Exploration of Astrophysics: From Newton's Law of Gravitation to General Relativity

Xintong Li *

Collège Alpin Beau Soleil, Rte du Village 1, Villars-sur-Ollon, Switzerland

* Corresponding Author Email: xintong_li@beausoleil.ch

Abstract. Science developments are cumulative, with each new discovery building on the foundations laid by previous knowledge, enabling further. This article discusses the evolution of how the reality of universe is gradually revealed. Where people first discussed about Geocentric and heliocentric models, continuing to the time where Kepler found Kepler's three laws, then to Newton's law of gravitation. Further, with Einstein building upon Newton's law and finding general relativity, process of recognizing knowledges on black hole and gravitational waves is finally speeding up. In this article, the author will give a brief understanding about these topics above, including their scientific definitions, interesting stories, and their relations between each other. From ancient to present, this paper will explain in simple words that are easy to understand for most age groups, gradually bring people into the world of astrophysics. Ending with the discoveries of gravitational waves which human are still looking forward to further findings, this will surely expand the overall knowledge and understanding on astrophysics.

Keywords: Geocentric and heliocentric models; Newton's law of gravitation; General relativity; Black hole; Gravitational wave.

1. Introduction

The importance of Astrophysics has never been overestimated throughout the past. Talking about the evolution of physics, it would be necessary to trace back until the Big Bang, where people could study fundamentally and shape how the universe developed. The importance of astrophysics reflects on other areas, it overlaps with other scientific fields, including chemistry, biology, and environmental science, it also drives the development of technologies such as GPS. Without the existence of satellites, it is not only hard to locate positions, telephones and internet are also not able to use.

Throughout the history of Astrophysics, several accomplishments were achieved. Understanding the Big Bang and the evolution of the universe, discovering thousands of planets, understanding the first image of black holes and gravitational waves [1]. These are all what humans have achieved, and many efforts was putted on it, especially on black holes and gravitational waves. From 1915, when Albert Einstein first created the mathematical formula of black holes to now, distinct types of black holes have discovered, huge steps are taken. The discovery of gravitational waves also thanks to laser Interferometer Gravitational wave Observatory (LIGO) [2], which first detected them and broke the ice.

Discovering the history of physics will be needing to trace back to the time when people believed in the hypothesis of the universe being Geocentric. After geocentric model proved to be correct, astrophysics starts to develop. With the appearance of Kepler's three laws, which explains how planets orbits and the relationship between their orbital period and radius; Newton's law of gravitation, which made an equation for the force of gravitation; General relativity, which improved based on Newton's formula and discussed more about the black hole, further discoveries of the black holes and gravitational waves are gradually discovered with more observations and details [3]. These are the topics forming astrophysics together, and this article is going to discuss about these in more details.

2. Classical Theory of Astrophysics

2.1. Geocentric and Heliocentric Model

In the past, when astronomers did not know the existence of gravity, they did not understand why if Earth did spin then why could people stay on the surface. Therefore, people believed that the sun and planets all orbited the Earth. This theory is called the geocentric theory. This theory was firstly raised by an astronomer named Eudoxus. His design of the model of universe was a series of cosmic spheres having the stars, the sun, and the moon all orbiting around the center, which is the Earth. However, they gradually found out that their model could not predict the motion of planets accurately. So nowadays people have recognized that the planets are orbiting the sun [4]. There are several philosophers and scientists who made contributions towards this development including Copernicus, Tycho Brahe, Kepler and Galileo.

At that time, Nicolaus Copernicus was the first one who proposed that the Earth was also a planet like Mercury or Mars, and they all orbit around the sun. However, it stayed as a theory from 1543 to 1610, when Galileo first observed that there are also moons orbiting around Jupiter, and he also observed the phases of Venus which than proves that the planets do orbit the sun and Copernicus' theory is correct. The schematic diagrams of geocentric model and heliocentric model are difference. The author could see that in the geocentric model, they putted Earth as the center of the system. While in Heliocentric model, the Earth is replaced, and the Sun is in the middle of the system.

