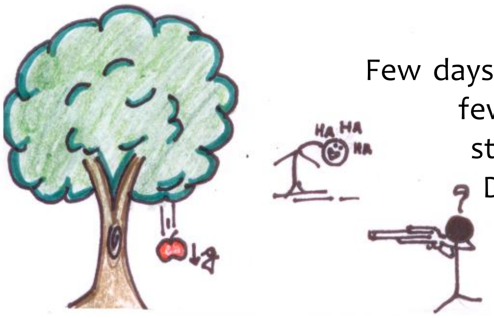
Hunting gravitational waves: Universe seen in a new light

- Archana Pai



Few days ago, I saw my small nephew playing a game. He placed few ants and few grains of sugar on a rubber sheet. Then he started alternatively stretching and releasing the sheet. During the stretch, the ants were going away from each other and away from the sugar. They were getting confused (!) unable to locate their food. Imagine a similar scenario takes place in our world where the distances between places increase/decrease just like the rubber sheet! Hold your breath... in fact, according to Einstein, we do live in such a world. The space-time around us does indeed behave like an elastic medium which can be stretched and squeezed. However, this variation of the space-time is not apparent to us unlike for those ants on the rubber sheet. Now you may ask, what are these oscillations which Einstein referred to? We will learn more about them in the rest of this article.

1. *What are gravitational waves?*

In the year 1912, Einstein proposed the General Theory of Relativity (GTR). This theory replaces the Newtonian picture of gravitation (two bodies attracting each other) by a *geometric* picture. If you are willing to accept that space and time are not two separate notions but a single entity, then the dynamics they follow as predicted by GTR are as follows. The massive bodies produce indentations in the space-time fabric. These indentations manifest themselves as the gravitational field of the object.

The massive bodies take the shortest path as they move on this space-time fabric; similar to the way the planets move around the sun. To give a (loose) analogy, let us consider a bunch of billiard balls on a springy surface. The billiard balls make the springy surface uneven, full of mountains and valleys. As they move along this surface, they continuously change this pattern of mountains and valleys.The space-time which we live-in is similar to this springy surface and the planets/stars are like the billiard balls moving on this surface. In other words, space-time behaves more or less like an elastic medium, a rather stiff one. One requires immense amount of energy to perturb or set the medium into oscillation.

According to GTR, when massive bodies rotate, explode asymmetrically or when two bodies follow a binary orbit just like our Earth-Moon system, the space-time indentations thus produced travel outwards like ripples in space-time fabric which are gravitational waves (GWaves). These are similar to water waves on the surface of ocean or light waves produced due to accelerated charges. The main difference between the light/water waves and the GWaves is that light/water waves travel in space-time whereas the GWaves are waves of the space-time fabric itself. Thus, when these waves are incident on any object, they deform the object because the underlined space-time fabric itself expands or contracts.

Now, you might wonder, there are so many things happening around us; so many vehicles accelerating, storms, earthquakes - don't they produce GWaves? They do but they are very very feeble. To give an example, the terrestrial merry-go-round with a diameter of a few meters, mass 100 kg and revolution period of 5 sec would produce GWaves of magnitude (h) $\sim 10^{-47}$. This means that the strain (dL/L) produced is too feeble to measure (many orders of magnitude below the size of the nucleus!). Astrophysical objects produce measurable GWaves e.g. an astronomical source like a supernova explosion or two binary stars spiralling around each other produce GWaves with strength of deforming the object's size by 10^{-12} m in one meter. This is like measuring the change in distance equal to the size of atom in the total distance of Earth-Moon distance! Measuring such small changes in lengths is experimentally the most challenging task. By now, you must have been convinced that GWaves have not been detected yet .

