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Progress in the Development of High Sensitivity Gravitational Radiation Antennas

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Abstract

This paper reviews the development of gravitational radiation antennas from the pioneering work of J. Weber during the 1960s to the present day. Major problems still to be overcome are outlined, and prospects for the detection of gravitational radiation from astrophysical sources are discussed. Major emphasis is placed on Weber bar antennas, with spacecraft Doppler ranging and laser interferometer antennas discussed briefly. (As this review is intended primarily for non-specialists, no attempt is made to cite all workers in the field.)

1. Introduction

Gravitational radiation (GR), predicted by Einstein (1916) in his paper 'Näherugsweise Integration der Feldgleichungen der Gravitation', was until the 1960s largely dismissed by experimentalists due to the extremely low energy emitted by known possible sources, whether astronomical or in the laboratory. To illustrate this, consider as a laboratory source a massive bar rotated about an axis perpendicular to its length. This would be one of the most efficient sources one could construct; it would produce GR at twice the frequency of rotation. However, a classical analysis shows that such a bar would emit *less than one quanta* of GR (i.e. less than 1 graviton) per cycle unless its mass exceeded several tonnes (Murphy 1978). The constraints of normal atomic matter limit the maximum mass of such an antenna to ~ 100 tonnes at a frequency ~ 100 Hz, so that one could not expect a laboratory source to produce more than 25 gravitons per cycle, or $\sim 10^3$ gravitons s^{-1} at 100 Hz. If GR was the only means of energy loss from the bar, its relaxation time would be 10^{40} s, that is, 10^{22} times the age of the universe!

One can define an effective absorption cross section for a GR antenna. For all presently conceived antennas this is a pitifully small quantity, $\lesssim 10^{-20}$. From this figure and our 10^3 gravitons s^{-1} emitted, it follows that in a laboratory experiment one quantum of GR would couple into the detector every 10^{10} yr. The 'average' power absorbed by the detector would be 10^{-48} W.

Einstein's geometrodynamics interprets gravitation as the curvature of space–time: however, the 'stiffness' of space–time is so great that the normal objects of classical astronomy cause near negligible perturbations to a flat space background. GR is a wave in the space–time curvature which travels, according to Einstein's theory, at the speed of light. Objects which themselves cause negligible curvature will be very weak sources of GR. Thus it follows that not only is a laboratory emission and detection experiment quite impossible, but also almost all classical astronomical sources are too weak to be directly detected. Only when it was discovered that gravitationally collapsed objects exist in Nature—neutron stars and black holes—was it clear that regions of high curvature do exist in the universe.

In contrast to laboratory sources, events where a time varying quadrupole moment is associated with gravitationally collapsed objects can be significant sources of GR. In particular, supernovae or other events leading to the birth of a neutron star or black hole may produce single intense millisecond pulses of GR. A few per cent of the rest mass energy of a star may convert to GR in a time of the order of 10^{-2} s. The flux density at the Earth could correspond to between about 10^{31} gravitons cm^{-2} (an optimistic estimate for sources in the Milky Way) and 10^{24} gravitons cm^{-2} (lower conversion efficiency for sources in the Virgo Cluster or the M 101 group galaxies) in the frequency range 10^2–10^4 Hz (see e.g. Smarr 1979). However, the effective cross section of a Weber bar antenna reduces the equivalent number of phonons induced in the antenna to the range 10^7–10^{-3}. In the optimistic instance of 10^7 phonons the detection can still be considered classically; an energy of 10^{-23} J is deposited in the antenna and the amplitude of oscillation is $\sim 10^{-17}$ m. It is, however, obviously absurd to speak of 10^{-3} phonons. This figure simply demonstrates (1) that the problem is now quantum mechanical and (2) that experimentalists must at least aim towards detecting $\sim 10^{-30}$ J corresponding to an equivalent energy absorption of a few phonons. In fact, methods known as quantum nondemolition are being studied which, through careful choice of the quantum mechanical observable, have the possibility of measuring the 'sub-quanta' events (Thorne *et al.* 1978).

It is notable that Weber began experimenting before the discovery of the first neutron star and the first possible black hole (Cygnus X-1). Without the strong theoretical support that one generally expects, he pioneered the principle of the resonant antennas now know as Weber bars. He set up massive aluminium bar antennas at Chicago and Maryland with the aim of detecting coincident excitation by incoming radiation. Although his reported results were never confirmed (Weber 1969), they served to stimulate the interest of the scientific community, and led to proposals for greatly improved antennas of various types. The first proposal was to develop Weber bar antennas of improved sensitivity by using cryogenic techniques (Boughn *et al.* 1974). Secondly, it was shown that high sensitivity could be achieved in principle by means of a laser interferometer between widely spaced masses (Weiss 1972). Thirdly, it has been shown more recently that Doppler tracking of interplanetary spacecraft can also in principle reach theoretically interesting levels of sensitivity (Estabrook and Wahlquist 1975).

2. Sources of Gravitational Radiation

(*a*) *Problem of efficiency and event frequency*

Hawking (1972) has shown that in a gravitational event up to 65% of the rest mass energy of a system can be converted into GR. However, efficient conversion to GR occurs only for events associated with collapsed objects: thus, much theoretical effort has gone into analysing events such as supernovae, neutron star–neutron star coalescence, neutron star–black hole and black hole–black hole collisions, and neutron star core quakes. Only in the last few years have computer codes enabled calculation of reasonably realistic events, but results are still limited by lack of knowledge of the systems of interest.

Of equal importance to calculating the efficiency for conversion to GR is an estimate of the event frequency and the expected flux at the Earth. There is still great uncertainty in these figures since they are related to a class of objects for which data are extremely sparse. In particular, we have very little evidence on the number of dead neutron stars and black holes which may be present in our Galaxy, since the only ones we observe are those that are interacting with other nearby matter, such as pulsars and X-ray bursters. Estimates of the galactic density of objects such as neutron star–neutron star binaries and black hole–neutron star binaries rely on evolutionary models for observed stellar populations and models for supernovae and stellar collapse (see Smarr 1979 for many examples). The known collapsed objects, i.e. pulsars, X-ray bursters and other X-ray sources, merely allow us to set lower limits for the population and frequency of gravitational collapse. It is fair to assume that Nature will always continue to surprise us, and that when we do look, we will find more and different objects beyond our expectations.

