ADVANCES IN GRAVITATIONAL WAVE DETECTION

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ABSTRACT

In this review paper we will discuss the latest developments in gravitational wave detection and present strategies to detect gravitational waves, discuss potential sources and the information which these detectors can provide. We also give particular attention to the LIGO/VIRGO network, an array of earth based, kilometre scale, laser interferometers currently under construction which will operate at the high frequency end (1 to 10,000 Hz), and the proposed Laser Interferometer Space Antenna (LISA), a five million kilometre long facility that will orbit the sun and operate at the low frequency end (10,000 to 1 Hz). LISA is planned to significantly increase the capabilities of LIGO/VIRGO by enhancing exploration of stellar mass black holes (a few to a few hundred solar mass) down to supermassive black holes (a few thousand to a hundred million solar masses) in the centres of galaxies and quasars.

Keywords: - Gravitational wave detection, LIGO/VIRGO network, Laser Interferometer Space Antenna (LISA), High-frequency range, Low-frequency range, Stellar-mass black holes, Supermassive black holes

1. INTRODUCTION

Einstein's General Theory of Relativity (hereafter: Using the equations of general relativity (which predict the existence of gravitational waves)) it has been known for some time that these waves should propagate at the speed of light with two transverse quadrupolar polarizations [1] and are generated by the acceleration of massive objects, such as colliding black holes or neutron stars. The elusive waves have eluded detection by the scientific community for decades. But with the commissioning of ultrahigh precision, advanced detectors such as Advanced LIGO (Laser Interferometer Gravitational Wave observatory) and Advanced Virgo, the direct discovery of gravitational waves is now within reach[2]. Another possible application would be to advance the first direct detection of gravitational waves from the effect on pulsar timing at such extremely low frequencies (~several nHz)[3]. This review article is intended to reach nuclear and particle physicists knowledgeable of special relativity and electrodynamics, so as to understand the importance of gravitational waves, the technical methods in direct searches for this expected radiation, and the likelihood of finding them in the next decade [4]. It is motivated by fundamental scientific curiosity about novel phenomena and offers a unique opportunity to test general relativity itself, including the transverse and quadrupolar nature of gravitational radiation and to verify whether this radiation travels at the speed of light consistent with that expected for massless gravitons [5]. Gravitational waves also give us a different perspective on the universe, since they are not appreciably absorbed by cosmic dust and stellar envelopes, offering opportunities to probe some of the most exciting, yet enigmatic, objects in the cosmos [6]. Gravitational wave astronomy thus expands the human enterprise into a new non-electromagnetic spectrum, following the development of a progression of light bands from radio to gamma rays since the mid-20th century that have exposed numerous cosmic surprises. The exact distribution of detectable sources is still uncertain, but it is probably made up of a mixture of local galactic plane components plus distant cosmological isotropic components [8]. The Hulse-Taylor binary pulsar system (PSR B1913+16), which has indeed shown a gradual and measurable decrease in orbital period consistent with the expected energy loss from gravitational waves and for which the Nobel Prize in Physics was awarded in 1993[9], is a source of strong indirect evidence for gravitational wave emission. Such binary systems remain too low in frequency to be directly observed with current detectors, however the coalescence of such binary systems is a promising source of future detection, e.g., this system will do a dramatic merger that can be detected with modern gravitational wave observatories in an approximately 300 million years [10]. Advanced LIGO could probably detect roughly 40 per year NS-NS coalescences, and other systems, NS-BH and BH-BH, are not well constrained by current estimates of coalescence rates. Reasonable waveforms can be produced using post-Newtonian waveforms models and numerical relativity calculations to improve our understanding of expected waveforms [12], and detection rates can be expected to increase substantially over what will be possible with second generation detectors. Also, they come from other sources besides merger events, such as supernovae and gamma ray bursts; in the former case, yielding simultaneous electromagnetic signals to aid in detection confidence [13]. Current ground based gravitational wave interferometers and second generation interferometers currently under construction are addressed in this review, and future underground interferometers 3rd generation are briefly noted [14]. It will also discuss searches for extremely low frequency waves and longer term prospects for space based gravitational wave observatories [15]. For further reading, there are a number of comprehensive textual treatments of gravitational waves, Saulson, Maggiore, Creighton & Anderson, Jaranowski & Krolák[16], or of gravitation and general relativity that include gravitational radiation, Hartle, Misner, Thorne & Wheeler, Schutz [17]. Early review articles to which I would add to the set above are those of Tyson & Giffard and Thorne and in Blair [18] with Sathyaprakash & Schutz, Pitkin et al., and Freise & Strain discussing plans for second and third generation detectors [19].

