Gravitational waves

B.S. Sathyaprakash1 and Walter Winkler[2]

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One of the open fundamental questions in physics is the direct observation of gravitational waves – an observation as important as Hertz's pioneering experiments with electromagnetic waves and the vindication of Maxwell's theory. Existence of gravitational waves is generally accepted, at least since their indirect observation via energy and angular momentum losses in binary pulsars, like in the Hulse-Taylor pulsar. Much more fascinating is the information we will get via direct observation of gravitational waves about the large-scale behaviour of matter under extreme density, temperature and magnetic fields. Examples include normal mode oscillations and quakes in neutron stars, catastrophic astrophysical events like gravitational collapse and the ensuing supernova, black hole formation, mergers of compact binaries, etc. Nowhere else one can learn in more detail about the conditions that prevailed at a time close to the creation of our universe in a big bang. Gravitational waves are hardly dispersed by surrounding matter, far less compared to neutrinos. However, it is only extremely non-linear and/or highly relativistic gravity that can produce detectable amounts of gravitational radiation. Therefore, the information we get from different windows of observation – electromagnetic, neutrinos, gravitational waves - complement each other.

Theory

According to Einstein's general relativity gravitation can be thought of as a consequence of curvature of space and time caused by the presence of matter and energy. The waves associated with gravitation can, therefore, be regarded as an oscillation in the curvature of space-time. One can imagine a passing gravitational wave to effect a strain in space very similar to the tidal deformation caused by an inhomogeneous gravitational field. Any matter present in its path will suffer a tidal force, which is the basic principle used in the construction of gravitational wave antennas or detectors. Gravitation being the weakest of all interactions, gravitational waves are difficult to generate and detect in the laboratory. However, a catastrophic astronomical event in the presence of strong gravitational fields, such as an exploding star or a coalescing and merging binary consisting of compact stars, constitutes a highly luminous source of gravitational radiation. Gravitational waves are characterised by a dimensionless amplitude – a measure of the strain in space they cause as they pass through. A supernova explosion at the centre of our Galaxy will give rise to waves of amplitude $h \sim 10^{-19}$ causing a sub-nuclear displacement of a tenth of a Fermi between two particles separated by a km. Most astronomical sources emit signals that will have even smaller amplitudes. Indeed, the product of the internal (i.e., on a scale equal to the size R of the source) and external (i.e., at the location of the Earth) Newtonian gravitational potentials (which for a source of mass M at a distance r is $G^2M^2/(rR)$), divided by the fourth power of the speed of light, is a good first-order approximation to the gravitational amplitude of a non-stationary source. This immediately implies that unless a source at a given distance is highly compact, hence under the influence of strong gravitational effects, it is unlikely to be a bright source of gravitational waves. Gravitational wave sources are, therefore, good test beds of non-linear gravity. Gravitational wave observations will offer a unique opportunity to conduct many new tests of Einstein's gravity.

Background

Experimental search for gravitational waves began in 1969 when Joseph Weber in the United States used huge aluminium cylinders as resonant antennas. These detectors couple to one axis of the elliptical "deformation" of space induced by a passing gravitational wave. As a consequence, one observes a change in the state of oscillation of the fundamental eigenmode. Since the time of the first experiments, the sensitivity of resonant bars has been improved to a level where rare signals from catastrophic events occurring in our Galaxy could be detected. On the other hand, in the seventies the development of interferometric detectors started. Basically, these detectors are Michelson interferometers wherein a gravitational wave typically changes the lengths of the arms with opposite sign, thus creating an output signal. For isolation against mechanical disturbances the optical components are carefully suspended in vacuum. For the measurement of the strain in space, the signal-to-noise ratio of such a detector improves with increasing light power and with increasing arm-length. In the early eighties the shot noise limited performance was first reached with the Garching 30 m prototype, followed soon by the 10 m experiment in Glasgow.

Ground-based detectors

Thanks to a worldwide effort, five long baseline interferometric detectors are now in operation or nearing completion (Figure 1):

- German-British GEO600 with 600 m arm-length near Hannover,
- American LIGO comprising 2 detectors one in Hanford (State of Washington) and one in Livingston (Louisiana) with 4 km arm-length each,
- Japanese 300 m detector TAMA at Mitaka City in Tokyo, and
- French-Italian VIRGO with a 3km detector in Cascina near Pisa.