It is convenient to partition the spectrum of possible GR sources between low and high frequencies, with the dividing line at about 100 Hz. To a large extent this distinguishes between sources of the order of one solar mass, which produce frequencies between 10^2 and 10^4 Hz and sources between 10^3 and 10^8 $M_{\odot}$, which may give rise to GR in the range 10^{-4}–10^2 Hz. This division also distinguishes between the present sensitivity ranges of current experiments, with Weber bars and laser experiments sensitive to high frequencies, and the Doppler spacecraft tracking experiment sensitive to frequencies of ~ 1–10^{-4} Hz.

(*b*) *Low frequency sources*

Most theoretical estimates for the GR spectrum are summarized in Fig. 1. If space was filled by a continuous background flux of GR sufficient to close the universe, the dimensionless amplitude h would be between 10^{-12} and 10^{-16} in the frequency range 10^{-4}–10^4 Hz (Zimmerman 1979). It is perhaps surprising that a GR energy density more than an order of magnitude greater than the presently estimated matter density of the universe would only have become detectable by experiment in the last few years. The fact that it has not been detected, already sets upper limits on the GR background.

There is observational evidence that many galaxies (Young *et al.* 1978), including our own (Lacy *et al.* 1979), and globular clusters may contain a central massive gravitationally collapsed object, presumably a black hole. Furthermore, it is thought likely that the power source for quasars, lacertids and Seyfert galaxies may be a central black hole accreting matter. Estimates for the masses of these objects vary from 10^3–10^{10} $M_{\odot}$. During black hole formation or when pairs coalesce, intense bursts of GR would occur, allowing us to at least consider detection for events occurring up to the redshift distance $Z = 2{\cdot}5$. The possible magnitudes of GR bursts are shown in Fig. 1 (Thorne and Braginsky 1976), varying according to the efficiency of conversion.

Fig. 1 also shows GR from one conventional astronomical source. This is the W Ursa Majoris class of short period binary stars in our Galaxy, which although too weak individually, as a galactic population will give rise to a continuous, stochastic amplitude as shown in Fig. 1 (Mironovskii 1966). As these are a well established galactic population, they must be the most certain of all the possible sources

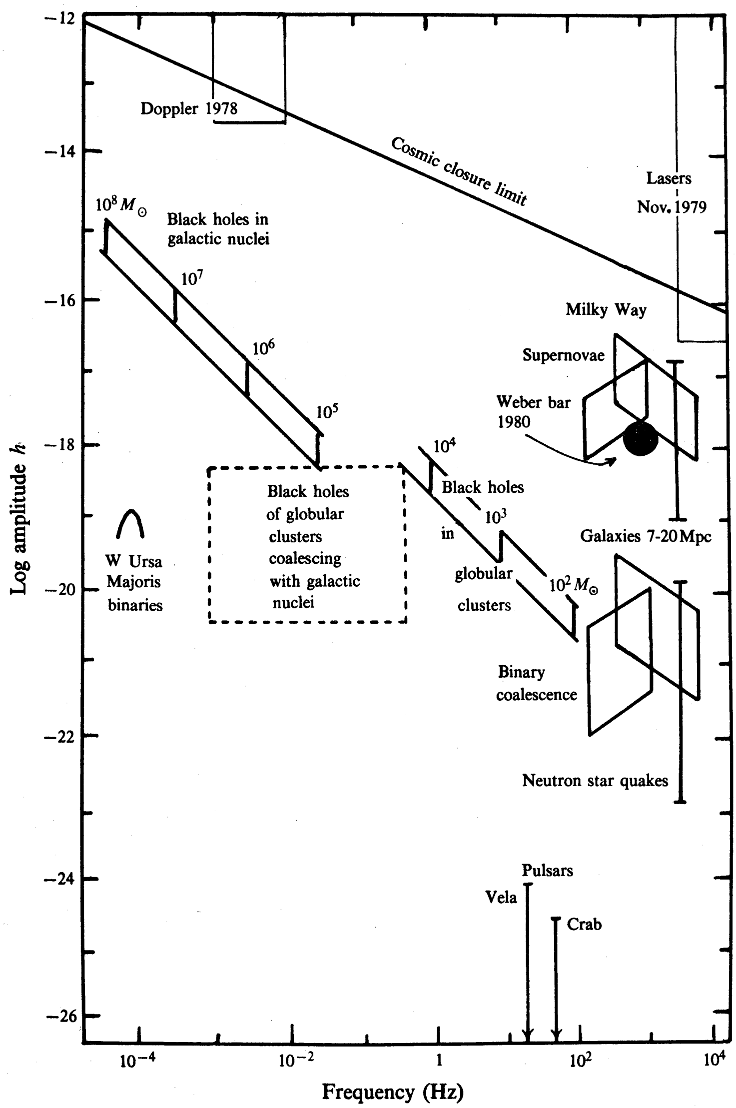

Fig. 1. Dimensionless amplitude h of GR at the solar system from possible astrophysical sources. The error boxes correspond to the range of efficiencies for GR conversion, the range of uncertainty about the sources and the distance ranges over which most events occur. Experimental sensitivities, marked Doppler, Laser and Weber bar, are the levels of sensitivities so far achieved. For the Laser and Weber bar data these do not represent upper limits on GR amplitudes as long runs have not taken place at this sensitivity.

of GR, although perhaps the least interesting as they are unlikely to give new astrophysical information.

Another possible class of intense GR bursts is shown by the dashed square in Fig. 1. This is the possible range of amplitudes expected at the solar system if the black hole cores of globular clusters spiral into the black holes of galactic nuclei (Blandford 1978). For the possible event frequency to be interesting ($\gtrsim 1\ \mathrm{yr}^{-1}$) the vast proportion of events will occur near the Hubble distance. The rate of low frequency events from supermassive black holes is highly uncertain. It could be as high as one detectable pulse per year, but could be zero if either the black hole models are false, or if the growth of black holes in galaxies occurs by small 'sips' instead of the occasional 'swallowing' of massive objects.

