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LASER INTERFEROMETER GRAVITATIONAL RADIATION DETECTORS

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ABSTRACT

Some techniques proposed or currently under development for detection of gravitational radiation by laser interferometers are reviewed, with particular emphasis on experiments covering the lower frequencies potentially accessible to ground based instruments.

INTRODUCTION

Surveys of expected sources of gravitational radiation[1] suggest that gravitational waves are arriving at the earth over a wide frequency spectrum and in a variety of forms - including pulses and bursts from stellar or black hole collapse or collision processes, periodic signals from pulsars or binary systems, and a general stochastic background. Most of the experimental work done in this field so far has used resonant bar gravitational wave detectors in searches for millisecond pulses which might be produced in collapse of stars to give supernova or black holes. An alternative detection technique, in which laser interferometers are used to sense relative motions of "free" test masses, is showing promise for future experiments of this type which may be significantly more sensitive; and also for wideband searches over an extensive range of frequencies for signals from various different kinds of source. We will review here some of these experimental developments, and possibilities which look likely to open up.

The experimental difficulties of gravitational wave detection arise almost entirely from the extremely small magnitude of the effects to be observed, and it may be useful to give an indication of these magnitudes. It is convenient to think here in terms of the amplitude of the gravitational radiation - which corresponds approximately to the maximum fractional change in apparent distance between two free test masses which can be produced by the passing wave. In these terms, a gravitational wave pulse from a star in our galaxy collapsing to give a supernova or a black hole might have an amplitude of order 10^{-18} to 10^{-20}, and a duration of order 1 millisecond. This is a small amplitude, and to bring it into perspective it might be noted that the most sensitive gravity wave detector to date - the cryogenic bar detector at Stanford University - has only recently approached this sensitivity. Moreover the number of such collapse events in our galaxy is expected to be small - perhaps only one per 10 to 30 years. It would clearly be desirable to observe signals more frequently than this; and one way of doing this would be to improve sensitivity sufficiently to detect events in a large number of galaxies. To detect signals of this type at the rate of once per month it is estimated that a detection

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sensitivity in the range 10^{-20} to 10^{-22} may be required. Considerations of this type make a sensitivity of about 10^{-21} seem a good target for future experiments, and indeed a number of other possible radiation mechanisms look likely to give signals of about this amplitude also. This target is not an easy one, however. It corresponds to achieving a gravitational wave flux sensitivity better by a factor of 10^6 than that of current instruments; and in test masses 1 kilometer apart it would correspond to relative motions of only 10^{-18} m.

Signals of larger amplitude may be expected at lower frequencies, from collapse or collision processes involving supermassive black holes. It has been suggested[2], for example, that black holes of mass 10^5 times the solar mass, at the Hubble distance, could lead to bursts of duration about 10 seconds and amplitude of order 10^{-18}. For this and other reasons there is considerable incentive for extending gravitational wave searches to lower frequencies.

Detection of periodic gravitational waves is also of considerable interest. It has been shown[3] that pulsars may in general be expected to radiate gravitational waves at frequencies near the radio pulse repetition frequency and at twice this frequency, and measurements of signal amplitudes would give information on the pulsar shape, orientation and structure. Estimates of amplitudes are uncertain at present, but for the Crab pulsar, for example, a gravitational wave amplitude of order 10^{-26} might be expected at a frequency of 60 Hz. In searches for a signal of known frequency, such as this, sensitivity can be significantly improved by suitable data analysis and integration over an extended observing time, and detection of this kind of signal may become quite practicable, although outside the range of current experiments.

The orders of magnitude of expected gravitational wave signals just quoted give some idea of the problems to be faced, and give good but difficult targets for planning experiments. It is not at all impossible that there are stronger signals than these, produced by mechanisms not yet considered, and the amplitudes could be much larger than those indicated without violating any basic ideas. Experiments at lower levels of sensitivity are well worth carrying out but the targets mentioned are interesting ones to aim at in the long term. We will consider now what might be done using laser interferometer techniques.