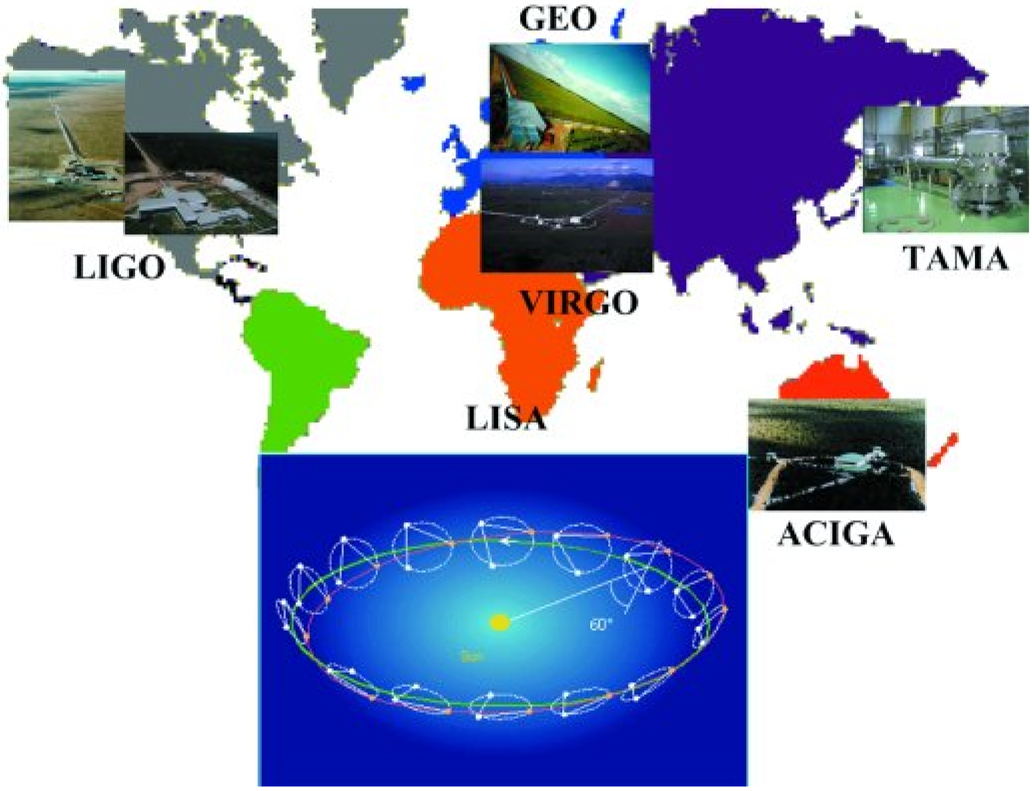

Fig 1 **A geographical view of the interferometer projects together with the orbit of LISA in the foreground.**

Gravitational wave antennas are almost omni-directional. Each interferometric detector has better than 50% sky coverage at sensitivity better than 50% of the rms sensitivity over the entire sky. However, this means a network of gravitational wave detectors will be needed to fully resolve an incident wave. A network of 4 to 5 detectors with a good sensitivity can monitor the entire sky over a wide range of frequencies for both transient and continuous wave sources.

First coincident observations are expected to take place in 2002 when the GEO and LIGO detectors come on-line. The expected initial sensitivity as a function of frequency is plotted in Figure 2, together with the performance of upgraded detectors.

The sensitivity is given in terms of the 1-σ noise background within a bandwidth of 1 Hz (i.e., linear amplitude spectral density) at the output of the interferometer. At low frequencies the performance will be limited by seismic noise, at medium frequencies by thermally induced motions of the optical components and at high frequencies by photo-electron shot noise. This sensitivity of initial instruments is sufficient to detect a rare supernova originating in our Galaxy or coalescence of a binary consisting of two stellar mass black holes at a distance of 100 Mpc. To start serious gravitational wave astronomical observations, a careful upgrading of the existing technology has to take place. This includes kW-type lasers to reduce the shot noise level, possibly purely diffractive optics to avoid problems with absorbed light inside optical components, new materials for mirror substrates and cooling of the main optics to reduce internal thermal noise. The fluctuating radiation pressure of the illuminating light requires mirror masses of up to tons.

