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GRAVITATIONAL WAVE DETECTION: WHAT IS NEW

O. D. Aguiar[1] for the Graviton Collaboration

RESUMEN

La búsqueda de la detección de ondas gravitacionales ha sido uno de los desafíos tecnológicos más difíciles a los que se han enfrentado jamás los físicos experimentales y los ingenieros. A pesar de los resultados nulos obtenidos hasta la fecha después de cuatro años de búsqueda, la comunidad involucrada en ésta área ha ido creciendo. Una de las principales razones de esto es que la primera detección de ondas gravitacionales y la observación regular de ellas son de las metas más importantes para el comienzo de este milenio. Ellas probarán uno de los fundamentos de la física, la teoría de la relatividad general de Einstein y abrirá una nueva ventana para la observación del universo, lo cual, seguramente causará una revolución en nuestra comprensión de la física y la astrofísica. En esta charla daré un reporte actualizado acerca de todos los detectores relevantes (interferómetros, barras, esferas, radio telescopios y satélites CMB) en operación, ó actualización y los que están en construcción o en proyecto. En particular hablaré con más detalle acerca del detector brasileiro Schenberg.

ABSTRACT

The quest for gravitational wave detection has been one of the toughest technological challenges ever faced by experimental physicists and engineers. Despite the null results to date, after four decades of research, the community involved in this area is continuously growing. One of the main reasons for this is because the first gravitational wave detection and the regular observation of gravitational waves are among the most important scientific goals for the beginning of this millennium. They will test one of the foundations of physics, Einstein's theory of general relativity, and will open a new window for the observation of the universe, which certainly will cause a revolution in our knowledge of physics and astrophysics. In this talk I will give an updated report about the status of all relevant detectors (interferometers, bars, spheres, radio-telescopes, and CMB satellites), in operation, going to an upgrading, under construction, or still as projects. In particular, I will give details about the Brazilian Schenberg detector.

Key Words: gravitational waves — instrumentation: detectors

1. GRAVITATIONAL WAVES: DO THEY REALLY EXIST?

In 1916, Einstein himself proved from his theory of General Relativity that gravitational waves should exist. These gravitational waves, caused by the accelerated movements of masses, would be distortions of the spacetime, travelling through the Universe at the speed of light.

According to Einstein's theory of General Relativity, these waves have two independent polarizations, named plus and cross, in the plane perpendicular to the direction of the wave propagation. Any wave polarization (linear, circular, and elliptical) can be decomposed in these two fundamental polarizations by a combination of their amplitudes and phases.

However, one may ask: Do they really exist? Because, after half a century of theoretical debate (from 1916 to 1965) and more than four decades (from 1965 to 2010) of observational search, a direct detection has yet to be confirmed.

Some good observational evidence, although indirect, comes from a few pulsar binary systems, such as the PSR 1913+16 discovered by Taylor and Hulse. These systems present decay in their orbital periods that can only be explained by energy removed from their orbital motion by the emission of gravitational waves. It is an indirect observation, because the waves are not directly detected, but rather an effect (orbital energy loss) caused by their emission.

Why haven't they been detected yet? The reason is because they are hard to detect.

So, why are they so hard to detect? It is because they have very tiny amplitudes.

The amplitude of $h = \delta L/L < 10^{-19}$, which is ten thousand times smaller than the diameter of a proton, is only expected to be observed for a gravitational "tsunami wave".

[1]Instituto Nacional de Pesquisas Espaciais, Divisão de Astrofísica, Avenida dos Astronautas 1758, São José dos Campos, SP 12227-010, Brazil (odylio@das.inpe.br).

Even in this case, and taking into account the Schenberg detector, the energies associated to these amplitudes ($\delta L \sim 10^{-19}$ meter) would deposit energy of $\sim 6 \times 10^{-28}$ Joules on the detector's natural quadrupolar modes around 3.2 kHz, which are only 290 gravitons! This is 10^{-9} times the energy of a photon of light!

