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# Gravitational Wave Astronomy*

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## SUMMARY

This introductory review deals particularly with experimental techniques used in searches for gravitational radiation, and prospects for developing gravitational wave detectors of very much higher sensitivity. Some of the factors which may limit the sensitivity of various types of detectors are discussed, and future possibilities assessed.

The subject of gravitational wave astronomy has had a certain amount of controversy associated with it, but it is developing fairly rapidly. Indeed certain aspects of the field have reached an exciting stage, although they have not produced any real astronomical data yet and may not do so for some time. In some ways there have been quite basic changes in the overall character of the field in the last year or two, and from an experimental point of view I think the field now looks much more promising than it did to many people a short time ago, when it began to be generally accepted that the experiments of Joseph Weber (1), which had stimulated the whole field, might not have been detecting gravitational waves.

This review fills in some of the background to the subject, briefly discussing what one might call the 'first generation' experiments, stimulated by those of Weber but generally giving negative results; it then describes some of the new ideas which have been produced for experiments of much higher sensitivity than had been thought practicable some time ago, and concludes with some speculations about possible future developments.

## I. INTRODUCTION

Gravitational radiation has been predicted for many years from general relativity, as a form of radiation which may carry away energy from accelerated masses. Certain analogies may be made between this

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*Based on a talk given at the Meeting of the Royal Astronomical Society on 1976 April 8 at Manchester (photographs used to illustrate the talk have been omitted in this version, which has been slightly updated and revised, and references have been added).

radiation and the electromagnetic radiation from accelerated charges – although care has to be taken to recognize the limitations of such analogies. The normally accepted version of general relativity predicts that gravitational radiation travels with the velocity of light in vacuum, for example. However, there are some important differences which make experiments on gravitational radiation much harder than experiments on electromagnetic radiation. First, the gravitational interaction is much weaker than electromagnetic interactions – the gravitational force between two stationary protons is about $10^{-36}$ of the electrostatic force – so gravitational effects tend to be small unless enormous masses are involved. There is, however, a more basic difference which may be described as arising from the observation that all gravitational mass appears to have the same sign; or perhaps more precisely from the observation that the ratio of gravitational mass to inertial mass seems to be the same constant for all bodies. This affects the process of generation of gravitational radiation, for if one tries to generate a gravitational wave by accelerating a mass, then conservation of momentum requires that some other mass must accelerate by a corresponding amount in the opposite direction – and its effect will, to some extent, counteract the effect of the first mass. A change of the quadrupole moment of the whole system may occur, however, and this will produce gravitational radiation.

To produce appreciable amounts of gravitational radiation large masses and large accelerations are required, and it is clear that such circumstances might arise in the collapse of a star to a neutron star or a black hole. As magnetic fields are likely to be present, as well as angular momentum, it seems unlikely that such a collapse would be spherically symmetrical. Indeed it seems probable that the rapid changes in quadrupole moment taking place in the final stages of the collapse would result in emission of a considerable fraction of the total energy involved in a burst of gravitational radiation, most of it coming out in about a millisecond for a system of mass equal to that of the Sun.

How might one detect a burst of gravitational radiation such as this? Again the problem is harder than detection of a radio wave, for one does not expect anything equivalent to the relative motion of positive and negative charges which occurs in a radio antenna exposed to an electromagnetic wave. A gravitational field would impose the same acceleration on all test objects at a given point (including an adjacent observer), and no effect would be noticed. In fact the gravitational wave produces a changing curvature of space, and this can cause an observable change in the separation of two test masses at some distance from one another. The effect is a maximum for gravitational radiation propagating in a direction at right angles to the line joining the centres of the masses, and is proportional to their separation.

Thus in principle a gravitational wave detector consists of two test masses and some method of monitoring changes in their separation. The problems become apparent when one considers the likely magnitude of the effects. For a supernova collapse taking place in our own Galaxy, for example, the ratio of the change in separation $\delta L$ to the initial separation $L$ is of order $10^{-17}$. Thus for masses one metre apart one would only expect motions of order $10^{-15}$ cm. As this is less than the diameter of a nucleus the task is not an easy one, and as supernova outbursts are not frequent events in our Galaxy it would be desirable to extend the range of observation to other galaxies, for which the motions would be still smaller. (For gravitational waves of a given frequency, energy flux is proportional to $(\delta L/L)^2$.)

