Introduction to Gravitational Waves

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ABSTRACT

Gravitational waves are an interesting but complex topic in the field of physics. Unfortunately, they are also challenging for people without a physics background to fully appreciate. The concept itself is highly specialised, so most of the sources you find on gravitational waves cover something specific that one would need a lot of background knowledge to understand. For this reason, simple diction has been used to introduce general relativity, spacetime, the causes of gravitational waves and their real-world applications. After reading this paper, readers will feel confident enough to dive deeper and explore gravitational waves further.

1. Introduction

Gravitational waves, which are more simply explained as ripples in the spacetime continuum, were first theorized by Albert Einstein in 1916. They are a result of his theory of general relativity, one of the most important scientific theories, which changed our understanding of gravity. After the theoretical postulation of gravitational waves, it took almost a century for scientists to develop the technology to detect these waves. The first direct detection was by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 2015. There are many high energy events that can produce gravitational waves, but the first detection came from the merger of two black holes. Since then, many other detectors, such as Laser Interferometer Space Antenna (LISA) and Virgo, are being developed to detect gravitational waves after LIGO. Overall, gravitational waves are important because they allow us to study events such as the mergers of black holes or the explosions of stars in a way that is not possible with a standard telescope, helping scientists learn more about the properties of black holes and the nature of gravity. In this paper, I will review what gravitational waves are, how they are created and detected, and how they have changed our knowledge of the universe.

2. Foundations of Gravitational Waves

The following section presents the necessary background information needed to understand gravitational waves and the implications of Einstein’s theory of general relativity on our understanding of gravity.

2.1 What is the Theory of General Relativity?

General relativity is Einstein’s theory of spacetime and gravity [4]. The theory of general relativity predicts that gravity is not a force, but rather the product of the curvature of spacetime and its effect on surrounding bodies.

2.1.1 What is Spacetime?

Simply put, spacetime is the space in which time exists. In a more complex manner, spacetime is a combination of the three dimensions of space with the dimension of time. There are limits to what one can experience in spacetime. One cannot move backwards in time, and one cannot move faster than the speed of light [5].

2.1.2 What is Gravity?

Gravity is caused by the attraction between masses where, for example, an object is attracted to the Earth due to Earth's large mass. This is why the legendary apple fell on Isaac Newton. However, Einstein's theory of general relativity shows that gravity is not a simple force, but rather is caused when a mass warps spacetime. It is an expansion of the theory of special relativity, which describes how speed affects mass, time and space. Overall, the theory of general relativity has been successful in explaining phenomena such as the bending of light and the orbit of planets, and is the foundation to understanding how gravitational waves are produced [5].

To understand gravity, one can substitute spacetime with a trampoline and use two individuals of different masses as the moon and the Earth. If the individual with a greater mass were to sit in the centre and the individual with less mass were to sit at the edge, what would happen? The individual with the lower mass would start to move towards the individual with the greater mass