2. GRAVITATIONAL WAVE DETECTORS

Since Weber's pioneering work in the 60's there have been dozens of proposed gravitational wave detector projects. Most of them have never been implemented. Of those implemented I will talk about interferometers, bars, spheres, radio telescopes, and CMB satellites. They cover many frequency bands in the range of 10^{-18} Hz all the way up to 10^4 Hz. I am not going to talk here about very high frequency (above 10 kHz) detection.

Using laser interferometry, interferometers detect differences between the distances of test bodies caused by the passage of a gravitational wave, while bars and spheres are very low loss (high mechanical Quality Factor) resonant bodies that absorb energy from the wave and mechanically resonate. An electromechanical transducer (resonant or not) converts this mechanical signal into an electrical one.

The seven long-base ground interferometer detectors that have been constructed so far are: three LIGO interferometers (two in Hanford and one in Livingston), VIRGO, TAMA300, GEO600, and CLIO. There are also two under construction: AIGO (or LIGO in Australia) and LCGT, and at least one big project for the future: the EINSTEIN Telescope.

The three LIGO interferometers are made up of two with 4 km arms and one with 2 km arms. One with 4 km arms is at the Livingston site and the other two at the Hanford site. Livingston and Hanford are 3030 km (about 10 light-milliseconds) apart. The LIGO collaboration involves more than 600 people and around 60 universities/institutions. The first engineering runs occurred in 2001 and the interferometers started runs in the so called science mode in September 2002. Six science runs have been performed so far. The last one ended in October 2010. From the fifth science run the sensitivity has been practically equal to that designed for the initial project. All the LIGO interferometers are now being upgraded to an advanced performance now. They will be back in operation in 2014. The six science run data is still being analyzed.

When LIGO resumes operation in 2014, it is expected to have a 10-12-fold increase in sensitivity, which will result in an increase of 1000–1500 in the rate of detectable events. One day of Advanced LIGO will be worth more than three years of Initial LIGO.

VIRGO is a collaboration involving France, Italy, Netherlands, and Poland. The 3 km arm interferometer, which started commissioning runs in 2003, is located in Cascina, near Pisa, Italy. The VIRGO collaboration has plans for a large underground interferometer in Europe, named EINSTEIN Telescope; when operational EINSTEIN will surpass all other interferometers in sensitivity. VIRGO, like LIGO, is now being upgraded to an advanced version now, which will come into operation in 2014.

TAMA300 is a 300 m arm Japonese interferometer located at the National Astronomical Observatory of Japan, in Tokyo. The project started in 2005. It was the first large interferometer to begin observations, achieving the best sensitivity in the world during the period of 2000–2002.

GEO600 is a collaboration involving German and British universities and the Universitat de les Illes Balears. The interferometer has arms of 600 m and is located in Hannover, Germany. It started commissioning operations in 2002. Its present sensitivity is pretty close to the designed one.

CLIO is a 100 m arm Japonese interferometer located in the Kamioka mine (underground). It is a cryogenic prototype detector for LCGT (Large-scale Cryogenic Gravitational wave Telescope), which will have arms of 3 km. LCGT is under construction and will operate, like CLIO, underground in the Kamioka mine with mirrors cooled down to very low temperatures.

AIGO, the Australian International Gravitational-wave Observatory, has, so far, only an 80 m high optical power interferometer test facility in collaboration with LIGO. The final decision for the installation of the hardware of the 2 km arm Hanford LIGO in Australia under the name LIGO-Australia will come in October 2011. IndIGO, a laser interferometer project from India, is also claiming this facility.

NAUTILUS and AURIGA are the names of the two ultra-cryogenic (cooled to about 100 mK) bar detectors (or antennas) in operation, both in Italy. NAUTILUS is located in Frascati (near Rome), and AURIGA in Legnaro (near Padova). They will remain operational during the upgrading of VIRGO (2011–2013). Ten years ago there were five cryogenic bars receiving data. The three others, which were cooled to about 4 K, were as follows: NIOBE, in Perth (Australia), ALLEGRO, in Baton Rouge (USA), and the Italian EXPLORER, in CERN

(Switzerland). They stopped operation, respectively, in 2001, 2007, and 2010.