2. FREQUENCY BANDS

There are four gravitational wave frequency bands that has been experimentally explored those are: the high-frequency band
(HF; $f \sim 10^4$ to 1 Hz),
the low-frequency band
(LF; $f \sim 1$ to 10^{-4} Hz),
the very-low frequency band
(VLF; $f \sim 10^{-7}$ to 10^{-9} Hz),
and the extremely-low frequency band
(ELF; $f \sim 10^{-15}$ to 10^{-18} Hz).

2.1 HIGH-FREQUENCY BANDS

A gravitational-wave source of mass M. The source is constrained by its gravitational radius, roughly $2GM/c^2$ and cannot happen at frequencies smaller than about $4GM/c^3$. Consequently, the emission frequencies for such a source are limited to: $f \leq \frac{1}{4\pi GM/c^3} \approx \frac{10^4 Hz}{M/M\odot}$, where $M\odot$ is the Sun's mass, and G and c In the gravitational constant c is replaced by 1, and in the speed of light G by 1. By this upper frequency limit, an object would have to have a mass into the Chandrasekhar limit, on the solar mass $M\odot$. Accordingly, the upper limit on gravitational waves in this range is expected to be $f_{max} \approx 10^4$Hz. The upper boundary of the high-frequency gravitational-wave spectrum is marked at ~Hz. Within this high frequency band, earth based detectors include laser interferometers and resonant mass antennas. Below about 1 Hz, these detectors are overwhelmed by noise from such things as Newtonian gravity gradients, vibrations from Earth, and sources that are difficult to mechanically filter below 1 Hz. The high ranging minimum of this noise defines the 1 Hz lower limit of the high frequency band, and realises require space based detectors for waves below 1 Hz. This band is dominated by key gravitational wave sources such as events like stellar collapse in our galaxy, black hole and neutron star and pulsar rotation and vibration, and the merging of neutron star and stellar mass black hole binaries (with masses as high as about $1000M\odot$). Other possible stochastic sources, such as loops from cosmic strings, early universe phase transitions, or the Big Bang itself, are also likely to be within this range.

2.2 LOW-FREQUENCY BANDS

This low frequency band is between 10^{-4} to 1 Hz. Space based detectors in Earth or inter planetary orbit watch primarily to 1 Hz. Primary detection methods include beacon tracking of spacecraft by microwave signals (used by NASA for more than just three decades now), and laser interferometry track between spacecraft currently in development. The upper edge of the low-frequency band at 1 Hz is defined by the noise thresholds in Earth-based instruments, while the lower edge near 10^{-4} Hz is set by challenges in isolating spacecraft from the fluctuating pressures of solar radiation, solar wind, and cosmic rays. The band in which this is true probably includes the sources such as short period binary stars in our own galaxy, as well as white dwarf, neutron star, or small black hole interactions with a massive black hole (within about 10^5 and $10^7M\odot$ The picture also includes mergers of supermassive black-hole binaries (with masses reaching $10^8M\odot$) in distant galaxies. This range may also be populated by background waves produced by early universe processes, e.g., cosmic strings, and the Big Bang.

