# Comparisons of Detection Paradigm of Planet: Transit and Radial Velocity

Wenlong Fang*

Guangdong Experimental Highschool AP Curriculum. Guangzhou, China.

*Corresponding author: wenlongfang@uchicago.edu.cn

**Abstract.** The transit and radial velocity method are two most widely used approach in exoplanet detection. This paper compares the advantages and disadvantages of two methods based on the characteristics of planets they found and different calculation results. Different distribution of parameters brings the preference for two methods. In detail, the radial velocity method discovered more gigantic planets while still have most planets with smaller size like that of the transit method. The minimum and maximum of orbital period are all relatively lower for transit method. Significant difference in the composition of planets found by two method occurs when combining mass and radius to compare density distribution. More Super-Earth planets seem to appear in transit data compared to radial velocity method in the same radius range. These patterns are closely related to the characteristics of observation condition. The various data processing method also affects the resulting parameters. This paper attempts to reach the calculation for transit and radial velocity method with basic fitting models, which will be compared with calculations of the same planets from previous researches. These results shed light on guiding further exploration of planet detections.

**Keywords:** Transit; Radial velocity; Exoplanet detection; planetary astrophysics.

## 1. Introduction

The existence of planets like those in the solar system were not confirmed until the very end of the 20th century because of the limitation in observation techniques. Since planets do not emit light like stars do, direct imaging for exoplanets were impossible until 2004 [1], almost 10 years after the discovery of first exoplanet. This first discovery in 1992 was not made directly but rather through indirect timing of the pulsar host star [2]. The pulsar's (PSR B1257+12) regular signal was affected by its orbit, and the planet was detected by carefully calculating this deviation. The radial velocity and transit are by far the two most successful methods in exoplanet detection regarding the number of planets discovered. Following the discovery, the exoplanet 51 Peg b, orbiting a solar-type star, was discovered in 1995 by observing the change in radial velocity of the host star [3]; the first success of transit method came 7 years later (OGLE-TR-56 b) [4]. Within the entire 30-year exoplanet detection, radial velocity and transit have always been the dominant methods among all detection methods, obtaining information about 936 and 3903 planets, respectively among the 5071 confirmed planets.

There are several notable observation projects that have obtained numerous results with either the radial velocity or transit. The W .M. Keck observatory with its twin 10-meter telescopes focuses on observing the doppler velocity of stars, obtaining data about 176 planets until now. This paper will attempt to analyze the radial velocity graph of the host stars from this project. The Kepler observatory made the greatest contribution in the detection of exoplanets with transit. With its initial launch in 2009 and extension of mission (K2) from 2014 to 2018, the Kepler telescope have observed 2699 planets, including famous Earth-like planets such as the Kepler-452 b. The data from K2 will also be the main source of transit light curve analyzed in this paper.

The transit method and radial velocity method differ in information available, requirement of observation, characteristics of planets found; the use of different calculation methods for the data also yield different results. The two methods do not always work independently. For example, transit and radial velocity method might be applied to the same planet for more complete data; additional methods, the transit timing method, can assist the transit method when exploring other possible planets in the same system. In detail, the characteristics of the data and planets discovered of the two

methods will be compared; with specific planets as examples, the result of the two methods and the results using different calculations will be compared, respectively. At last, a brief conclusion of the two methods will be presented.

## 2. Data & Method

### 2.1. Data source

For sources of data in this paper, the statistics of confirmed planets and results of parameters are from the NASA Exoplanets Archive. The transit curves from K2 observatory are available at the Mikulski Archive for space telescopes, and the radial velocity data comes from the HIRES/Keck data on Carnegie Science. In the part about the characteristics of discovered exoplanets for both methods, the statistic histograms of planet radius, planet mass, orbit period, and orbital semi-major axis are graphed with 100 bins using planetary systems composite data from NASA Exoplanet Archive [5].