2.2. Kepler's three laws

The three laws of Kepler given descriptions as the characteristics of how planetary bodies orbit around the sun. Kepler's first law explains that, unlike what most people thought, planets do not orbit in circles, they orbit in an ellipse shape with the Sun's center being one of the foci. Kepler's second law states that the sectorial area which the straight line connecting the sun and planet travelled are the same when they travel for the same time intervals. Which means that when planets move along their orbit, they are not at constant speed all along. Kepler's third law states that the square of the planet's orbital period is directly proportional to the cubes of their orbits' semi-major axes, if transfer this to mathematical language, it is written as $T^2 \propto r^3$. The way to prove this is the formula below

$$T^2 = \left(\frac{4\pi^2}{GM}\right) r^3. \tag{1}$$

In this formula, T is the period, G is gravitational constant, M is the mass of the planet and r is the mean distance of the planet from the sun. Due to the number in front being a constant, one can conclude that period squared over radius cubed is a constant for all circumstances. From the Table 1, Kepler's formula for his third law is proven to be correct. Period squared always have a same proportion to orbital radius cubed.

Table 1. Different planets with their ratio between period squared and radius cubed.

	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
T/days	87.97	224.70	365.26	686.98	11.86	29.46	84.01	164.79
r/$10^6 km$	57.9	108.2	149.6	228.0	778.5	1432.0	2867.0	4515.0
T^2/r^3	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040

Kepler's laws are still useful for science developments in different areas nowadays. It helps to predict how natural and artificial satellites acts and orbits. In additional, Kepler's laws do not only apply for gravitational, they also work for other inverse-square-law forces. However, according to Kepler himself, when more than two bodies are under their mutual attractions, it would be too complicated to predict their motions using Kepler's laws.

2.3. Newton's Law of Universal Gravitation

Newton's law of universal gravitation was first generated in 1687 by Sir Isaac Newton. It could explain the motions of planets and moons when observed. In this law, he extended his earlier formula beyond Earth, which is $F = ma$. Due to Newton's third law, each force has a force pair against it. So, in this law, Newton said that all objects have an attraction force between one another which is called the force of gravitational attraction. This force is calculated by the formula

$$F = \frac{GMm}{r^2}. \tag{2}$$

In this formula, F is the force of gravitational attraction, G is the gravitational constant, M and m are the two objects attracting each other and r is the distance in between of them.

Although Newton's laws satisfy most practical experiments, it still has limitations. It does work for most of people's real-life crisis, but it will make a wrong calculation in strong gravitational fields or at extremely high velocities. However, Albert Einstein later found the problem in newton's formula and did some corrections and changes based on Newton and said the General Theory of Relativity, which is than published in 1915. It helped the understanding of gravitation by describing gravity as a curvature of space time instead of understanding it as a force.

3. General Theory of Astrophysics

3.1. General Relativity

Albert Einstein first produced the theory of special relativity in 1905, and after only ten years of work, he later produced the theory of general relativity. First, the author shall talk about special relativity. The main idea of special relativity is that it described how speed effects time, space and mass, it concluded a way that puts energy, mass and speed of light together, which is the famous equation $E = mc^2$ [5]. According to this formula, due to the speed of light being fast, even a tiny amount mass could be converted easily into a large amount of energy. The theory of special relativity also has the other two key concepts. The first one is that the natural world does not have a privileged frame of reference. Which means that. If an object is moving at constant speed, then people could not tell if it is themselves that is moving or the object. The second one is that light has a fixed speed of 3×10^8 m/s in vacuum, no matter how people change the other exponents of the experiment like how fast the observer travels. From these theories above, he found out that space and time were a single continuum called space-time.

