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Gravitational wave astronomy: Recent advances

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Abstract. Several groundbased gravitational wave (GW) laser interferometric projects have completed construction and are currently involved in conducting engineering runs. The spacebased NASA-ESA mission, LISA is expected to be launched in ten years' time. With the data around the corner exciting times lie ahead for GW astronomy. A brief introduction to GW detection, the principle of GW detection, the current status of ground based detectors, the space based detector LISA, GW sources and the data analysis necessary to extract the weak GW signal from the detector noise will be presented.

Keywords : Gravitational waves - interferometric detectors - astrophysical GW sources

1. Introduction

Gravitational waves(GW) can be described as a space-time warpage which travels with the speed of light. Astrophysical GW will bring us information complementary to that obtained from electromagenetic observations, because the GW have very different properties. GW are produced in compact, dense, high-velocity regions of matter in the universe and are not easily scattered, unlike electromagnetic waves. Therefore, it seems reasonable to expect a revolution in our understanding of the universe akin to the one brought on by radio astronomy in the last half a century.

In the near future, on the time scale of a few years, several large-scale detectors will come online. These include the LIGO, composed of two Laser Interferometer Gravitational-wave Observatories situated in the United States each with a baseline of 4 km, VIRGO, an

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Italian/French project located near Pisa with a baseline of 3 km, GEO600, a British/German interferometer under construction near Hannover with a baseline of 600 m, TAMA in Japan, a medium-scale laser interferometer with a baseline of 300 m, and with funding approval AIGO500, the proposed 500 m project sponsored by ACIGA [1]. TAMA is currently the world's largest detector in operation since 1999. The first long-term continuous data was taken in the autumn of 1999 and recently about 1000 hours of the data have been taken and a substantial part of it is sufficiently good for a serious search of GW. LIGO and VIRGO detectors have completed engineering data runs and serious GW data from LIGO should be available by the end of 2002.

With ground-based detectors it seems impossible to go below the 10 Hz limit due to gravity gradient noise as well as technological limitations. The solution is to go into space. The premier instrument in the low-frequency band is the Laser Interferometer Space Antenna (LISA). The LISA is a NASA and ESA project and there is good chance of LISA flying as early as 2011. LISA's goal is to detect and study low-frequency astrophysical GW [2]. While the Earth based detectors will operate in the high-frequency band $\sim 10 - 10^4$ Hz, the space based detectors will operate in the low-frequency band $10^{-4} - 10^{-1}$ Hz.

2. Gravitational wave detection

2.1 Gravitational Waves

A weak gravitational wave is described by a metric perturbation $h_{\mu\nu}$ in general relativity. Typically, for the astrophysical GW sources which are amenable to detection, $h_{\mu\nu} \sim 10^{-22}$. In the transverse-traceless (TT) gauge, the $h_{\mu\nu}$ can be expressed in terms of just two amplitudes, h_+ and $h_\times$, called the 'plus' and 'cross' polarisations. If a weak monochromatic gravitational wave of + polarisation is incident on a ring of test-particles, the ring is deformed into an ellipse as shown in Fig. 1. Phases, quarter cycle apart, of the GW are shown in the figure for the two polarisation states.

2.2 Principle of GW detection

The key to GW detection is the very precise measurement of small changes in distance. For laser interferometers, this is the distance between pairs of mirrors hanging at either end of two long, mutually perpendicular vacuum chambers. GW passing through the instrument will shorten one arm while lengthening the other. By using an interferometer design, the relative change in length of the two arms can be measured, thus signalling the passage of a gravitational wave at the detector site. For the + polarisation, a schematic of the interferometer is drawn in Fig. 1, which displays the shortening of one arm and lengthening of the other as the GW passes. If the change in the armlength L is δL, then,

$$\delta L \sim hL, \qquad (1)$$

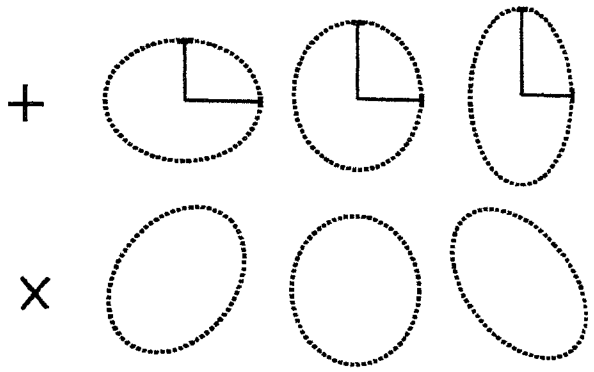

Figure 1. Deformation of a ring of test particles by GW with + (top row) and × polarisation (bottom row). Effect of different phases of the GW on the test-particle ring have been shown.

where h is a typical component of the metric perturbation.