## 2. SOME POSSIBLE SOURCES

To give some idea of the problems facing experimenters in this field I have collected together in Table I some estimates of energy fluxes and amplitudes of motion $\delta L/L$ at the Earth from various types of source. Maximum intensity would be expected from collapse events forming supernovae or black holes and experiments carried out so far have been aimed at sources of this nature. (I have included an estimate of the flux which might be obtained at 10 metres from a small atom bomb to indicate the difficulties of generating gravitational waves

TABLE I

*Some possible sources of gravitational radiation*

*Pulsed sources*

| | Flux at Earth ($\mathrm{J\,m^{-2}\,s^{-1}}$) | $\delta L/L$ |
|---|---|---|
| Stellar collapse: | | |
| Our Galaxy | $10^{7}$ | $10^{-17}$ |
| Virgo cluster of galaxies | 10 | $10^{-20}$ |
| Atom bomb (17 kiloton) | $10^{-14}$ (at distance of 10 m) | |

*Continuous sources*

| | Period | Flux ($\mathrm{J\,m^{-2}s^{-1}}$) | $\delta L/L$ |
|---|---|---|---|
| Crab Nebula Pulsar | 1/60 s | Upper limit $3\times10^{-10}$ | $10^{-24}$ |
| | | Best guess $10^{-13}$–$10^{-16}$ | $10^{-27}$ |
| Binary stars: | | | |
| Iota Bootes | 3·2 hr | $1{\cdot}8\times10^{-13}$ | $5\times10^{-21}$ |
| HZ 29 | 8·7 min | $3\times10^{-13}$ | $1{\cdot}3\times10^{-21}$ |
| Total from all binaries in our Galaxy | minutes to hours | $10^{-10}$ | $10^{-19}$ to $10^{-20}$ |

from obvious terrestrial sources. More promising methods of generating gravitational radiation artifically have been suggested recently (6).) Possible continuous sources of gravitational radiation are also indicated. In the case of a pulsar, the radiated flux depends on the size of the quadrupole moment, which is not known, and the upper limit given corresponds to a hypothetical situation in which all of the energy loss of the pulsar goes into gravitational radiation. Experiments to search for gravitational radiation from these pulsars or binary star systems could take advantage of known frequency and phase of the signal but the anticipated fluxes are so small that, although they remain a definite target for the future, I do not think they will be easy to observe. Some other interesting types of possible source have been suggested recently, and will be mentioned later. (Much of the data in Table I is from Press & Thorne (7), Misner, Thorne & Wheeler (8), and Braginsky (9); the flux estimate for HZ 29 is by W.P.S.Meikle.)

## 3. THE 'FIRST GENERATION' OF GRAVITATIONAL WAVE EXPERIMENTS

In spite of the extremely small effects to be expected from known sources, Joseph Weber began experiments in this field some 17 years ago. His work has directly stimulated a range of experiments by various groups, most of which have had claimed sensitivities rather better than those of Weber's original experiments, but within about an order of magnitude of them. The type of gravitational wave detector developed by Weber consists essentially of a massive aluminium bar, suspended in vacuum by a wire around its centre, as indicated schematically in Fig. 1. The weight of the bar is typically about $1\frac{1}{2}$ tons. The two halves of the bar may be taken to correspond to two test masses, and a gravitational wave propagating in a direction at right angles to the axis of the cylinder might be expected to set up longitudinal vibrations. To look for such vibrations, Weber used piezoelectric strain transducers bonded to the surface of the bar, near its centre. He has built several

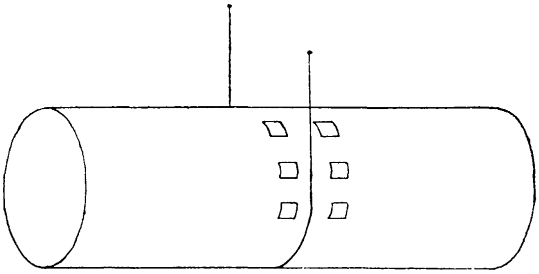

FIG. 1. The bar type of gravitational wave detector, devised by J.Weber. The rectangles represent piezolectric strain gauges bonded to the bar, which is suspended inside a vacuum tank from antivibration supports.

detectors of this kind, and has observed signals from them which he has interpreted as due to gravitational waves. The amplitudes of motion recorded were larger than those expected from the sources in Table I, and the rate of events was several per day. Signals of this magnitude and rate are not easily explained on the basis of known astrophysical phenomena; and if they originated from a source near the centre of our Galaxy, as some of the data suggested, it is rather hard to reconcile the energy fluxes implied with other estimates of rate of energy loss by the Galaxy (10, 11). There has been, however, some controversy about the analysis and interpretation of the experimental data, and subsequent experiments by other workers have not confirmed Weber's findings.

One of the first experiments to give results which might be directly compared with those of Weber was carried out by a group led by Braginsky in Moscow. This group used aluminium bars of the same size as those of Weber, but they observed motions of the bars by a capacity transducer system. Results obtained were negative (12).

