After 35 years of experimental research, we are rapidly approaching the point at which gravitational waves (GWs) from astrophysical sources may be directly detected by the long-baseline detectors LIGO (USA), GEO 600 (Germany/UK), VIRGO (Italy/France) and TAMA 300 (Japan), which are now in or coming into operation.

A promising source of GWs is the coalescence of compact binary systems, events which are now believed to be the origin of short gamma-ray bursts (GRBs).

In this paper, a brief review of the state of the art in detector development and exploitation will be given, with particular relevance to a search for signals associated with GRBs, and plans for the future will be discussed.

Keywords: gravitational waves; laser interferometer; gamma-ray bursts; LIGO; GEO 600

1. Introduction

For many years, there has been controversy over research into the existence of gravitational waves (GWs). Indeed, several early relativists were sceptical about their existence. However, the field has been recognized by the 1993 Nobel Prize in Physics being awarded to Hulse and Taylor for their experimental observations and subsequent interpretations of the evolution of the orbit of the binary pulsar PSR 1913+16, the decay of the binary orbit being consistent with angular momentum and energy being carried away from this system by GWs (Hulse 1994; Taylor 1994). Further, long-baseline detectors—LIGO, VIRGO, GEO 600 and TAMA 300—with a sensitivity sufficient to allow some possibility for the detection of astrophysical sources, including GW signals associated with gamma-ray bursts (GRBs) and soft gamma-ray repeaters (SGRs), are now coming into operation (Takahashi et al. 2004; Acernese et al. 2006; Hild 2006; Waldman 2006).

These detectors use laser interferometry for motion sensing over kilometre-scale distances.

2. Gravitational waves

GWs, predicted in General Relativity to be produced by the acceleration of mass (Einstein 1916), are propagating strains in space that in their simplest form lead to tiny quadrupole deformations of mechanical systems with which they interact.
The strain ($\delta l/l$), between objects a distance $l$ apart, is represented by the GW amplitude ($h$) where $h = 2\delta l/l$. For quadrupole radiation, there are two orthogonal polarizations of the wave at 45° to each other, of amplitude $h_+$ and $h_{\times}$, and each of these is equal to twice the strain in space in the relevant direction. Thus, a Michelson interferometer formed between freely hanging mirrors might undergo a differential change in its arm lengths.

Owing to the very weak nature of gravity and lack of dipole radiation, the efficiency of converting mechanical energy in a system into gravitational radiation is very low and thus signals produced by accelerating systems tend to be very weak. Indeed, the only sources of GWs that are likely to be detected are astrophysical, where there are potentially huge masses accelerating very strongly. Thus, GW detectors will uncover dark secrets of the Universe by helping us to study the sources in extreme physical conditions: strong nonlinear gravity and relativistic motion, extremely high density, temperature and magnetic fields, to list a few. GW signals are expected over a wide range of frequencies, from $10^{-17}$ Hz in the case of ripples in the cosmological background to $10^{3}$ Hz or greater. These higher frequency signals can originate from a number of sources, for example, when compact neutron star or black hole binaries coalesce (believed to have short GRBs associations; Eichler et al. 1989; Paczynski 1991) or in the collapse resulting from supernova explosions (believed to have long time-scale GRB associations; Woosley 1993) or when quakes take place in the crusts of neutron stars as may be associated with SGRs. For a recent review of a range of GW sources see Grishchuk (2004) and references therein. It is important to note that predicted strains in space at the Earth are typically of the order of $10^{-21}$ or smaller.

3. Long-baseline interferometric detectors on Earth

This idea of using laser interferometry between freely suspended test masses was proposed in 1962 (Gertsenshtein & Pustovoit 1962), but its implementation had been awaiting the availability of relevant laser and optical technologies. Indeed, Robert Forward (a former student of Weber) built the first laser interferometric prototype in the early 1970s at the Hughes Aircraft Laboratories in Malibu, although the sensitivity was limited by the short distance between the masses and the low power of the helium–neon laser used (Moss et al. 1971). The concept is very attractive in that it offers the possibility of very high sensitivities over a wide range of frequency (Weiss 1972).

This technique is based on the Michelson interferometer and is particularly suited to the detection of GWs, as they have a quadrupole nature (figure 1). The waves propagating perpendicular to the plane of the interferometer will result in one arm of the interferometer being increased in length while the other arm is decreased and vice versa. The induced change in the length of the interferometer arms results in a small change in the intensity of the light observed at the interferometer output.

