Analysis of the Principle for Exoplanet Searching and the State-of-art Detections

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Abstract. In recent years, the exoplanet searching remain a hot topic among cosmology and astrophysics. In this case, this paper analyzes the methods and facilities used to detect exoplanets. To be specific, 7 main methods are discussed and transit method contributes most in the detection. However, some methods need restrict condition to happen and some has a high rate of misjudge. With regard to facilities, space telescopes are widely used and provide most data and images. Nevertheless, the quality of spectra is not enough so that some theory of early universe cannot be test yet. Previsou studies mainly focus on galaxies with high red shift which are old and faint, while in fact the information is enough to make prediction but not enough to confirm. In the future, those limitations will be improved by new facilities and new methods. On this basis, future research's direction is clear and will help to improve methods and facilities. Overall, these results shed light on guiding further exploration of exoplanets searching.

Keywords: Exoplanets, mass detection, exoplanet searching methods.

1. Introduction

Searching for exoplanets has long been an important part of astrophysics because of its significance. Searching exoplanets provide information to explore the early universe. For example, scientists can find habitable zones on exoplanets and make prediction about whether there is life on the planet. One instance is Kepler series of planets, which is a series of super-Earth. Lots of scientists has analyzed it and proved that it is in the habitable zone [1]. Besides, it can also help detecting new habitats for human so that human can live on new planets in the future. This not only contributes to astrophysics; it also helps solving some social problems such as the overwhelming population and lack of resources. Searching exoplanets has a long history and lots of scientists had joined to help. The first planetary disk was observed in April, 1984. In April 23, 1990, the Hubble Space Telescope was launched and later helped discover exoplanets. Afterwards, the first exoplanet was discovered in 1992 [2]. In 1999, the first transiting exoplanet is observed. After 2 years, the first planet that is inside the habitable zone is found. In 2009, the Kepler planet-finding mission launched. Later, more exoplanets of all types are found. In 2018, TESS launched. In 2021, James Webb Space Telescope (JWST) launched [2].

Scholars have discovered 5477 exoplanets (already confirmed), 9766 candidates, and 4220 planetary systems by August 3, 2023 [3]. Besides, the discoveries including 4 types of exoplanets: Gas giant, Neptunian, super-Earth and terrestrial [4]. To be specific, among all planets that have been confirmed, 1731 are Gas Giant, 1664 are Super-Earth, 198 are Terrestrial, and 1884 are Neptune-like. Moreover, different ways of discovering planets have been developed including transit and radial velocity. Lots of telescopes are also launched in space in order to discover more. This includes JWST, Hubble Telescope, Kepler and TESS. By 2023, there's more than 100 telescopes that have been launched. Additionally, there's about 500 observatories in the world which contribute to observation [5]. Besides the results of those, there's still a lot of discovery of planets that are in habitable zone, habitable planets and other aspect of the universe.

Searching for exoplanets is very important. Once new development is made, more exoplanets will be discovered and some problems may get an answer. By analyzing the principle for planet searching, the advantages and limitation of methods can be shown clearly. This will help making development can contribute to exploring new exoplanets. By exploring more in the future, more planets are found

and some problems can be solved. In this article, some basic information about detecting exoplanets will be introduced first. This include what are being detected and what one obtains from detection. Then, serval ways of detection will be introduced with explanation. Facilities that are used in detection will be followed. After that, some state-of-art results will be shown. Finally, some limitations about methods that are used now will be shown. Some future outlooks will accompany including some suggestion of improvement.

2. Basic Descriptions

Detection of planets, or searching exoplanets, refers to discovering other planets by telescope or other facilities. Usually, scientists use telescope to gain data they need and then use different methods to search for planets. There are 7 main methods that are used to detect which will be discussed in Section 3. Besides finding planets, some properties of planets are also being detected in order to know more about the planet. In the detection of planets, because of different methods, lots of properties can be detected. However, one method cannot detect all properties so that different methods are needed to gain more information. Usually, mass, volume (size), density, period, and orbit will be detected. In this section, the method for detecting properties will be introduced but the detailed principle will be shown in section 3. Some examples will also be showed here.