2.3 VERY-LOW-FREQUENCY BANDS

Joseph Taylor and his colleagues have remarkably high sensitivity to gravitational waves, by observing the timing of millisecond pulsars in the very-low-frequency range. A gravitational wave that passes over Earth modulates the flow of time via tiny fluctuations in the arrival time of pulsar signals, which relies on precise clocks to measure the flow of time. If no such fluctuations are seen, it means that pulsar or Earth is not being rocked by gravitational waves above a certain level. But if a pulsar shows the same timing fluctuations as all the others, that could be a sign that gravitational waves really are messing with Earth. Repeated averaging of these arrival times over extended durations—namely, for periods of several months to decades—allows a truly remarkable degree of timing precision. Relatively high accuracy for this means researchers can be very stringent on the existence of gravitational waves that affects either Earth or the pulsar. The upper limit of the VLF range, approximately 10^{-7} Hz, is determined by the minimum averaging period necessary to obtain high accuracy, while the lower limit, around 10^{-9} Hz. The corresponding timespan, of order 20 years, corresponds to the timespan since stable millisecond pulsars were first identified. Normally, strong gravitational-wave sources are small and near to their gravitational radii. Massive compact bodies of sizes $10^{11}M\odot$theoretically, they are capable of emission within the VLF or lower frequency bands (1–30 solar masses). Yet, as usual, conventional astronomy implies this mass does not exist, so strong gravitational waves in this band probably come from early universe phenomena like cosmic strings, phase transitions, or the Big Bang itself. Measurements in this frequency band are often described stochastically as a parameter, this is the background. $\Omega_g(f)$, the fraction of the energy required to close the universe over a frequency range) $\Delta f = f$. Currently, the 95% confidence limit for Ω_g is based on pulsar timing in the VLF band.

$\Omega_g(4 \times 10^{-9}\text{Hz}) < 6 \times 10^{-8} H^2$, where H is the Hubble constant, given in units of 100 km/s/Mpc. Now this limit challenges the idea that the universe might be filled with enough cosmic string loops to get the job done.

2.4 EXTREMELY-LOW-FREQUENCY BANDS

The gravitational waves in the extremely-low-frequency band span frequencies from 10^{-15} to 10^{-18} Hz, bear unique insight into the structure and evolution of the universe. Due to their large wavelengths, these waves are expected to cause small distortions in the cosmic microwave background-the residual radiation from the early universe. The ELF band lies at frequencies so low that gravitational wavelengths extend close to the Hubble distance, or the size of the observable universe. This huge span in wavelength allows such waves to affect the CMB on a cosmological scale, and in so doing induce a quadrupolar-or four-lobed-anisotropy pattern in the radiation that can be returned as a detectable signature of gravity's action on the infant universe. The most accurate observations in this frequency range are those from its low-frequency edge, at 10^{-18} Hz. Here, the theoretical gravitational waves are stretching and compressing all of the space within the cosmological horizon, which affects the CMB with quadrupole distortions indicative of energy density across those frequencies. This quadrupolar effect is a result of wave-induced stretches of space in one direction while compressing it in another. These would, in turn, produce temperature fluctuations within the CMB proportional to gravitational wave intensity. Importantly, the COBE satellite has made measurements of this quadrupolar anisotropy in the CMB. The results from COBE have set some of the most stringent limits on the energy density of gravitational waves in the ELF band. Given these measured anisotropies are caused indeed by gravity waves, they imply an energy density for $\Omega_g(10^{-18}\text{Hz}) \approx 10^{-9}$. This now puts a constraint in trying to model those early-universe processes which might have given rise to such waves. The research in gravitational waves of the ELF band is necessary for understanding the stochastic background-a random, low-level gravitational wave "noise" created by an enormous number of sources from all over the universe, including the cosmic strings, phase transitions, and other processes that may have occurred shortly after the Big Bang. In the ELF range, the stochastic gravitational wave background would carry important implications for both standard and exotic models of cosmology. For example, if cosmic strings of the early universe existed and were sufficiently dense to produce these gravitational waves, they may have played a role in the large-scale structure formation of galaxies. This low-frequency limit of ELF gravitational waves also signifies a frontier for astrophysical research, since it pushes against our present capability of measuring and interpreting gravitational effects across huge expanses of time and space. The ELF band thus represents both a measurement boundary and a test of current models in cosmology, whereby alternative theories may explain energy densities which COBE and other instruments have inferred. Advances in the detection technology could allow future space-based observatories to scan this frequency range in far greater detail than is currently possible, unravelling additional secrets about the universe's evolution from its very earliest moments.