For a GW source, h can be estimated from the well-known Landau-Lifschitz quadrupole formula. The GW amplitude h is related to the second time derivative of the quadrupole moment (which has dimensions of energy) of the source:

$$h \sim \frac{1}{r}\,\frac{G}{c^4}\,E^{\mathrm{kinetic}}_{\mathrm{nonspherical}}, \tag{2}$$

where r is the distance to the source, G is the gravitational constant, c the speed of light and $E^{\mathrm{kinetic}}_{\mathrm{nonspherical}}$ is the kinetic energy in the ***nonspherical*** motion of the source. If we consider $E^{\mathrm{kinetic}}_{\mathrm{nonspherical}}/c^2$ of the order of a solar mass and the distance to the source ranging from galactic scales of tens of kpc to cosmological distances of Gpc, then h ranges from 10^{-17} to 10^{-22}. These numbers then set the scale for the sensitivities at which the detectors must operate. Long arm lengths, high laser power, and extremely well-controlled laser stability are essential to reach the requisite sensitivity.

3. Ground-based laser interferometric detector network

Ground-based detectors fall broadly into two categories: (i) Resonant mass detectors, (ii) laser interferometric detectors. The resonant mass detectors consist of the bar type detectors and spheres. But because of their scalability and their broad band-width the laser interferometers have been favoured. Nevertheless, the resonant mass detectors can play a specialised role in GW detection. For example, at high frequencies, about a few kHz, such detectors would be useful, because the shot noise in the interferometers is large. Here, I will deal with interferometric detectors.

There are a host of noise sources in interferometric detectors which contaminate the data. At low frequencies there is the seismic noise. The seismic isolation is a sequence of stages consisting of springs/pendulums and heavy masses. Each stage has a low resonant frequency about a fraction of a Hz. The seismic isolation acts as a low pass filter, attenuating high frequencies, but low frequencies get through. This results in a 'wall' at low frequencies at around 10 Hz. At mid-frequencies up to a few hundred Hz, the thermal noise is important and is due to the thermal excitations both in the test mass - the mirror - as well as the seismic suspension. At high frequencies the shot noise from the laser dominates. This noise is due to the quantum nature of light. From photon counting statistics and the uncertainty principle, the phase fluctuation is inversely proportional to the square root of the mean number of photons arriving during a period of the wave.

Five interferometric detectors (perhaps six including AIGO) will be in operation soon. It is advantageous to have a network over a single detector because (i) we can improve on the confidence in detection by coincidence analysis, (ii) ascertain the location of a GW source, and (iii) obtain polarisation information of GW.

4. GW sources and data analysis

Several types of GW sources have been envisaged which could be directly observed by Earth-based detectors (see [3] and references therein for recent reviews): (i) Burst sources – such as binary systems of neutron stars (NS) and/or black holes (BH) in their in-spiral phase, BH/BH and/or BH/NS mergers, and supernovae explosions – whose signals last for a time much shorter, typically between a few milli-seconds and a few minutes, than the planned observational time; (ii) stochastic backgrounds of radiation, either of primordial or astrophysical origin, and (iii) continuous wave sources – e.g. rapidly rotating neutron stars – where a weak deterministic signal is continuously present in the data stream.

Inspiraling binaries have been considered highly promising sources not only because of the enormous GW energy they emit, but also because they are such 'clean' systems; the inspiral waveform can be computed accurately to several post-Newtonian orders adequate for optimal signal extraction techniques such as matched filtering to be used. In the past decade IUCAA has focussed on the design, validation and implementation of search algorithms for inspiraling binaries. Hierarchical search algorithms have been designed and are being improved to reduce the cost over a flat search [4].