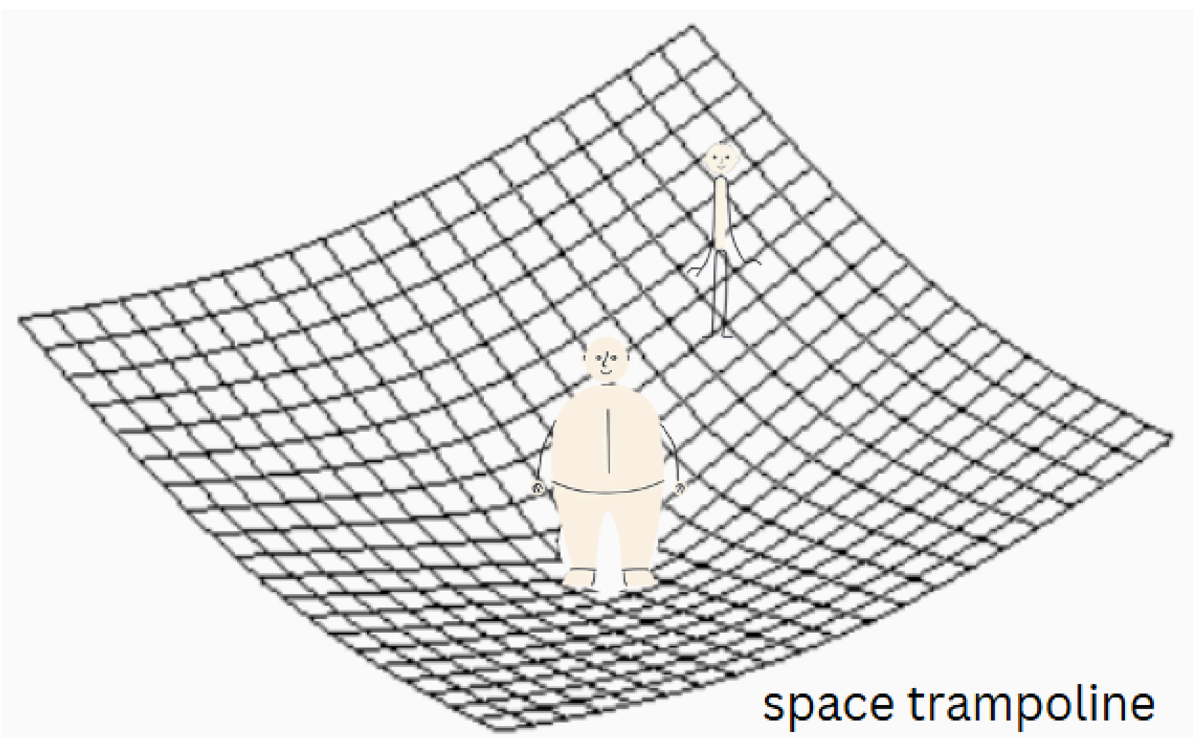

Figure 1. Spacetime trampoline with two individuals of different masses (Ying-Tung Hsiang).

A gravitational field is necessary because an action at a distance is not possible without the intervention of a third party medium. For example, when a magnet attracts iron without coming into contact with it, it does not mean that the magnet is directly acting on the iron through the empty space. It means that the magnet creates something that does not affect us, but that affects the iron. This invisible medium created by the magnet is called the magnetic field. The field is what connects the magnet and the iron and what compels the iron to move towards the magnet. Similarly, if an apple is dropped, the Earth's gravitational field pulls it in. This gravitational field pulls the ball towards the Earth, creating the motion of a fall, which manifests itself as gravity.

However, gravitational fields are special when compared to magnetic fields. For bodies under the influence of a gravitational field, the rate at which their direction and speed change is the same. This is called acceleration. The acceleration is not affected by the chemical or physical properties of the body such as mass. If a feather and a bowling ball were dropped from the same height in a space without any air, gases, or other substances, they would hit the ground at the same time. This can be interpreted using Newton's 2nd law of motion as such:

$$F = m_i a$$

where F is force, m_i is the inertial mass, and a is acceleration. Here, "inertial mass" is a constant characteristic of the body. It is a measure of an object's resistance to motion when a force is applied. If the cause of the acceleration is gravity, the resulting equation is:

$$F = mg$$

where m is the gravitational mass and g is gravitational field intensity. Just like in the above equation, "gravitational mass" is a constant characteristic of the body. It is a measure of how strongly an object is attracted to another object's gravity. From these two related equations, acceleration is given by:

$$a = (\frac{m}{m_i}) \times g$$

Because of this, we come to understand that the ratio of inertial to gravitational mass is the same for all bodies. Now we can see that acceleration is not affected by the nature of the body, and that it is always the same for a given gravitational field. In conclusion, we are left with the law: The inertial mass of a body is equal to its gravitational mass. (Einstein 1916)

2.2 What is a Wave?

A wave is a medium that transfers energy without transferring matter. Objects floating on water provide evidence that waves transfer energy without transferring matter. The effect is similar to floating in the ocean and being able to feel the force of the waves moving your body (matter). They are caused by disturbances. For example, sound waves are created when air particles are made to vibrate [1].