### 2.2. Methods

For the transit curve of the host star, smoothing spline fit is applied to predict the complete transit of the planet. The transit depth is determined with relative brightness 100% as the normal brightness (unless obvious error of the normal brightness occurs) and the average depth of transit as the minimum brightness. With multiple transit presented in the same set of data, the period is calculated with the average time between two consecutive transits. The planet radius can be calculated as:

$$R_{planet} = R_{star}\sqrt{Depth} \tag{1}$$

In which the depth comes from calculation above and radius of star comes from parameter available on the archive. After acquiring radial velocity data at different phase of orbit for the host stars, the sine curve fit of the data are made; the resulting amplitude of the wave motion represents the orbital speed of the host star, and the mass of the planet is calculated using the following formula:

$$M_{planet} = \frac{Radial\ Velocity\ \times M_{star}^{\frac{2}{3}}\ \times Period^{\frac{1}{3}}}{(2\pi G)^{\frac{1}{3}}} \tag{2}$$

Since the corrected date used only contains radial velocity versus phase, the mass of star and period are from available parameters in the archive, while the resulting orbital velocity of the star comes from the fitting of the radial velocity data.

## 3. Results & Discussion

### 3.1. Methods

As the method that contributed the most discovery in exoplanet detection, the transit method provides accurate data about the planet's radius with the help of precise detection of variation in light intensity. The frequency of transit also provides information about the period of the planets. Since one telescope, such as Kepler, can observe up to thousands of stars at one time, the method is able to keep such frequency of discovery. However, it still cannot apply to all the case. Transit only happens when the plane of the planet's orbit is approximately parallel to the observation sight, i.e., impossible to observe planets at non-transiting orbits without data about mass of the planet. This study will cover detail comparison of the planets found by transit and calculation in this paper and previous research.

Among the 5084 confirmed planets (until August 30$^{th}$), the transit method covered 3902 among them, exceeding the sum of the rest of the methods. This is mostly because of the ability for a single telescope to observe thousands of stars at once. As shown in Fig. 1, a great proportion of the planets fall around the Super Earth radius. Since smaller radius generates smaller variation in the light of the host star, such distribution of radius would be impossible without precise equipment of observation.

The formation of rocky planets may partly account for this distribution. Since the elements for these planets are usually at the inner part of the disk of matter during the formation of systems around the star, rocky planets tend to locate closer to the host star; As the closer the orbit, the higher the chance for transit to be observed, more planets with such size would be discovered with transit.

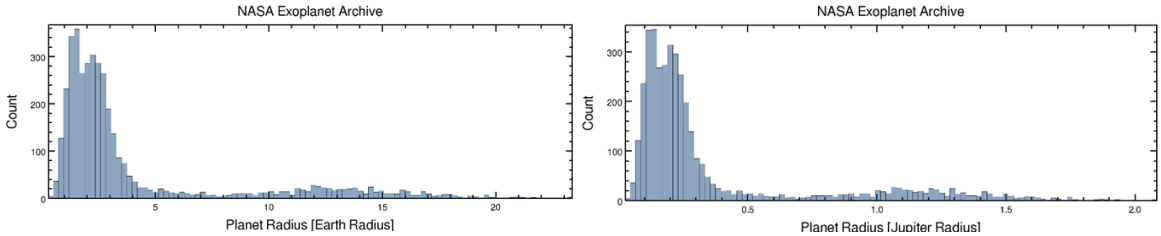



**Fig. 1** distribution of planet radius in Earth (left panel) and Jupiter (right panel) radius for exoplanets discovered by transit.

Combining the conclusion of radius and mass further distinguish the Super-Earth rocky planets and the Neptune-like gas planets. With the help of reference line of density of known planets, the characteristics of planets become obvious. As the radius of the planets increases, more planets have density close to or lower than the known gas giants, while a great number of planets with radius less than 3 Earth radius have density greater or close to the two rocky planets in the solar system. For an approximate conclusion of the cluster of planets below 5 Earth radius, Super-Earth and Earth-like planets are abundant below about 2.5 Earth radius, and gas planets begin to occur after that and become relatively dominant after 3 Earth radius. It does not contain independent analysis on the distribution of planet mass since the mass without radial velocity data cannot be determined. The distribution of planet mass may be biased with the absence of a number of planets' mass information.