(c) *High frequency sources*

High frequency sources of GR are associated with collapsed objects of the order of a solar mass. As mentioned above supernovae are the most likely sources of detectable GR: the details however are complex as many factors must be considered in calculating the conversion efficiency (see e.g. Arnett 1979). The gravitational collapse may lead to the formation of a neutron star or a black hole. In the case of the neutron star, bounce of the core after the initial collapse may lead to more radiation than the collapse itself. In the black hole case there can be no bounce radiation, and some of the collapse radiation is red shifted, but the increased curvature associated with the black hole leads to a stronger initial radiation pulse. The efficiency of conversion is strongly dependent on the initial angular momentum of the star and the stellar magnetic field, which largely determine the degree of symmetry and quadrupole moment of the collapsing core. Other factors which determine the conversion efficiency are the energy loss to neutrinos and the GR pulse due to the time varying quadrupole moment of the expanding neutrino pulse (Kazanas and Schramm 1979; Shapiro 1979). In the first instance neutrinos act to dampen the collapse, reducing the GR conversion efficiency, and in the second they actually act as a source of GR.

Estimates for total GR efficiency for supernovae vary between 10^{-1}–10^{-5} depending on the initial conditions assumed. Without far more complete knowledge of stellar evolution enabling us to determine the distribution of initial conditions for supernovae, it is very difficult to estimate the true GR efficiency distribution of supernovae.

Binary systems consisting of two collapsed objects will emit GR, and slowly spiral together. If the system forms with an orbital decay time due to GR of less than 10^9–10^{10} yr (for solar mass objects the binary period should be less than ~ 1 day), then in a galactic population of 10^9 such objects one would expect that about 1 per year would coalesce. (There is no evidence that such a population exists however.) During most of its lifetime the binary would be a weak source of periodic GR, gradually increasing in frequency. In its last milliseconds the frequency would rise rapidly to give a peak luminosity at ~ 700 Hz. Clarke (1979) has shown that $\sim 2\%$ of the rest mass energy of the binary can be radiated as GR in this manner.

The question of detectability of high frequency GR sources depends most strongly on the possible event frequency. We know that one compact binary exists (the binary pulsar PSR 1913+16) and we know that supernovae at least sometimes lead to the formation of neutron stars (e.g. the Crab pulsar). Present detectors are already sensitive enough to register GR from the coalescence of the binary pulsar, and from supernovae. However, coalescence of the binary pulsar will not occur for 10^9 yr, and the last supernova seen in our Galaxy was Kepler's supernova in 1609. Experimentalists can expect little joy on the basis of our direct observational data! Fortunately, evidence of the supernovae rate in external galaxies (Tammann 1977) indicates that we observe less than 10% of all supernovae in our Galaxy; the rate of supernovae is about one every 20 ± 10 yr in typical spirals. Observations of pulsars indicate a pulsar formation rate in the range of one every 2–7 yr (Lande and Stephens 1977; Manchester 1979), but the range of uncertainty could reduce this rate to be consistent with the supernova rate. The population of collapsed objects also includes X-ray sources, but with little knowledge of the lifetime of these objects it is difficult to make any estimates of their formation rate.

It is not obvious that all collapsed objects have supernovae as precursors. Observational evidence seems at least to leave open the possibility that pulsars may form without supernovae, particularly as only two pulsars are known to be associated with supernova remnants. There is reason to believe that the total gravitational collapse rate in our Galaxy may be closer to the sum of the pulsar formation rate, X-ray source formation rate and supernova rate. The optimistic experimentalist might hope with some justification that the total collapse rate in the Galaxy could be as high as one per year. However, it could be as low as the supernovae rate alone (assuming supernovae to be progenitors of all collapsed objects) forcing experimentalists to resort to detecting events over a larger (more distant) sample of stars. The sample is increased by a factor of $\sim 10^2$ if one looks out to the distance of M 101 (7 Mpc) and by $\sim 10^3$ if one looks as far as the Virgo cluster (19 Mpc), but the GR amplitude at the Earth is reduced by three or four orders of magnitude requiring increased sensitivity and/or higher GR conversion efficiencies for events to be detectable.

Returning to Fig. 1, we see on the right-hand side possible dimensionless amplitudes for GR bursts from various high frequency sources. The rather high amplitudes for binary coalescence should be read in the light of the absence of knowledge of the event frequency.

3. Weber Bar Antennas

(*a*) *Thermal noise in a Weber bar*

The Weber bar antenna consists of a massive cylindrical bar, suspended so that its fundamental mechanical longitudinal resonance has a high quality factor Q. The Q factor is basically a measure of the coupling between the fundamental mode ω_m and the thermal reservoir. Since the thermal reservoir is the source of all fluctuations (Brownian motion), a high Q antenna with reduced coupling to the thermal reservoir can have an effective noise temperature lower than the reservoir temperature (which is the thermodynamic temperature of the bar).

In a high Q antenna the fundamental mode comes into equilibrium with the thermal reservoir in a time $\tau_m = Q/\omega_m$. If one samples the amplitude of the antenna in a time τ_s, the change in the mean energy kT of the mode will be to first order $(\tau_s/\tau_m)kT$. Thus, if one looks for changes in the energy of the mode ω_m due to sources other than the thermal reservoir (such as vibrations induced by a GR pulse), in a time τ_s the best resolution one can expect is $(\tau_s/\tau_m)kT$. This defines the effective noise temperature of the antenna

$$T_m = (\tau_s/\tau_m)T = (\tau_s\,\omega_m/Q)T,$$

and for an antenna with $Q = 10^8$, $\omega_m = 10^4$ Hz and $\tau_s = 0\cdot01$ s, we have $T_m = 10^{-6}T$, allowing for the possibility of antennas operating at liquid helium temperatures with noise temperatures in the μK range.

