Studying the Exoplanets HAT-P-56 b and HATS-36 b with Kepler

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Abstract. Exoplanet has become one of the most popular research subjects in astronomy. This study analyzes light curve data from the K2 mission of the Kepler space telescope and measure the properties of two exoplanets, HAT-P-56 b and HATS-36 b. With the transit method, the radii are obtained, orbital periods and semi-major axes of these two exoplanets. For HAT-P-56 b, the period is $T_{average} = 2.79233$ days, the radius is $R_{average} = 1.40514\mathrm{R_J}$ and the semi-major axis is $a = 0.0423553$ AU. For HATS-36 b, the period is $T_{average} = 4.17563$ days, the radius is $R_{average} = 1.18519\mathrm{R_J}$ and the semi-major axis is $a = 0.052385$ AU. Compared to previous studies, it is found that radii and semi-major axes measured in this paper are consistent with their results, whereas the calculated orbital period is a bit bigger. In addition, the large radii and short orbital periods suggest that both exoplanets are Hot Jupiters. These results shed light on the exploring of the exoplanets around the two host stars, HAT-P-56 and HATS-36.

Keywords: Exoplanets; solar-type stars; transit method; data analysis.

1. Introduction

Exoplanets are planets outside our solar system. As early as the 19th century, some astronomers claimed to have discovered exoplanets. It was not until 1992 that Wolszczan and Alexander first find two earth-like planets orbiting around a radio pulsar PSR B1257+12 [1]. In addition, in 1995, Mayor and Queloz detected planets around the main sequence star 51 Pegasi using the radial velocity method [2]. These discoveries are considered as important milestones in astronomy, and the research in 1992 is actually the first time that scientists gave out a clear answer to the fundamental scientific question of whether planets exist around sun-like stars outside the solar system. In recent decades, the search for exoplanets has gradually become one of the most active research topics in astronomy [3]. There are countless stars in the universe. Even in the Milky Way, there are at least hundreds of billions of stars, and every star would probably be surrounded by numbers of planets, which would made up a planetary system. Different star systems may have been born at various times. Some may have just been born, while others may have reached the end of their lives. Thus, by looking at planetary systems of different ages in the universe, one can not only learn about the early evolution patterns of the Earth, but also learn about the future evolution direction of our solar system and the fate of the Earth. If young terrestrial exoplanets are found, it is possible to learn the early evolution of the Earth by studying how these planets changed within a large sample group, and how life evolved from simple to advanced, if scientists successfully find life in outer space.

According to the NASA exoplanet archive [4], until August 16, 2022, 5,071 exoplanets have been discovered and confirmed, and there are 5,808 exoplanet candidates. In general, most exoplanets were discovered with the transit method, and the radial velocity method is in the second place for the number of discovered exoplanets, while other methods had much less discoveries [5]. In addition, transit method is the method using in this research paper. The transit method is arguably the most successful exoplanet discovery method now. It has a big advantage is that it can obtain a wealth of parameters from transiting planets, especially when combined with radial velocity observations. However, it has non-negligible disadvantages, the low probability of transits in a randomly oriented planetary system and the existence of astrophysical phenomena that may simulate transits, which can lead to false positives. Current and future experiments with transit method will focus on bright or special targets, because transits of dimmer stars are not well judged and observed [6].

So far, previous scientists have analyzed and studied many exoplanets using the transit method. In the previous study by Stassun et al. in 2017 [7], they observed 116 stars that host transiting planets and one of them is HAT-P-56 b, a planet that this research paper will discuss. In their research, they used the star's mass and radius they got from the data in turn to determine the radius and the mass of the exoplanet that could cause the transit. They found that the median uncertainties on of the stellar radii and masses are 8% and 30%, respectively, and the resulting uncertainties on the planet radii and masses are 9% and 22%, respectively. This difference appear in the data could explain why in processing the data one will always meet the bias. In another research done by D. Bayliss et al. in 2017 [8], they observed 25 HATSouth candidates in Campaign 7 of the K2 mission, which includes HATS-36 b. In the study, they find four exoplanets, which are HATS-9b, HATS-11b, HATS-12 b and HATS-13b. In addition, they identified other 18 systems' type. Moreover, in the research done by John H. Livingston et al. in 2018 [9], they analyzed 155 candidate exoplanets from NASA's K2 mission Campaigns 5-8, including HATS-36 b. From the data they used, they found that the sample includes 24 planets in 11 multi-planetary systems, as well as 18 false positives, and 77 remaining planet candidates.