3. DETECTORS

3.1 OVERVIEW

Gravitational wave detection has seen significant development since the middle of the last century, when one topic of debate was whether gravitational waves were an actual prediction of general relativity or just artefacts of coordinate transformations. The physicalness of gravitational wave phenomena was then modified by recognition that energy could be extracted from the waves; thus, at least in principle, it should be possible to build a detector which would register their passage [20]. The following thought experiment inspired the first early gravitational wave detectors: if a gravitational wave passes through two masses coupled by a spring, it will in fact stretch and compress them, hence delivering energy to the spring, independent of the coordinate system used [21]. Initial experimental efforts searched for Earth's crustal vibrations, since the crust's normal modes could conceivably be excited by gravitational waves. This was not ideal because it was interfered with by natural seismic events for precise detection. The first physical detectors were metal bars designed to resonate with gravitational waves; these "bar detectors" measured wave-induced longitudinal oscillations using piezoelectric transducers. Joseph Weber of the University of Maryland pioneered this approach, reporting anomalies that were ascribed to gravitational waves, though other experiments failed to replicate his results [23]. The more sensitive bar detectors over the next several decades utilised cryogenic design to minimise thermal noise while utilising sophisticated transducers to increase sensitivity; by the late 1990s, five major bar detectors included Allegro at Louisiana State University and Nautilus at Frascati Laboratory and formed collaborations, such as the International Gravitational Event Collaboration (IGEC), that achieved strain sensitivities near 10^{-21}Hz Instructions: in narrow frequency bands around their resonances (700-900 Hz)[25]. They were, however, also restricted to detective only narrowband sources, unlike their modern interferometer counterparts. Gravitational wave interferometers heralded a revolution when laser-based Michelson interferometry was employed. This fully conceptual design first theorised by Gertsenshtein and Pustovoit in 1962[26] uses phase differences between light waves travelling in perpendicular arms to register gravitational waves. As Rai Weiss later emphasised, laser interferometers could be much more sensitive than bar detectors might ever hope to be [27]. Early prototypes, such as that built by Robert Forward at Hughes Aircraft, were the precursors to the large systems now operating as LIGO and Virgo. With the introduction of Fabry-Perot cavities into the interferometer arms, as well as "recycling" mirrors to increase laser power and tuning mirrors dynamically adjusting signal frequency, interferometers today are far more sensitive than had been thought possible [28].

3.2 DETECTORS AND THEIR DEVELOPMENT

About 30 years ago, the University of Maryland's Joseph Weber led some gravity wave detection experiments on Earth that were among the first. He first worked out low frequency gravitational waves by studying the excitation of Earth's normal modes [36]. He then began detecting gravitational waves, keeping aluminium bars at room temperature isolated from ground vibrations and lab noise [37, 38]. Tuned to 1600 Hz, these bars were to resonate at a frequency that is expected to pick signals from collapsing stars. Coincident detector excitations separated up to 1000 km apart occurred at a rate of roughly one event per day, according to Weber. While other studies in the U.S., Germany, the U.K. and Russia failed to reproduce his findings, doubts were cast as to whether he really had seen signals of gravitational waves. However, Weber's detectors were so sensitive (able to register strains on the order of 10^{-15} over milliseconds) that this was much too high. Weber bar detectors which combine sensitivity levels of 10^{-18} for brief millisecond signals with noise reduction achieved by cooling at Rome [39], Louisiana [40], and Perth, Western Australia [41] continue to evolve as research centres. But bar detectors have a limitation in that they are only capable of detecting signals at their resonant frequency.