These formulae indicate that T_m can be reduced indefinitely by raising the Q factor. However, at $T_m \sim 10^{-7}$ K one reaches the point where $kT_m \sim \hbar\omega_m$ and the mean level of fluctuations is about one quantum. This is the *quantum limit*, at which point the antenna and detection system must be analysed in terms of quantum mechanics. The Q value at which $kT_m = \hbar\omega_m$ is the quantum limiting value, beyond which one obtains no noise advantage except that it can allow the use of longer sampling times and higher temperatures.

(*b*) *The problem of antenna material*

The GR couples to the mass quadrupole moment of the bar and induces a vibration of amplitude $\Delta l \sim lh$, where h is the GR dimensionless amplitude (i.e. strain amplitude) and l is the length of the antenna. Since we are expecting values of $h \sim 10^{-17}$–10^{-21}, it follows that the amplitude of vibration at the end of the bar due to the GR pulse will be 10^{-17}–10^{-21} m for l a few metres.

The length of the antenna is dictated by the requirement that the fundamental mode ω_m, which is the only one with a large quadrupole moment, should be near the expected maxima in the intensity distribution of the GR pulse ($\sim$1 kHz). The velocity of sound v_s in the antenna material determines this. Still, one wants the length to be as large as possible to maximize the antenna quadrupole moment $\sim Ml^2$ at this chosen frequency.

Table 1. Comparison of properties for possible antenna materials

Material	ρ (10^3 kg m^{-3})	v_s (km s^{-1})	Q ($\times 10^7$)	ρv_s^3 (10^{13} kg s^{-3})	$Q\rho v_s^3$ (10^{20} kg s^{-3})	Comments
Aluminium (6061)	2·7	5·1	0·45	36	16	
Aluminium (5056)	2·7	5·1	7	36	252	
Lead	11·36	1·1	—	1·5	—	Q not known
Niobium	8·57	3·4	6	34	204	
Tungsten	18·8	4·3	—	150	—	Q not known
Sapphire	3·98	9·4	300	330	10^5	Q measured at 40 kHz
Silicon	2·33	8·5	200	143	$2·8\times10^4$	Q measured at 20 kHz

The optimum antenna will be the one with the highest value of the quantity $Q\rho v_s^3$, where ρ is the density. Table 1 compares the relevant properties for possible antenna materials. Sapphire and silicon are clearly superior materials with both high Q factors and high values of ρv_s^3. Unfortunately, unlike aluminium and niobium, they are not available in large ingots and there appears to be no immediate prospect of the development of manufacturing techniques for making them in sizes much larger than the present limit of $\sim$100 kg. Unfortunately also, the high value of $Q\rho v_s^3$ does not allow one to compromise on the mass of the antenna, because the quantum limit makes the Q factor relevant only up to the limit of detection of one quantum.

Most experimentalists so far have used the 6000 series aluminium alloys (6061, 6063). Recently, Suzuki *et al.* (1978) discovered that the 5056 alloy has a far superior Q factor, as shown in Table 1. Prior to this discovery, niobium was found to have a high Q factor (Blair *et al.* 1979) and has been proposed as an antenna by the Perth

GR group. Niobium has practical advantages in that it is superconducting, can be magnetically levitated and can be simply used in conjunction with vibration transducers. However, it is expensive and at present it is not known whether larger ingots can be made with the correct metallurgy to produce the high Q factor which has been achieved in smaller samples. There is hope that Q factors greater than 10^8 may be achievable in Nb and Al alloys, particularly if operated well below the superconducting transition temperature.

(*c*) *Environmental noise*

Weber bar antennas must necessarily be operated at cryogenic temperatures so as to reduce Brownian noise, to enable the use of superconducting vibration transducers and to obtain a high antenna Q factor. The cryogenic environment enables the use of magnetic levitation to reduce suspension losses and attenuate external vibrations: it can however also introduce noise from boiling cryogenic fluids unless great care is taken in isolating against vibration within the cryostat.

It was first hoped that aluminium bars up to 1 m in diameter could be plasma sprayed with an NbTi superconductor to enable magnetic levitation (Boughn *et al.* 1974). This was abandoned about 1975, and attempts at using bars with superconducting foil glued to the outside have also been rather unsuccessful due to the degradation of the Q factor by the glue. Small niobium bars have been magnetically levitated at Perth, and these have shown a high degree of immunity to environmental vibration. The acoustic losses associated with magnetic levitation are also low, so that high Q factors can be reliably achieved. Unfortunately, however, the critical field of niobium limits the maximum diameter which can be levitated to about 200 mm, setting the maximum mass for such an antenna to ~ 1 tonne.

Mechanical suspension can in principle always introduce unwanted vibration, particularly by the frictional upconversion of low frequency vibrations (Blair 1979). Recently, a simple suspension using four welded lugs has been successfully used at Stanford, and in other laboratories 'dead bugs' have been used (so called because the bar sits on four legs resembling those of an inverted cockroach). It is still not certain that these suspensions can sufficiently reduce the coupling of external noise into the antenna.

(*d*) *Achievements*

Second generation cryogenic Weber bars have been constructed at Louisiana, Maryland, Moscow, Perth, Rochester, Rome and Stanford, with new experiments also under way at Beijing and Guangchow. Various full scale and prototype antennas have been tested with varying successes. Much effort has gone into learning how to handle massive cryogenic installations and to reduce environmental vibration. The ultimate sensitivity expected by these experiments is determined by the quantum limit (neglecting quantum nondemolition). This corresponds to GR amplitudes of $h \sim 10^{-21}$ which is well within the interesting regime of Fig. 1. The best sensitivity achieved to date is more than three orders of magnitude from this limit, as shown by the solid circle in Fig. 1. This result has been attained with a 4800 kg aluminium (6061) bar operated at $4 \cdot 3$ K with a Q factor of $\sim 4 \cdot 5 \times 10^6$ at Stanford University in a run which began in April 1980. To reach the quantum limit it is essential that low noise vibration transducers be developed which themselves reach the quantum mechanical limit of noise performance.