Special relativity was expanded later by Einstein to General relativity. The theory of general relativity first started as an equation, which described space-time as a 4-dimensional object that obeys the equation. It is also a theory of gravity that changed the concept of gravity from a force to a curving or warping of space, showing the difference to Sir Isaac Newton's law of gravity. In Einstein's perspective, this warping of space can also affect time. Different strength of gravity effects the rate of how fast time runs. Lots of phenomena such as the birth and death of starts and black holes, planetary dynamics, and the evolution of the universe, which was difficult to explain for us in the past, could be explained easily now using this theory. The Einstein Field equation is given by the formula below [6]

$$R_{\mu\nu} - \frac{1}{2}\mathrm{R}g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{3}$$

The definitions of these symbols are shown in Table 2.

Table 2. Different symbols in relate to their definitions.

Symbol	Definition	Symbol	Definition
$R_{\mu\nu}$	Ricci tensor curvature	R	Ricci scalar curvature
$g_{\mu\nu}$	metric tensor	$T_{\mu\nu}$	stress-energy tensor
c	speed of light in a vacuum	G	Universal gravitational constant

3.2. Black Hole

Here, the author will talk about the black hole. Firstly, what is black hole? It is a region of the spacetime that gravity is extremely strong, nothing can escape of communicate with the exterior region, even light could not get out [7]. Therefore, people cannot see them. The history of black hole needs to trace back until 1783, when someone first raised up the idea of faint star. It was a British called Michael who found out from the formula of escape speed from a star that, if a star has a huge mass, then even light could not escape from its surface. In 1915, when Albert Einstein stated the general theory of relativity, which then created the mathematical model for black hole. From the perspective of general relativity, black hole is when gravity collapses, the volume of an object would be ridiculously small, and density would be exceptionally large, then it will cause time-space to warp and form a hole where anything could not escape once they fall into it [8]. This hole is black hole. Nowadays, at least two classes of black holes are discovered. Stellar-mass black holes and supermassive black holes. People predict that there probably are a third class of objects which is intermediate mass black holes.

3.3. Gravitational Wave

Gravitational wave was first formulated by Einstein's general theory of relativity. It is when a substance is in the process of moving, contracting, expanding, it would lead to the change in Spacetime metric, which would then spread and cause gravitational wave. However, it is extremely hard to be detect straight forward due to its weak in energy and strength. Gravitational wave was first detected by a group called LIGO in 2015 [9]. At the beginning, which is from 2002 to 2010, for eight years sadly LIGO did not detect anything. However, after 4 years of upgrading technologies, they detected the first gravitational wave on September 14th. This huge finding results in LIGO's detectors which was in Livingston and Hanford, they are called the twin LIGO detectors. The gravitational wave they detected was a fabric of spacetime arriving the Earth from a cataclysmic event in the distant universe. This was not long after the new advanced LIGO detector was first brought into operation, and strong signal was surprisingly captured [10].

People also found out that if two black holes meet each other, then they will devour each other and combine into a larger black hole. In the process, significant amount of energy would be released by gravitational wave. Black holes are among the most powerful sources of gravitational wave, so successfully detected the gravitational waves provides an important role in astrophysics discovery by introducing a new field to research, providing more information to continue with the studies towards black holes.

4. Conclusion

In conclusion, this article discussed about different topics of astrophysics. In the second part of this article, which is the classical theory of astrophysics, there are Geocentric and Heliocentric models, Kepler's three laws and Newton's law of universal gravitations. From the origin when the Greeks believed in geocentric models, the discovery of astrophysics progressed significantly. In this article the readers will be able to know how the reality of solar system is found by Nicolaus, who stated the heliocentric model. Then the orbital period and condition is found by Kepler's observation. After that, Newton stated the formula for universal gravitation field. Continue with Newton's laws, the third part of this article started by Albert Einstein improving the law of gravitation and created General relativity. Finally, the paper mentions the discovery of black holes and gravitational wave. From the origin of astrophysics, this article gradually developed into deeper subjects, which are harder to understand, and closer to the present. This article explains everything in a simple way. Still there are many details that have not been discussed and explained. However, it is just an introduction to astrophysics. Nowadays, humans are still trying hard to extend people's understanding of the space, and hopefully, with better technologies being build up, the image of universe could be revealed more and more.

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