As mentioned in the possible cause of the distribution of radius, most planets discovered through this method have relatively short orbital period and orbit semi-major axis. For orbital period, there are only 10 planets with period longer than 1000 days and 8 planets with period in the range of 500-1000 days. Fig. 2 illustrates the distribution of orbital period in the range of 100-500 and 0-100, respectively. With only 159 planets scattered in the range of 100-500 days, the rest have period even smaller than that of Mercury. Such great number of planets with period different to the solar system may result from the lower difficulty to detect closer and more frequent transit besides the actual trends in the universe. Similarly for orbit semi-major axis depicted in Fig. 3, only 21 planets are 1-4.5 away from their host stars, with the rest all closer than 1au. Cold gas giants seem to be rare among such great number of planets. Putting together the information of the host stars in Table. 1, these planets with such close orbits do not necessarily orbit smaller red dwarfs. Instead, stars ranging from less than half of Sun radius to more than 2 Sun radius are included in the systems discovered. It also proofed the existence of planets within the orbit of Mercury even with Sun-like stars. To summarize briefly, planets discovered by transit mostly resemble radius near Super-Earth size, occupy orbits within the Mercury while still having a wide range of host star.

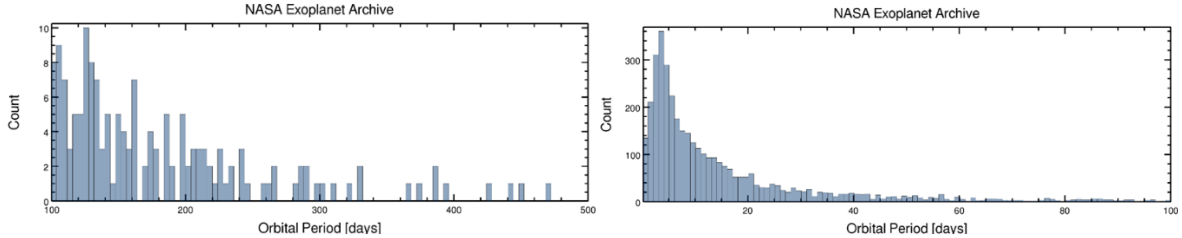



**Fig. 2** distribution of orbital period in range of 100-500 (left panel) and 0-100 (right panel) of planets discovered by transit.

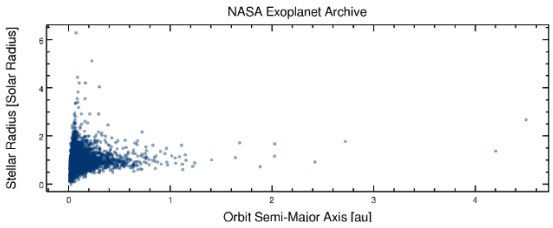



**Fig. 3** Plot of stellar radius to orbit semi-major axis of planets discovered by transit.

**Table 1**. Calculated parameters of HAT-P-56 b. each radius result uses the same parameter of stellar radius as that of in the corresponding reference

| Result(P) | reference calculation(P) | result(R) | reference calculation(R) | Reference |
|---|---|---|---|---|
| | 2.7908327 | 15.31 | 16.43 | Huang et al. 2015 [6] |
| 2.791707 | 2.79083 | 15.76 | 16.9 | Stassun et al. 2017 [7] |
| | 2.790862 | 15.43 | 16.72 | Kruse et al. 2019 [8] |

Besides the analysis of characteristics of planets discovered, comparison of calculation on the same planet is made. The Table. 1 shows the comparison of calculated orbital period and radius. Each calculation of radius in this paper uses the same stellar parameter as that of the reference paper. In the calculation of HAT-P-56 b, the result of orbital period is slightly higher than all three calculations in the reference, and three results about radius, although using the same stellar parameters, are still different to the reference calculations, respectively. Moreover, there lacks the calculation of error range for the results since the results from the 3 reference all contain error bound that are not listed in this table. The final formula to convert the stellar radius to planet radius with the transit depth does not change in all the interpretation. However, the model used to fit the transit curve varies among different calculation. Huang et al. used a Mandel & Agol transit model to fit the light curves and the TFA algorithm for K2 light curves meanwhile [6]; Stassun et al. imported multiple calculations of transit depth from exoplanets.org and determined the ultimate value and uncertainty [7]; Kruse et al. selected the EVEREST 1.0 detrended light curves for K2 and further removed bad data due to either equipment error or incoming lights like stellar flares and cosmic rays [8]. Since this paper only used basic smoothing spline model to process the transit curve and did not alter the original data for error reducing, the resulting light curve may be affected by error data or inappropriate modelling of the transit. For example, while the basic smoothing fit approaches the perfect transit curve, the TFA algorithm used 43 nearby stars as reference to infer the shape of transit curve.