Fig. 2*a* shows the cryostat at the University of Western Australia, with various cryogenic shields inside a $1 \cdot 7$ m diameter vacuum chamber. In the centre is a vibration isolated experimental chamber suspended on a lead and rubber vibration isolation stack. Fig. 2*b* shows a cross-sectional view of the cryostat.

4. Transducers for Weber Bars

(*a*) *Introduction*

Essential to a Weber bar antenna is the transducer for detecting the bar's acoustic vibrations. The original room temperature antennas used piezoelectric crystals (PZT) as transducers (Weber 1969). The barium titanate–zirconate ceramic used has extremely high sensitivity to vibration (up to 10^{10} V m^{-1}), but it has the disadvantage that the quality factor of the PZT itself is low. Thus, when tightly coupled to a bar, the Q factor is reduced and the overall noise performance is degraded. PZT transducers are most easily matched to semiconductor voltage amplifiers which themselves have rather high input noise. Since the PZT is a reciprocal transducer with equal forward and reverse transductance, this input noise is transformed to mechanical excitation of the bar, further degrading the noise performance. This problem is solvable in principal by using a lower noise amplifier on the input, which in practice can only mean a SQUID (Josephson effect) magnetometer. There are however severe problems in matching the very low input impedance of the SQUID (superconducting quantum interference devices) to the high impedance PZT, so this approach has been largely abandoned.

In selecting a transducer it is instructive to compare the noise performance of amplifiers across the frequency spectrum. Fundamental limits on the performance of linear amplifiers follow from quantum mechanics: Heffner (1962) has shown that the maximum energy resolution of a high gain linear amplifier is $\sim\hbar\omega/\ln 2$. In other words, the energy resolution of a linear amplifier is fundamentally limited to a level just above the energy of a photon at that frequency. This fact was realized by Weber (1957) who proposed the use of 'noise number', the noise equivalent number of photons, to characterize the noise performance of real amplifiers. Fig. 3 shows data collected for typical amplifiers expressed as figure of merit (FOM), which is the reciprocal of the noise number. Most conventional amplifiers have noise numbers many orders of magnitude above the quantum limit; only SQUID magnetometers in the audio frequency range, and parametric amplifiers and masers in the microwave range, start to approach the quantum limit.

Both the low and high frequency amplifiers can be used in principle to construct transducers near the quantum limit for Weber bars. The two types of transducer are described below.

(*b*) *SQUID transducers*

SQUID Noise Limits

SQUIDS have been developed in the form of DC biased devices (DC SQUIDS), using a superconducting loop containing two *weak links* or Josephson junctions, and radio frequency (RF) biased devices containing one junction. SQUIDS, making use of the quantization of magnetic flux in superconductors, are extremely sensitive magnetometers. A signal is coupled to a SQUID magnetically, and as such it acts as an extremely low input impedance superconducting amplifier. In principle, the energy resolution of a SQUID amplifier is limited to $\sim 2\hbar\omega$ for signals of frequency ω.

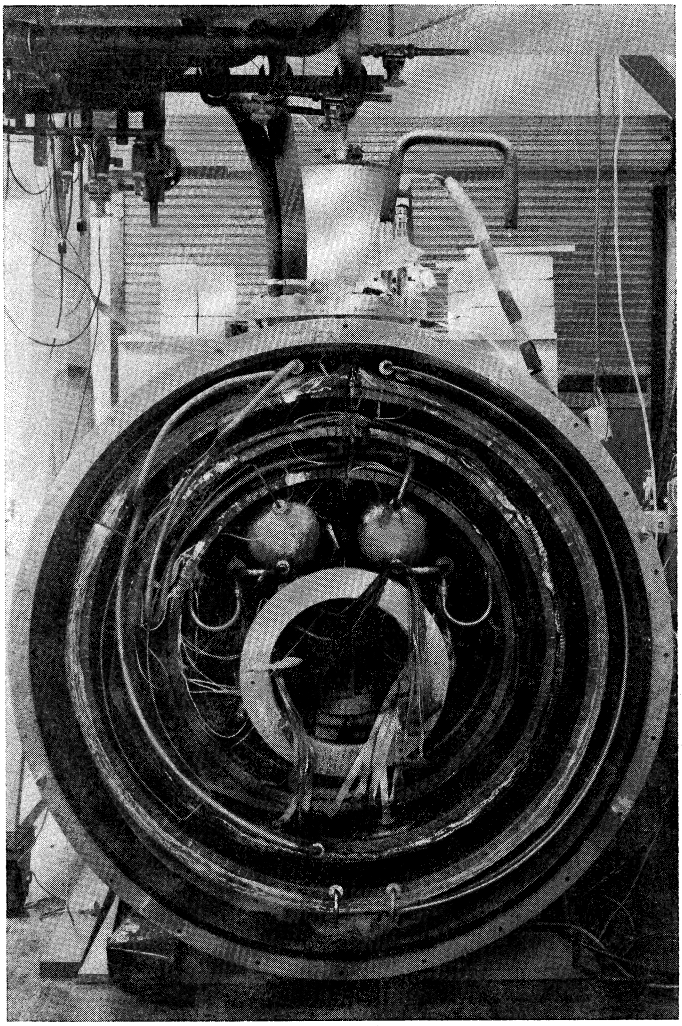

Fig. 2*a*. GR antenna cryostat at Perth, Western Australia. The cryostat is 4 m long and 1·6 m in diameter. It is a conventional cryogenic system except that the experimental chamber, shown housing a large bar, is isolated from vibrations associated with the cryogenic fluids by means of a lead and rubber vibration isolator. Bundles of fine copper wires (just visible here) make thermal contact between the liquid helium shield and the experimental chamber.