To measure the mass of a planet, the microlensing method, pulsar timing method and transit method can be used. For microlensing method, it is developed on the gravitational microlensing effect. This is the phenomenon that the light will be slightly bent when it passes the star or planet. Its effect can be viewed as a magnifier. An example is that scientists measure the mass of the lens (the lens star or planet) of microlensing event CP J05074264+2447555 (Kojima-1) [6]. For pulsar timing method, it used the little time difference of detecting radio. However, this method is not widely used. Usually, scientists use it to find exoplanets. Transit method is also widely used to get the mass. In fact, Exoplanets are mainly focused so methods such as parallax will not be introduced. The most common method is transit which get the volume of the planet by measuring how much light is blocked. One example is Kepler-138b. After using transit method, the volume of Kepler-138b is shown [7]. Density of a planet can also be got from the detection. However, the value of density doesn't come from observation or detection. In fact, it comes from calculation by the formula of $\rho = \mathrm{m}/\mathrm{v}$. Thus, to get the density, the value of mass and volume is needed. For further explanation, let's use Kepler-138b as an example. The mass of Kepler-138b is got from the transit method and it is estimated to be $0.66^{+0.059}_{-0.037}$ Earth masses [7]. By using the formula, the density of Kepler-138b is estimated to be $2.6^{+2.4}_{-1.5}\ gcm^{-1}$. Usually, reearchers use transit method to detect the planet's period. By measuring the period of transit, the period of planet is shown. Lots of planet's period is measured by transit method. This method can usually give accurate method. However, the transit can be misunderstood which means sometimes there's not transit but people think that there is a transit. This will lead to a wrong result. To know the orbit of a planet, the Kepler's Third Law is used. The formulas is:

$$\frac{a^3}{T^2} = \frac{GM}{4\pi^2} \tag{1}$$

where a is the length of its semi-major of axis of its orbit; T is its period; and M is the mass of central star. Before calculating the orbit, other information is needed so that other method is used to gain that information.

3. Principle

There are 7 main methods used to explore exoplanets: transit, radial velocity, direct imaging, gravitational microlensing, astronomy, pulsar timing, and relativistic beaming. In this section, all methods will be introduced and transit method will be introduced specifically. Among all the methods, transit is the most successful one and about 74.8% exoplanets are discovered by transit [8]. When the

star passes directly between the star and the observer, the star's light received by the observer becomes dimmer. By observing the changes in light, scientists are able to determine whether there is a planet. A sketch for the principle is shown in Fig. 1. Transit method is very useful because it not only can detect exoplanets, it can also detect their size, period and mass as section 2 introduced. Since transit occur usually, it is useful to discover exoplanets. Those are the 2 main advantages of transit method. This method also has some disadvantages. For example, the result of transit usually depends on the relative size of the planet and star. If the planet is much smaller than the star, the transit effect will be very small. Besides, only when the star passes directly between the star and the observer can the effect been saw. In addition, this method also has a rate of confusion. Overall, this method is still successful and contributes to lots of discovery.

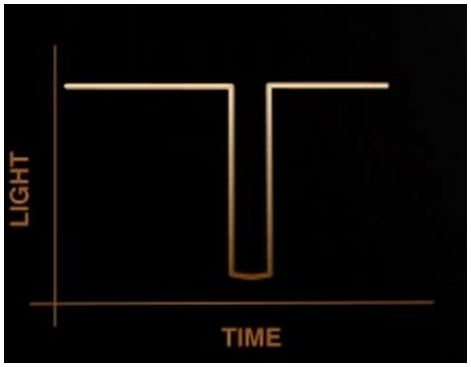

Figure 1. The light changes through time when the transit happens.

