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The Way to Detect Exoplanetary Systems and the Limitations of the Doppler Method

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Abstract. According to current astronomical developments, Doppler and lensing methods are the two most important methods used by astronomers to detect extrasolar planetary systems. Unlike the lensing method, which requires the use of high-precision astronomical telescopes to measure stellar luminosity variations, the Doppler method can rely on simple stellar redshift phenomena and calculations to accurately predict the existence of extraterrestrial planets, their masses, orbital radii, and other basic characteristics. Therefore, Doppler's method will be the most widely used method to measure planetary systems. Based on the derivation of Kepler's third law, the formulas for calculating the masses and orbital distances of planets are discussed and a python program for easy calculation is presented. Also, the limitations of Doppler's method and possible calculation errors are collected, organized, and explained.

Keywords: Exoplanets, Astrometry, Astrophysics.

1. Introduction

Since ancient times, the detection of exoplanets has always been a concern for astronomers. The existence of exoplanets directly affects scientists' studies of possible extraterrestrial intelligent life. The telescopic imaging method commonly used by astronomers did not make a significant contribution to the detection of exoplanet systems because of the large luminosity differences between the planets and the stars.

Subsequently, as astronomical observation techniques evolved and human understanding of the universe increased, such as the discovery of stellar redshifts, a variety of more feasible techniques for exoplanet system detection were discovered and used.

The most widely used and most productive technique for detecting extraterrestrial planetary systems by modern astronomers is the lensing method. Based on this method, astronomers can determine the presence of planets visually and precisely. However, due to the accuracy and duration of the telescope equipment required for the lensing method, and the simplicity of the detection method sought in this paper, we will focus on a more accessible method. This paper will focus on the more easily implemented Doppler method.

The widespread use of programming techniques to assist astronomical observations has greatly improved efficiency and reduced the cost of human exploration of the universe. This paper will also discuss the feasibility of using python to assist in the Doppler method, aiming to program the exact calculation of the formulas covered by the method.

Finally, the paper will discuss three possible scenarios of planetary systems using the Doppler method and the computational errors associated with the different scenarios, and try to provide solutions. The identification and correction of errors will directly affect the accuracy of astronomers' predictions of exoplanet masses, orbital distances, and other characteristics.

2. Literature Review

The discovery of the planet Pegasus 51b by two Swiss astronomers, Mayor and Queloz, in October 1995, was the first true extraterrestrial planet discovered by astrometry and the first exoplanet system in human history [1]. By observing the periodic vibrations of the star, Mayor and Queloz confirmed that these vibrations originate from the influence of the planets in the galaxy on the star, and thus confirmed the existence of exoplanet systems.

Considering the influence of environmental factors on the observed stellar vibrations in practice, subsequent astronomers began to use stellar spectral variations, or Doppler, instead of traditional astrometry for their observations [2]. By observing the periodic variation of stellar redshift phenomena, astronomers can analyze the velocity variation of stellar vibrations and derive the period of radial velocity variation from it. By relying on the magnitude of the period and Kepler's third law, astronomers can derive basic information about the mass, velocity, and orbit of the target planetary system.

After the successful launch of the Kepler space telescope by NASA, the lensing method has become the mainstream solution for exoplanet detection [3]. Currently, the results of the Kepler space telescope using the lensing method include more than 1200 exoplanets. The lensing method is a direct observation method that measures the change in the luminosity of a target star over some time to directly determine if an intra-galactic planet is passing by and causing an occultation. However, due to the huge difference in the volume of planets and stars, even if a planet passes by and causes an occlusion to the star, the magnitude of the decrease in stellar luminosity is almost negligible, so this method can only work with the support of high-precision equipment like the Kepler Space Telescope. When the Kepler space telescope was permanently shut down after May 2013 due to a technical failure, the Gaia space telescope, launched by the European Space Agency, became the workhorse for the detection of exoplanetary systems(European Space Agency [4]. Gaia is capable of observing billions of stars and processing data from more than a thousand stars simultaneously. Undoubtedly, Gaia will provide a huge amount of data for the Doppler and Lyrae methods.

Humans are not destined to be able to distinguish the luminosity variations of stars on their own, but we can use formulas to measure potential exoplanet systems.