Data from four of these bars have already been analyzed together with data from LIGO and VIRGO over the last decade, when they had similar sensitivities with the interferometers. Finally, there are two detectors composed of resonant-mass spherical antennas: Mini-GRAIL and Mario SCHENBERG to which I will return later.

There are also interferometer projects in space, such as the NASA-ESA LISA (Laser Interferometer Space Antenna), the Japonese DECIGO (Deci-hertz Interferometer Gravitational wave Observatory) and BBO (Big Bang Observer). Because they are free from the seismic motions of Earth's crust, which couples mechanically and also gravitationally to the detectors, they are able to cover a much lower range of frequencies. While the ground interferometers, resonant-bars and resonant-spheres, cover the frequency range of 10 Hz–10 kHz, the space interferometers will cover the 10^{-4} Hz–10^{2} Hz frequency band.

Pulsar Timing Arrays is a new way of searching for the detection of gravitational waves. The pulse time series of dozens of extremely regular single pulsars are monitored every once in a while by radio telescopes and compared with their respective theoretical pulse time series models in the hope of finding discrepancies (residuals) between the time arrivals of the measured pulses and the model pulses. These discrepancies would be caused by the passage of a long wavelength gravitational wave in the space between Earth and these better-than-nuclear-clock-pulsars.

Three major groups were formed for these searches: NANOGrav (North American Nanohertz Observatory of Gravitational Waves), the Parkes Pulsar Timing Array (PPTA), and the European Pulsar Timing Array (EPTA). They cover GW frequencies between 10^{-9} and 10^{-8} Hz – complementary to LIGO and LISA.

Current data sets are ruling out a few cosmic string (CS) models, and the Square Kilometer Array (SKY) should detect GWs or rule out most CS models.

Covering the very low frequency band, from 10^{-18} to 10^{-15} Hz, there are the electromagnetic CMB (Cosmic Microwave Background) detectors searching (on land or onboard satellites, such as Planck) for electromagnetic B-mode polarization. Here the principle of detection is simple: these almost Universe size wavelength gravitational waves leave an imprint on the electromagnetic CMB.

All this effort is to fill up the maps of the sky in the different frequency bands (from 10^{-18} to 10^{10} Hz) of the gravitational wave window as the scientific community has done in the past 400 years for the electromagnetic window.

3. GRAVITATIONAL WAVE ASTRONOMY: A NEW WINDOW TO OBSERVE THE UNIVERSE

Gravitational Wave Astronomy will open a new window to observe the Universe, which will probably revolutionize our knowledge of it.

There is a host of possible astrophysical sources of gravitational waves: namely, supernovae, the collapse of a star or star cluster to form a black hole, inspiral and coalescence of compact binaries, MACHOs as primordial black holes (PBHs), pulsars and rotating neutron stars, quark stars, boson stars, neutron star modes, the fall of stars and black holes into supermassive black holes, rotating neutron stars, ordinary binary stars, relics of the Big Bang, vibrations or collisions of monopoles, cosmic strings and cosmic bubbles, and other exotic events, anticipated from theory, which may be confirmed when gravitational wave astronomy becomes a reality, besides phenomena not yet known or even anticipated, and other surprises.

If nature has more dimensions than the four of spacetime, gravity will have "transit" in these extra dimensions, and special effects on the intensity, propagation and polarization of gravitational waves may occur differently from the ones anticipated by the General Relativity. The study of these effects on the gravitational waves would be, therefore, a tool for the investigation of extra dimensions in the Universe and to formulate an auto consistent theory of quantum gravity.

Gravitational Waves will tell us even if there was or was not a Big Bang. If there was no Big Bang, gravitational waves will provide us with important details of this or these previous phases of our bouncing Universe.