3.3 LONG BASELINE DETECTORS

Such a design is innovative and versatile, and can provide exceptional sensitivity over an extremely wide frequency range [1, 2, 4]. In this design, test masses located at a separation comparable to the distance of the masses from the Sun are separated and suspended as pendulums. In this configuration isolation of the system from seismic disturbances and damping of the thermal noise are needed to mitigate the signal of interest. Detecting gravitational waves requires that this test masses' minute displacements be measured by the laser interferometry (Figure 1),

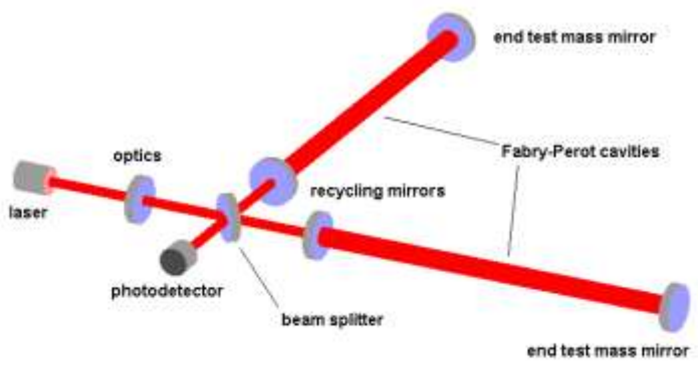

Figure 1: Schematic of gravitational wave detector using laser interferometry.

which uses passing gravitational waves to do so. This technique is based on fundamentally the same principles as the Michelson interferometer and, as such, is particularly suited to detect gravitational waves of quadrupole nature. When gravitational waves propagate perpendicularly to the plane of the interferometer, they induce a differential change in length between the two arms of the interferometer: The other arm shortens, while the one arm elongates. The stretching and compression of the system produce a slight up or down modulation in the interference pattern of the laser light at the output, which is a sensitive detection of the laser light.

Typically a design specification requires achieving a strain noise floor below $2 \times 10^{-21}/\sqrt{\text{Hz}}$ so that a reasonable probability for detection of potential sources is assured. But practical restraints on Earth impose a bound on the distance between the test masses only a few kilometres because of geographical restrictions and cost. For example, in this specification we assume an arm length of roughly 3 km, and thus the residual motion of each test mass must remain below $3 \times 10^{-20}\text{m}/\sqrt{\text{Hz}}$ over the entire detector operational range, which is roughly ~ 10 Hz to a few kHz. Furthermore, it must be possible for this optical detection system to accurately detect such minute displacements if the overall system is to accurately capture and interpret the very subtle signals that represent gravitational waves.

3.4 FACTORS CONTRIBUTING TO NOISE THAT IMPACTS THE SENSITIVITY OF INTERFEROMETRIC GRAVITATIONAL WAVE DETECTORS

In practical terms, the laser interferometry systems can theoretically detect strains in space limited only by the Heisenberg Uncertainty Principle. Nevertheless, there are practical barriers to deployment in actual applications. Variability in gravitational gradients is one of the major challenges faced by the interferometer, especially at low frequencies. Such a level of noise is critical, for example, to permit experiments aimed at detecting gravitational wave signals down to less than 1 Hz are done aboard space, far removed from the disturbance of our own surrounding environment[43,44]. The primary limitations of the sensitivity of detectors based on ground-based detectors are determined by several important factors. Transmission through the ground is quite difficult to deal with: the transmitted field is predominantly due to seismic vibrations and other types of mechanical noise. Together, thermal noise of the test masses and their suspensions also form the overall noise floor. Another important factor is shot noise of the type due to fluctuations of the photocurrent measured by the photodiode recording the interference pattern. We will provide in the following sections a concise exploration of the individual impacts of each of these noise sources on the overall sensitivity of gravitational wave detectors.

Seismic Noise:

Seismic Noise Seismic noise in relatively quiet areas of Earth is approximately a result of spectral behaviour in all three spatial dimensions $10^{-7}/f^2$mHz$^{-1/2}$. To prevent each test mass to move more than 3×10^{-20}m/√Hz at frequencies around 30 Hz, levels of seismic isolation greater than 10^9 in the horizontal plane. In addition, due to likely some vertical noise transmission into the horizontal axis, we also need to provide for a significant amount of isolation in the vertical direction. Therefore, the suspension systems for the test masses are designed with this very large degree of seismic isolation. By suspending each test mass from a plate either mounted on passive rubber isolation mounts or coupled with an active electro-mechanical anti-vibration system, one effective approach for achieving this isolation is to use a multiple pendulum system for each test mass. At the same time, the pendulum system is subject to multiple stiffness's, but needs to be in a soft vertical direction, in order to allow proper vertical isolation.