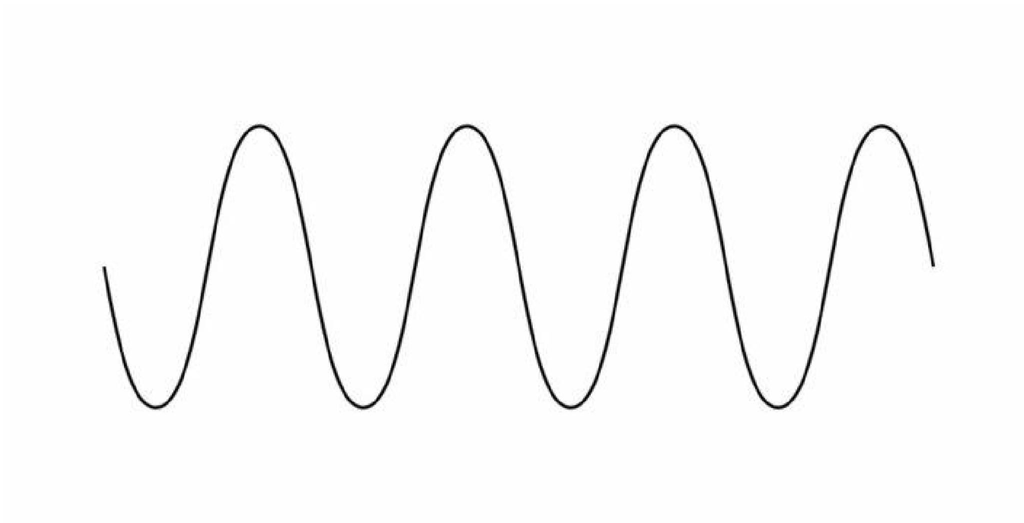

Figure 2. An illustration of a wave (Adobe Stock by Zizo).

2.3 What is a Gravitational Wave?

Gravitational waves are caused by massive objects with high accelerations and they can pass through anything. These ripples travel at the speed of light, and they do not decay. Many people think that because gravitational waves have these properties, they are electromagnetic. This is not the case.