In the universe, if the object is moving away from us, a red shift will be observed. In opposite, a blue shift will be observed. This is called the Doppler shifst. When a planet is rotating around its star, a change in wobble effect will be observed and enable scientists to discover it. Sometimes, the change in velocity is also observed. This method is called Radial Velocity or Wobble method. For example, β Pictoris c is discovered by this method [9]. Direct imaging simply means to discover new planets by taking their photos. However, this is a difficult task since exoplanets are far away from us and they are very dim in the photo. Scientists build up large telescopes and observatories to take photos. Those facilities will be introduced in section 4. This method has discovered 68 planets [8]. During the process that the light of a star passes the universe and reach the observer, some light will be bent by gravity of a planet. This enables some light of distant star to be observed by scientists. In this case, it shows that there's an exoplanet which is known as gravitational micorlensing (seen from Fig. 2) [10].

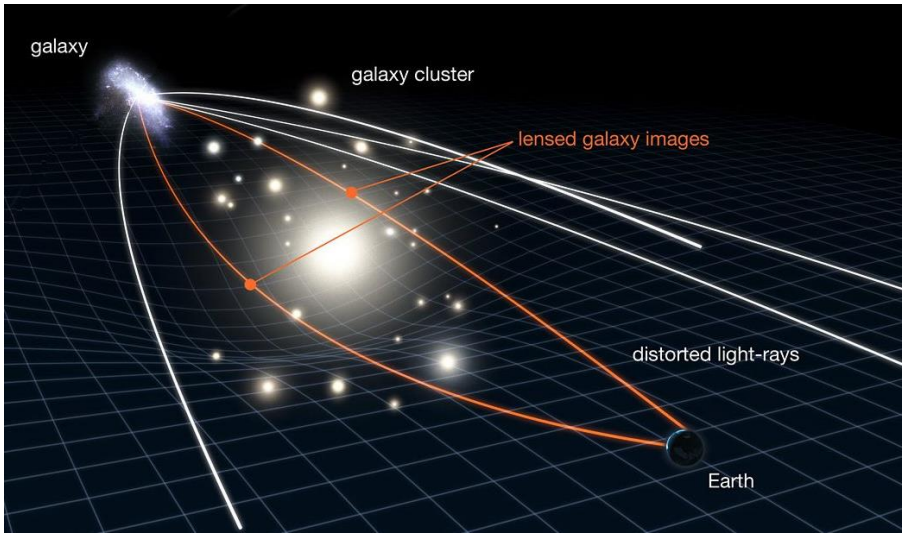

Figure 2. The mechanism of gravitational microlensing works.

Astronomy is similar to radial velocity but this method detects the doppler shift of the star. Because of the gravity of the planet, its star will wobble in the universe. By comparing its position at different

time, scientists can determine that there's a planet around the star. This method has just detected 2 planets [8]. Pulsar is a type of neutron star and it has exploded as a supernova. A pulsar will emit radio waves regularly (usually with negligible time difference). When there's a planet on its path, there will be a time difference in receiving the radio. By this method, scientists can explore new exoplanets. When the planet's gravity is dragging the star, the observer will observe a change in density of photons and the apparent brightness. By observing this phenomenon, a new exoplanet can be discovered. However, since the change of light is very small, this method doesn't contribute much.

4. Facilities

When finding exoplanets, telescopes always paly an important role as they are needed to receive lots of wave and light. Now, the most widely use telescopes are space telescopes such as James Webb Space Telescope and Hubble Space Telescope. Besides those have already launched, new facilities such as coronagraph and starshade are developing and will be used in the future.