BASIC ARRANGEMENT

In this approach changes in separation between test masses induced by the gravitational wave are sensed optically; and to avoid need for extreme absolute stability a differential measurement is made along two baselines perpendicular to one another, which may be oppositely affected by a gravitational wave. A possible arrangement, in principle, is indicated in Fig. 1. Here three test masses are suspended like pendulums, with periods long compared with the period of the gravitational waves of interest, and are placed to

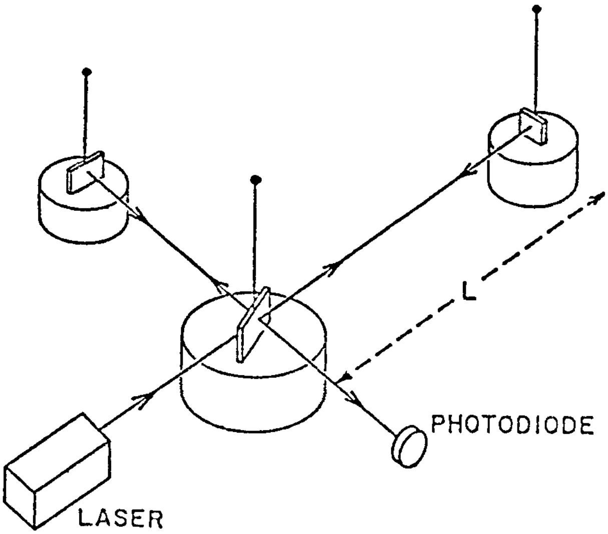

Figure 1

form a pair of perpendicular baselines, each of length L. Gravitational waves travelling in a vertical direction may give a differential motion which could be detected by a Michelson interferometer which monitors distances between two mirrors and a beamsplitter attached to the masses as indicated.

Several factors could limit the sensitivity of this simple gravity wave detector. A fundamental one is the quantum limit to detectable change in position of the test masses corresponding to the uncertainty principle, which sets a limit to displacement detectable over time τ of $(2\hbar\tau/m)^{\frac{1}{2}}$ where m is the mass and $2\pi\hbar$ is Planck's constant. With a baseline of 40 m, and 100 kg masses, the corresponding gravity wave amplitude for a 1 millisecond pulse is about 10^{-21}. This quantum limit is near our target sensitivity but it can be reduced by increasing the baseline or the size of the masses, and is unlikely to be the most serious difficulty.

A more important practical limit may come from photon counting error. Statistical fluctuations in photon counting rate in the output light from the interferometer set a limit to the change in optical path which is detectable. The corresponding limit to detectable gravitational wave amplitude is given approximately by $(\lambda\hbar\, c/8\pi\, L^2 I\tau)^{\frac{1}{2}}$, where I is the power of the laser illuminating the interferometer, λ is the wavelength of the light, c is the velocity of light, and the photodiode is assumed to have unity quantum efficiency. With a 40 m baseline and a laser giving 1 watt of light at 500 nm the photon counting limit to gravitational wave amplitude sensitivity is of order 2×10^{-17} for a 1 millisecond pulse duration - which is far from our target sensitivity. Sensitivity might be improved by increasing baseline length or laser power, but it would be difficult to reach our target by doing this alone, and other methods are necessary. It may be noted here, however, that pioneering experiments with a laser interferometer gravity wave detector were carried out with a configuration essentially similar to this one by Forward[4], who achieved performance near the photon noise limit with a low power laser.

The displacement sensitivity of a Michelson interferometer may be improved considerably by arranging that the light within each arm is reflected back and forwards many times between mirrors attached to the test masses before recombining at the beamsplitter, so that the optical path difference resulting from a given mirror motion is increased. This multireflection technique was suggested in this context by R. Weiss[5], who proposed use of Herriott delay lines to achieve the many reflections.

MULTIREFLECTION MICHELSON INTERFEROMETERS

A schematic diagram of one arrangement for a multireflection Michelson interferometer gravity wave detector is shown in Fig. 2.