### 3.2. Radial Velocity

Instead of the variation in intensity, radial velocity method focuses on the doppler shift of the star's light to determine its velocity component along the observer's sight. Radial velocity observation provides precise information on the mass of the planet from the orbital velocity of the stars. Stars with lower mass, such as the red dwarf, are more affected by the gravitational field of the planet, which is easier to be detected with radial velocity. In systems with only one planet, it is even possible to determine the shape of the plane's orbit. This method also does not work when the shift of the star's spectrum is hard to detect; for example, the star's spectrum barely shifts if the orbit of the star is perpendicular to the direction of sight. Moreover, the radius of the planet cannot be calculation with this method. Similarly, the following parts are about the characteristics of planets found and comparison of calculation.

935 planets in total, the second highest number among all the methods, are discovered using radial velocity method. Since the method relies on the orbital motion of the host star, either greater planet mass or smaller orbits generate orbital motion of greater amplitude and make it easier to observe. There are 46 extremely heavy planets, 12-55.59 Jupiter mass, among the 935 planets, and the rest are shown in the series of histogram in Fig. 4. While the greatest number of planets concentrate within the range of 0.7-15 Earth mass, certain amounts of planets possess Jupiter-like mass. Planets with

Earth-like or Super-Earth mass tend to have smaller orbits, while gigantic planets generate greater movement of the host star; this could be the reason for a relatively high proportion of rocky planets with certain number of gas giants. Similar to the transit part, the mass to radius plot of planets discovered by radial velocity is compared with the reference density line of 4 known solar-system planets to examine the property of planets within the mass range of 50 Earth mass. There are few planets with density close to the two known rocky planets after 2 Earth radius, and most planets in 2-3 Earth radius have density lower than the two rocky planets. As the radius further increases, most planets' density keeps decreasing, reaching the density of the two gas planets. Similarly, the specific analysis of distribution of planet radius will not be included in this part because most planets without transit observation do not have information about radius.

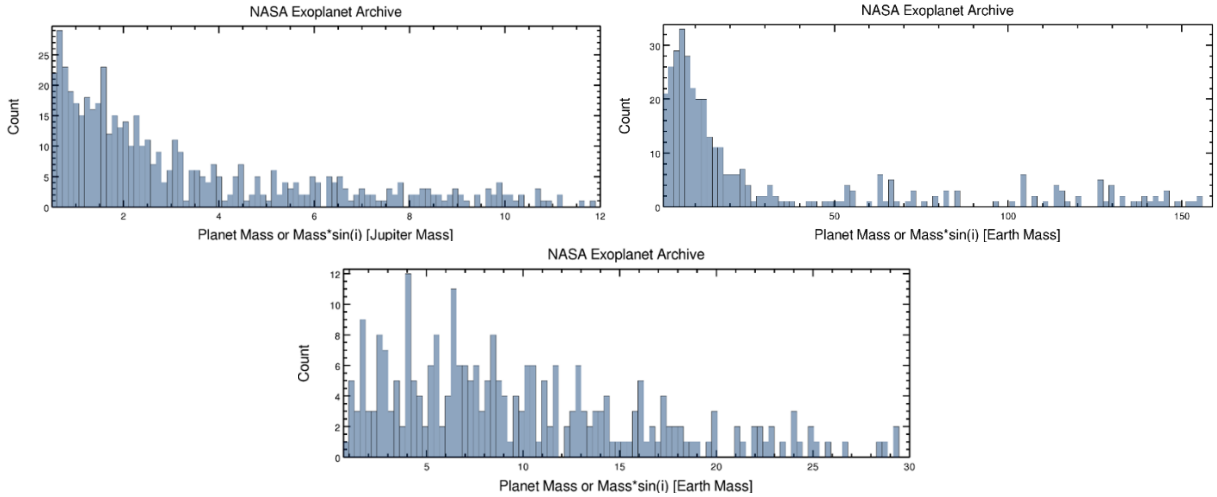



**Fig. 4**. Distribution of planet mass in Jupiter and Earth mass of planets discovered by radial velocity: range 0.5-12(upper left panel), 0.7-158.9(upper right panel) and 0.7-30 (lower panel).