Experiments were also carried out at Glasgow, and I might describe these briefly for they used a slightly different type of detector which illustrates well some points that I shall come back to later. Instead of a single bar, we used a system more like the basic pair of test masses; in fact, two separate aluminium bars with piezoelectric transducers cemented between them to monitor changes in their separation. The arrangement is shown schematically in Fig. 2. In some ways the system of two bars connected by transducers behaves rather like the single Weber bar, but a much larger fraction of any mechanical energy in

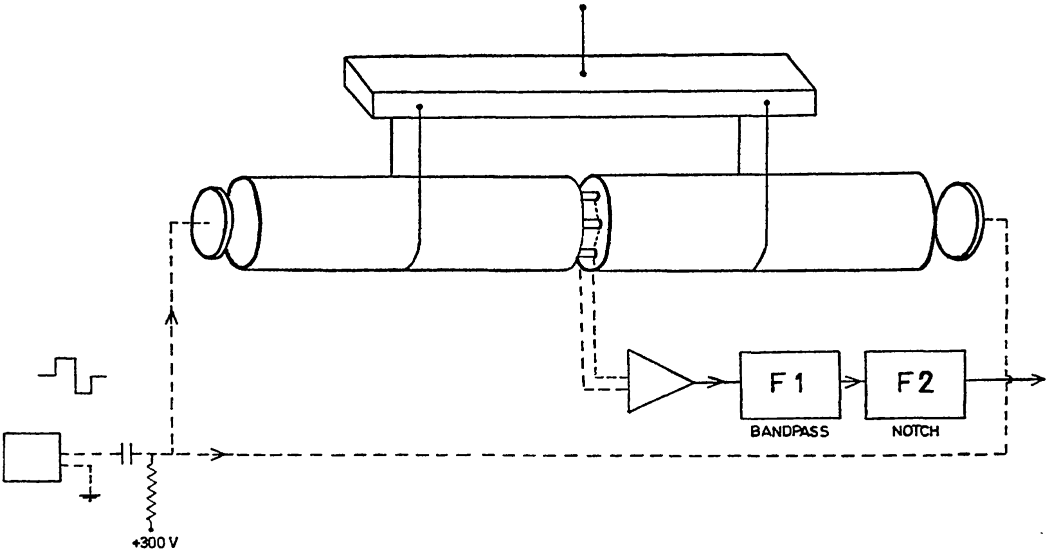

Fig. 2. A 'divided-bar' gravitational radiation detector, as used in experiments at Glasgow.

the system is communicated to the transducers, so a larger electrical output is obtained than in a Weber detector. As all the signals involved in such experiments are small ones, not far from amplifier noise or thermal noise from components such as the transducers, this is an important advantage. In particular it makes it practicable to use an amplifier and electronic system of much larger bandwidth than with the single-bar detectors, and thus follow the motion of the bars with a time resolution of the order of a millisecond (instead of about 0·1 second as in previous experiments). Indeed by passing the signal through suitable filter circuits, indicated by F1 and F2 in the diagram, it is possible to obtain information on the waveform of a force acting on the bars. There is, however, a more important advantage of short time resolution: the thermal noise from the bar system itself can be effectively reduced.

It is worth discussing this latter point in more detail, as it affects most other detectors also. A basic limitation to measurement of small motions arises from the thermal vibration of any piece of metal or other object. At a temperature $T$, each normal mode of vibration has a mean energy $kT$, where $k$ is Boltzmann's Constant. The corresponding amplitude of vibration depends on the mass and frequency involved; and it is to keep the amplitude of thermal vibration small that the masses used in gravitational wave experiments are usually made large. For a Weber bar of mass about one ton, for example, the amplitude of thermal vibration for the first longitudinal mode (the one of interest for gravitational radiation detection) is of order $10^{-14}$ cm at room temperature. It might at first be thought impossible to measure any effects which correspond to motions smaller than the mean amplitude of thermal motion, but this is not so if the mode of mechanical vibration of interest has small damping, or large 'quality factor', $Q$. In this case the energy of thermal motion in the mode changes relatively slowly, with a relaxation time of $Q\tau/2\pi$ where $\tau$ is the period of the vibration. If the gravitational wave pulse has a duration much less than the relaxation time then the energy change which it causes in the bar will occur in a correspondingly short time, and discrimination against larger but slower thermal energy changes may be possible. For a pulse of duration equal to one period of vibration of the bar, and an electronic system with response time less than this, then an energy change of order $2\pi kT/Q$ might be detectable if there were no other source of noise. As values of $Q$ may approach $10^6$ for certain aluminium alloys, energy changes of a very small fraction of $kT$ might be detected in principle; but in practical detectors sensitivity is reduced by electrical noise from amplifiers and transducers, reductions in $Q$ due to mechanical losses in transducer materials and bonding, and limitations in electronic response time. (Detailed analyses have been published by

Gibbons & Hawking (**13**), Buckingham & Faulkner (**14**), Maeder (**15**) and others.)