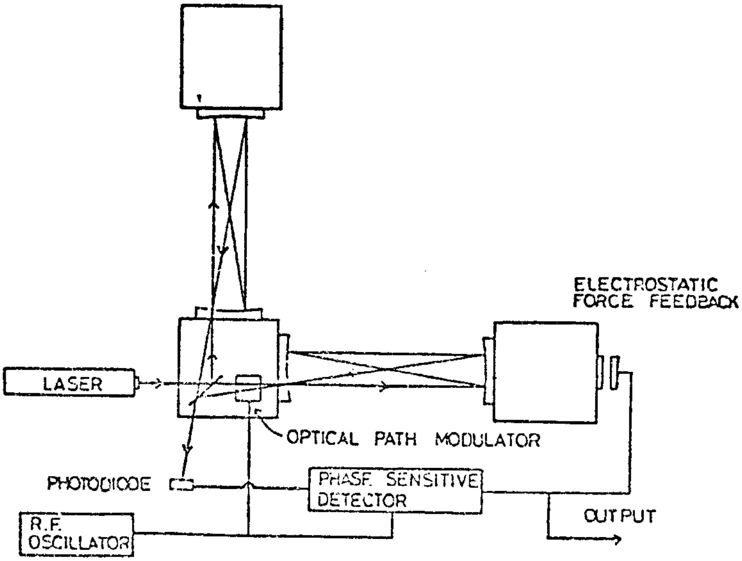

Figure 2

Here one of the optical paths is phase modulated at a high radiofrequency and an electrostatic force feedback system is used to control the position of one of the masses, and lock the interferometer onto a dark fringe of the interference pattern, where in this case the optimum photon-noise-limited sensitivity and useful rejection of low-frequency laser intensity noise is obtained.

If reflection losses in the mirrors are negligible, then the improvement in gravity wave sensitivity obtained by this type of multireflection system is proportional to the number of round-trip traversals between the test masses made by the light. In a large instrument with low-loss mirrors a limit to the number of useful reflections may be reached when the light spends a time within the system comparable to the time-scale of the gravitational wave, and the photon noise limit to sensitivity then becomes independent of the arm length L, and is better than that of a simple Michelson interferometer by the factor $2L/c\tau$. For a 1 millisecond pulse and a laser power of 1 w, this limiting sensitivity is about 2×10^{-21} (at unity signal to noise ratio).

Early experimental work on multireflection Michelson interferometers at the Max Planck Institute in Munich and at the University of Glasgow showed that incoherent scattering at the mirrors can give serious noise in these systems, since light which reaches the photodetector by a path different from that of the main beam can have its phase modulated significantly by quite small fluctuations in laser frequency. The Munich group suggested[6] avoiding this problem by carefully controlled frequency modulation of the laser, designed to cause the phase of scattered light to average to zero; while the Glasgow group suggested use of a different type of optical system[7] based on Fabry-Perot optical cavities, which looked likely to be less affected by scattering,and to have other useful properties in addition. A considerable amount of experimental work has now been carried out at Glasgow, and also in a newer project at the California Institute of Technology, on these Fabry-Perot cavity interferometers.

OPTICAL CAVITY INTERFEROMETERS

A simplified diagram of one type of optical cavity gravitational wave detector is shown in Fig. 3. Here Fabry-Perot optical cavities are formed along each baseline between highly-reflecting mirrors attached to the test masses. Light from the laser passes through a beamsplitter into both cavities. If the length of one of the cavities matches an integral multiple of the laser wavelength then resonance occurs, light entering via the small transmissivity of the input cavity mirror makes many reflections back and forth between the cavity mirrors, building up to a high stored intensity, and the phase of the light emerging backwards from the input mirror then varies very rapidly with small changes in either cavity length or laser wavelength. The cavity behaves in some ways like an optical delay line with all the beams folded on top of one another. The phase difference between the light emerging from within the cavity