Thermal Noise:

The sensitivity limitations observed in ground based laser interferometric gravitational wave detectors are limited by thermal noise. This noise type is dominant in the final stages of the suspenders for mirror masses, which makes it most severe at low frequency ranges of the detector's operational capacity [47]. The resonant frequencies resulting from the test masses and their pendulum suspensions, however, fundamentally limit the sensitivity of these detectors, such that thermal noise is important in the lower tails of these resonant modes to set the overall performance. Low mechanical loss factors for the test mass materials and the fibres or wires by which they are suspended are necessary to minimise the effective off resonant thermal noise that needs to be mitigated. The low mechanical losses are so important that they permit a cleaner signal since they reduce the background noise that could obscure gravitational wave signals. Both the test masses and the pendulum resonances require high mechanical quality factors. For example, to reach the appropriate sensitivity levels, the quality factor of the test masses, generally ranging from 15 to 20 kilos, has to be equivalent to 3×10^7. Likewise, the pendulum resonant quality factor should also ideally be 10^8[48]. However, with these stringent requirements, material selection is a difficult problem. The selection of materials for the test masses and suspending fibres is critically dictated in order to minimise losses. Due to its favourable property, fused silica appears as a highly promising material, which allows not only for the construction of the masses but also the construction of the fibres [49, 50]. For this application, its low mechanical loss characteristics are particularly useful. Other materials, such as sapphire, can be used, but offer a different set of challenges and benefits that need to be carefully weighed against the operation requirements of the detector [51, 48]. This work highlights the field of thermal noise, material selection, and mechanical design because the interplay between thermal noise and material selection in combination with mechanical design is a key to further sensitivity of gravitational wave detection technology.

Photoelectron Shot Noise:

The strain sensitivity level was essential to detect minuscule changes in the interferometer's arms 2×10^{-23}/√Hz. This translates to being able to distinguish arm length differences of approximately 10^9m [52]. Shot noise at the output of the interferometer, which we detect photocurrent from, limits this sensitivity. Relationships between detectable strain sensitivity and the laser's power I_0, wavelength λ, interferometer arm length L, and measurement time τ is given by:

$$\text{Detectable strain in time } \tau = \frac{1}{L}\sqrt{\frac{\lambda h c}{4\pi^2 I_0 \tau}}$$

or in terms of frequency:

Detectable strain /√Hz= $\frac{1}{L}\sqrt{\frac{\lambda hc}{2\pi^2 I_0}}$ where c is the speed of light [52]. A powerful laser operating around a wavelength of 10^{-6} is needed in order to meet these high sensitivity demands. Any metres would need to supply about 3×10^{6} which is an enormous requirement [52] in watts at the interferometer's input. In effect, this signal can be 'amplified' by increasing the number of all the reflections (or 'bounces') of light through in the interferometer arms using a Fabry-Perot cavity or an optical delay line, but using only a multipass configuration, which effectively reduces the required laser power[53]. For example, signal cancellation can be avoided if the signal characteristic timescale is, say, 1 millisecond, allowing the maximum number of bounces to be limited to 50 for a 3 km arm length [53]. By operating the interferometer close to its minimum output point, further improvement in the interferometer’s signal to noise ratio can be made. If enough light escapes from a cavity, low optical loss mirrors may be needed to reflect most of the light back into the laser toward low impedance matching through the addition of a power recycling mirror. A resonant cavity is formed with this mirror, located between the laser and the interferometer, which allows for considerable growth in power of light within the interferometer, yielding the kilowatt levels needed for some input under about 10 watts [54]. Signal recycling, another kind of technique, and increases sensitivity by allowing sidebands generated during gravitational wave interactions to get resonant in the interferometer. We achieve this by retro reflecting these sidebands back using a signal recycling mirror located at the output, thus increasing the signal strength in a given bandwidth [55].