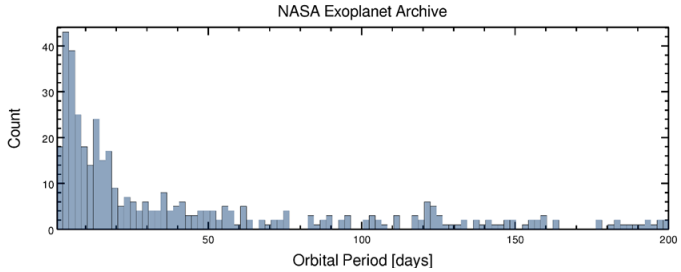



**Fig. 5** Distribution of orbital period of planets discovered by radial velocity within range 0.7365-200d.

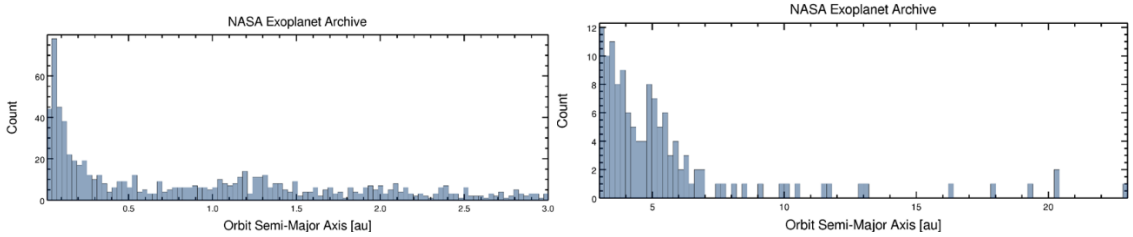



**Fig. 6** distribution of orbit semi-major axis in range 3-23 and 0.01544-3 au of planets discovered by radial velocity.

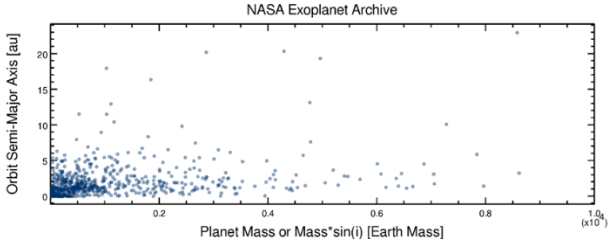



**Fig. 7** Orbit semi-major axis to planet mass (Earth mass) plot with range 0-23au and 0-$10^4$ Earth mass for planets discovered by radial velocity.

The planets discovered by radial velocity method also includes some extremely long orbital period. 39 of the planets have period longer than 5000 days, exceeding the period of Jupiter, 4332.589 days. Below that, the number of planets increases as the orbital period decreases, reaching the peak at period slightly shorter than 10 days. Fig. 5 exhibits the distribution of orbital period from 0.7365 to 200 days, with the peak occurring below 10 days. Some planets have orbit semi-major axis longer than that of the Jupiter, 5.2au, while most planets fall at the region below 0.5au (depicted in Fig. 6). Although distant orbits are supposed to be difficult to be detected, the mass of the planets may partly compensate the effect. Seen from Fig. 7, a large cluster of planets appears at the region with short orbit semi-major axis and low mass, but there are still many massive planets extend rightward at similar orbital position or upward. Planets with orbit semi-major axis greater than 5au mostly have mass greater than 500 Earth mass (greater than 1 Jupiter mass or 317.8 Earth mass).

**Table. 2** Calculated parameters of WASP-2 b. Each result of the mass of the planet uses stellar mass and period from the reference.

| results(R_star) | results(M_planet) | reference calculation(M_planet) | reference |
|---|---|---|---|
| | 253.7 | 279.68 | Collier Cameron et al. 2007 [9] |
| 0.147 | 274.6 | 294.0 | Bonomo et al. 2017 [10] |
| | 266 | 292 | Knutson et al. 2014 [11] |