Sir Arthur Eddington[1],an eminent scientist, was skeptical about GWaves and commented that 'GWaves propagate at the speed of thought!'[1]

2. *Evidence of GWaves : Hulse-Taylor binary pulsar*

Not only Eddington but many scientists thought GWaves were mathematical artifacts. The evidence for the existence of GWaves was a distant dream for scientists until the discovery of an unusual binary pulsar PSR 1913+16. In the year 1974, two American radio astronomers - Russel Hulse and Joseph Taylor from Princeton University discovered this binary system. It involves a pulsar (rotating neutron star) and a companion neutron star which move in an orbit of period 7.75 hours. Radio observations of this system revealed that the orbit of this pulsar around its companion was shrinking by 3 mm/orbit. This will cause the two stars to merge 300 billion years from now. The shrinkage of the orbit was accounted by the loss of energy in the form of GWaves. When the binary orbit shrinks, the two stars come close to each other and attract each other further more. As a result, they orbit around each other faster than before decreasing the orbital period. This decay in the period measured for PSR 1913+16 over a decade was in very good agreement with the prediction of GTR. In 1993, the American scientists were conferred with the Nobel Prize for this discovery. These measurements have laid to rest any doubts regarding the existence of GWaves. However, this is an indirect evidence, direct detection is still required.

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[1] Eddington performed the first test of GTR. He measured the bending of light during 1919 total solar eclipse.

3. *What new information do GWaves carry?*

Almost all the current knowledge about our universe is based on our ability to use electromagnetic (EM) radiation like visible light, X-rays, radio and infrared waves. Over the last five decades, along-with optical telescopes, radio, X-ray and γ-ray telescopes have revolutionized our view of the universe with more understanding about exploding galaxies, quasars, pulsars, neutron stars, black-holes, star birth triggered by supernovae, cosmic masers, organic interstellar molecules and gamma ray bursts. The universe has turned out to be more bizarre and violent than we humans had ever dreamt before. Scientists are optimistic that the detection of GWaves will open a new unexplored window of our universe full of very many treasures.

The GWaves carry information complementary to its EM counterpart. EM waves have wavelength (length of one pulse) of the size or smaller than the source, hence they carry information of the interiors of the source. For example, hot stars show yellow color in visible band while comparatively cold stars show red color. The temperature is the signature of the evolutionary stage of the star and hence conveys information of its structure. Another example is with X-rays, we get an image of our chest and other interior parts of our body. On the contrary, the wavelength of astrophysical GWaves is larger than the typical size of the source. Hence, they carry information about the overall bulk motion of the system and not the interior. They span the frequency (number of pulses per second) range of 10^{-6} Hz-10^{4} Hz; much lower than the EM spectrum (10^{5}-10^{20} Hz). Thus, the GWaves might provide us insight into areas that cannot be probed using EM waves. The typical astrophysical sources of GWaves are inspiraling or coalescing binary systems harbouring neutron stars or black holes (or both) , inner cores of exploding stars, black hole formation and collisions of compact objects. They could also provide important input for our understanding of how the universe came to be the way it looks today and its ultimate fate. GWaves might unveil phenomena never considered before. After all, Nature has proven to be much smarter than any theorist imagining what might be out there!

4. *Towards detection of GWaves*

Over the last four decades, there have been an enormous effort towards the detection of GWaves. In 1961, Joseph Weber was the first to attempt building an instrument for direct detection of GWaves. He set out to measure the displacements of the size of the nucleus in a macroscopic object. The instrument designed was a cylindrical rod of aluminum weighing several metric tons and kept at room temperature. The bar was expected to be set into oscillation due to the tidal force produced by incoming GWaves. The amplitude of these oscillations could then be measured using piezoelectric strain gauges. Weber announced the detection of GWaves using the bar detector in 1969, thus arousing excitement in the scientific community. Various groups started building resonant bar detectors to check the validity of Weber's result. Later, however, Weber's detection was refuted but the pursuit of GWaves detection continued.

The advent of laser technology in 1970's was the impetus for the growth of GWave detection using laser interferometric detectors[2]. The working principle of these detectors is based on the interference of light waves. By early 1980's, there were three prototype interferometers (arm-length of few tens of meters) functioning at Glasgow, Garching and at Massachusetts Institute