3.5 LONG BASELINE DETECTORS UNDER CONSTRUCTION

We are developing prototype laser interferometers for gravitational wave detection around the world. Examples of notable prototypes include, among others, those at Max-Planck-Institut für Quantenoptik in Garching[56], at the University of Glasgow[57], at the California Institute of Technology[58], at the Massachusetts Institute of Technology[59], at the Tokyo's Institute of Space and Astronautical Science[60], and at the Tokyo astronomical observatory[61]. These early detectors, using either multibeam delay lines or Fabry-Perot resonant cavities, have arm lengths from 10 to 100 metres. Several such prototypes have reached as low a sensitivity as 10^{-18} this justifies the building of much longer baseline detectors, which-while offering a more realistically sensible possibility of detecting gravitational wave signals-are only relevant for millisecond pulses. A global network of interferometers is now under construction to improve detection accuracy and to determine the position of the wave sources. For example, the U.S. LIGO project consists of two detector systems each one 4 kilometres long, located in Livingston, Louisiana, and Hanford, Washington. The vacuum system, as well as the laser and input optics and an initial suspension system, are installed at the Hanford site; the Louisiana site has installed its vacuum system. The French/Italian VIRGO detector, at Cascina near Pisa, meanwhile, has nearly finished its central structures, and is beginning to install vacuum tanks for interferometry. Designed for sensitivity down to 10 Hz, this detector, which is characterised by a specialised five stage multi pendulum suspension system of its test masses, will be used to probe this patch of parameter space. Although under advanced construction at the Tokyo Astronomical Observatory, Japan's TAMA 300 detector, with 300m arms is not yet operative. The TAMA 300 is mainly underground, with a complete vacuum system, and preliminary testing with light in the arms has already been started. These systems are all designed with resonant arm cavities, test mass suspensions by standard wire sling methods, and Nd lasers for illumination. The German/British GEO 600 project near Hanover (300 km, 600 m baseline) is closest to GEO 2000m, with a four pass delay line and enhanced optical signal transmission. The test masses utilize low loss fused silica suspensions, and the test masses sensitivity above a few hundred Hz should be comparable to initial operational phases of VIRGO and LIGO. In addition, the GEO 600 detector will use the infrared light of a 10 watt single frequency YAG laser. Buildings have been constructed, with vacuum pipes in place and optical element suspension installations well under way. The design of GEO 600 makes use of fundamental research achieved in the last several years at such institutions as Max-Planck-Institut für Quantenoptik, Garching; University of Glasgow; University of Wales in Cardiff; and most recently, University of Hanover and Albert Einstein Institute in Potsdam. An initial operating date is envisioned within two years, opening an opportunity for gravitational wave coincidence detection to within approximately 10^{-21} for pulses lasting several milliseconds.