Taking WASP-2 b as an example, its host star's radial velocity is calculated by fitting the corrected radial velocity graph. Since the period of this planet is calculated with its transit data, the mass of the planet is calculated with star parameters and period in the previous researches. Although using the same stellar mass and period for calculation, each result of the mass of the planet is lower than the respective reference calculation as listed in Table. 2. One possible difference is the eccentricity of the planet's orbit [9]. Knutson et al. [10] and Bonomo et al. [11] reported the eccentricity of the orbit to be around 0.00540 and <0.013, respectively; the formula used to derive the mass of the planet assumes the orbit to be a perfect circle with e=0, so this eccentricity may result in part of the error. The model used to fit the radial velocity data and additional methods to correct the data are different. Collier Cameron et al. used basic sinusoidal model in fitting the radial-velocity measurements, but the radial-velocity data underwent a series of error estimation including the semi-empirical estimator and velocity drift measurement [9]; Bonomo et al. used four different model for the radial velocity analysis, including the basic Keplerian orbit model and 3 models for velocity drift in different cases [10]; Knutson et al. used the DE-MCMC algorithm to detect long-term accelerations in the radial velocity data [11]. Both Knutson [11] et al. and Collier Cameron et al. [9] mentioned the RV "jitter", which is commonly caused by the magnetic activity in the stellar chromosphere and photosphere. Finally, the three reference calculations all involved multiple radial velocity observation data (including the keck observatory in this paper) and reference parameters from transit data; this allows the error or bias in a single data to be identified. In conclusion, the eccentricity of the orbit, the use of basic sinusoidal model, lack of error data identifying, and the use of single source may result in the difference of the calculation in this paper.

### 3.3. Comparisons

After analyzing the characteristics of discovered planets and different calculations, this part will compare these factors of the two methods. In the aspect of the radius and mass of the planets, both methods made more discovery of smaller and lighter planets because these planets tend to be found at orbits close to the host star; a smaller orbit can increase the possibility of successful observation for both methods. It is not easy to reach obvious conclusion of comparison between data of radius and data of mass, but if using the density of Jupiter as rough approximation for giant planets, there are obviously more gigantic, massive planets discovered by radial velocity than that of by transit method. While the planets discovered by transit reach 2 Jupiter radius, equivalent of 8 Jupiter mass assuming Jupiter density, planets discovered by radial velocity reach 12-55.59 Jupiter mass; the effect of planet mass in the detection of host star in radial velocity as mentioned in 3.2.1 may results in this difference. It is interesting that much more Super-Earth planets within the range of 1-3 Earth radius appear among those discovered by transit. Whether the calculation of planet parameters when one of the two methods are absent caused this difference is unsure.

The difference in the orbital period and orbit semi-major axis seems to follow the same trend. More planets are found at orbits within that of the Mercury with both methods, proofing the existence of planets at such short distance. However, the maximum period and semi-major axis are still significantly greater for the radial velocity method. While 10 planets discovered by transit fall at the range of 1000-3650 days, 39 planets discovered by radial velocity appear at the range of 5000-39000 days. Compared to planets discovered by transit with range of orbit semi-major axis of 0.0058-4.5au, those discovered by radial velocity have a higher minimum of 0.01544 and higher maximum of 23au. Both range's maxima are obviously higher for radial velocity, and from the distribution aspect, more proportion of planets discovered by transit concentrate at the peak at small orbits. As shown in the Fig. 8, a greater proportion of planets discovered by radial velocity spread to the orbits of Jupiter. As mentioned before, the radial velocity method may have greater ability to detect farther planets with mass great enough to generate wobble of the host star.