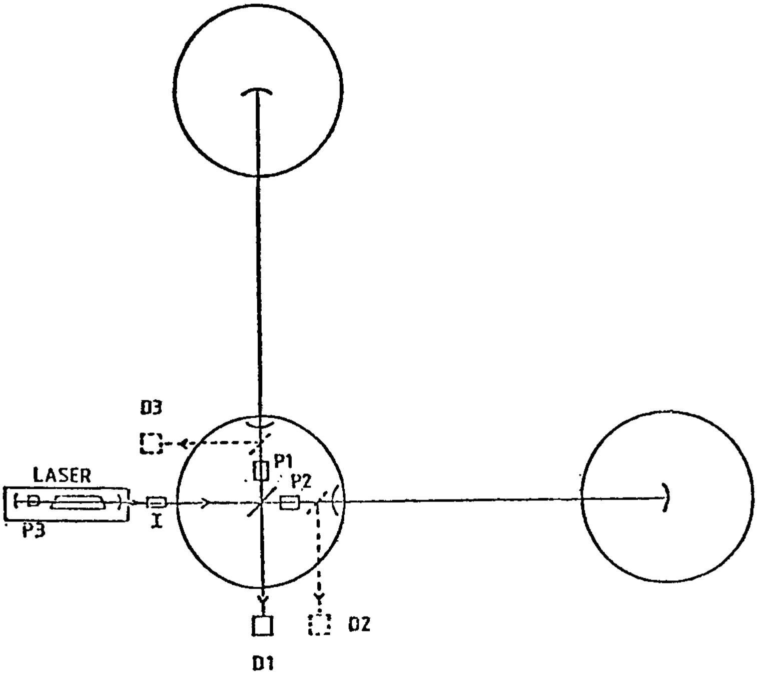

Figure 3

and the light from the laser can be monitored by phase modulating the input light at a high radiofrequency using electro-optical modulators P1 and P2, and synchronously demodulating the signal from photodiodes D2 and D3 which detect part of the light coming back from the cavity mirror. For each of the cavities, the optical phase difference obtained is a measure of the amount by which the cavity resonance deviates from the wavelength of the light. If one of the phase signals is used to stabilise the laser wavelength, and lock the laser to that cavity, and the other is used to adjust the average length of the second cavity to match the laser, then it would be possible to look for gravity wave signals by taking a difference between the two phase error signals. Slightly higher sensitivity may in principle be achieved by directly measuring the difference in phase between light from the two cavities by means of photodetector D1, if the modulators P1 and P2 are driven in antiphase with one another.

This complete interferometer behaves in some respects like a multiple reflection Michelson interferometer; and it can be shown that the sensitivity is effectively similar to that of a multireflection Michelson with the same light storage time, provided absorption losses in the input mirrors are not important. The system is slightly more complex than the Michelson interferometer due to the requirement for precise control of the laser frequency, but there is the practical advantage that the cavity mirrors and the vacuum pipes enclosing the beams between the test masses can be relatively small in diameter. Mirrors of diameter 18 cm would be quite adequate even for an interferometer with arms 10 km long.

Experimental development of gravitational wave detectors based on both the multireflection Michelson system and the optical cavity system just described is now at a fairly advanced stage, and in each case has led to overall experimental arrangements which are considerably more complex than suggested by the simple diagrams here. Additional feedback systems are necessary to control orientation and position of the test masses, and it has been found important to reduce fluctuations in direction and position of the laser beam by active or passive optical systems. Although there are still many technical problems to be overcome, the work has gone far enough to suggest that optical sensing performance close to theoretical estimates is likely to be achievable. And methods which may improve optical performance further are still being devised[8]. It may be useful to consider now some of the other basic noise sources in these gravity wave detectors.

THERMAL NOISE

Thermal noise is much less important in laser interferometer gravity wave detectors than in resonant bar detectors since there is no direct connection between the test masses at the gravitational wave frequency. Some thermal noise may enter the system through losses in the pendulum suspension, however, along with Brownian noise from collisions of residual gas molecules. A separate source of thermal noise arises in the internal thermal motions of the test masses themselves and of associated structures supporting mirrors and other components. We will not take space to discuss these noise sources in detail here, since they are covered in the companion paper by Spero[9] and in other accounts[5,8], but we note that with careful mechanical design it would seem practicable to keep this noise small in the kiloherz region of the spectrum. At lower gravity wave frequencies - approaching 1 Hz or lower, suspension and gas noise may become a major problem.