3.6 LONG BASELINE DETECTORS IN SPACE

We have been working to identify low frequency gravitational wave sources for several years. The impact on phase of radio signals emitted by millisecond pulsars such as PSR 1937+21 and PSR 1855+09[62] have been studied using the potential effect of gravitational waves on the phase. Researchers have also looked at how the Doppler shift of radar signals repelled from spacecraft like Ulysses [63] is affected. The first experiment, adequately sensitive to signals at frequencies of about one cycle per year or lower, has placed a limit on the gravitational wave background at this low frequency, converting to an energy density per logarithmic frequency interval less than 6×10^{-18} The closure density of the universe. The cascade of latter experiments has concerned continuous wave signals of the order of milli-hertz, with a limit of approximately 3×10^{-15} for such signals. Meanwhile, the most promising gravitational wave sources—black hole formation and merger—lie in the frequency range 10^{-4} Hz to 10^{-1} Hz. To detect these signals requires a detector with strain sensitivity of order 10^{-23} over appropriate timescales. Deploying a laser interferometer in space is a promising way to detect such signals. The principle of this concept is to launch multiple drag free spacecraft into orbit and measure the distances between test masses, inside these spacecraft, using laser interferometry from remote sections of extremely large angles from one another. This approach has been proposed to be pursued with two experiments. The first is known as LISA [65], and is a collaborative effort between American and European teams. Three drag free spacecraft (which has the length of each side equal to) 5×10^{6} km. Orbiting a distance of 1 AU from the Sun at an Earth-like distance and 20 degrees behind the Earth is this triangular formation. Two proof masses each reside on the inside of each spacecraft as an endpoint of three combinations of the same, self-intersecting interferometers, but they are not connected in the same way. Each of these two arm Michelson type interferometers is made up of a vertex (proof masses located at a central spacecraft) plus two remote spacecraft. The three interferometer setup improves reliability against component failure, improves detection probability, and facilitates the determination of the polarisation of incoming gravitational waves. They thus shield the proof masses from external effects of solar radiation pressure and drag free control systems use proportional electric thrusters to closely follow the proof masses with high precision. The Nd Yag is considered highly stabilised at a wavelength of 1.064 microns of laser light. The two lasers are phase locked within the central spacecraft to act as a single laser. The incoming light is phase locked to the lasers in the distant spacecraft, which act as amplifying mirrors to the laser beam in the spacecraft. LISA was originally conceived in a form with six spacecraft, two at each vertex, which the European Space Agency (ESA) selected as one of their Cornerstone projects in the post Horizon 2000 program. It should take some time before this program is fully realised, however. A JPL project that explores a more cost effective version of LISA with three spacecraft has been recommended following the LISA team at JILA recommendations, which could allow for earlier launch and constitutes an international collaboration mission that may be conducted by either NASA or ESA. The second proposed experiment, OMEGA [64], involves deploying three spacecraft into a geocentric orbit, with each arm extending 10^9 m, and this proposal is currently under consideration by NASA as a Medium Explorer (MIDEX) mission.

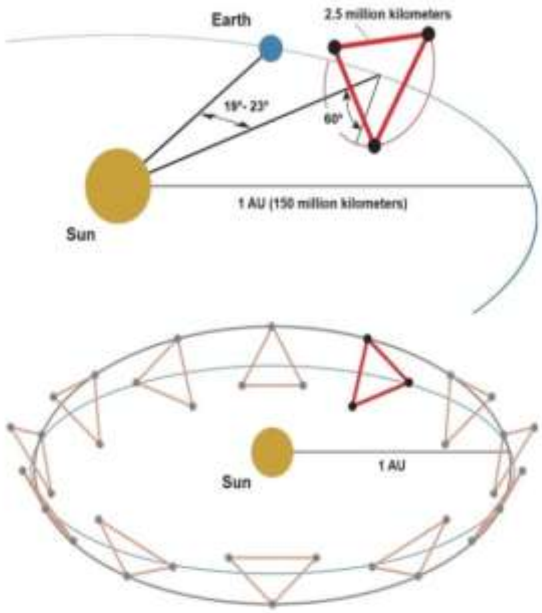

Figure 2: The proposed LISA detector

4. CONCLUSION

In the end, this fortnight on gravitational wave detection leaped from theoretical prediction to real observation; a confirmation of Einstein's General Theory of Relativity. Indeed, even the very construction of sophisticated detectors like LIGO, Virgo, and the forthcoming mission LISA testifies to continuous efforts made with the purpose of investigating the universe by means of gravitational waves. These observatories open a new, non-electromagnetic window into the cosmos, thus allowing phenomena such as black hole mergers, neutron star collisions, and supernovae, which would otherwise be invisible, to be studied. The dawn of Gravity Wave Astronomy provides insights into stellar evolution, cosmology, and the fundamental nature of gravity itself, each pushing the boundaries of our knowledge about the universe. Where there is continuously improving detection technology with third-generation ground-based interferometers and more sophisticated data analysis methods, the possibilities get even bigger. The future observations are bound to refine our understanding of the dynamics of black holes, properties of neutron stars, and cosmic expansion, all together with unprecedented tests of general relativity in extreme conditions. This progress underlines the wider trend in physics and astronomy-a trend of broadening our observational capability and challenging our theoretical frameworks. The detection of gravitational waves has enlarged our cosmic vista but also shown humankind's capability to detect and interpret some of the subtlest phenomena in the universe, which in turn was fostering ground-breaking discoveries for decades to come.

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