To design a SQUID as an amplifier capable of reaching the quantum limit one must solve two problems. The first is to make a SQUID which has intrinsic sensitivity near the quantum limit. This requires the device to have low inductance and low junction resistance (since normal junction resistance contributes Nyquist noise). DC SQUIDS are self-resonant due to the AC Josephson effect, and the low inductance requirement implies that the self-resonant frequency of the loop should also be in the range 10^{10}–10^{11} Hz. For RF SQUIDS the low inductance requires that the RF bias frequency also be 10^{10}–10^{11} Hz. Commercially available RF SQUIDS use much lower frequencies and have a noise performance several orders of magnitude from

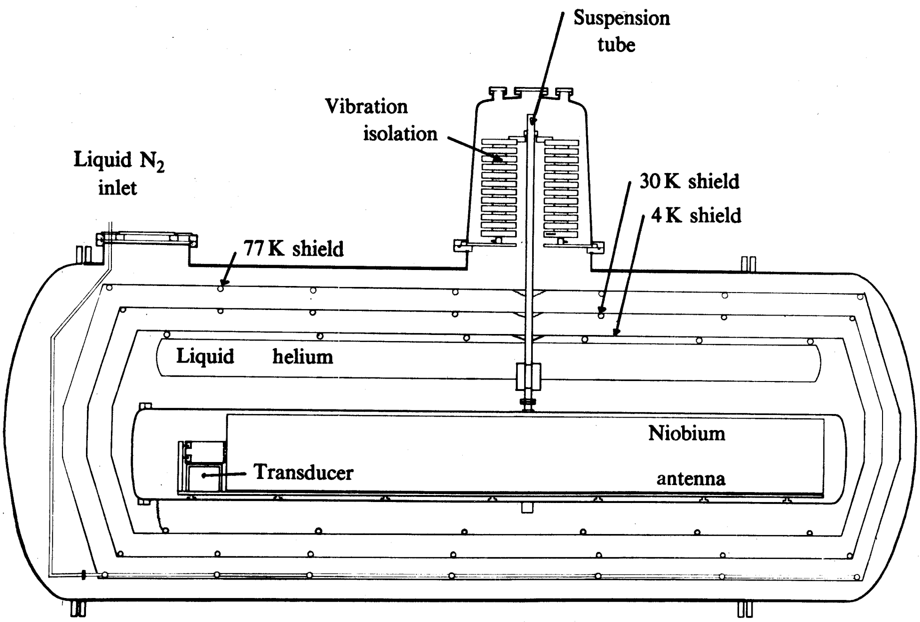

Fig. 2*b*. Cross-sectional diagram of the cryostat shown in Fig. 2*a*.

the quantum limit. A 9 GHz SQUID constructed by Hollenhorst and Giffard (1979) has a noise performance closer to the quantum limit as shown in Fig. 3; this device has been successfully used in the transducer for the Stanford GR antenna.

The second problem to solve is how to couple magnetic flux from a signal source efficiently to the SQUID loop. For RF SQUIDS this problem was solved by the development of a toroidal geometry giving near 100% flux coupling to the SQUID. However, for DC SQUIDS which show greater promise of reaching the quantum limit, this flux coupling is more difficult to achieve due to the usual planar geometry adopted. A planar DC SQUID has recently achieved a noise level of $\sim 5h\ \mathrm{J\,Hz^{-1}}$, only a factor of 2·5 from the quantum limit, but this has been without solving the problem of flux coupling, and so the device does not constitute an amplifier with this noise level. A DC SQUID which holds the promise of solving the coupling problem is a toroidal DC SQUID under development at Maryland (Paik 1980).

Signal Coupling to SQUID

A SQUID can be used in a vibration transducer by allowing the motion of the antenna to modulate the inductance of a superconducting pancake coil. For the transducer to be well impedance matched to the bar a large area pancake coil is needed with high quality factor so that the coil does not dampen the motion of the bar. The coil carries a persistent current, and changes in this current can be coupled into a SQUID by the circuit illustrated in Fig. 4*a*. A system of this sort is under development at Rochester (Douglass 1979).

At Stanford a transducer has been developed which uses a niobium diaphragm with persistent currents passing through two pancake coils on either side, as shown in Fig. 4*b*. The diaphragm acts as a mechanical impedance transformer. The bar–diaphragm system acts as a coupled resonator, and the amplitude of the bar's fundamental mode is coupled into the diaphragm. The diaphragm exhibits beats at the difference frequency, and the current differences between the two coils are coupled into the SQUID.

The effective noise temperature of the 4800 kg antenna at Stanford with this transducer system is 10^{-2} K. Although far from the quantum limit of $\sim 10^{-7}$ K, this represents the highest sensitivity yet achieved by a GR antenna. This result is shown as 'Weber bar (1980)' in Fig. 1.

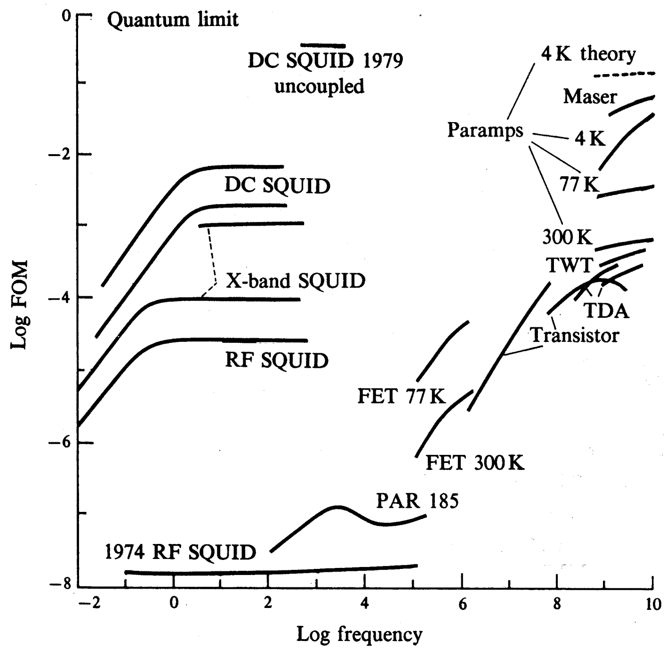

Fig. 3. Noise data for various types of amplifier (see text). Best performance with practical amplifiers has been achieved with masers and paramps at microwave frequencies. SQUIDS have demonstrated comparable noise performance but this has been achieved without signal coupling.