4.1. Hubble Space Telescope

Hubble Space Telescope (HST)was launched in1990 and aimed to discover more exoplanets. It took pictures of sky in different position and let scientists used those pictures to find new planets. HST has finished some important programs, such as Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey and Frontier Fields program. HST is about 1,825 pounds with a primary mirror of 7.8-foot diameter. This mirror is used to collect light and then reflect it to a secondary mirror with 12-inch diameter. The light is then reflected again through the whole. Finally, the image is shown [11]. Seen from Fig. 3, it is clear how HST works. Besides, because of the think material use to make the reflecting surfaces, this telescope is very reflective to ultraviolet light [11]. When the telescope was first launched, there was some problems on the mirror. To solve this problem, there was serval servicing missions. The problem was finally solved and HST helped discvoer lots of exoplanets. It is still working in space.

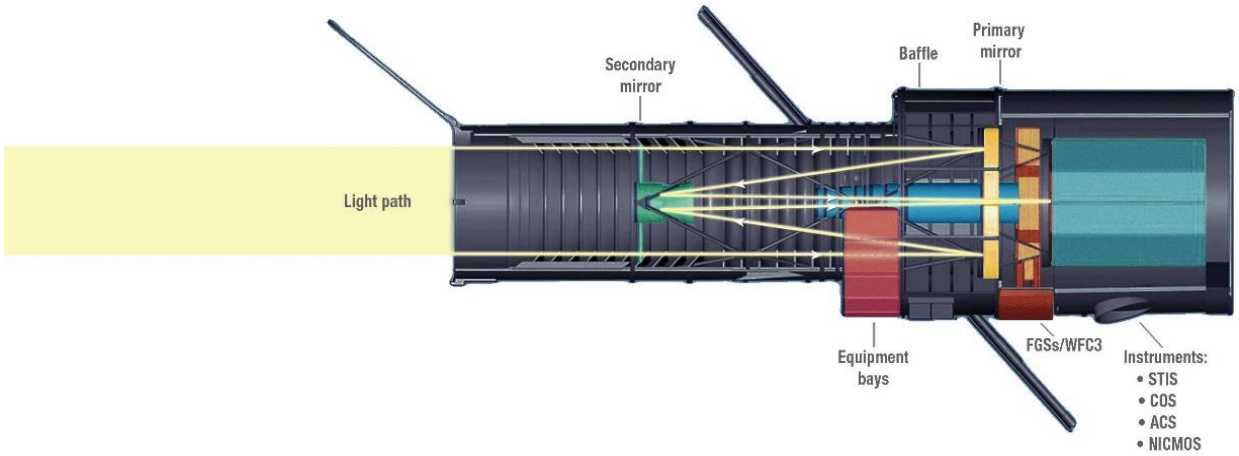

Figure 3. The mechanism of HST.

4.2. James Webb Space Telescope

James Webb Space Telescope (JWST) was launched in Dec.25, 2021. It is developed to conduct infrared astronomy. Compare to HST, it is high-resolution and high-sensitive. Thus, it can observe some old, distant or faint galaxies and planets. For example, it can observe galaxies of redshift of 15 for an idealized. To be specific, this section will compare JWST with HST. For the wavelength they can observe, JWST mainly focus on infrared red wave and a little visible light. The wavelength been observed by JWST is 0.6-2.8 micrometers while that been observed by HST is 0.1-0.8 micrometers. Thus, JWST performed better in infrared red range. Mirror is an important part of a telescope since the properties of the mirror will determine the resolution and the result of the image. Thus, by

comparing the mirror, the difference and advantages of telescopes can be shown clearly. JWST has a mirror with 6.5 meters diameter while HST's mirror has only 2.4 meters diameter (as given in Fig. 4). JWST can collect information of a larger scale. After calculation, JWST can collect about 6.25 times area more than HST [12]. HST flies at 570km away from Earth while JSWT files at 1.5 million km away from Earth. Actually, it flies at L2 which is Lagrange Point (seen from Fig. 5) [12]. At this point, the light of Sun, Earth and moon is blocked and helped to detect infrared red wave. In addition, it is estimated that this telescope can observe very old universe.