With the increasing availability of argon-ion lasers and then neodymium YAG lasers with the capability of producing watts of single frequency light, a number of prototype detectors were constructed around the world (see Hough et al. (2005) for more discussion on this) leading to the funding and building of the

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current generation of long-baseline instruments—LIGO, VIRGO, GEO 600 and TAMA 300 (Takahashi et al. 2004; Acernese et al. 2006; Hild 2006; Waldman 2006)—which will be described in a later section.

In order to observe a full range of sources and initiate GW astronomy, a sensitivity or noise performance in strain of below $10^{-23}/\sqrt{\text{Hz}}$ has to be achieved over most of the proposed operating range from 10 Hz to a few kilohertz. For an Earth-based detector, the distance between the test masses is limited to a few kilometres by geographical and cost factors. If we assume an arm length of 3–4 km, detecting a strain in space of the above level implies measuring a residual motion of each of the test masses of around $10^{-20}$ m $\sqrt{\text{Hz}}^{-1}$. This sets a formidable but achievable goal for both the fine mechanics and the optical detection system of the interferometer.

(a) Current situation with interferometric detectors

The American LIGO project comprises two detector systems with arms of 4 km length, one in Hanford, Washington State, and one in Livingston, Louisiana. One half-length, 2 km, interferometer has also been built inside the same evacuated enclosure at Hanford (Waldman 2006). A bird’s eye view of the Hanford site showing the central building and the directions of the two arms is shown in figure 2. Construction of LIGO began in 1996 and progress has been outstanding with the instruments currently (September 2006) being at design sensitivity.

The French/Italian VIRGO detector of 3 km arm length at Cascina near Pisa is designed to have similar minimum sensitivity but a better performance at lower frequencies, down to 10 Hz, and is coming into operation (Acernese et al. 2006). The Japanese TAMA 300 detector, which has arms of length 300 m, is operating at the Tokyo Astronomical Observatory (Takahashi et al. 2004).

All the systems mentioned above are designed to use resonant cavities in the arms of the detectors to enhance their responses and use simple wire sling techniques for suspending the test masses. However, the German/British detector, GEO 600, is somewhat different (Hild 2006). It makes use of a four-pass-delay-line system with a novel optical technique known as signal recycling (Meers 1988; Strain & Meers 1991; Grote et al. 2004) and uses fused silica suspensions of very low mechanical loss for the test masses to help reduce thermal noise (Strain et al. 2004; Rowan et al. 2005). GEO is reaching a sensitivity at frequencies above a few hundred hertz,
Figure 2. (a) Schematic diagram and (b) bird’s eye view of LIGO (Hanford), with current strain sensitivity curves for the LIGO 4 km interferometers S5 performance, June 2006 LIGO-G060293-01-Z (c). Images and figure courtesy of the LIGO Scientific Collaboration.
approaching that of LIGO. GEO is now fully built and its sensitivity is being continuously improved. Currently, it is within a factor of approximately 3 of its broadband design sensitivity over much of its frequency range.

Four science runs, ranging from 17 to 70 days in length, have so far been carried out with these new interferometric detectors and a fifth has currently been underway for nearly a year. All have involved the LIGO detectors, and the GEO detector was involved in three of the first four data runs and has been operating fully in the fifth data run for the past five months. From the earlier science runs, upper limit results on the signals from a number of potential sources such as pulsars and coalescing compact binary stars, as well as on burst events and the level of a stochastic background, have been set (Abbott et al. 2005a,b, 2006a,b) and a limit on the GW flux associated with GRB030329 has been set (Abbott et al. 2005c). It should be noted that there had been early searches for correlations between GRBs and GW bursts using low-temperature bar detectors, see Tricarico et al. (2003) and Abbott et al. (2005c) for example.

During the period of the first four science runs, there has been a search with the LIGO detectors for short duration GW bursts coincident with 39 GRBs (Leonor 2006). Triggers for the GRBs were provided by the GCN and IPN networks, and searches were carried out over a time-interval of 120 s before the reported burst (to allow for delays in the em signal) and 60 s after. Waveforms of the GW bursts potentially associated with the GRBs were not known and thus cross-correlation of the signals from two LIGO interferometers were used to look for enhanced correlations over time-scales of 25 and 100 ms, signal bandwidth being from 40 Hz to 2 kHz. Using this sample, there was no evidence for coincident GW bursts and the best level of strain sensitivity set was approximately $7 \times 10^{-22}$ for circularly polarized GWs.