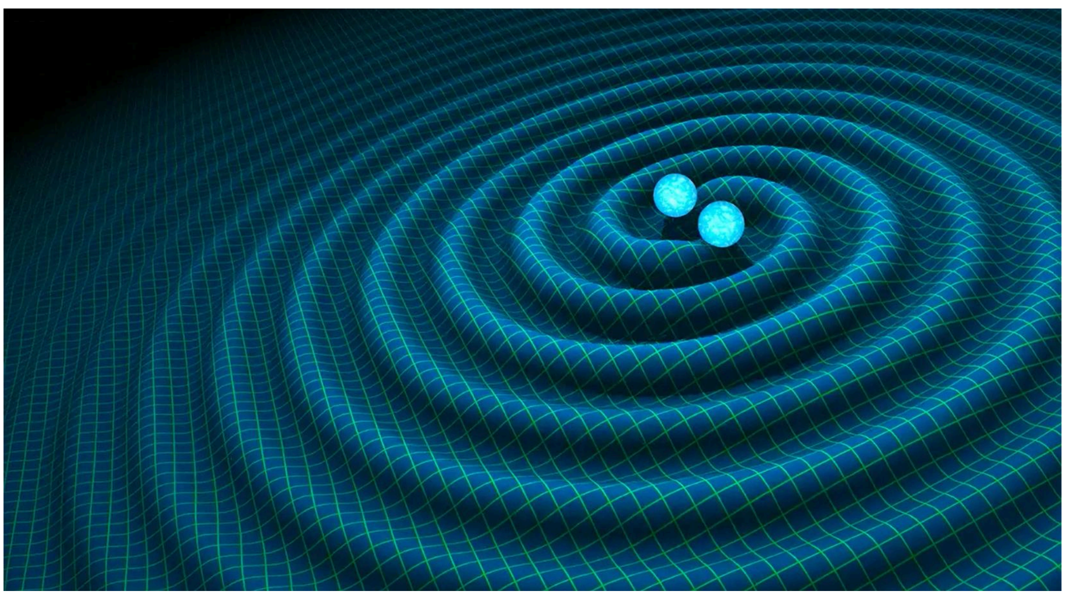

Figure 3. An illustration of two stars spinning to produce the ripples that are (R.Hurt/ Caltech-JPL 2017).

2.3.1 Properties of Gravitational Waves

1. **Gravitational waves are transverse waves.** This means that the disturbances (oscillations) they create are perpendicular to the direction the wave is travelling. They behave in the same way as light waves and waves in water. [1] The only difference is that the disturbances are in the fabric of spacetime.
2. **Gravitational waves can be polarised.** This means that spacetime can be distorted in different directions as the wave passes through [1].
3. **When a gravitational wave passes through an object, it experiences a dilation too small to be seen by the naked eye.** As a gravitational wave passes through an object, it causes tiny distortions in spacetime. This leads to objects being stretched and squeezed. However, these distortions are a fraction of the size of the nucleus of an atom so the effect is too small to be seen by the eye alone. Highly sensitive instruments like Michelson Interferometers are used to measure these small distortions.

3. Sources of Gravitational Waves

Gravitational waves are disturbances in the fabric of spacetime. A large amount of mass and energy are needed to create these disturbances. Binary systems, neutron stars and supernovae are the main causes of these disturbances, because they fill the requirements necessary to cause them.

3.1 Binary Systems

A binary system is a system where two astrophysical bodies orbit each other around a common centre of mass. They are held together by their mutual gravitational attraction [3].