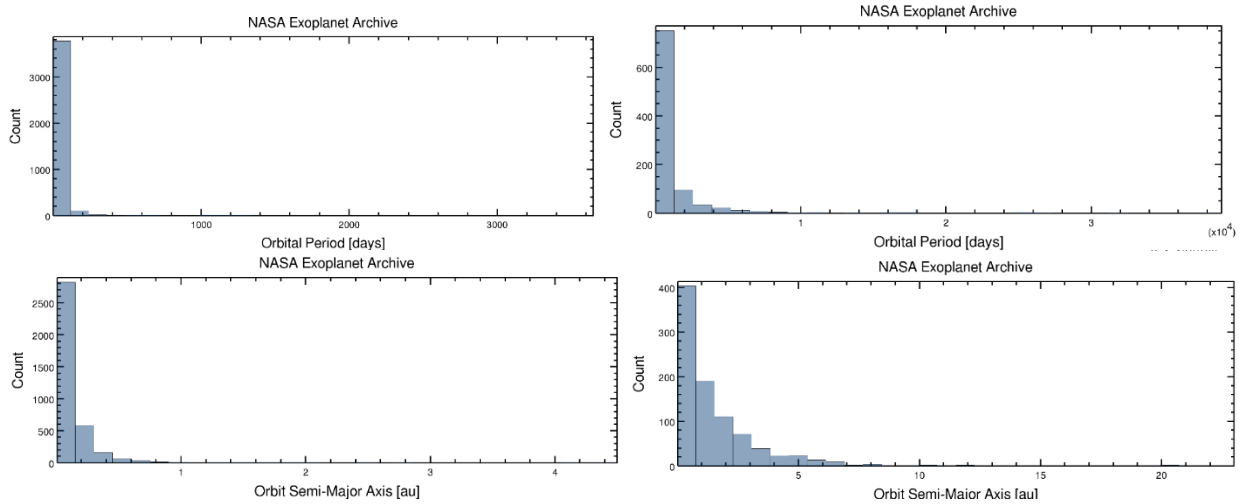



**Fig. 8** Full-range orbital period distribution with 30 bins for transit (upper left panel) and radial velocity (upper right panel), and full-range orbit semi-major axis distribution with 30 bins for transit (lower left panel) and radial velocity (lower right panel).

The modelling of data with similar nearby observation is used in the calculation of both methods. The calculation in this paper used the basic model the fit the theoretical trend of the transit curve and radial velocity graph, but the reference calculation mentioned above used the nearby data from other K2 observation and similar Keck observatory results to identify possible error in the data. In order to calculate all parameters of a planets, the transit and radial velocity method are frequently used together in data analysis. For example, the transit of planet WASP-2 b was also observed, and the data was combined with the radial velocity data from Keck to calculate the radius and mass of WASP-2 [6]. On this basis, radial velocity method is still used in many follow up observation even though

its efficiency is much lower than that of the transit method. Other methods can also be involved in the exploration of exoplanet systems. For example, the transit timing method determines the existence of additional planets within the same system of a known transit planet by calculating the other planets' effect on the period of the transit. In Kepler-160 system, Kepler-160 b's transit data was obtained first, and the other two planets in the same system, Kepler-160 c and Kepler-160 d, were discovered by the transit timing variations of Kepler-160 b [6].

## 4. Conclusion

In conclusion, this paper examines the difference between the two methods by comparing the characteristics of discovered planets and calculation methods. The difference in the range, extreme value, and peak distribution of the radius, mass, orbital period, and orbit semi-major axis reflects the advantages and disadvantages of the two methods. For example, the transit method has high detection efficiency and is more sensitive within small orbit even with subtle variation in intensity; the radial velocity method can detect distant giant gas planets. The comparison of mass to radius pattern shows the different composition of planets indicated by the two methods.

Given the other listed reference calculation, there is great space for this paper's basic analysis to expand. Before the fitting step, comparison of different observation and the identification of equipment error or interference like cosmic rays should be added to the calculation process. For further accuracy, established model or reference model from nearby observation should be used to fit the result. The calculation of error bond is also necessary process in evaluating the accuracy of the parameter. In summary, the level of calculation in this paper is still far from determining precise parameters of exoplanets.

The comparison of these aspects of the two methods gives insight into the combined use of the two methods in further study. With new planets being confirmed frequently, there are still lots of opportunity to apply transit and radial velocity observation and increase the understanding of the composition of exoplanets. Besides the basic parameters mentioned in this paper, parameters (e.g., the composition of atmosphere) have caught attention because of their role in determining the habitability of a planet. With good condition of secondary eclipse of a planet, its theoretical surface temperature and even the composition of atmosphere may be determined. The spectrum of a host star may also indicate the composition of nearby planets from its own element composition. One of the primary missions of exoplanet detection is to find if any hospitable world like the Earth exists outside the solar system, with more complete calculation and analysis over multiple parameters, further steps towards this mission could be made with the two most successful methods. Overall, the detection of exoplanets began late in the entire history of astronomy, and the emergence of radial velocity and transit method allowed researchers to precisely determine parameters of exoplanets. Observing the shift in host star spectrum and the variation in the host star's intensity, the two methods provide different parameters of planets with different detection trends.

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