There are three more or less well defined plans for future upgraded detectors: advanced LIGO, the Japanese Large Scale Cryogenic Gravitational Wave Telescope (LCGT), and EURO – a third generation gravitational wave interferometer in Europe. The performance of EURO, the most ambitious future detector, is described at frequencies above a few hundred Hz by the standard quantum limit, where shot noise and radiation pressure noise are balanced; at lower frequencies there is the Newtonian gravity gradient noise. The sensitivity of EURO as shown in Figure 2 represents the limits possibly reached when different topologies, like recycling parameters, are chosen for optimum sensitivity at each particular frequency. A network of upgraded interferometers and enhanced bar detectors will be able to register signals from stellar mass black holes from cosmological distances, quakes in neutron star cores (and hence an understanding of the state of matter at very high densities) in our Galaxy, supernovae and coalescing neutron star binaries at a redshift of z=1, etc. This is truly an attractive scenario for gravitational wave astronomy.

Space

At low frequencies – below a few Hz - the performance of ground-based detectors is limited by gravitational gradient noise, as caused, for instance, by motions inside the Earth’s crust or in the atmosphere. Measurement and subtraction of this disturbance can only work to a certain extent. To enter this very interesting frequency range it is necessary to go into space, as it is planned with the Laser Interferometric Space

Antenna (LISA). LISA is a *cornerstone mission* of ESA, and included in NASA's *Structure and Evolution of the Universe Roadmap.* The scheduled launch is around 2011. The technology will be tested in the precursor mission SMART II in 2006. In LISA, three spacecraft are arranged in an equilateral triangle of side $5x10^6$ km, trailing the Earth by 20 degrees in a heliocentric orbit (cf. Figure 1). Each of the three craft follows its own elliptic orbit slightly out of the ecliptic. Over the course of a year, the triangle seems to rotate about its centre-of-mass, maintaining the relative distances constant to within a percent, without any active corrections. Under the influence of gravitational waves the relative distances between the craft change. These are, therefore, continuously registered with laser interferometry. To avoid the noise caused by the fluctuating solar-wind and radiation pressure, the distance is measured between free flying test masses, each shielded by its surrounding spacecraft – by use of the so-called drag-free technique.