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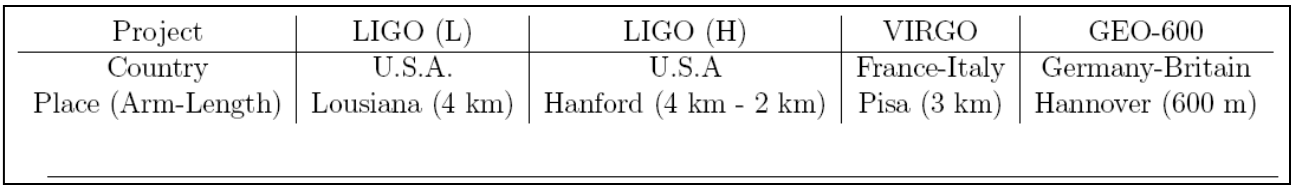
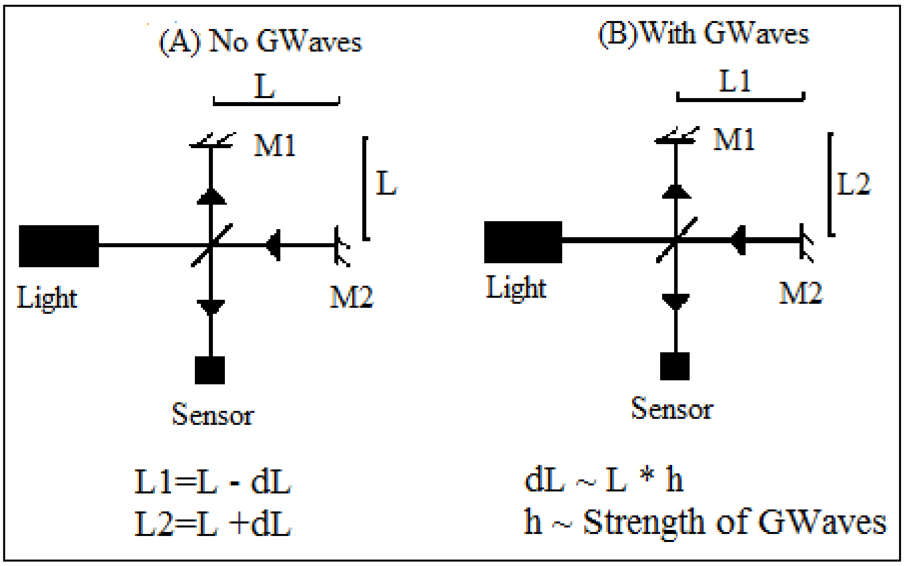
[2] Michelson-Morley used similar apparatus to test the aether hypothesis

of Technology. The sensitivity of such an instrument is proportional to the arm-length of the interferometer; longer the arm, larger is the change in length due to incident GWaves. At present, a worldwide network of kilometre arm-length broadband interferometric detectors is up and taking scientific data with sensitivity of h ~10^{-22} in the frequency band of 10 - 10^4 Hz [see Table below]. Such a sensitivity implies that the instrument observes a neutron star binary event upto the distance of 15 Megaparsecs [3].



Project	LIGO (L)	LIGO (H)	VIRGO	GEO-600
Country	U.S.A.	U.S.A	France-Italy	Germany-Britain
Place (Arm-Length)	Lousiana (4 km)	Hanford (4 km - 2 km)	Pisa (3 km)	Hannover (600 m)

Laser Interferometeric GWave detector: Laser light travels through beamsplitter (a flat mirror at 45°) which divides the beam and sends it along two perpendicular directions; one along M1 and another along M2. The M1 and M2 mirrors are kept at distance L from the beamsplitter. The reflected beams from M1 and M2 are then combined at the output where the photosensor is placed. When there are no GWaves, the reflected light beams re-combine and the phase matches at the output [see Fig.(A)]. With incoming GWaves, length of one of the arms of the interferometer increases (L2) whereas the other arm decreases (L1) [see Fig.(B)]. Now, the two light beams travel different distances along the two arms. At the output when the crest of one light wave falls on the crest of other wave, a bright spot appears and if the trough of one falls on the crest of other, the dark spot appears. This alternate bright and dark pattern is known as interference pattern. The photodiode measures the variation in the light intensity.



With such sensitive instruments, the direct observation of GWaves is not very far. Such a detection would open up a new window for observing the universe. History has witnessed how radio waves, X-ray and gamma ray observations have immesely altered our view of the universe. With the detection of Gwaves, Nature will reveal some of Her mysteries to us and GWave astronomy will soon be a new and exciting branch of astronomy of this century[4].

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[3] 1 parsec = 3.09 x 10^{16} m

[4] For further technical details: Visit LIGO :- www.ligo.caltech.edu, VIRGO :- www.virgo.infn.it