ISOLATION FROM SEISMIC DISTURBANCES

Seismic noise is a well recognised problem for all gravitational wave detection experiments, and very effective isolation techniques have been developed for frequencies in the neighbourhood of 1 kiloherz for work with resonant bar detectors. Stacks of alternate layers of rubber and lead or steel give good attenuation at these frequencies, and even the simple pendulum suspension of the test masses in a free mass detector can give useful high frequency isolation. As we consider looking for gravitational waves at lower frequencies, however, the problems become rapidly more difficult. Seismic noise amplitudes increase, and as the attenuation of a simple spring-mass isolator at a frequency f, well above its resonance frequency f_0, is proportional to $(f_0/f)^2$ it becomes harder to achieve good passive isolation. There do exist several special suspension systems with very low natural frequencies, and we have considered, for example, a differential torsion balance arrangement as shown in Fig. 4. as a low frequency gravitational wave detector[10], with an interferometer to sense changes in distances between the four test masses. However this would be an awkward arrangement to make on a large scale. For experiments in the frequency range from 1 kHz down to about 10 Hz there are several ways of improving the effective isolation achievable with a pendulum suspension. One relatively simple possibility is to monitor changes in inclination of the wire suspending the test mass, and from this deduce, and correct for, accelerations due to ground motion. To make such horizontal acceleration monitoring independent of tilts of the ground we introduced the idea of a "reference arm" - a bar freely pivoted close to its center of gravity so that it retains its orientation unchanged over the time scale of interest - and the measurements are made relative to this as indicated in Fig. 5. This reference arm technique has been experimentally developed by N. Robertson et al. at Glasgow[11]. Such an arrangement is effectively a horizontal accelerometer or displacement monitor using the whole test mass, and if the sensing to the reference arm is done with an interferometer comparable to that used between the test masses high sensitivity can be achieved, and accurate compensation for seismic noise can in principle be made. Systems of this type can be extended

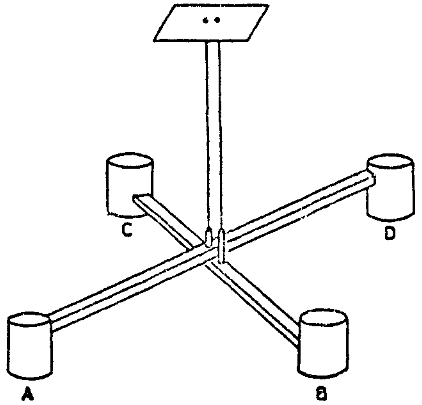

Figure 4

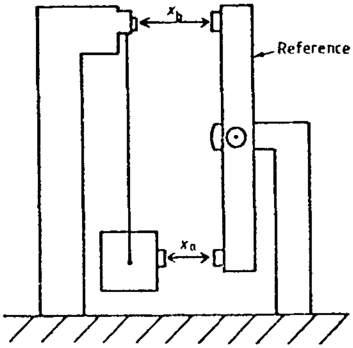

Figure 5

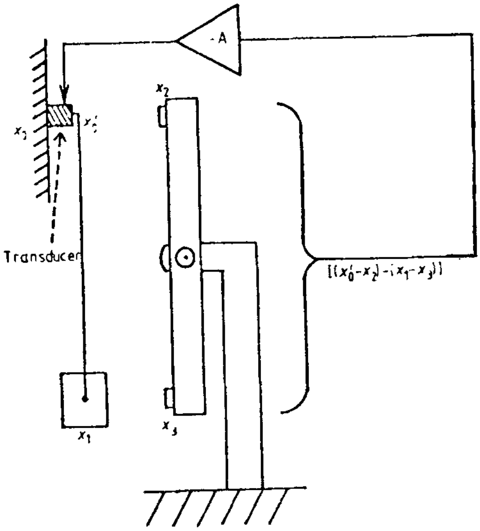

Figure 6

to directly reduce the seismically induced motion of the test mass by using feedback to move the point from which the test mass is suspended, as indicated in Fig. 6., and experimental work on several arrangements of this type has been done at Glasgow[11], while some preliminary tests have also been made at Caltech. It may be noted also that a feedback antiseismic system equivalent in principle to these but operating in a vertical direction - where tilts are unimportant - has been developed by Faller and Rinker[12] at JILA for measurements of acceleration due to gravity.

We have discussed seismic isolation at some length here because it seems to be generally considered that seismic noise will be the main factor limiting low frequency gravitational radiation experiments, and we think it more likely that changing gravity gradients from moving objects will be a more serious problem. It is possible that some of these gravity gradient fluctuations may be reduced by performing the experiments in a suitably quiet underground location, and an underground laboratory may well be a suitable site for a range of gravitational wave experiments.

We may conclude this review by noting that the laser interferometer gravitational radiation detectors described probably still require a considerable amount of development before detection of predicted gravitational waves can be expected. The prospects look good, however, and possibilities for real development of gravitational wave astronomy look interesting and exciting.

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