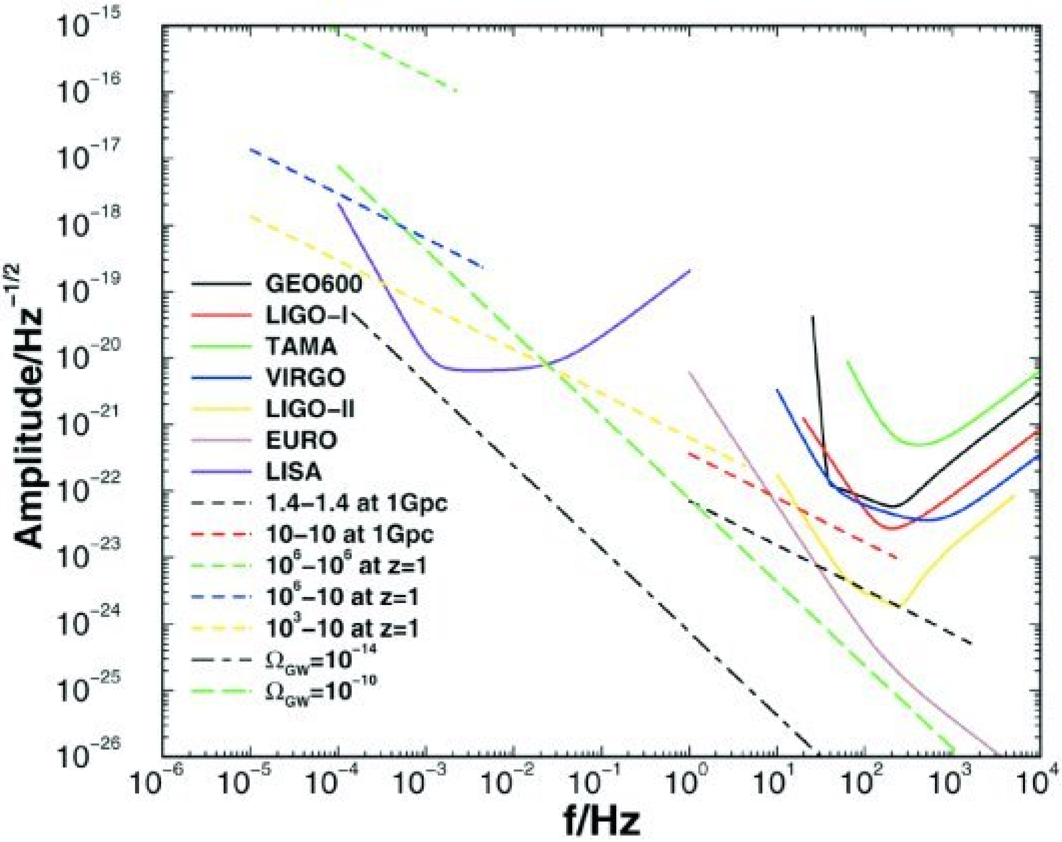

Fig 2 **The amplitude spectral density of noise (solid lines) expected in various ground-based interferometers and LISA. Also plotted are signal strengths (dashed lines) of two types of sources: (1) Inspiral and merger of compact binaries consisting of stars of masses m1-m2 (measured in solar masses) at a distance R and (2) primordial stochastic background whose energy density WGW is a certain raction of the closure density of the Universe.**

The sensitive frequency range of LISA is between 0.1 mHz and 1 Hz (Figure 2). For LISA there are guaranteed sources: Galactic compact binaries of period in the relevant range will be observed with a signal-to- noise ratio of up to 1000. But much more fascinating are the signals to be expected from a variety of less well- known origin – namely, events involving super-massive black holes that are believed to exist at the centre of every galaxy in the Universe. It is not clear how such black holes formed. It is possible that a mid-sized black hole forms simultaneously with the formation of the galaxy and then grows in size by accreting matter in the form of ordinary stars and black holes found in their vicinity. If this is so then a small black hole or a neutron star falling into a super-massive black hole emits gravitational waves. As the body slowly spirals into the hole both its orbit and spin are expected to precess, more violently as the body approaches the black hole, and it samples the geometry of space-time as it tumbles round. The dynamics of the body, as well as the nature of the space-time in which the body whirls around will be encoded in the waves we can potentially observe with LISA. In the early history of their formation galaxies are believed to have interacted strongly with one another leading to their mutual collision and merger. Such mergers should also involve the coalescence of the associated black holes. The waves emitted in the process will be visible at a very high signal-to-noise ratio wherever in the Universe the source might be. Thus, LISA should single-handedly give us a complete census of the super- massive black hole population in the Universe. Finally, and most importantly, it is hoped that LISA, or one of its successors, will shed light on the conditions that prevailed when the Universe was born. Nothing could be more exciting.

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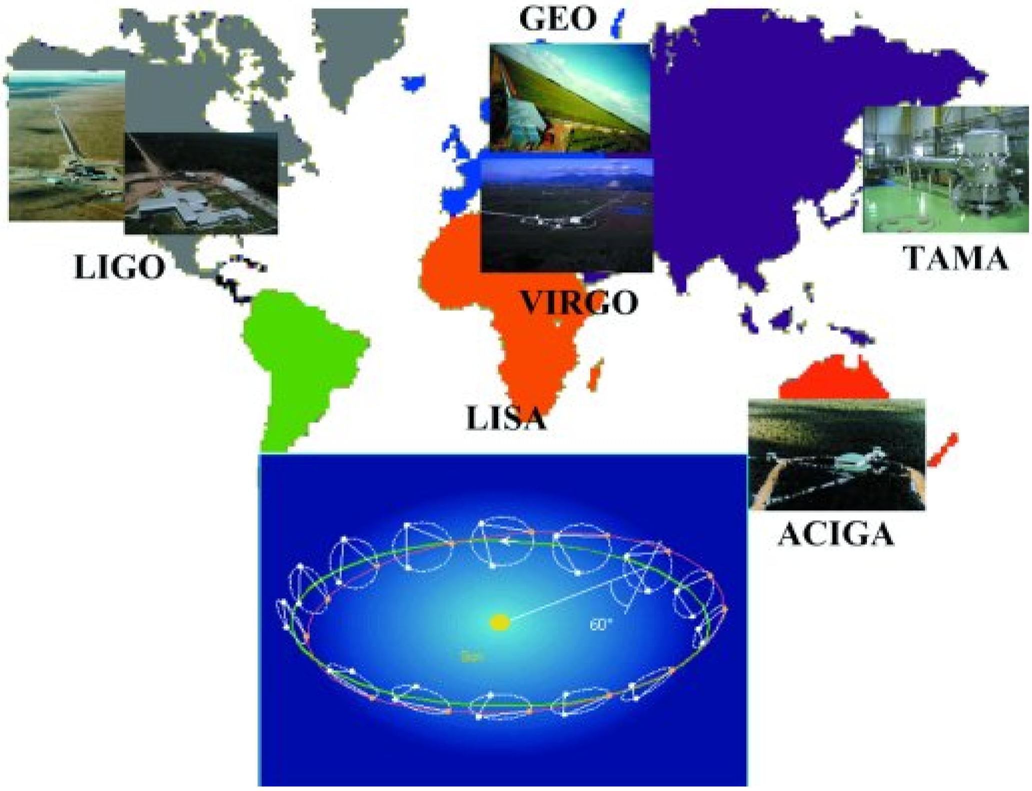