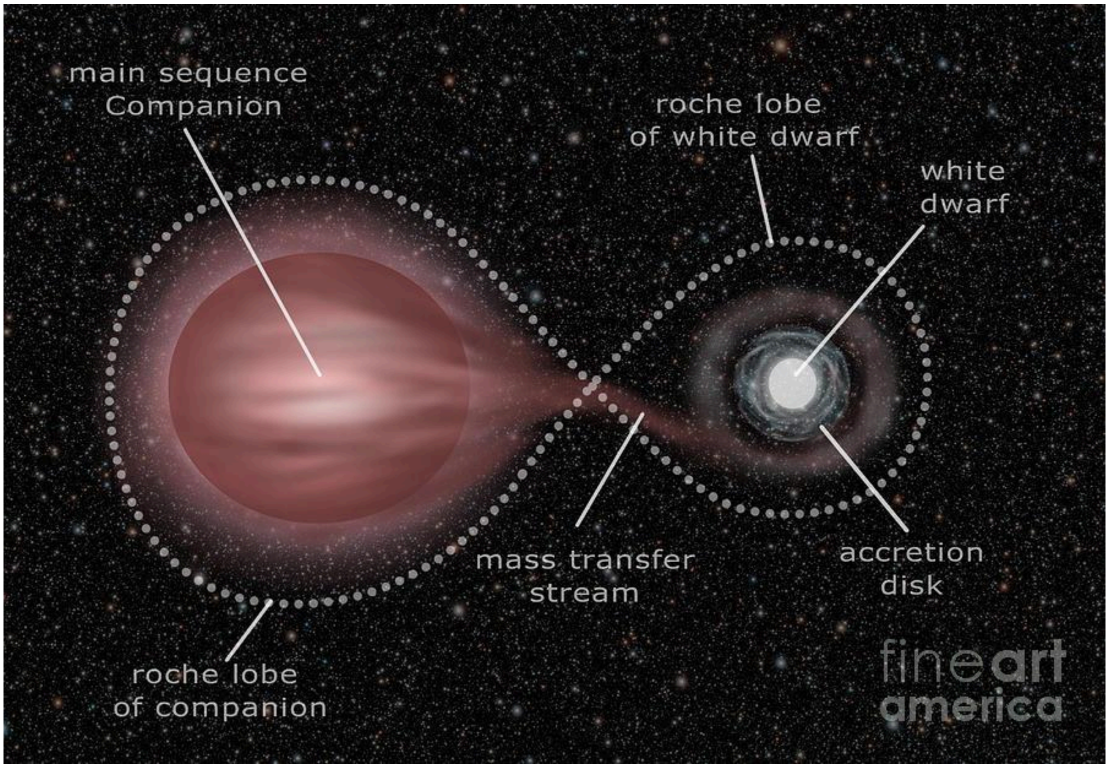

Figure 4. The Roche Lobe is a region around a star in a binary system where the gravity of one star dominates the gravity of another star. If a star expands beyond its Roche Lobe, it can begin to transfer matter to the other star (Spencer Sutton 2015).

3.1.1 Black Hole/Black hole (BH/BH)

BH/BH is a binary made up of two black holes. For BH/BH binaries much heavier than or equal to 10 times the mass of our sun/10 times the mass of our sun, gravitational waves will be generated by the inspiral of the binary because it is so powerful. When a BH/BH binary less massive than that creates ripples in spacetime, the signal is more likely to come from two black holes coming close enough together to eventually collide and form a larger, more massive black hole, and the vibrations caused by the final black hole than the inspiral. [3]

3.1.2 Neutron Star/Neutron Star (NS/NS)

Like the BH/BH binary, the NS/NS binary is made up of two incredibly dense stars called neutron stars.The NS/NS binary generates gravitational waves when the two NSs orbit each other. Unlike the BH/BH binary, the waves are very weak, but they can still be detected by gravitational wave detectors. It is also theorized that the final merge of a NS/NS binary will trigger an extremely energetic explosion that emits the most energetic form of electromagnetic waves called gamma rays in what is called a gamma-ray burst. Just like gravitational waves, gamma-ray bursts would teach us a lot about the universe. [3]

3.1.3 Neutron Star/Black Hole (NS/BH)

Just like the other two binaries, the inspiral of the bodies generates gravitational waves. The waves are weak, but they can still be picked up by gravitational wave detectors. However, NS/BH binaries are special. They can also produce gravitational waves with the tidal disruption of a NS by its BH companion. Tidal disruption is when the gravity of a BH pulls on the star and stretches it out into a long, thin stream of gas. [2]