(c) *Parametric upconverter transducers*

Parametric upconverter transducers operate by letting the sensing surface of a Weber bar modulate the capacitance or inductance in a high Q superconducting resonator. The resonator may be designed to operate at any arbitrary frequency: it is excited by a pump source which applies a signal at or near the resonant frequency of the device.

Vibration of the antenna introduces sidebands on the signal removed from the resonator. One can consider the device to operate by scattering signal phonons ω_m (in the antenna) with pump photons ω_p to produce upconverted photons, which appear as sidebands at frequencies $\omega_p \pm \omega_m$. The upper sideband is caused by outgoing phonons adding to the pump photon energy, while the lower sideband is caused by phonons being returned to the bar. Information is extracted from the sideband signal, and since the photons in the sidebands are coherent with the signal phonons, the power gain of the device is proportional to the ratio ω_p/ω_m. Thus, it is advantageous to use a high pump frequency and, from Fig. 3, we see that 10 GHz is a good choice, where microwave amplifiers approach the quantum limit.

A transducer of this sort is under development at Perth. It consists of the microwave re-entrant cavity illustrated in Fig. 5. The small cavity (4 mm in diameter and 2 mm long) in Fig. 5*a* resonates when its central capacitance plate is 10^{-3} cm from the surface of the antenna. Complex levitation and servo-control systems, shown schematically in Fig. 5*b*, allow the entire transducer assembly to be levitated and held onto resonance to within an accuracy of $\sim 10^{-11}$ m.

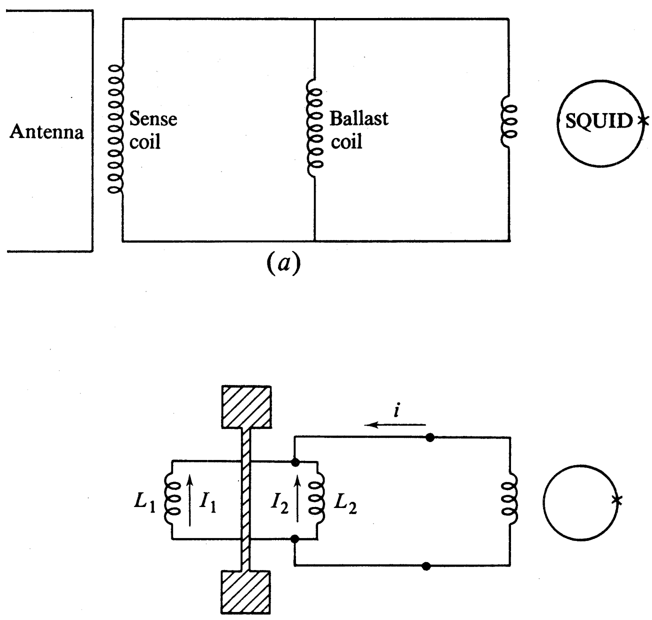

Fig. 4. Schematic diagram of (*a*) direct inductive transducer using a SQUID amplifier and (*b*) inductive transducer using two pick-up coils coupled to a superconducting diaphragm. In (*b*) the diaphragm is mounted on the end of the antenna and resonates near the antenna frequency.

The chief problem in constructing a low noise parametric transducer is in obtaining a sufficiently pure pump frequency, since frequency fluctuations in the pump are indistinguishable from vibrations in the antenna. Two solutions are possible. One is to use a balanced system, with two cavities to balance out the pump signal fluctuations. The second is to eliminate the fluctuations by filtering the pump signal. Both approaches are being pursued separately. At Perth (Blair *et al.* 1979) we have constructed a superconducting cavity stabilized oscillator (SCSO) which almost totally eliminates this noise source. In conjunction we have constructed a parametric amplifier which should have an FOM of $\sim 0 \cdot 3$ at low temperatures. A balanced cavity transducer has been built at Louisiana (Hamilton *et al.* 1980), also combined with a parametric amplifier, and similar systems are under construction in Moscow (Braginsky 1980).

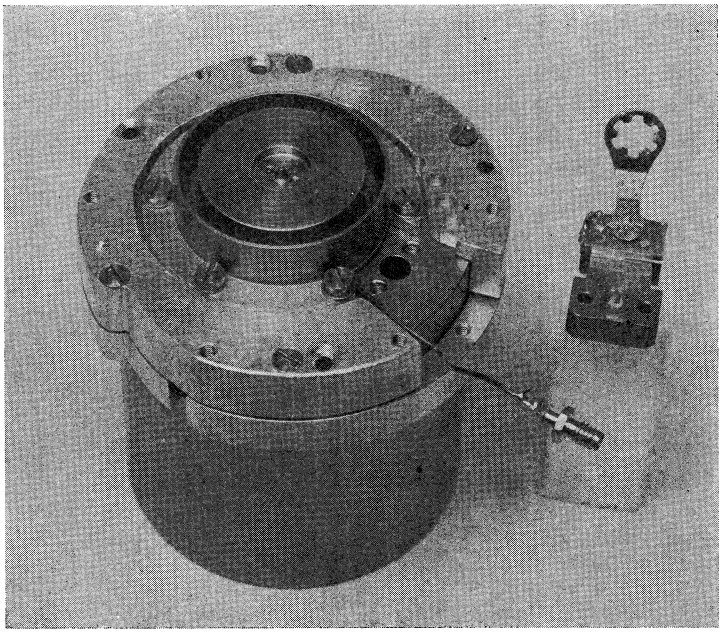

Fig. 5*a*. Re-entrant cavity shown mounted on the stabilization cavity. The component on the right is part of the coupling network.