3. Methods for detecting exoplanetary systems using Doppler methods

When one or more planets are present in a stellar system, the gravitational force exerted by the planets on the star causes a change in the spatial position of the star. This change in position is reflected in a change in the distance between the star and the Earth, and this change leads to a change in the redshift value of the target star. By recording the stellar redshift and blueshift phenomena over time, it is possible to derive the change in the velocity of the star moving toward or away from the Earth over time.

The change in the star's radial velocity is found to be periodic according to the image of the change in velocity with observation time. By recording the length of this period, it is possible to derive the length of a single period in which the star undergoes a circular-like motion influenced by the gravitational force of the planet. Based on the law of conservation of momentum, it is assumed that in an exoplanetary system containing only one planet, the angular velocity of the star should be equal to the angular velocity of the planet, and therefore the measured length of the period of rotation of the star should be equal to the length of the period of revolution of the planet [5].

According to Kepler's third law, the third power of the semi-long axis of the planet's orbit around the star is proportional to the square of the planet's rotation period. Therefore, when the rotation period is known, the distance of the planet from its star can be found. Also, an approximation of the radial velocity of the star can be derived from the image of the velocity of the star's movement with the observed time. The approximate value of the linear velocity of the target planet's revolution can be found from the formula that the velocity is equal to the ratio of the distance and time.

The stellar mass can be derived by using stellar luminosity extrapolation. According to the law of conservation of momentum: when the system and external forces are zero, the product of the mass and velocity of object one is equal to the product of the mass and velocity of object two. Therefore, when the stellar mass, the stellar radial velocity, and the linear velocity of the planet's revolution are known, the mass of the target planet can be derived by using the law of conservation of momentum.

Once the mass and orbital radius of the planet is known, astronomers can deduce the basic information about the planet's surface temperature, day and night length, and atmosphere, thanks to the similar formation process and composition of the planetary system. Up to the present step, even though astronomers have never directly observed the exoplanet, humans have all the basic information about the planet and can use it to determine whether the planet has the potential to harbor extraterrestrial life.

Since the Kepler method is computationally intensive and involves the conversion of different units such as astronomical units, meters, meters per second, etc., it is necessary to use programming techniques to improve the efficiency and accuracy of the calculation. With the help of python operators, the program can quickly calculate the orbital radius, linear velocity, and mass of the target planet after entering the stellar motion period, stellar radial velocity, stellar mass, and circumference.

4. Limitations of using Doppler methods to detect exoplanetary systems

Doppler calculations of the masses of extraterrestrial planets are based on measurements of the radial velocities of the stars in the galaxy, so the accuracy of the radial velocity measurements will directly affect the calculated masses of the planets. Since the stellar radial velocity observed by astronomers is essentially the component of the star's velocity in the direction of the line between the star and the Earth, astronomers will not be able to measure the true linear velocity of the star if the orbital planes of the stars and planets in the planetary system are not in the same plane as the line between the star and the Earth.

The probability that the orbital planes of the stars and planets in a planetary system are exactly in the same plane as the line between the star and the Earth is extremely low, so when the orbital plane is tilted at an unknown angle, astronomers can only measure the magnitude of the component of the stellar linear velocity on the line between the star and the Earth. Since the radial velocity of the star involved in the calculation is usually smaller than the actual velocity, and this value is in the denominator of the planetary mass formula, the mass of the planet calculated by the formula is usually the minimum possible mass of the planet, 80% of the true mass.

When the line between the star and the planet in a planetary system is perpendicular to the line between the star and the Earth, the component of the linear velocity of the star on the line between the star and the Earth is zero, as obtained by the cosine function. Therefore, in this particular case, astronomers cannot even detect the existence of the planetary system due to the limitations of the Doppler method.

5. Conclusions and Discussion

This paper discusses how to use the stellar radial velocity variations to infer the existence of planets in a galaxy based on the use of the Doppler method to detect stellar radial velocities and to derive basic information about the planetary system when the target planet cannot be practically observed. Formulas are given for calculating the orbital radius of a planet using Kepler's third law; the use of the law of conservation of momentum to calculate the mass of a planet and the use of the velocity formula to estimate the linear velocity of a planet's revolution are also explained. This paper also attempts to use programming techniques to assist the calculation, which significantly improves the calculation efficiency.

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Due to equipment and time constraints, this paper does not cover calculations of unknown exoplanet systems using the methods in this paper. In the future, if field observations are available, the masses, orbital radii, and linear velocities of the unknown planets will be calculated using the above method based on real observations.

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