In practice the detectors built at Glasgow gave better sensitivity per unit mass for short pulses than Weber detectors, as well as shorter response time, and detailed searches for various types of gravitational waves have been made. Results were almost entirely negative (**16**, **17**), with the possible exception of one single interesting coincidence pulse which has not been repeated. Similar detectors were built at Reading University and Rutherford Laboratory by Allen & Christodoulides (**18**), also with negative results. A slightly different variety of divided-bar detector was developed at Bristol University by P.S.Aplin, the first person to propose this general mechanical arrangement (**19**).

Other searches for gravitational wave pulses using detectors based more closely on those of Weber were carried out by various groups in the USA and elsewhere, all with predominantly negative results. I might just mention experiments with 4-ton detectors by J.A.Tyson (**20**) at Bell Laboratories and Douglass *et al.* (**21**) at Rochester University; some careful observations with a relatively small single bar and very detailed analyses and comparison with Weber's work by Levine & Garwin (**22**); joint experiments using improved Weber-type detectors at Munich (**23**) and Frascati (**24**), which are probably the most sensitive published so far; and experiments at Meudon (**25**).

Most of the above experiments have been designed to search for short pulses, and in the coincidence experiments simultaneity in pulse arrival time was sought. Some improvement in selection of events from noise may be obtained by taking phase into account, as was in fact done in the Glasgow experiments (**16**), and some further improvement might be obtained by using efficient techniques for searching for particular types of signal (Fellgett **26**). Two experiments have used a different analysis method – continuous cross correlation of the outputs of a pair of detectors – to make searches sensitive for continuous fluxes of gravitational radiation, or possibly for long bursts or accumulations of many small pulses. In one experiment at Glasgow (**17**), the detectors described above were used, with a minicomputer to perform the cross correlation. Results obtained were negative, and were sufficiently sensitive incidentally to rule out a possible interpretation of Weber's data in terms of a very large flux of very small pulses. In recent work at Tokyo (**27**), a pair of detectors using square aluminium resonators were used to set limits to flux in the region of 145 Hz. Although neither of these searches was sensitive enough to detect expected sources, the techniques are likely to prove useful in future experiments.

The apparent disagreement between the results of Weber's experiments and those of other workers has led to a certain amount of controversy, but I do not think it useful to deal with this at length here. (Several discussions relevant to the problem have been published (**28**).) It is perhaps unfortunate that none of the independent experiments has used exactly the same techniques of experiment and signal processing as those employed by Weber over periods during which he recorded positive effects; but the consensus view that Weber's results are not due to gravitational radiation seems to me so likely to be correct that it is more profitable to concentrate now on development of detectors of very much greater sensitivity.

## 4. POSSIBILITIES OF DETECTORS OF MUCH IMPROVED SENSITIVITY

Let us consider again some targets one might like to aim at if one wishes to detect gravitational radiation pulses from stellar collapse events. In Table II I give some rough estimates, probably correct only to order of magnitude, of rates of detected events which might be expected from millisecond pulse detectors of various ranges of sensitivity. In this table the sensitivities are expressed in terms of the integrated energy flux over the duration of the pulse; and it might be noted for comparison with the figures in the first column that the sensitivity of present gravitational wave detectors is of order $10^5$ J m$^{-2}$. Thus the first value of detector sensitivity quoted in the table corresponds to an improvement by about 5 orders of magnitude over anything achieved in practice to date, and even with this sensitivity the event rate might be low – although if 10 events per year were recorded this would be quite acceptable, and would give interesting data for astronomy. An improvement by a further 3 orders of magnitude to $10^{-3}$ J m$^{-2}$ would bring a significantly larger number of collapses within range, and would almost certainly give interesting results. It should be stressed, of course, that the estimates in this table have very large uncertainties, and only apply to this type of millisecond pulse source in any case; but it is clear that very large improvements in detector sensitivity are desirable. To achieve this in a field which is

TABLE II

*Event rates which might be expected in detectors of given sensitivity for millisecond pulses*

| Sensitivity (Integrated flux over pulse) J m$^{-2}$ | Range for collapse events (m) | Event Rates which might be expected |
|---|---|---|
| $3\times10^{-1}$ | $10^{23}$ | 10/yr–20/century |
| $3\times10^{-2}$ | $4\times10^{23}$ (Virgo distance) | 10/month–4/yr |
| $3\times10^{-6}$ | $3\times10^{25}$ | 1/min–1/s |

already near the limits of current technology will not be easy, but I feel it is not out of the question. In fact I think at the moment that there are at least three different and promising approaches to the problem.