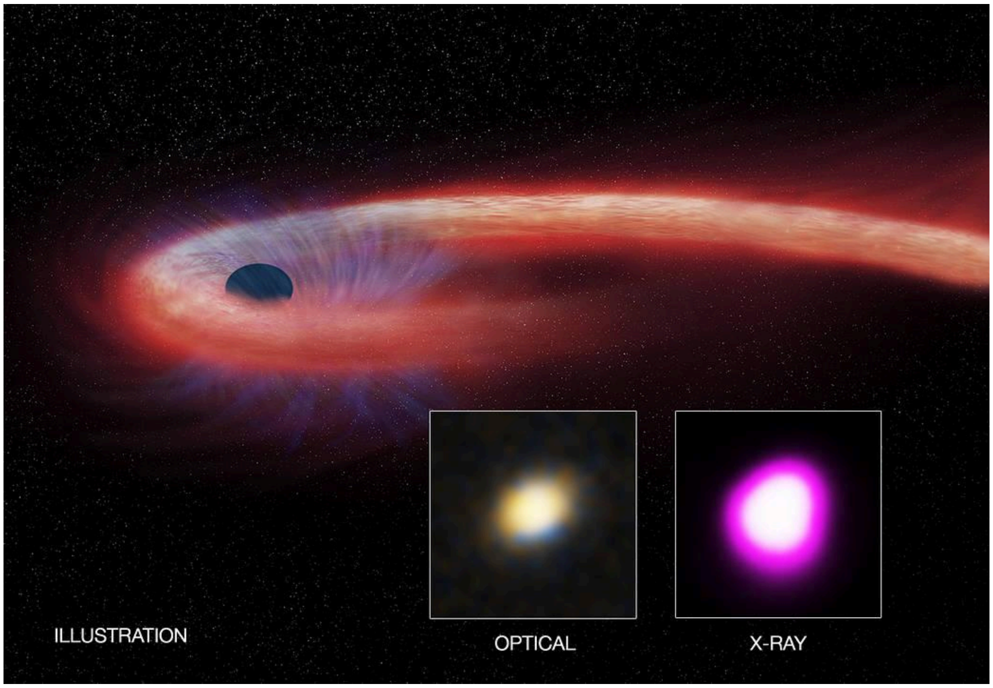

Figure 5. An illustration of tidal disruption (NASA).

The gas then forms a disk around the BH and falls into the BH. As the gas falls into the BH, it heats up and releases a lot of energy. Tidal disruption events are rare, but they provide astronomers with information about the star that was destroyed and the BH. [2]

3.2 Supernovae (SNe)

A supernova is a high energy, luminous stellar explosion that marks the death of certain types of stars. Some supernovae experience stellar collapse and evolve into neutron stars or black holes. There are two main mechanisms that lead to stellar collapse:

1. The exhaustion of the nuclear fuel that feeds the reactions inside the star.
2. The explosion of a white dwarf from gathering too much matter from its surroundings using its gravity.

There are various ways that gravitational waves can be produced by SNe. One way is if the core is rotating fast enough during collapse and bounce, which is when the core of a star collapses under its own gravity and then rebounds into a new stage in its life. Unfortunately, the required conditions only take place in a small population of massive stars. Thus, the amount of gravitational wave emissions from collapse and bounce are very limited. [3]

3.3 Rotating Neutron Stars

When the core of a star does not collapse into a BH during a SN, a Rotating NS is formed. The rotation of the NS, along with its magnetic field, is what causes the gravitational wave. [2]

4. Detection of Gravitational Waves

4.1 Laser Interferometer Gravitational-wave Observatory (LIGO)

LIGO was designed by scientists and engineers from the California Institute of Technology and the Massachusetts Institute of Technology. It is a very important observatory because it detected gravitational waves for the first time in 2015, confirming Einstein's prediction of gravitational waves from his theory of relativity. In addition, a new field of astrophysics was introduced, which allowed scientists to study gravitational waves from a variety of sources [6].

Along with being a very important observatory, LIGO is also the most sensitive of all of them. It can detect gravitational waves within a frequency range of 40-7000 Hz with a distance from the top of the wave to the bottom of the wave (amplitude) of 10^{-21} (This refers to a change in length of 10^{-21} times the original length).

LIGO uses three specialized Michelson interferometers located at Hanford, Washington and Livingston Parish, Louisiana. Washington houses the 4 km-long H1 and the km-long H2 detectors and Louisiana houses the 4 km-long L1 detector. Instrumental and environmental artifacts in the data are eliminated by making coincident detections a requirement [6].

Figure 6. Aerial view of LIGO(from VIRGO).

4.2 Future gravitational wave detectors

4.2.1 Laser Interferometer Space Antenna (LISA)

LISA is a gravitational wave detector just like LIGO. However, unlike LIGO, LISA will be in space. LISA's launch is expected to take place in 2035 on an Ariane 6. The waves LISA will be looking for have a longer wavelength than the waves LIGO detects.

Three spacecraft positioned in a triangular formation will be launched into space millions of kilometers apart. Each spacecraft will contain free-floating test masses. Laser beams will then be used to precisely measure tiny changes between the distances between the masses. The method of separating the masses to eliminate instrumental and environmental artifacts in the data is seen again in this method.