Abbott et al. (2005a,b, 2006a,b)
The search has continued during the fifth science run. In this case, there were 53 GRB triggers in the first five months of the run, six of these being associated with short GRBs. Again, in the case where there was at least coverage by two detectors, no events outside of the expected statistics have been observed (Leonor 2006). In addition, it should be noted that a more targeted search for signals associated with short GRBs using template techniques for searching for binary coalescence signals is also underway (Dietz in preparation).

A search for quasi-periodic oscillations following the SGR 1806-20 hyperflare has also been carried out with a bound on the GW strain set at the LIGO Hanford detector (Matone 2006). This corresponds to a characteristic isotropic energy release at the source of the order of $10^{-8}$ solar masses for the 100 Hz frequency region, where the predicted QPO frequencies and LIGO’s best sensitivity match. The previous search carried out with the Auriga detector (Baggio et al. 2005) reported a limit of the order of $10^{-6}$ solar masses for the 900 Hz frequency region where this detector is sensitive. Analyses of the LIGO data for more recent flares (SGR 1900+14 and SGR 1806-20) are being carried out. Further discussion on the detection of GWs from SGRs, as discussed in a poster at this meeting, can be found in Clark et al. (2006).

(b) The next steps

During the next few years, we can expect to see a series of increasingly sensitive searches for GW signals at a sensitivity level of approximately $10^{-21}$ for millisecond pulses or close to $10^{-26}$ for pulsars, to take two examples. This latter level is equivalent to a neutron star having an ellipticity of approximately $10^{-8}$ and is astrophysically feasible. Thus, the detection of GWs from pulsars in the near term is a real possibility. Further, the recent discovery of another compact binary system in the galaxy—the double pulsar J0737-3039—has improved the statistics for the expected rate of binary coalescences by a significant factor, implying that the most probable rate of binary neutron star coalescences detectable by the current LIGO system now lies between 1 per 10 years and 1 per 600 years (Kalogera et al. 2004). Many people expect the rate of black hole/neutron star (and black hole/black hole) coalescences to be significantly higher. This is of particular significance for the potential detection of signals associated with short GRBs.

Since detection at the level of sensitivity of the initial detectors is no way guaranteed, some enhancement of performance by increasing laser power and by improving the optical and suspension systems is envisaged over the next few years and may well yield exciting returns. But, improvement of the order of a factor of 10 to 15 in sensitivity of the current interferometric detectors is essential to allow compact binary coalescences to be detected at a useful rate. Plans for a significantly rebuilt LIGO, ‘Advanced LIGO’, are already mature and the project has been approved by the National Science Board in the USA, funding being expected to start in the financial year 2008. The proposed design for Advanced LIGO has 40 kg silica test masses, suspended by fused silica fibres (as used in GEO 600) or ribbons, along with an improved seismic isolation system, increased laser power (approx. 200 W) and signal recycling (Fritschel 2001). The upgrade is now expected to commence in 2010, and it is exciting to note that the most probable rate of detectable binary neutron star coalescences is now expected to be in the range of 10–500 per year (Kalogera et al. 2004). The noise anatomy for Advanced LIGO is shown in figure 3. Similar plans for upgrading VIRGO on essentially the
same time-scale are under development. Further, a proposal and underpinning research is well advanced for an underground detector (LCGT) with cooled test masses to be built in Japan (Kuroda 2006). There is also a significant effort to find funding to expand an 80 m interferometer—currently used for technological developments—in Western Australia to kilometre scale.

For GEO, a different upgrade strategy is being adopted. A proposed upgrade will be targeted at the observation of the oscillations of neutron stars resulting from quakes in pulsars or magnetars, possibly associated with SGRs, and detector improvement will be in the area of enhancing narrowband sensitivity around a few kilohertz (Willke et al. 2006).

4. The future

The next stage forward in interferometric detectors is well defined with the proposed upgrades in the US and Europe, and with proposals for new detectors in Japan and Australia. We can see a really exciting future ahead as fundamentally new information about many violent astrophysical events including GRBs and SGRs is uncovered.

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