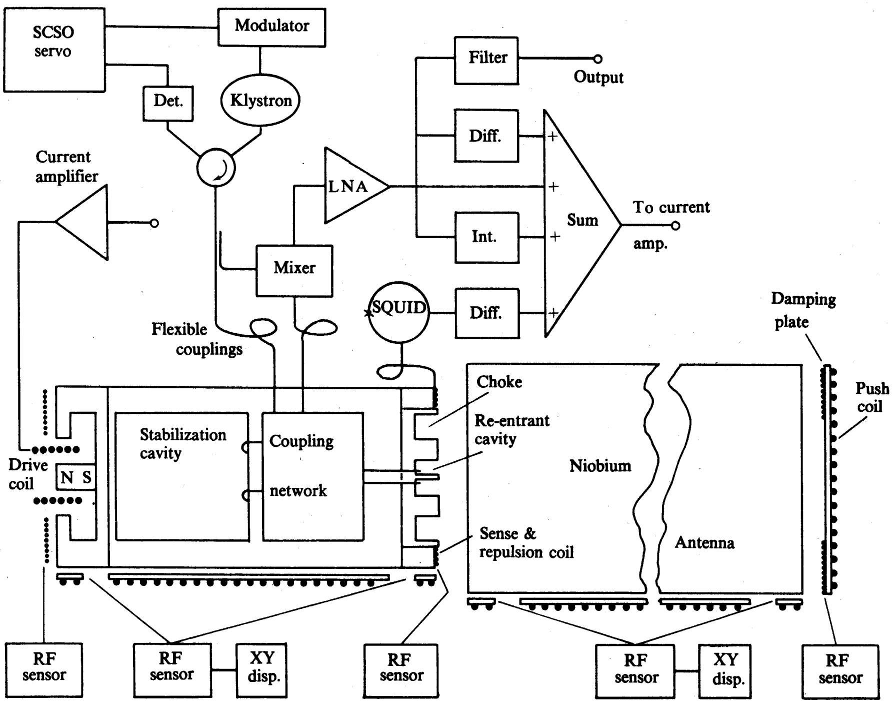

Fig. 5b. Schematic diagram of the antenna–parametric transducer system showing sensors for levitation monitoring and the feedback control system. The servo-electronics and magnetic drive enable the superconducting re-entrant cavity to be held on resonance at a spacing of 10^{-3} cm from the end of the bar. Microwave power is obtained from a klystron and its associated SCSO servo.

At present the parametric transducer system in Perth has been operated without a full SCSO system or low noise amplifier. With a small prototype antenna an effective noise temperature of $\sim 40 \times 10^{-3}$ K has been achieved, corresponding to an amplitude sensitivity of $\sim 10^{-17}$ m. Great improvements over this figure are possible.

5. Laser and Doppler Experiments

(*a*) *Introduction*

I will conclude by briefly describing two other methods of GR detection which are being actively pursued by several research groups. If an electromagnetic wave is used to monitor the spacing of two or more inertial masses, the passage of a gravitational wave will give rise to a variation in the measured spacing of the masses. Peak response will occur if the light travel time between the masses is equal to half the gravitational wave period, or odd multiples of this. For high frequency GR events the light travel time between the masses corresponds to about 300 km, whereas at the low end of the spectrum it may be 10^8 km. In the first case laser interferometers are ideally suited, whereas in the second Doppler spacecraft tracking can give low frequency resolution.

(*b*) *Laser interferometers*

An Earth based laser interferometer which is physically 300 km long would be unrealistic, if only because it would be extremely expensive. However, this can be avoided by allowing a laser beam to undergo say 300 reflections between masses 1 km apart. To achieve high sensitivity the laser must have high intensity (to avoid shot noise due to photon statistics), an ultra high vacuum must be maintained along the optical path, the mirror reflectivity should be extremely high (99·9%), and the masses should be highly isolated from seismic noise.

Although the problems are very serious, two groups at Munich (Billing *et al.* 1979) and Glasgow (Drever 1979) have made impressive progress towards solving many of the problems involved. The best noise performance obtained by the Munich group with a small scale prototype is illustrated in Fig. 1. Several orders of magnitude improvement over this figure should be attainable as higher laser power and longer path lengths are realized.

(*c*) *Doppler ranging*

Spacecraft tracking conventionally uses Doppler ranging, whereby a signal is transmitted from an Earth station to a spacecraft where the signal is amplified, frequency multiplied by a simple ratio, and retransmitted back to the Earth station. The Doppler signal is seen as a beat frequency between the incoming multiplied frequency, and the outgoing frequency after it has been multiplied by the same factor at the Earth station. The Doppler beat frequency is proportional to the spacecraft velocity and the total beat cycle count is related to the spacecraft distance.

In the absence of noise the Doppler signal would contain a characteristic signature for a passing pulse of GR (Estabrook and Wahlquist 1975). The problem as always is to reduce the noise level of the measurement so that the very small displacements due to GR can be detected. For amplitudes $h = 10^{-16}$, this requires the detection of motions of amplitude $<0 \cdot 1$ mm between the Earth and a spacecraft during typical interplanetary missions.

The chief sources of noise are frequency instability in the transmitted signal and fluctuations in the solar wind and troposphere which cause propagation delays. Recent improvements in frequency standards using cryogenic hydrogen masers (Smarr *et al.* 1979) have significantly reduced frequency instability noise.

The maximum sensitivity achieved to date of $h \sim 3 \times 10^{-14}$ for time scales of ~ 100 s is shown in Fig. 1. This sensitivity, representing the measurement of errors in spacecraft trajectories of ~ 1 mm, is only just within the cosmic closure limit for GR. Significant improvements are possible however, particularly if future spacecraft carry two separate frequencies for both the uplink and downlink, which enables correction for many of the propagation delays. It has recently been shown (Hellings 1979) that autocovariance analysis of data can improve sensitivity, particularly at frequencies of $\sim 10^{-4}$ Hz. However, to reach the desirable $h = 10^{-16}$ level of sensitivity it may be necessary to set up geostationary troposphere monitoring satellites to enable direct measurement and subtraction of propagation delays.

6. Conclusions

GR has still not been directly detected. An improvement of three orders of magnitude in the energy sensitivity of Weber bar antennas has been achieved since 1974, and the first cryogenic antenna is now operating at a level well within theoretical predictions for gravitational events in the Milky Way. Such events could occur as often as once per year. Prospects for further improvement of several orders of magnitude are good, but to reach the sensitivity necessary to observe frequent events from the nearest 1000 galaxies will require antenna and transducer technology to be optimized close to the quantum limit.

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