4. SPHERICAL ANTENNAS AND THE SCHENBERG DETECTOR

One can increase the sensitivity of a resonant-mass detector by maximizing signal-to-noise ratio. Maximization of the signal to noise ratio can go in two directions: the minimization of noise or the maximization of signal. If it is hard to decrease the noise, one can try to increase the signal. A GW antenna with a spherical shape (massive or hollow) seems to be the best solution for a given choice of frequency;

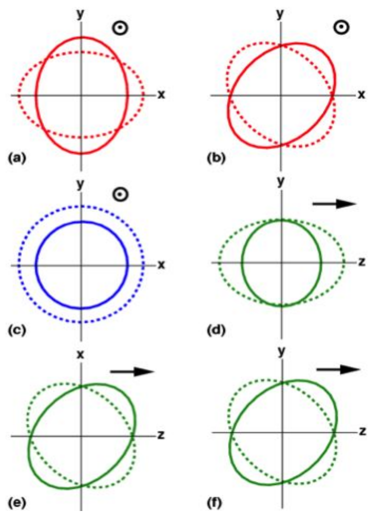

Fig. 1. A schematic view of the detector. The explosive view explains the principle of the two mode resonant transducer coupled to the spherical antenna.

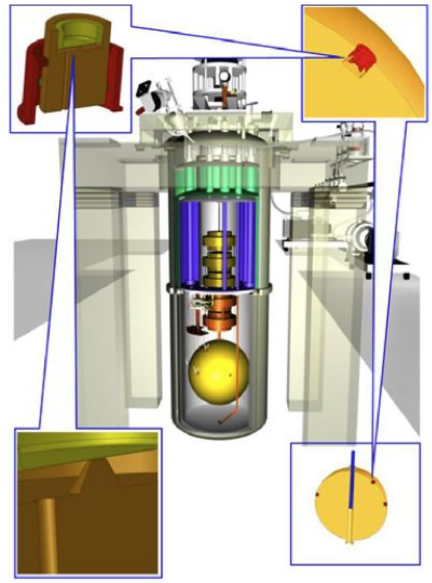

Fig. 2. A schematic view of the detector. The explosive view explains the principle of the two mode resonant transducer coupled to the spherical antenna.

because it maximizes the GW absorption (the transformation of gravitons into phonons) and is omnidirectional (it has equal sensitivity in any direction). Robert Forward, one of Weber's formers graduate students in the early 60s, was the first to realize this.

MiniGRAIL, in Leiden (the Netherlands), and SCHENBERG, in Sao Paulo (Brazil), were the first spherical antennas to go into commissioning operation. This happened in 2004 and 2006, respectively. Spherical antennas have the advantage of omnidirectionality. This means they have the same sensitivity in any direction of observation, which also implies that they are not blind to any direction. In order to accomplish this, one needs to install enough electromechanical transducers to monitor all five first mechanical quadrupolar modes of the sphere. In doing so, one can determine, in principle, the direction and polarizations of the incoming wave with a single detector. Furthermore, because they have multi-sensor (transducer) devices, their information is more complex and complete. It is possible to identify much of the noise just because it did not pass in the criterion of a quadrupolar signal. If the wave direction is determined by an observation in the electromagnetic window, monitoring the first five quadrupolar modes and the first monopolar mode of a spherical antenna will allow one to identify the six general polarizations in the weak field approximation and, so, test General Relativity and other theories of gravitation (Figure 1).

As mentioned before, spherical antennas convert part of the gravitational wave energy into mechanical oscillation of the sphere's quadrupolar modes. Then, a few transducers installed on its surface convert the mechanical energy stored in these modes into an electrical signal, which is processed, recorded and analyzed.