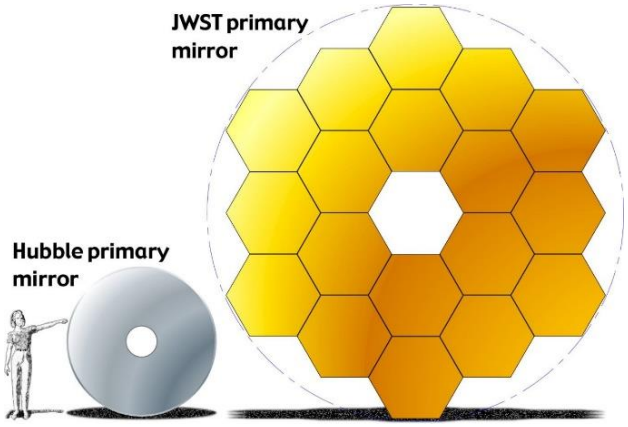

Figure 4. This image compares the size and shape of 2 telescopes.

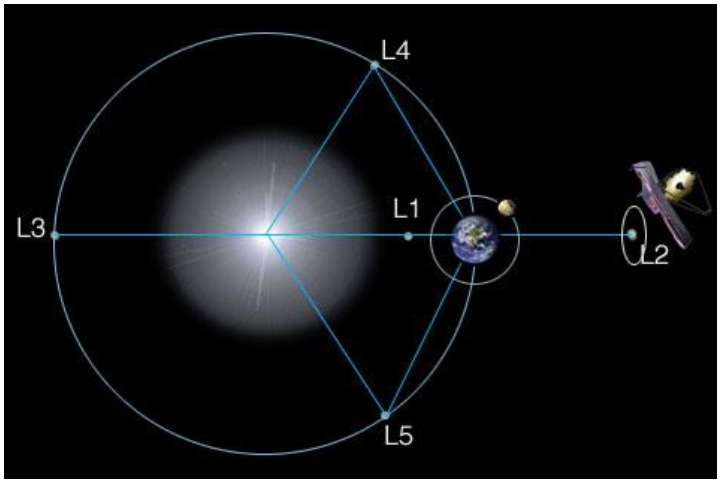

Figure 5. JWST's location.

Coronagraph is a facility used to make the light of star become dimmer in order to make planets visible. It is placed inside the telescope which used an arrangement of masks, prisms, and detectors. There's also lots of mirrors and actuators to capture light. Since those mirrors are deformable, it squelches the light of star and make the light of planet becomes clearer [13]. Starshade is another facility which can be folded up. After expanding it, it has a size of basketball court. Because of its sunflower shape, it can stop tiny lights from leaking around edges and also block some star light [13].

5. State-of-art Results

In this section, the past results of discovering exoplanets of different methods will be first introduced. Following that, the discover of candidates of dark star will be introduced as a represent of state-of-art result. Among 7 methods used to discover exoplanets, transit, radial velocity, microlensing and imaging are the 4 main methods. Most of exoplanets are discovered by them as shwon in Table. 1 [8]. Overall, it is clear that transit and radial velocity contributes to most of observation and can be recognized as the most successful method. This is because the phenomenon

that is needed to observe in these 2 methods occurs regularly. Additionally, it is very common in the universe. They are widely used and many telescopes can also help.

Table 1. Methods and number of exoplanets discovered by this method.

Transit	Radial Velocity	Microlensing	Imaging	Astronomy	Pulsar Timming	Relativistic Beaming
4074	1037	10	20	2	6	unknown

The idea of dark star was first proposed in 2007. Dark star is similar to normal star-they are both made up of hydrogen and helium. The main difference between them is that dark star is powered by heat produced from dark matter annihilation instead of by fusion. Although it has a name of "Dark Star", the dark matter only constitutes $\lesssim 0.1\%$ [14]. The dark matter annihilation can transfer mass into energy much more effective than that of fusion. Thus, dark star doesn't need a hot core which makes it stay cool (about 1,000K for the surface). This is also the reason why scientists thinks that the first phase of stellar evolution may be dark star. Besides, dark star only forms in the center of a galaxy which provides adequate dark matter. As predicted, when the dark matter is used up, the dark star will turn into a supermassive black whole [14].