### 4.1 *Large Low-temperature Detectors*

The first approach is perhaps an obvious one, and involves using a very large aluminium bar as the detector, and cooling it down to a very low temperature to reduce thermal noise. Development of equipment of this type has been proceeding for several years now in three laboratories, at Stanford University (**30**, **31**), at Louisiana State University (**30**, **33**), and in Rome (**34**). In the Stanford and Louisiana projects it is planned to employ bars of mass 6 tons, levitate them using magnetic fields produced by superconducting coils, and eventually cool them down to temperatures of the order of 50 millikelvin. The work at Rome is on a similar scale. These are all extremely difficult technical projects, but they are nevertheless proceeding fairly well. However, there is a serious fundamental problem in addition to the technical ones of large-scale cryogenics; the problem of sensing the very small motions of the bars without introducing a serious amount of additional noise. This is likely to be the hardest problem in these projects, and each group is developing its own technique: the Stanford and Rome groups plan to use superconducting Josephson junction magnetometers (SQUID sensors), and the Louisiana group is working on a form of superconducting parametric amplifier in which the acceleration of the end of the bar modulates two resonant radiofrequency cavities. Unfortunately it seems quite likely that none of these devices will have sufficiently good performance to enable full advantage to be taken of the very small thermal noise in large bars at very low temperatures. Theoretical work by the group led by Braginsky (**29**, **35**) has recently drawn attention to the general problem of feedback of noise from any amplifier or sensing system to the object being monitored. Analyses by this group (and also at Glasgow by J.Hough, W.A.Edelstein and J.R.Pugh) suggest that noise from the sensing systems may set a practical limit to the performance of these very low temperature detectors. However, it can nevertheless be fully expected that these large-scale projects will advance the sensitivity of gravitational radiation experiments by several orders of magnitude.

### 4.2 *High-$Q$ Detectors*

Another very interesting proposal has come from the group at Moscow University. Instead of using very large aluminium bars, they propose (**29**, **35**, **36**) to make relatively small gravitational wave detectors using material of very high quality factor $Q$. As indicated before, the effective thermal noise in a bar depends on its $Q$, as well as on its mass and temperature, and Braginsky has pointed out that it is possible to obtain single crystals of certain materials, such as sapphire, with values of mechanical $Q$ very much higher than found in normal metals. Theoretical calculations suggest that the $Q$ of sapphire should increase as the temperature is reduced, and values as large as $10^{13}$ are predicted at a temperature of a few degrees Kelvin, for perfect crystals. If such values of $Q$ were achieved in practice, and problems of sensing the motion were overcome, then it might be possible to build small detectors having sensitivity better than any of the values quoted in Table II. The Moscow group are therefore putting some effort into the production of high-$Q$ sapphire crystals, and they have already obtained values for $Q$ of order $10^9$. This is extremely encouraging, but the problem of sensing the motion of these relatively small crystals without damping them is even more severe than in the case of the large aluminium bars. In order to tackle this, the Moscow group have proposed an extension of their earlier capacity sensing system. The end of the sapphire bar would be coated with a superconducting film, arranged to form part of a superconducting microwave cavity in such a way that motion of the bar modulates the resonant frequency of the cavity. With the cavity fed from a suitably stable oscillator, motion of the bar will generate sidebands which may be detected. It is important, however, that the detection process does not introduce significant damping.

Analysis of the operation of this type of sapphire detector and sensing system indicates that quantum phenomena become important at the levels of sensitivity of interest. For example, if a gravity wave pulse of energy $10^{-3}$ J m$^{-2}$ were incident on a 1-kg sapphire crystal initially in the lowest quantum state of the fundamental longitudinal mode of vibration it would not impart sufficient energy to make a transition likely to even the next quantum level. However, this particular problem becomes unimportant when it is realized that if the temperature were 4 K, the bar would probably be in a relatively high quantum state initially, and the forces induced by the gravitational wave can then cause a much larger energy change in it. Consideration of the electrical quantum state of the microwave cavity is more worrying. It turns out that to achieve a sensitivity of $10^{-3}$ J m$^{-2}$ it is necessary to be able to detect a change in the state of the cavity amounting to only one or two quanta, and moreover to do this without significant probability of disturbing the state of the cavity in the process. At first sight this might seem an impossible task, perhaps even in principle, but Braginsky suggests a technique for attempting it. He proposes to direct an electron beam through a high-field region of the cavity being investigated (possibly not the one directly modulated by the bar), and deduce the field strength and thus the state from the electron diffraction pattern. Such a procedure alone would have a high probability of stimulating a change of state in the cavity, and to reduce this probability it is proposed to observe only a very small number of the electrons in the diffraction pattern, near the minima, and to reflect and refocus the remainder back into the field in the cavity in such a way as to compensate the disturbance induced in their first passage through the field. A detailed analysis of such a procedure has been made by Braginsky & Vorontsov (37), and it is concluded that it should in principle be possible to determine whether or not a cavity is in the ground state with a probability of changing the state of only a few per cent. This proposal raises some interesting questions in quantum mechanics as well as in experimental technique. However, if the performance suggested were achieved it might make it possible to construct a gravitational radiation detector of unprecedented sensitivity using a sapphire crystal weighing only a few kilograms.