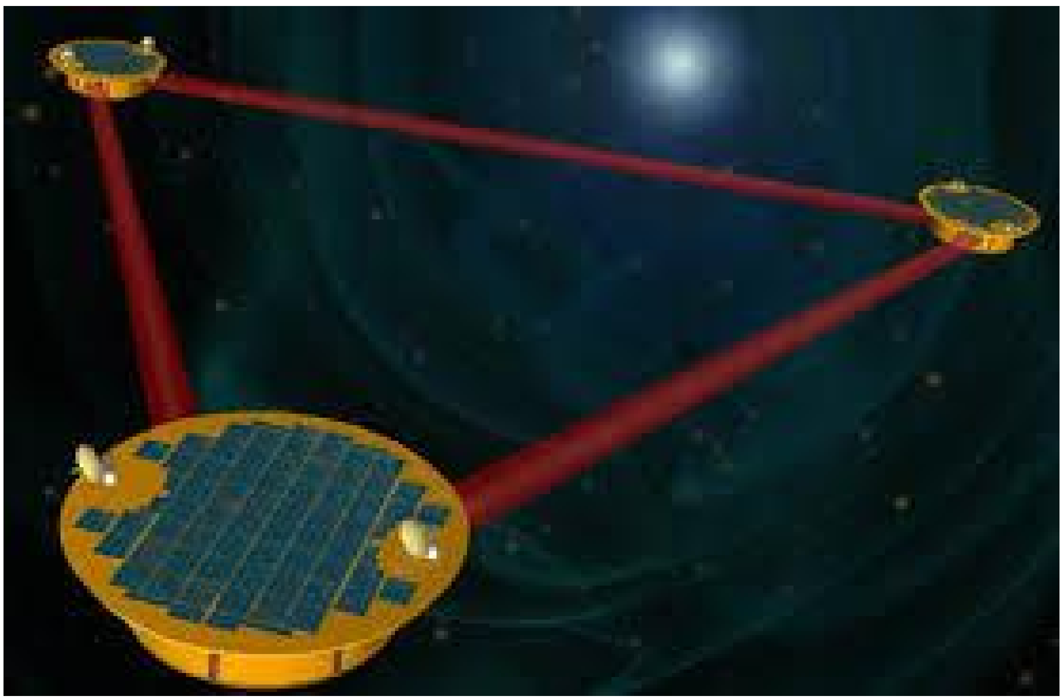

Figure 7. The three spacecrafts that will make up LISA. (from NASA)

4.2.2 Taiji

Taiji is a Chinese space mission. It aims to detect gravitational waves within the frequency range of 0.1mHz to 1Hz. This makes the primary target of Taiji super and intermediate BH mergers as they are the only gravitational wave sources massive enough to produce such low frequency waves. If the Taiji mission is successful, it will be able to provide information on the history and evolution of BH. [8]

5. Applications of Gravitational Waves

At the moment, gravitational waves are used to study powerful events in the universe. They carry information about the events that created them so scientists analyze the waves. An example of this is NANOGrav analyzing the gravitational waves caused by rotating neutron stars to learn more about them.They also reveal events that cannot be detected with a telescope because they do not produce light.

6. Conclusion

Gravitational waves are a fascinating and complex topic covering their creation, theoretical foundations, cosmic sources, detection methods and practical applications. While the subject may seem overwhelming at first, especially for those new to physics, breaking it down can make it more accessible. We gain a deeper appreciation for the universe and the technology that allows us to “listen” to its secrets by exploring how gravitational waves are formed, how they travel through spacetime, and how scientists detect them. Whether you use this knowledge for a science project, share it with others, or simply marvel at the wonders of astrophysics, understanding gravitational waves opens a window into the continuously evolving cosmos.

References

[1] Cambridge IGCSE Physics (0625). *Cambridge International*, www.cambridgeinternational.org/programmes-and-qualifications/cambridge-igcse-physics-0625/published-resources/. Accessed October 26, 2024

[2] CUTLER, CURT, and KIP S. THORNE. “An overview of gravitational-wave sources.” *General Relativity and Gravitation*, Sept. 2002, pp. 72–111, https://doi.org/10.1142/9789812776556_0004.