In April, 2023, research studies 4 galaxies with high red shift which is pictured by JWST before. In this research, three of the four galaxies show the same result of supermassive dark star theory. Besides, they are very similar to the simulation and observation result. Thus, the author predicts that more candidates will soon be found [15]. Another research result finds 3 candidates of dark star which are JADES-GS-z13- 0, JADES-GS-z12-0, and JADES-GS-z11-0. Researchers have made serval experiments and get evidence to show star's properties [16]. If one can be confirmed to be dark star, the new age of astrophysics and cosmology will begin. Compared to other old galaxies, the model of dark star is simpler. However, one still needs spectra of higher quality in order to reach the final result.

6. Limitations and Prospects

Overall, methods used to discover exoplanets still have disadvantages which stops human to have a deeper understanding of universe. Some models or theory are also unable to test because of those limitations. In this section, some main limitations will be discussed and some suggestion and future outlook will be introduced. Methods used to discover exoplanets all required images to detect those phenomena. Thus, telescope is essential in this process. Nowadays, telescopes have lots of limitations and needed to be improved. First, the quality of light spectra and image that is taken. Although JWST has a great improvement compared to HST, the resolution and quality is still not enough to solve more problem. For example, for the dark star model discussed in Section 5, a spectrum with higher quality is needed. Second, telescopes still cannot detect very old planets or galaxies clearly. The information they can provide is too limit with poor quality. This causes many theories about the early universe become hard to test. Third, some celestial cannot be detected now. For example, white hole is hard to detect and no telescope has succeeded before. Besides limitations of telescope, methods also need improvement. Usually, transit and radial velocity are widely used. However, some strict conditions are required in order to observe transit. Additionally, there's a high rate of misjudgment of whether there's a transit. For other methods, they highly depend on technology such as telescope and receptor. In addition, not all planets or galaxies can be detected by methods scientists currently used. Because of their special location or properties, some of them may be unable to detect.

In the future, in order to explore more, there will probably lots of improvement in both facilities and methods. For telescopes, they might become larger and contain more equipment. As the mirror becomes larger, the image may have a larger scale and include more information. Moreover, the resolution will be increased. Besides, more equipment such as coronagraph will be included in telescope. It enables planets that are dim and faint to be observed. In addition, new type of energy might be used in the future so that telescopes can move further away from Earth and take more pictures. More telescopes will be launched in the future and they will probably focus on different wavelength depend on their mission. By making further development on different telescope, they will

be able to detect more planets with higher quality. For methods, more scenarios will be propsoed developed. After more simulation and analysis is done, more characteristics of different types of planets and galaxies will be shown. Thus, by focusing more on those parts, more methods will develop which help to discover more. In addition, there's still methods that haven't been used yet such as Flare and variability echo detection. Those methods will also be used in the future so that some limitation of current methods will be solved.

7. Conclusion

To sum up, this study analyzes the principle of discovering exoplanets by discussing methods and facilities. Now, 5477 exoplanets are discovered and confirmed. They all come from 7 main methods. Those methods help discover many exoplanets but they all have limitations. They may only happen under strict condition or have a high rate of misjudge. For facilities, further improvements are needed in order to provide better data. Spectra with higher quality are also needed which means that bigger mirror are needed. To fly further away from the Earth, new resources needed to be developed. Recently, there's some interesting findings such as the candidate of supermassive dark star. There might be more in the future. Human has already found lots of exoplanets but few of them are from early universe. Thus, the improvement will aim to solve those problems. Also, new methods will be developed to observe those old galaxies or planets. By analyzing the principle of discovering exoplanets, the disadvantages are shown clear which enable future improvement to be better. Also, it helps discover the future research's direction.

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