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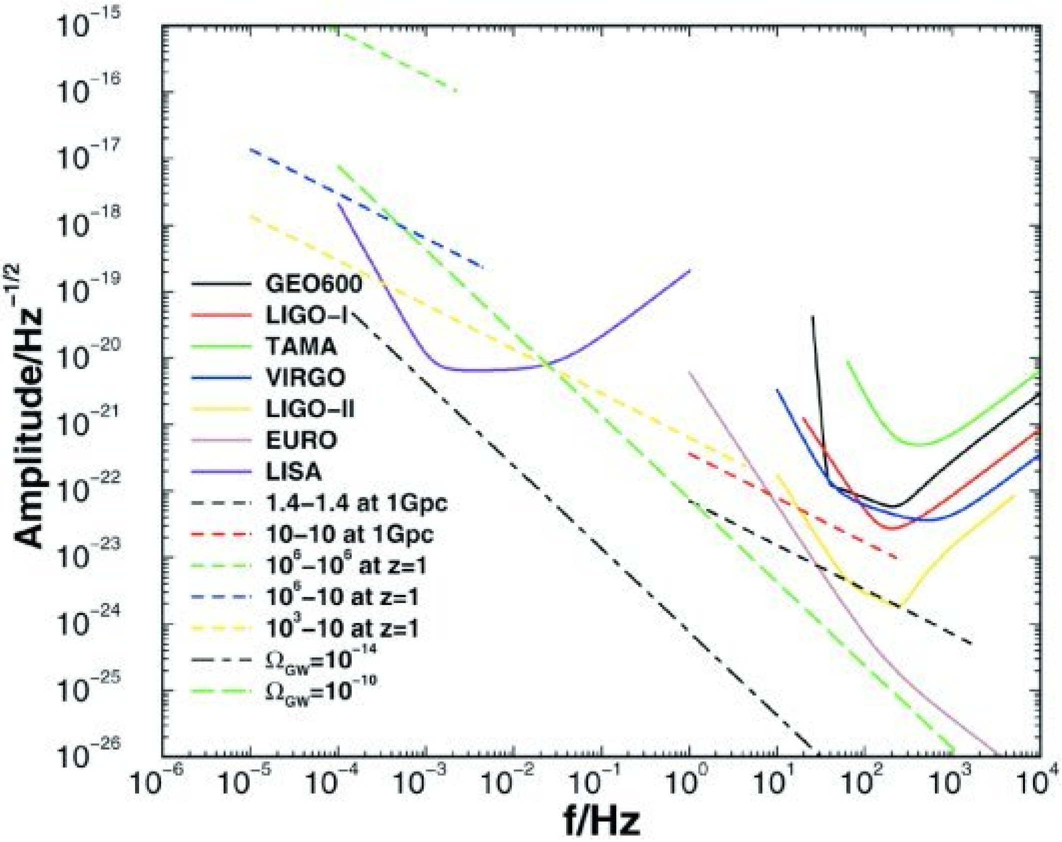

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