The technical problems of developing detectors of this type are clearly difficult ones and will probably not be solved quickly. However, large sapphire crystals are now being manufactured commercially in the USA for other purposes, and the long-term prospects for gravitational radiation detectors using this or other types of high-$Q$ material seem very promising.

### 4.3 *Separated-mass Detectors*

Instead of concentrating on reduction of the background effects in gravitational wave detection, an alternative approach to improving sensitivity amounts to increasing the displacement caused by the wave. This may be done by making the separation L between a pair of test masses large. An optical interferometer provides an obvious method of observing a change in separation of two objects, although there are clearly difficulties in such an arrangement as no simple laser or other source would have sufficient stability to act as a reference, and it would be necessary to detect motions of the order of $10^{-10}$ of the wavelength of the light. The first problem can be overcome by using three masses, and looking for relative distance changes in two optical paths at right angles to one another, the changes being of opposite sign for a suitably polarized gravitational wave propagating in a direction normal to the plane of the system. Interferometry techniques like this have been considered by several workers in the field. The first experiments with a gravity-wave detector of this type were carried out by a group led by R.L.Forward (38) at Hughes Research Laboratories, who used a Michelson interferometer to look for changes in separation of masses about 3 metres apart. The sensitivity achieved was of order $10^{-13}$ cm in this baseline, which although inferior to that obtained with bar detectors designed for millisecond pulses, was encouraging in a relatively small and simple system.

Several ways of improving the performance of detectors of this general type have been suggested by R.Weiss (39), who is carrying out experiments in this direction at MIT. The changes in optical path may be increased by reflecting each beam back and forward many times between each pair of masses, and one way of doing this efficiently is by using a pair of nearly confocal mirrors, as in a Herriott optical delay line. Diffraction losses can be made small in such an arrangement (as in a laser cavity), and with multilayer dielectric reflectors it is quite practical to have several hundred discrete reflections in each arm of the interferometer. It is important, of course, that the total light travel time be kept less than the period of the gravitational wave. Statistical fluctuations in the numbers of photons observed during the pulse introduce unavoidable noise into the measurement; but additional noise arising from low-frequency fluctuations in the laser output may be reduced by modulating the length of one of the optical paths at a frequency of several megahertz and subsequently picking out the modulation of the fringe pattern using a phase sensitive detector.

A schematic diagram indicating a possible arrangement for a gravitational wave detector incorporating these techniques is given in Fig. 3. (The diagram also shows a force feedback system which is

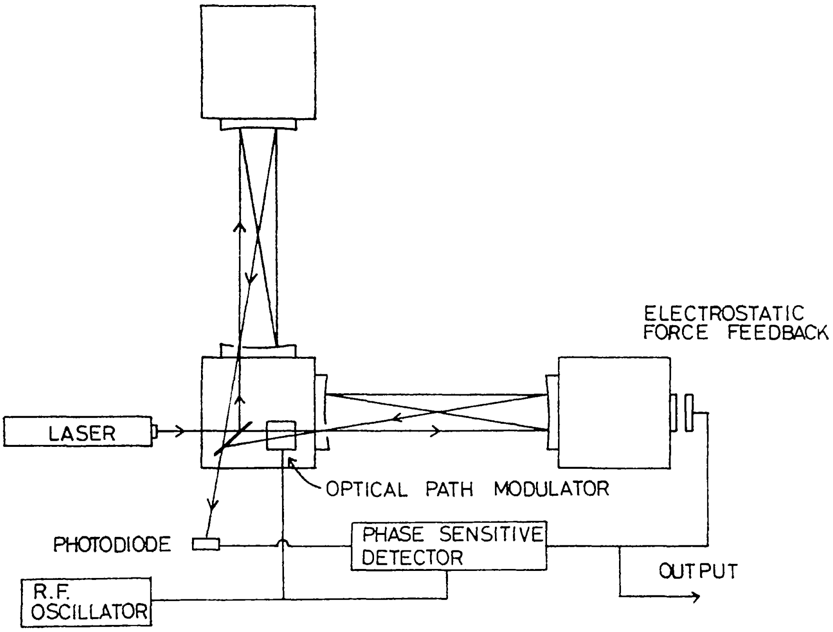

FIG. 3. One possible arrangement for a gravitational radiation detector with separated masses, using a modified Michelson interferometer to detect displacements.

being used in some preliminary experiments at Glasgow using optical sensing. The output of the interferometer is used to apply a force electrostatically to one of the masses, so that the two optical paths are kept almost precisely equal, and the output may then give a measure of forces induced by a gravitational wave.)