The other important burst sources of GW are supernovae. It is difficult to reliably compute the waveforms for supernovae, because complex physical processes are involved in the collapse and the resulting GW emission. This limits the data analysis.

Continuous wave sources pose one of the most computationally intensive problems in GW data analysis. A rapidly rotating asymmetrical neutron star is a source of continuous gravitational waves. Long integration times, typically of the order of a few months or years are needed to build up sufficient signal power. Earth's motion around itself, the

Sun and the Moon Doppler modulates the signal, the Doppler modulation being dependent on the direction of the GW source. Thus, coherent extraction of the signal whose direction and frequency is unknown is impossibly computationally expensive. However, targeted searches are computationally viable, for example, if the direction to the source is known. In this context, LMXBs are extremely interesting candidate sources for Earth-based detectors. Several systems would be detectable by enhanced LIGO operating in the narrow-band configuration.

To detect stochastic background one needs a network of detectors, ideally say two detectors preferably identically oriented and close to one another. The signal is extracted by cross-correlating the outputs.

5. The space-based detector LISA

The lower (floor) limit of a few Hz of the band-width of the ground-based detectors is a serious limitation to observing GW events. Applying the general theory of relativity to astronomy, physicists have realised that the most predictable and most powerful sources of GW (such as supermassive blackholes) emit GW below 10 mHz. Also there are guaranteed sources in this regime which are observed from conventional astronomy. The floor limit is due to our inability to shield against gravity gradient noise arising from seismic activity, atmospheric disturbances etc. and also because of the technological limitations on long armlengths due to the earth's curvature. The solution is a detector in space.

LISA is a collaborative ESA(European Space Agency)/NASA mission. It will consist of three drag-free space-crafts - space-crafts shielded from buffeting by solar wind and radiation pressure - in heliocentric orbits following 20° behind the earth. They will form an equilateral triangle with sides 5×10^6 km inclined at an angle of 60° with earth's orbital plane. Each space-craft houses two lasers (1 Watt Yag) and each laser is phase locked to its companion and to the incoming light from the distant space-craft.The space-crafts rotate in a circle drawn through the vertices of the triangle and the LISA constellation as a whole revolves around the Sun. The goal of LISA is to detect and study low-frequency astrophysical GW. It will be sensitive in the band 10^{-4} Hz to 10^{-1} Hz. The astrophysical sources that LISA could observe include Galactic binaries, extragalactic supermassive blackhole binaries and coalescences, stochastic GW background from the Early Universe. The LISA and the ground-based detectors complement each other in an essential way. Since both types of detectors have similar energy sensitivities, their different observing frequency bands will provide crucial spectral information about the source. This is as important as complementing the optical and radio observations from the ground with observations in space at submillimetre, infrared, ultraviolet, X-ray and gamma-ray frequencies.

LISA data analysis differs from the data analysis for ground-based detectors in one crucial way: because the observations will be at low frequencies, the computational cost, data storage is not an important issue here. Also the GW sources tend to be relatively strong at low frequencies because the GW amplitude scales inversely with the frequency for a given energy. This in turn will give rise to high signal-to-noise ratios (SNR) for several GW sources. Since LISA consists of two partially independent interferometers, it can also detect stochastic background of GW produced in the Early Universe. The cancellation of laser phase noise is an important problem in LISA data analysis, since it is impossible to maintain equal distances between space-craft. Recently, we [5] have been able to span the space of all data combinations of the six laser beams which cancel the laser phase noise. This is likely to have a wide range of applications.

6. Future developments

The network of LIGO, VIRGO, GEO and TAMA will operate continuously for many years to come. It is possible that these first generation detectors might make the first detections of GW. Series of upgrades have been planned for the future. The second generation detectors will aim at increasing sensitivity and bandwidth and should come into operation after 2006. Work on the third generation of detectors is being strongly pursued now. They should start operating after 2010. Each generation will improve the amplitude senstivity by an order of magnitude. In the meanwhile LISA will open the low sensitivity window and should make several detections, some with high SNR. We therefore expect exciting times in the next decade in gravitational wave astronomy.

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