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Prophetic detection and discovery of gravitational waves

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Abstract. Einstein's general relativity theory includes the gravitational wave as a key prediction. One of the most crucial areas of contemporary physics is gravitational wave detection. A fantastic addition to conventional electromagnetic radiation astronomy, gravitational wave astronomy is a brand-new field of study based on the discovery of gravitational waves. In this paper, the prediction and characteristics of gravitational waves are discussed, and the detection methods of gravitational waves are given, such as the limitations of the resonant rod of gravitational waves, the working principle and basic structure of the gravitational wave probe, the laser interferometer. The gravitational wave signal of the binary black hole merger detected by the LIGO laser interferometer gravitational wave detector in the United States for the first time on September 14, 2015, which opens a new "gravitational wave window" for human astronomy research. It is foreseeable that in the near future gravitational wave research will explore the unknown information of the universe from various gravitational wave frequency bands.

Keywords: Gravitational Wave, General Relativity, Laser Interferometer Gravitational Wave Probe, Resonant Rob.

1. Introduction

Gravitational wave is an important prediction of Einstein's general relativity theory, gravitational wave detection definitely has a place at the forefront of modern physics, gravitational wave astronomy based on gravitational wave detection is a rising emerging crossover science, is a new window for human observation of the universe after the traditional astronomy with electromagnetic radiation as a means of detection, to study the origin and evolution of the universe. It is of great significance to expand the field of astronomy [1]. The discovery of gravitational waves is an epoch-making scientific achievement, which marks the breakthrough of a physics problem that has puzzled scientists for a hundred years, and the historic turning point of gravitational wave astronomy has been completed from the search for gravitational waves to the study of astronomy.

The development of theoretical research and experimental detection of gravitational waves has given birth to a new interdisciplinary discipline, gravitational wave astronomy. Due to the unique physical mechanism and characteristics of gravitational radiation, the research scope of gravitational wave astronomy is wider, which can provide information that is impossible to obtain by other methods of astronomical observation, and it's very helpful in expanding people’s understanding of the structure of the universe [2]. It employs novel techniques to investigate the universe's undiscovered mass system, and is a new window for human observation of the universe after the traditional astronomy with electromagnetic radiation as the means of detection. With the deepening of theoretical research and the progress of experimental technology, the detection of gravitational waves was finally carried out half a century after the publication of general relativity. However, because the gravitational wave signal is very weak and the various noises are very strong, it was not actually detected until 2015.

In what follows, Section 2 will introduce the general relativity and gravitational waves, and detection of gravitational wave is presented in Section 3. The last Section is devoted to the conclusion.

2. General relativity and gravitational waves

2.1. *From general relativity to Gravitational wave*

The general relativity is often regarded as a very difficult and derealistic thinking theory. It is about the space, time and gravitation. Before the special relativity, these physics laws such as space and time have existed. However, the special relativity overthrown them, and give these physics concept another way to expression [3].

In 1915, Albert Einstein completes his theory on general relativity, and formulated the equation of the gravitational field. In 1916, Einstein predict the existing of gravitational wave. The Einstein gravitational field equation is [4]

$$R_{\mu v}-\frac{1}{2}g_{\mu v}R=\frac{8\pi G}{c^4}T_{\mu v}(\mu,v=1,2,3,4), \tag{1}$$

where $R_{\mu v}$ is Ricci tensor, $g_{\mu v}$ is the space-time metric tensor, $T_{\mu v}$ is the energy of mass, the momentum tensor, used to describe the mass and energy distribution of gravitational field source. Through this function and compare with the Newton-Euler's equation, use the Minkowski metric the space-time metric tensor $g_{\mu v}$ can be represent as this function [5]

$$g_{\mu v}=\eta_{\mu v}+h_{\mu v}. \tag{2}$$

In this function the $h_{\mu v}$ is a small perturbation term. Substitute the $h_{\mu v}$ back to Einstein gravitational field equation, the vacuum function can get and in vacuum the simplest solution is plane wave.

2.2. *Formation of gravitational wave*

When gravity is unstable, that instability will spread through the universe. Gravitational waves are propagating waves that bend space-time. Gravitational wave theory states that gravitational waves radiate when the motion or mass distribution of matter in a system change. In mathematics, the mass distribution can be expressed in terms of mass multipolar moments, and gravitational waves are caused by changes in mass multipolar moments over time. According to the energy law, the total mass multipole moment is a constant, which means that it does not change with time. Therefore, there is no gravitational radiation from a single mass moment [6]. The derivative of the mass dipole moment is the momentum of the source. Due to the conversational nature of momentum, momentum also does not change over time. Gravitational radiation comes from the mass quadrupole moment. If there is a mass flow, then the mass multipole moment can also be represented. Therefore, the rotation of binary star systems, the explosion of supernovae caused by gravitational collapse, and the rotation of non-spherically symmetric objects can all produce gravitational waves.