It might be mentioned that experimental work on gravitational wave detectors of this type, incorporating the methods suggested by Weiss, is also being carried out at the Max Planck Institute in Munich.

Let us now consider some of the possibilities of separated-mass detectors in a more general way, and speculate about some of their future prospects. What factors are likely to limit the sensitivity of detectors of this type? One obvious fundamental one arises from the statistical fluctuations in the number of photons detected during the effective observing time (corresponding approximately to the period of the gravitational wave). This factor depends on laser power, baseline, mirror reflectivity and quantum efficiency of the photodetector, as well as on pulse duration. For millisecond pulses, and a baseline approaching that set by light travel time (perhaps about 100 metres), it seems that photon statistics alone would not rule out a sensitivity better by several orders of magnitude than that of present detectors. There may, of course, be many other problems (some of the difficulties one could expect have been discussed by Weiss (**39**), and in publications by Braginsky, Rudenko, & Manukin (**40**, **35**), and others); and the experimental difficulties of suspending the separate masses in such a way that significant thermal noise is not introduced and there is sufficient isolation from ground vibrations may prove critical ones. However, I think it quite possible that this kind of detector may prove useful for millisecond pulses.

I think I might take the opportunity to point out also that this general type of separated-mass gravitational radiation detector may also have applications in other regions of the frequency spectrum. If the masses can be suspended in a way that does not restrict their motion significantly, then the system can be sensitive over a much wider range of frequencies than has been practicable with bar detectors. It would be very unwise to predict the sensitivity of such a system, with so many unknown problems, in advance; but perhaps I might take the risk of indicating how I think the limits to sensitivity set by three of the many possible significant factors might vary with duration of gravity-wave pulse. I consider here just statistical fluctuations in numbers of photons detected, Brownian motion of the masses caused by residual gas in the vacuum system, and statistical fluctuations in recoil momentum imparted to the masses by the photons. In Fig. 4 are given order-of-magnitude estimates based on these effects, for a system with 100-metre baseline, masses of 150 kg, and an ultrahigh vacuum ($10^{-10}$ torr). The quantum efficiency of the photodetector is taken as 50 per cent and the reflectivity of the mirrors 0·997. The vertical scale indicates limits to integrated flux over the pulse, for a gravitational wave pulse of waveform corresponding to a single cycle of a sine wave, of period equal to burst duration, and with optimum polarization and direction of propagation. (The line indicating photon statistical fluctuations is drawn assuming laser power used in region BC was adjusted at each particular burst duration to minimize the joint effect of photon statistics in the sensing process, and photon recoil fluctuations.) It should be emphasized that at least three more factors which are likely to be very important in experiments on long pulses are *not* shown here – thermal noise from the system suspending the masses, effects of seismic vibrations communicated via the suspensions, and effects of changing gravitational fields produced by local moving objects. Indeed thermal noise from the suspension alone would dominate the gas Brownian noise indicated unless the system had extremely high $Q$ and quite long period.

