 15 mK. The principal refrigeration design problem is to establish adequate thermal contact with the antenna without introducing additional vibration noise from the refrigerator.

Future Developments: Amplifier-Transducer Noise Reduction

Several groups will be relying on dc SQUID amplifiers for the foreseeable future. A dc SQUID connected to a matched lossy inductor has a usable noise temperature limited, in part, by the Nyquist noise in the inductor. The noise temperature of the combined SQUID and inductor will be

$$T_{\text{combined}} > 2^{3/2} \left(\frac{T\omega S_{\text{E}}}{Q_{\text{elec}} k_{\text{B}}} \right)^{1/2} \tag{17}$$

where S_{E} is the SQUID energy sensitivity (half the current noise spectral density times the input inductance) and Q_{elec} is the electrical Q of the magnetic pickup coil. The transducer and SQUID used most recently at Stanford have $Q_{\text{elec}} = 2.5 \times 10^4$ and $S_{\text{E}} = 1 \times 10^{-29}$ J/Hz, yielding a combined noise temperature of 3 mK (*23*). There are prospects for improving this situation. For example, the SQUID presently in use is a commercial unit with an energy sensitivity that is inferior to the microwave SQUID previously used at Stanford by a factor of 15. The combined noise temperature could be improved by the square root of this ratio. Prototype transducers have been built with electrical Q's as high as several million but there is, as yet, no reliable method for obtaining Q's this high. To obtain better repeatability in transducer electrical Q, the Stanford group is developing a technology that uses integrated circuit fabrication techniques to make thin-film niobium circuits for a transducer fabricated from high mechanical–Q silicon.

The group at Louisiana State University is exploring the applicability of recent advances in bulk niobium processing technology. This work originated at CERN as part of an effort to develop improved radio-frequency superconducting accelerator cavities. Techniques have been developed that produce samples of niobium with markedly improved electrical resistivity ratios. Such samples may also have significantly reduced audio frequency electrical losses.

Until substantial improvement in electrical Q is obtained, the Stanford, Louisiana State, and Maryland detectors will be limited primarily by the electrical Q. The Stanford detector, for example, has demonstrated an overall system noise temperature approaching the limit set by the SQUID-inductor combined noise temperature. Thus, increases in the mechanical coupling coefficient and antenna Q will not be particularly useful until the SQUID performance and pickup inductor Q are improved.

On the other hand, the University of Rome detector at CERN is in a somewhat different regime. This group's transducer consists of a mechanically resonant capacitor in the form of flat plates, 17 cm in diameter with a 45-μm gap. The capacitor is biased to a 500-V potential and the ac signal resulting from displacement is coupled through a 1250 to 1 turns-ratio transformer to a dc SQUID. Considerable effort has already been expended to obtain the smallest possible gap with the highest possible field strength, so a substantial increase in r_n should not be expected. As mentioned earlier, it appears doubtful that an optimal mechanical matching network can be devised that would be compatible with the constraints of this device. Because they have not reached the limit of the noise temperature of their mechanical amplifier, improvement in antenna Q and reduction of the temperature would be useful. The noise temperature of their mechanical amplifier can be improved by increasing the electrical Q of the transformer, decreasing the transformer temperature, or improving the SQUID. The Rome group is utilizing a SQUID with an energy sensitivity of 7×10^{-31} J/Hz, equal to the best of SQUIDs so far used for gravity wave detectors, but still three orders of magnitude from the quantum limit (*18*). Any combination of these measures would require a commensurate improvement in Q/T for the antenna.

The role of transducer electrical Q can be substantially diminished by operating the transducer as a parametric amplifier. If a capacitive transducer is operated with a high-frequency bias voltage, the electrical Q requirement decreases in proportion to the ratio of the bias frequency to the signal frequency. The most prominent remaining problem is that the bias signal must be spectrally pure (*24*). Several groups (Tokyo, Western Australia, and Louisiana State) are developing parametric transducers. The most successful parametric transducer so far, developed at the University of Tokyo, has a transducer noise temperature of 20 mK (*25*). Several of the parametric transducer designs currently being studied provide the advantage that the transducer does not contact the antenna itself, thereby minimizing the antenna-Q degradation. Such transducers typically offer extremely small values of R_n, so an extremely high antenna Q appears to be a necessity for such systems.

Conclusions

Gravitational wave astronomy is not yet a reality (*26*). However, in the next decade we can look forward to the operation of resonant-mass detectors with energy sensitivities about five orders of magnitude beyond that of present detectors. Although there are no guarantees, this effort and the parallel effort of developing long baseline laser interferometers hold the promise of opening a whole new window on the universe that is largely inaccessible by conventional astronomy. For example, binary neutron stars or black holes, otherwise undetectable, will be detectable to a distance of at least a few hundred megaparsecs when they coalesce and emit energetic bursts of gravitational radiation. Very little is known about the number of such sources. It is possible that a significant component of the missing mass of galaxies is in the form of these gravitationally collapsed objects (*27*). If so, we can expect to see frequent bursts of gravitational radiation from coalescence events. At a sufficient sensitivity level, the nondetection of such events would be significant.