However, to produce gravitational waves large enough to have an observational effect, the celestial system that produces them needs to release a large enough amount of energy over a short period of time. One natural candidate is a black hole binary star system. As early as 1972, Thorne had thought deeply about the theory that black holes produce gravitational waves. Conceptually, as binary black holes orbit, they will dramatically perturb the space-time around them, so that the space-time pattern will gradually increase in fluctuations, and the information of the black hole's motion will travel outward at the speed of light. Therefore, Thorne emphasized in the article that gravitational waves must open a new window for us to probe the universe.

3. Gravitational waves: Evidences and detection

In 1916, on the basis of the weak field approximation, Einstein predicted the existence of gravitational waves. But it was impossible to confirm gravitational waves because of two major theoretical difficulties:

first, the theory of gravitational waves was originally related to the selection of coordinates, so it was not clear whether gravitational waves were intrinsic to the gravitational field or some kind of bogus coordinate effect. Second, whether gravitational waves carry energy away from the emission source is also a very vague question, which makes the detection of gravitational waves lack a theoretical basis. It was not until the 1950s that the theory of gravitational radiation, independent of coordinate selection, was completed, and a strict wave solution to Einstein's vacuum equation was obtained [7]. In the 1960s, physicists rigorously proved that gravitational radiation carries energy by studying the initial value problem on the zero surface, testing that mass moves under the action of gravitational waves. At this point, after more than 50 years of careful research, the two major problems have been overcome, and gravitational wave detection has a reliable theoretical basis. The detection of gravitational waves is on the agenda.

3.1. The indirect and direct evidences

In 1974, American physicists Taylor and Hulse use the radio astronomy telescope in Puerto Rico discover Binary pulsar PSR1913+16, which is two neutron star have close mass with sun entangled rotation. In this system, from the radio sign they get the accurate data of the period and major semi axis of the orbit. In Ref. [1], the major semi axis of the system was decreasing with the time and the period of the stars rotating respect to the centre of mass have been shorter. In the general relativity, Einstein says when two mass rotating respect to their centre of mass will radiate the gravitational wave, which can carry the energy out of the system, and because the total energy of the system loss, the major semi axis and period will decrease [8].

The first time binary black hole merging event was observed on September 14th, 2015, by the American Laser Interferometer GW Observatory using an improved Laser Interferometric Gravity-wave Observatory (LIGO) sensor. GW150914, a binary black hole merger, was seen by LIGO. When two large things fall into black holes separately, binary black hole systems may result. Gravitational waves are emitted by the black holes as they orbit one another, slowly draining the energy of the black hole system. The orbital energy of the double black hole is where this energy comes from. The binary black hole system spins closer until it eventually merges as a result of energy loss. The orbital speed of the black hole approaches the speed of light during this last merger step. The gravitational field around it is very strong, which makes the dynamics of space-time very violent, and radiates a large number of gravitational waves.

3.2. Detection of gravitational wave

In 1962, a team of researchers at the University of Maryland, led by J. Weber, complete the world first one gravitational wave detect sensor, resonance rod. Weber use massive aluminum rod to be the receiving antenna for gravitational wave. By being suspended at the center of mass in the central position, it is free to vibrate longitudinally. When the gravitational wave arrives in the direction perpendicular to the rod, it will lengthen or shorten the space where the rod is located. Since the direction of the polarization of the gravitational wave is basically parallel to the longitudinal axis of the rod, the metal rod will vibrate with the frequency elongation of the gravitational wave. The rod resonates and the amplitude increases to its maximum when the frequency of the gravitational wave is equal to the natural frequency of the rod. Although in June 1969, at the Academic Conference on Relativity held in Cincinnati, USA, J. Weber and others announced the successful detection of gravitational waves, through analysis these signs are all fake, not the gravitational wave sign [9]. Since the 1980s, the world's resonant rod gravitational wave detectors have been shut down. The reason is the resonance rod can only detect a small range of frequency, almost all of the resonance rods in the world have resonance frequencies near 1000 Hz, gravitational wave cases are already very rare, and the detection window is limited to 100 plus or minus a few Hertz, which greatly reduces the probability of detection of gravitational waves.

3.3. Laser interferometer GW detector

The appearance of laser interferometer gravitational wave detector opens up a new era of gravitational wave detection. Its detection sensitivity is high, detection frequency band. It is wide and has great potential for upgrading, bringing new hope to gravitational wave detection. Professor R. Weiss of the Massachusetts Institute of Technology came up with the notion of employing interferometers to detect gravitational waves. In the 1980s, a number of modest prototypes were made, and a great deal of basic research was done with them. This experience proved to be extremely beneficial. By the early 1990s, some large laser interferometer gravitational wave detectors began to be built, and the world quickly set off a new upsurge in gravitational wave detection. In under ten years, the laser interferometer's gravitational wave detector's sensitivity has increased by four orders of magnitude from prototype to initial update., which is extremely rare in the history of detector development, showing huge development potential, and bringing great hope to gravitational wave detection. Gravitational waves are confirmed by this invention, September 14, 2015, in the advanced LIGO just completed the trial operation stage found the gravitational wave case GW150914, has made an epoch-making scientific research achievements [10]. The half-century-long human gravitational wave detection has finally had the result, which marks the completion of gravitational wave astronomy from the search for gravitational waves to astronomical research this historic turning point.

