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The Search for Gravitational Waves

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Abstract. An extended data taking run involving the long baseline gravitational wave detectors – LIGO, Virgo and GEO 600 – is close to an end and results of astrophysical significance are being produced. In this short review the development of the detectors and plans for the future will be discussed.

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INTRODUCTION

Ever since their prediction by Einstein in 1917, gravitational waves have been the subject of some controversy as to whether they can be directly detected. However with the commissioning, operation and potential upgrading of the long baseline detectors LIGO (USA), GEO 600 (Germany/UK), Virgo (Italy, France) and TAMA 300 (Japan) we are heading into an era where this controversy will be resolved. A full discussion may be found in [1].

GRAVITATIONAL WAVES

Gravitational wave signals are expected over a wide range of frequencies; from 10^{-17} Hz in the case of ripples in the cosmological background, through signals in the audio band from the formation of neutron stars in supernova explosions, to 10^{10} Hz from the cosmological background itself. The most predictable sources are binary star systems. However there are many sources of much greater astrophysical interest associated with black hole interactions and coalescences, neutron star coalescences, low-mass X-ray binaries such as Sco-X1, stellar collapses to neutron stars and black holes (supernova explosions), rotating asymmetric neutron stars such as pulsars, and the physics of the early Universe. The signals from all these sources are at a level where detectors of very high strain sensitivity – of the order of 10^{-22} to 10^{-23} over relevant timescales – will be eventually required to allow a full range of observations and such detectors may be on ground or in space. From an experimentalist's point of view gravitational waves are best thought of as fluctuating strains in space-time.

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LONG BASELINE INTERFEROMETRIC DETECTORS

There are currently in operation, or in final stages of commissioning, a network of gravitational wave detectors each of which is based on using laser interferometric sensing to detect the changes, induced by gravitational waves, in the relative arm lengths of large-scale variants of Michelson-type interferometers, where the arms are formed between freely-hung mirrors.

The American LIGO project [2] 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. Construction of LIGO began in 1996 and progress has been outstanding with operation at instrumental design sensitivity now having been achieved as is indicated in Fig.1.

The French/Italian Virgo detector [3] of 3 km arm length at Cascina near Pisa, as shown in Fig.2, is close to completing commissioning and the Japanese TAMA 300 detector [4], which has arms of length 300 m, is operating at the Tokyo Astronomical Observatory.

All the systems mentioned above are designed to use resonant cavities in the arms of the detectors and use standard wire sling techniques for suspending the test masses.

However the German/British detector, GEO 600 [5], is somewhat different. It makes use of a four pass delay line system with an advanced optical signal enhancement technique known as signal recycling and utilises very low loss fused silica suspensions for the test masses.

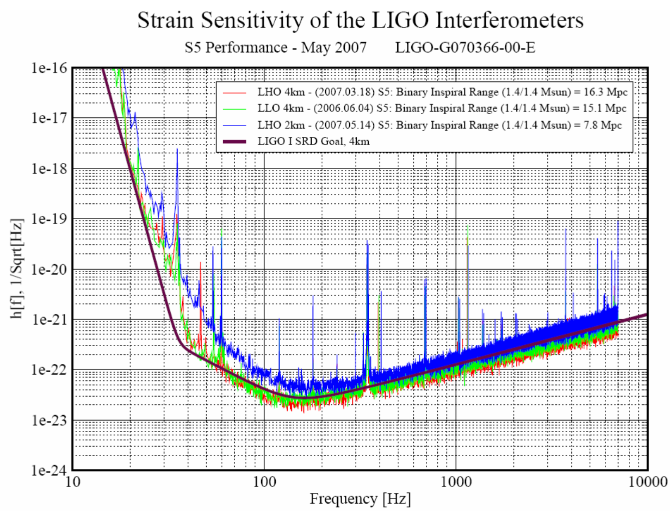

FIGURE 1. Amplitude spectral density of the noise from the LIGO detectors compared with the design goal (Courtesy of LIGO).

FIGURE 2. Bird's eye view a) of the LIGO detector site at Hanford (courtesy of the LIGO project) and b) of the Virgo detector site at Cascina in Italy (courtesy of the Virgo project).

GEO is now fully built and its sensitivity is being continuously improved. Currently it is within a factor of 3 of design sensitivity over a significant fraction of its frequency range.

Four science runs have so far been completed with these new interferometric detectors. All have involved the LIGO detectors, three have involved the GEO detector and two had TAMA involvement. The TAMA collaboration has completed 9 runs, 2 jointly with LIGO.