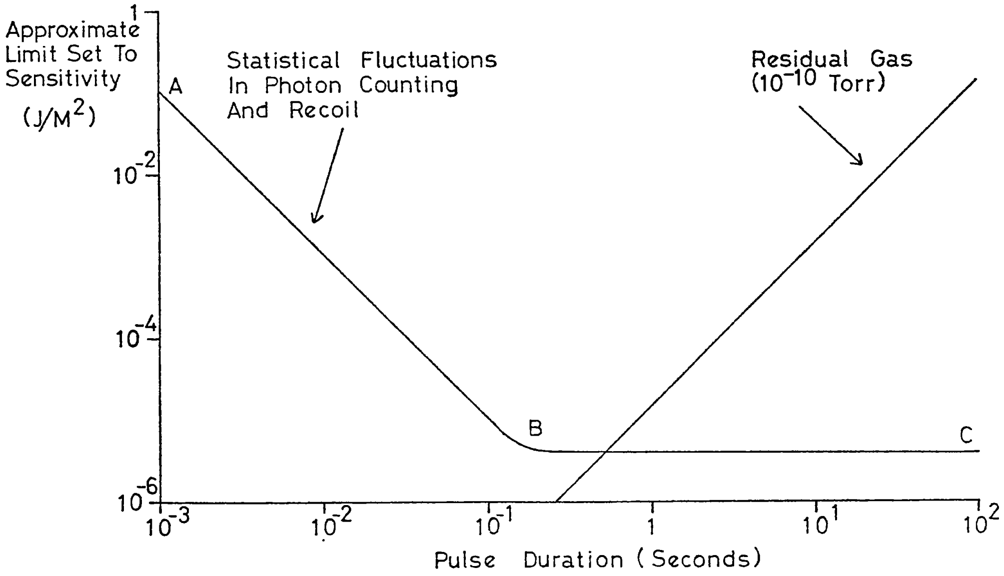

FIG. 4. Approximate dependence on pulse duration of some fundamental limits to sensitivity of a separated-mass detector of fixed baseline imposed by photon statistics, photon recoil fluctuations and Brownian motion from residual gas. Curve ABC is drawn for a maximum laser power of 2 watts, for which photon recoil is unimportant in region AB. In region BC power is assumed adjusted to minimize total fluctuations from photon statistics and recoil. Line BC is close to a limit set by the uncertainty principle for observations based on position measurement. (In a practical ground-based detector other factors, such as thermal noise from suspensions, ground vibrations, and local gravity-gradient fluctuations are likely to become significant before some of the basic limits shown are reached.)

The magnitudes shown in Fig. 4 should not be regarded as real estimates of sensitivity of any practical gravitational radiation detector, but I felt the diagram might usefully indicate how *some* of the factors which might set limits to sensitivity could vary with pulse period. Although the experimental problems of seismic isolation and varying local gravity gradients become rapidly more serious as signal frequency decreases (unless avoided by doing the whole experiment in an orbiting satellite) it does seem possible that separated-mass detectors may eventually prove useful for investigating longer-period gravity wave signals than those searched for with present bar detectors. In this connection it may be worth remarking that in a very recent paper, Thorne & Braginsky (41) have discussed possibilities of production of relatively long gravitational-wave bursts from super-massive black holes in the nuclei of distant galaxies and quasars, and the fluxes from such sources (and perhaps from massive black holes in other locations) may well provide interesting targets for future experiments.

Overall, I think the future for separated-mass gravitational wave detectors looks reasonably encouraging. There are difficult experimental problems to be overcome, but, as with the two other techniques described here, improvements in sensitivity by several orders of magnitude do not seem to be ruled out.

## 5. THE FUTURE

In the second half of this review I have discussed three quite different techniques, each one of which may in the future lead to improvements by many orders of magnitude in the sensitivity of experiments on gravitational radiation. There are other possibilities, too (such as spacecraft tracking experiments, for example). It is clear that detection of gravitational radiation presents a considerable challenge to experimental physicists and astronomers, as well as raising some fundamental questions. A sustained further effort is quite likely to be required in development of experimental techniques, but I think it probable that this will be well worth while. When gravitational waves are detected simultaneously at a few locations spaced around the Earth then interesting information could be expected to come in rapidly, for directions of the sources could be deduced from phase differences or arrival times. Pulse waveforms and polarization data would be of interest; and if gravity-wave pulses could be correlated with optically observed phenomena such as supernova outbursts, then the precise check of velocity of propagation could provide a valuable test of gravitation theory (42). At that stage important new results for astronomy and physics can be confidently expected. This may be some time in the future, but I hope I have discussed in this review enough of the recent developments in this rapidly changing subject to explain the renewed excitement felt by some of the workers in the field at the present time.

## ADDITIONAL NOTE

In this mixture of review with some new material I have concentrated on experimental techniques, for this seems to me one of the parts of the subject most urgently in need of development at present. In spite of this I have had to omit mention of many important pieces of experimental work, and significant ideas. For example, it has not been possible to discuss the interesting experiments which have been attempted using the Earth's crust, the Earth as a whole, or the Moon, as a gravitational wave detector (43), or possible experiments using spacecraft (44). I have also had to miss out many other ingenious and interesting suggestions and proposals which have been made for detection of gravitational radiation. For anyone interested in following the subject further, I might mention that a number of good reviews have been published. Some have already been quoted: Press & Thorne (7), Misner, Thorne & Wheeler (8), Braginsky (9), Braginsky & Rudenko (40), and Rees (10). Other interesting reviews include those by Fellgett & Sciama (45), Ruffini & Wheeler (46), Sciama (47), Hawking (48), Aplin (49), Logan (50), Misner (51), Sejnowski (52), Papini (53), and Pizzella (54). These papers, taken together, give a much more detailed picture of the development of the subject up to a year or two ago than has been possible in the present review, and contain many additional references.

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