[3] Rong-Gen Cai et al. "The gravitational-wave physics." *National Science Review*, vol. 4, no. 5, 2017, pp. 687–689. *Oxford Academic*, doi:10.1093/nsr/nwx099. Accessed October 26, 2024.

[4] A, Einstein., N, Rosen. "On gravitational waves." *Forensic Science International*, vol. 223, no. 1, 1937, pp. 43-54. *ScienceDirect*, doi:10.1016/S0016-0032(37)90583-0. Accessed October 26, 2024

[5] CARROLL, Sean M. “*Spacetime and Geometry: An Introduction to General Relativity” Sean Carroll*. Addison Wesley, 2004.

[6] B, P, Abbott et al. "LIGO: The Laser Interferometer Gravitational-Wave Observatory." *arXiv*, 2007, arXiv:0711.3041 October 26, 2024

[7] Travis Robson et al. "The construction and use of LISA sensitivity curves." *arXiv*, 2018, arXiv:1803.01944. Accessed October 26, 2024.

[8] Wen-Rui Hu and Yue-Liang Wu. "The Taiji Program in Space for gravitational wave physics and the nature of gravity." *Silverchair*, watermark.silverchair.com/nwx116.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAA0kwggNFBgkqhkiG9w0BBwagggM2MIIDMgIBADCCAysGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQM7-_cp62NPoHeNJZaAgEQgIIC_G9HiAQZFntR5EiqaMzzEepxMOG_3_wNzXkKBGm8U12G1pHQpfkQVgzwXbxY-4x4jKA07tmAB1_IPrwmeqSilLZwktTOFvwwQOwiNkhwbpX1g3HxN7wGNV2YgL0ac3aU0l5I5ILRgqvMoGHHssQgme9NB5anMoaJDvxgXreP968aByIA8MtwBQXF-p7vJ4x2kUCqON1OKUv3UUf8rY056P4oZKFIRJOiWW74mNpweWcS7XBYLA1zs8W7zf_kZkNY7AysdaXfVx3Np6lsvFwDIncLfCyH91W7h-qq86BfQlEoQqiHNvAhRuJy1CVTRN4Y4q_J3SJuCo_Vj_gR5j_1kKBCIPRPo2H3Xxe2lUisMpV5f_Inqkx3CX06nvgUPvDjS6bfcDnEw1kr1cMqZ6wsSvxIPM3ic1elUAQHZvmkQuBhkRb4AC0TSQHV4KNVbBAGfAXUqk0YI7dUlaDWZqdF3sp8wnw19Te4qtCPsfloUdlDcyXIP3XfAg9Z3U67WDVQl8F3bcQMgteAhbpumu61W6rRoxqdU1OVT0HO9QRlvyX-f_DHuja9RVKTaOTU4MRwgqkty2plw9ka_m3yclKk4jLgQksj1UhAFR1mSdWHBbNC3r5bggxUBzvyn0KR0Hts4-3CC9y-HQdgXiE-HiCLe6XhC70XxprjsNsgcx8KDmGIAbi71Xvgj4dzdJxcHBQLyzjGL_x996EG8SVMwVk2Qncn48VkwyrFlfkTQkJiaOZeuRi4u4CN2cPC2o6andHCb0w5n0-ioDdWwhxk3_Bo7t_aal8IEodmmN6AkQ3gvE6bUMWXwU9xOSR0pD5g13E0k_Qt3DPfq2eQBnddbwJBtqxv9ne35tcftZxbfZv3xcGfC3_tGdvpEXMyMT7-hWxZcRpPAjzt3eYyAEAGyItz2BPjsxM6RuZ-bAPL8evaDVSUHnC5_ABAnAHZtOjDfR3xSzgy1rBgp8B5KQIU1FZeZ7ujcdUqp3PJ41uZdz_KW3jw9WBQVAPb4rMgOYHo. Accessed November 3, 2024.