New 'upper limits' have been set on the strength of gravitational waves from a range of sources: coalescing compact binaries, pulsars, burst sources and a stochastic background of gravitational waves [6]. The fifth science run of the LIGO detectors started on 4th Nov 2005 with GEO having joined for data taking periods from January 2006 and Virgo from May 2007. This run is expected to terminate at 0000 UTC 1st October 2007 when the LIGO system will have one complete year of 'triple coincidence' data from all three of its detectors and will be the longest stretch of data taking with interferometric detectors to date.

During the next few years following intermediate upgrades to the LIGO and Virgo detectors we can expect to see searches for gravitational wave signals at a sensitivity level where a detection could be made. Recent discoveries of additional compact binary systems have improved the statistics for the expected rate of binary coalescences detectable by the LIGO system by a significant factor, giving some possibility of a first detection over the next few years [7]. An upper limit on the rate of BH-BH coalescences could be around 2 events per year.

However detection at the current level of sensitivity of the initial detectors is in no way guaranteed; thus improvement of the order of a factor of 10 to 15 in sensitivity of the current interferometric detectors is needed to reach sensitivity levels where many signals are expected.

Thus plans for an upgraded LIGO, 'Advanced LIGO', are already well formed. Advanced LIGO will incorporate 40 kg fused silica test mass mirrors, suspended by fused silica fibers or ribbons, along with an improved seismic isolation system, and increased laser power, close to 200 W. The upgrade is expected to commence in 2010, with full installation and initial operation of the upgraded system by 2014. On approximately the same timescale we can expect to see a similar upgrade to VIRGO, the rebuilding of GEO as a detector aiming at high sensitivity in the kHz frequency region and the building of a long-baseline underground detector, LCGT [8], in Japan. To go beyond this point, however, a number of challenges involving mechanical losses in coatings, thermal loading effects, and the use of non-classical light to bypass the standard quantum limit will have to be met. Cryogenic test mirrors and non-transmissive optics [9] are likely to be adopted, using materials of high thermal conductivity such as silicon.

Thus research groups in the field are already looking towards the next generation of ground-based detectors and a European design study for such a system funded under the EC Framework 7 programme is expected to commence early in 2008. Meanwhile there is a high level of activity in research towards the space-borne detector LISA, the Laser Interferometer Space Antenna [10] illustrated in Fig.3.

LONG BASELINE DETECTORS IN SPACE

Perhaps the most interesting gravitational wave signals (those resulting from the formation and coalescence of black holes in the range 10^3 to 10^6 solar masses) will lie in the region of 10^{-4} Hz to 10^{-1} Hz, and a detector whose strain sensitivity is approximately 10^{-23} over relevant timescales is required to search for these. The most promising way of looking for such signals is to fly a laser interferometer in space. LISA is being proposed by an American/European team; it consists of an array of three drag-free spacecraft at the vertices of an equilateral triangle of length of side 5 x 10^6 km. This cluster is placed in an Earth-like orbit at a distance of 1 AU from the Sun, and 20 degrees behind the Earth. Proof masses inside the spacecraft (two in each spacecraft) form the end points of three separate but not independent interferometers. LISA is a project in NASA's Beyond Einstein Program and the advisory committee reviewing the program (BEPAC) has very recently recommended that LISA be the Flagship mission for the program. They have recommended that LISA be preceded by the Joint Dark Energy Mission (JDEM) and thus LISA is expected to be launched as a joint NASA/ESA mission in 2018 and to be producing data for up to ten years. A demonstrator mission, LISA Pathfinder, is in phase C/D of development and hardware is being built for a launch in late 2010.

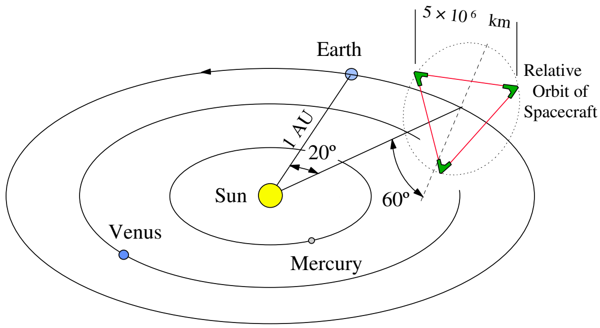

FIGURE 3. Schematic diagram of LISA and its orbit around the sun

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