Transducers can be resonant or non-resonant. Non-resonant transducers can give the detector the capability to be wideband or, in other words, to have good sensitivity in a wide frequency band. However, they lose the amplification factor, which is equal to the square root of the ratio between the sphere's effective mass and the transducer sensor mass. For the SCHENBERG detector (Figure 2) this amplification factor is 10,000, because the spheres effective mass for a quadrupolar oscillation is 287 kg, and the transducer sensor mass is about 3 mg. This means that if a gravitational wave causes the SCHENBERG's spherical antenna to oscillate with a surface amplitude of 10^{-21} m, the transducer sensor mass will oscillate with an amplitude of 10^{-17} m, which facilitates the detection. In order to compensate this amplification factor loss, the non-resonant transducer must have its sensitivity increased by the same factor of 10,000, which is not easy to accomplish. However, the group involved in this research has been trying to design and construct a non-resonant transducer with sensitivity 10,000 times higher than the traditional resonant one. In the case o the SCHENBERG detector, which uses parametric transducers composed of klystron microwave cavities, the major difficulty

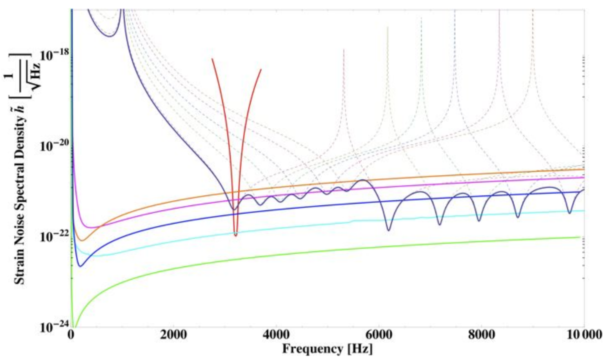

Fig. 3. The sensitivity curve for the Schenberg broadband detector using a nanogap klystron cavity nonresonant transducer. The dashed curves represent each of the 6 spheres we chose for the array (masses: 1150 kg (Schenberg), 744 kg, 547 kg, 414 kg, 301 kg, 239 kg), the lowest frequency being Schenberg. The V-shaped red curve is Schenberg with its usual configuration operating at dilution fridge temperatures (10 mK). Interferometer curves are also plotted: advanced LIGO (green), LIGO (blue), VIRGO (light blue), TAMA300 (pink) and GEO600 (orange). All of these are project curves, not actual data.

is to reduce the gap between the sensor silicon membrane and the cavity at the top of the post from about 10 micron to one nanometer! It is a challenge we hope to solve by using the recent achievements in nanotechnology together with those to come in the near future (Figure 3).

The Mario SCHENBERG Gravitational Wave Detector (Brazil) started commissioning operation on the 8th of September, 2006. It involves a collaboration between many Brazilian institutions such as INPE, USP, ITA, UNIFESP, IFSP, UNICAMP, UFABC, IAE, and UNIPAMPA, and also some foreign universities as the Leiden University, UWA, and LSU and it has been supported by FAPESP (the São Paulo State Foundation for Research), CAPES, CNPq, and MCT.

We performed a few runs during the period of 2006 and 2008, testing the system (Figure 4 and 5). Since 2008, we have been upgrading the detector. We have designed a new suspension and vibration isolation system for the cabling and microstrip antennas, we have designed a complete new set of transducers, which is under construction now, and we have installed a dilution refrigerator's 1K pot (Figure 6). We hope to start a run with the new set of resonant transducers soon.

Spherical detectors, when fully operational at their designed sensitivities, will be very reliable instruments. The reason is because they are six-sensor detectors while the interferometers, like the bars, are only single sensor detectors. A gravitational wave burst signal arrives at the interferometers and to the bars at different times, therefore it is very difficult to confirm a burst signal if it comes close to the noise level. In these cases, a confirmation from the electromagnetic band is necessary, which provides valuable information about the wave direction and arrival time. On the other hand, being a six-sensor instrument, a spherical antenna always has robust information about a detected signal, which already helps to separate a real signal from ordinary noise with a high probability.