Stochastic gravitational radiation (*28*) produced by various processes occurring in the early universe may be accessible to direct detection by low-frequency ($f < 100$ Hz) detectors. The successful operation of these detectors will depend crucially on the development of low-frequency vibration isolation methods.

Gravitational radiation may also be a powerful probe of processes occurring in sources that are accessible by conventional astronomy. For example, a weakly magnetized neutron star in a binary system with a low-mass companion star may be spun up by accretion to a period near 1 msec. In this region the neutron star is unstable to nonaxisymmetric modes that grow by gravitational radiation reaction (*29*). The viscosity of the stars damps these modes and determines which mode will dominate. A steady state will be reached in which most of the angular momentum transferred to the star by accretion is radiated away in coherent gravitational waves (*30*). Without a priori knowledge of the frequency of this radiation, its detection would at best be difficult. However, we can expect the x-ray emission from the system, generated by the accretion process, to be weakly modulated at the same frequency as the gravity wave signal. Such an x-ray–gravity-wave pulsar could be detected first in a detailed fast x-ray pulsar search. The X-ray Large Array (XLA), a new concept for a space station–based 100-m^2 x-ray detector proposed by the Naval Research Laboratory, Stanford University, and the University of Washington (*31*), offers the best prospect for detecting this phenomenon.

The technological effort required to develop resonant-mass gravity wave detectors has led to a number of spin-offs. These include high phase-stability superconducting cavity microwave sources (*24*), gravity gradiometers (*32*) that will be useful in fundamental physics as well as geophysics and satellite navigation, and vibration isolation techniques that yield isolation values in excess of 10^{-10}. The gravity wave detection effort will continue to be a stimulus for the development of low-noise SQUIDs and the investigation of quantum nondemolition measurement techniques. These spin-offs will certainly lead to new breakthroughs in the science of precision measurements.

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Cellular Mechanisms of Epilepsy: A Status Report

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The cellular phenomena underlying focal epilepsy are currently understood in the context of contemporary concepts of cellular and synaptic function. Interictal discharges appear to be due to a combination of synaptic events and intrinsic currents, the exact proportion of which in any given neuron may vary according to the anatomic and functional substrate involved in the epileptic discharge and the epileptogenic agent used in a given model. The transition to seizure appears to be due to simultaneous increments in excitatory influences and decrements in inhibitory processes—both related to frequency-dependent neuronal events. A variety of specific hypotheses have been proposed to account for the increased excitability that occurs during epileptiform activity. Although each of the proposed mechanisms is likely to contribute significantly to the epileptic process, no single hypothesis provides an exclusive unifying framework within which all kinds of focal epilepsy can be understood. The spread of epileptic activity throughout the brain, the development of primary generalized epilepsy, the existence of "gating" mechanisms in specific anatomic locations, and the extrapolation of hypotheses derived from simple models of focal epilepsy to explain more complex forms of human epilepsy, all are not yet fully understood.

THE EPILEPSIES ARE A FAMILY OF NEUROLOGICAL DISORders that have in common a transient, recurrent, self-sustained interruption of normal brain functions and a simultaneous hypersynchronous activation of a large population of neurons in one focal area or generally throughout the brain. Attempts to understand epilepsy have always been based on prevailing concepts of central nervous system (CNS) physiology, and over many years, advances in understanding CNS function have provided progressively more sophisticated hypotheses to explain epileptic activity. In this article we examine the hypotheses that have been proposed and discuss the data supporting them, distinguishing evidence derived from studies of epileptic models from arguments based on extrapolations from normal cellular physiology. This article also indicates areas in which important information is still lacking and attempts to relate current hypotheses about cellular mechanisms of focal epilepsy to the larger context of a network analysis of epilepsy in other kinds of models and, where possible, the phenomenology of human epilepsy.

One of the most influential early conceptual models of epileptic mechanisms, based on clinical and electroencephalographic (EEG) observations, postulated that epilepsy existed in two broad forms—focal or partial epilepsy due to a discrete cortical abnormality and generalized or centrencephalic epilepsy due to an abnormality in deep subcortical gray matter. It was suggested that the paroxysmal activity of the latter type invaded the forebrain through neuronal structures with diffuse projections (*1*). This model implied (i) that the generalization of a seizure initiated at a cortical focus would occur when the cortical paroxysmal activity spread to these deep structures and (ii) that the primary generalized form of epilepsy was also the expression of a "focal" activity localized in deep structures. Many different kinds of experimental models that reproduced the two hallmarks of these forms of human epilepsy, clinical convulsions and EEG "spikes," were used to study the roles of different brain structures and anatomic pathways in the development and spread of epileptiform activity.

Modern research into the cellular mechanisms of epilepsy began 30 years ago when extracellular and intracellular recordings from the vertebrate CNS became possible and, more importantly, the mechanisms underlying neuronal excitability and synaptic functions began to be unraveled (*2*). Research was concentrated on models of cortical focal epilepsy, both acute and chronic, as these provided scientists with a clear target for their microelectrodes and anatomic probes, and these models appeared to represent several components of the human condition. The goals were to understand the altered physiology of individual neurons or synaptic function that underlies the regional epileptiform activity, with the hope of developing pharmacological tools that could be used to suppress the abnormal activity. By 1970, the phenomena that occur in neurons within these experimental foci during cortical interictal discharges and seizures

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