3.4. The working principle of the laser interferometer GW detector

Laser interferometry is the principle behind LIGO's detection of GW. In the illustration below, a laser beam is produced by a laser machine, passed through a spectroscope with a 45° inclination, split into two laser beams with the same precise phase, and then transmitted in two directions perpendicular to one another. The two beams interfere when they bounce back along their original paths after reaching the two mirrors at an equal distance. If the beams travel the same exact distance, their light waves will precisely stagger and produce absolutely destructive interference, which will prevent the laser signal from being detected by the detector. When a gravitational wave is detected, the area around the detector is perturbed, causing the area to expand in one direction and contract in the opposite direction. As a result, the two laser beams' paths will differ slightly, their phases will differ, and the amount of light that strikes the detector will change significantly. The Michelson Morley interferometer is another name for this interferometer design. In 1887, Michelson and Morley used this interferometer in Cleveland, United States, to measure the difference in the speed of light between two vertical light, thus negating the existence of the past, and directly leading to the production of special relativity. Scale is the primary distinction between LIGO and a normal Michelson Morley interferometer. The longer the interferometer's arms, the smaller the measurements it can take, the more sensitive it is, and the more effectively gravitational waves can be detected. In terms of LIGO's arm length alone, that's still not enough. The LIGO team placed an additional mirror in each arm of the spectrometer near (positioned at an Angle of 45° in the middle), 4 km away from the mirror at the end. The space between these two mirrors forms a "Fabry Perot cavity". The travel distance of each laser in each arm is increased from 4 km to 1,200 km by approximately 300 reflections between these two mirrors, considerably extending the effective arm length and enhancing the device's sensitivity.

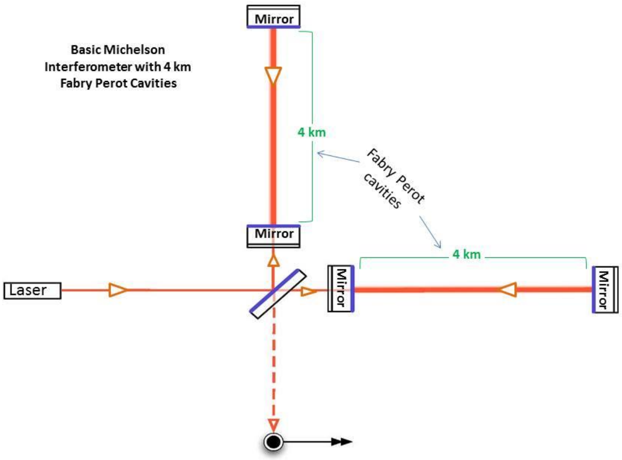

Figure 1. Laser interferometer gravitational wave detector working principal schematic [10].

3.5. Basic structure of laser interferometer GW detector

Laser interferometer gravitational wave detector is composed of optical part, mechanical part and electronic part. The main structure of the optical part includes the laser, the mode cleaner, the Fabry-Perot cavity on the arm, the optical circulation mirror, and the auxiliary optical systems and devices, see Figure 1. The laser interferometer gravitational wave detector has very strict criteria for lasers: it needs to have a high laser power and very high-power stability and frequency stability in order to eliminate shot noise and improve sensitivity. The function of the mold cleaner is to remove the residual higher-order mode in the input laser beam. The role of the Fabry-Perot cavity is important because the sensitivity of the interferometer is proportional to the length of the arm, and it is not practical to build an interferometer ten of kilometers long, and using the Fabry-Perot cavity to make the laser beam resonate in the cavity is equivalent to folding the arm. The laser interferometer works in the dark grain state, and most of the light is emitted from the bright grain mouth. The power cycle technology can be used to reflect the light emitted from the bright grain mouth of the interferometer back for recycling, so as to improve the laser power in the interferometer.

4. Conclusion

One of the main predictions of Einstein's "general relativity" was the gravitational wave, but its detection has been a difficult and protracted procedure. The development of the gravitational wave detector known as the laser interferometer provides great hope for gravitational wave detection and directly aids in their discovery. The study of gravitational wave astronomy has advanced to a new stage as a result of the worldwide surge in laser interferometer gravitational wave detector research, development, and construction. At the same time, GW150914 was detected by high-tech LIGO in the engineering phase, and the upgrade of high-tech LIGO has not been completely completed. With the advanced LIGO upgrade, it will be more sensitive, which has the potential to detect more gravitational wave events. The study of gravitational waves can bring many new understandings and new discoveries about the unknown universe, such as studying the formation of supermassive black holes, and providing clues for unifying general relativity and quantum theory. The measurement of gravitational waves integrates the technology of many disciplines such as physics, astronomy, precision measurement, navigation, materials science and space engineering, and can promote the development of related disciplines by actively participating in gravitational wave research. The implementation of the gravitational wave detection mission will also play a positive role in the application fields of inertial navigation, earth science, and the construction of high-precision satellite platforms.

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