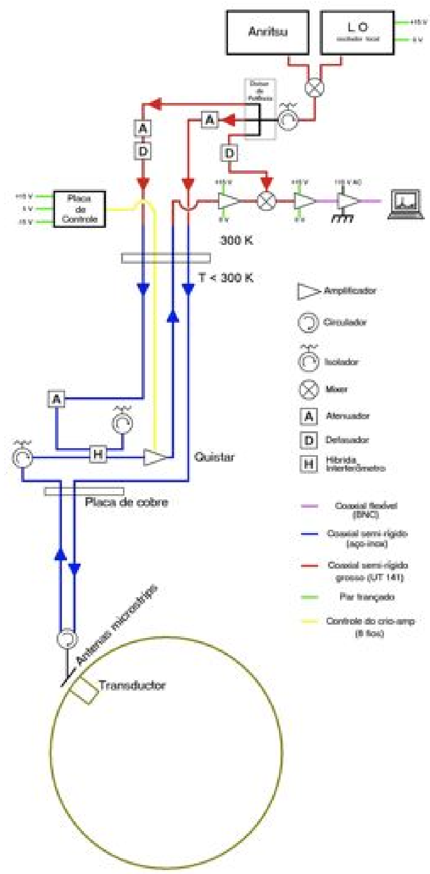

Fig. 4. The schematic diagram of the transducer's electronic circuit (for one transducer).

An array of six spheres, when placed close enough together (only a few meters apart) and sampled with the same A/D converter system, is an even more reliable system. They will form a coherent system able to provide the correct phase in various frequency bands, because the wave is a coherent source of energy in the various frequency bands

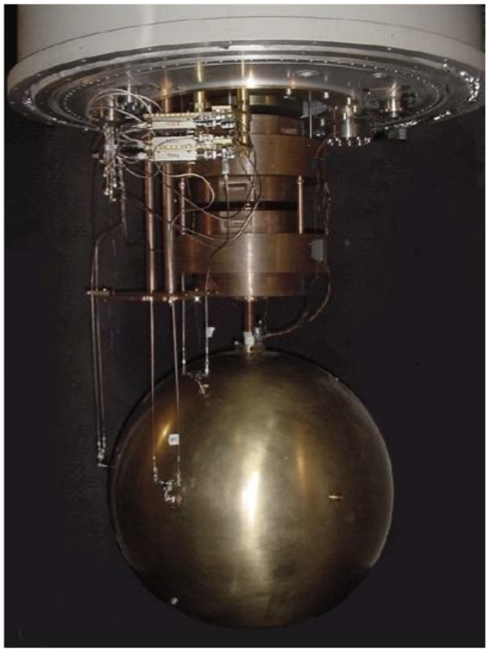

Fig. 5. The position on the sphere surface of the three initial transducers can be seen. It is also possible to see the cabling lines going and coming from these transducers and the three cryogenic microwave amplifiers installed close to the bottom wall of the liquid helium reservoir.

of such a detecting system. Furthermore, detecting a wave with a different physical principle (absorption of the wave energy by the resonant-mass) will certainly contribute to our knowledge of it.

5. CONCLUSIONS

The sources of gravitational waves can be: galactic, extragalactic, cosmological, and even from previous universes.

The spectrum goes from 10^{-18} Hz to 10^{10} Hz.

If extra-dimensions exist, gravitational waves have transit in them.

The probability of new revolutionary discoveries is very high.

Explained by the importance of these discoveries, the gravitational wave community has been growing significantly in the past decade. In the 80s, a gravitational wave data analysis paper would involve only about thirty authors, now it can involve 700.

Because spherical antennas are able to determine the origin of the signal in the sky and its polarizations, they will probably play an important role on these new discoveries.

Fig. 6. The sphere was raised about 1.5 meters and immobilized. Beneath it a wooden floor was mounted, which made the assembly work easier. Two nine steps swimming pool ladders were built to provide access to the top of the detector.

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