This research is based on Kepler K2 mission. While both HAT-P-56 and HATS-36 are very young stars, it is curious about what kind of planets are orbiting around them. This paper is organized as follows. Sec. 2 introduced the data originaton of the two exoplanet which are HAT-P-56 b and HATS-36 b from Kepler K2 mission's public website. In addition, transit method and the way used it in the research will be demonstrated. Sec. 3 is mainly about analyzing data and graphs, the usage of Plotly [10], a website that could help to draw the Kepler light curve of the exoplanet's host star, will be introduced. After analyzed the graphs,one could each get the radius, period and semi-major axis of both the exoplanet. Then, comparions between the calculated results in this study and online daya by pervious researchers are presented, and made some conclusion. Afterwards, s all the limitation of the research and expressed of the future study are presented. Eventually, Sec. 4 gives a brief summary.

2. Data and method

2.1. Data

All the data is collected from NASA's K2 mission of the Kepler space telescope. Kepler's initial main scientific goal is to find habitable exoplanets. However, after Kepler accidentally lost the second of four gyroscope-like reaction wheels, scientists designed a new method to use the Sun and two remaining reaction wheels to control the telescope in all three directions of motion. To achieve the necessary stability for observation, the orientation of the telescope must be nearly parallel to its orbital path around the Sun while using the Sun as the "third wheel". This method could stick the telescope in a specific portion of the sky for up to 83 days, until it is necessary to rotate the spacecraft to prevent sunlight from entering the telescope. Using the new technique, scientists started NASA's K2 mission to discover distant exoplanet, young open clusters, bright stars, galaxies, supernovae and so on. By the end of 2018, Kepler telescope had completed its four-year K2 mission and was officially dormant due to running out of fuel.

Table 1. A sample of the primary data of HAT-P-56 b

BJD - 2454833	Corrected Flux
1939.109452833	0.998295278
1939.129884554	0.998195540
1939.150316075	0.998490869
1939.170747696	0.998423130
1939.191179417	0.998453408

As it shown in Table 1, this is a part of the whole primary data of HAT-P-56 b that provided on the K2 Photometry (a website) [11]. HAT-P-56 is a star 301.5 million kilometers from the Sun, with a mass 1.3 times that of the Sun and a radius 1.466 times that of the Sun [12]. The observations of HAT-P-56b made by Kepler began on April 24, 2014 and ended on May 27, 2014. During the observation period, data were recorded approximately every half hour.

Table 2. A sample of the primary data of HATS-36 b

BJD - 2454833	Corrected Flux
2468.486716523	0.994721807
2468.507148805	0.994722061
2468.527581287	0.993806676
2468.548013668	0.994137486
2468.568446149	0.993630972

As it shown in Table 2, this is a part of the whole primary data of HATS-36 b that provided on the K2 Photometry (a website) [11]. HATS-36 is a star 510 million kilometers from the Sun, with a mass 1.1 times that of the Sun and a radius 1.1 times that of the Sun [12]. The observations of HATS-36b made by Kepler began on October 5, 2015 and ended on December 26, 2015. During the observation period, data were recorded approximately every half hour.

2.2. Transit Method

Transit is a photometry method designed to detect the presence of one or more exoplanets in orbit around a star directly. Using the transit method, periodic dimming of light could be seen in the light curve graph as an exoplanet passes in front of its host star and casts its shadow on the telescope, so that a light curve of the exoplanet could be created. The light curve is the observational brightness of the star over time, and is the measurement Kepler makes to discover exoplanets. The dip in light happens when a planet passes in front of the star, which is known as "transit" (seen in Fig. 1 for an illustration). Transits give information about the planet's size and orbit. The size of the exoplanet's orbit can be calculated from how long it takes to orbit once, and the size of the planet itself can be calculated based on how much the star's brightness lowered.

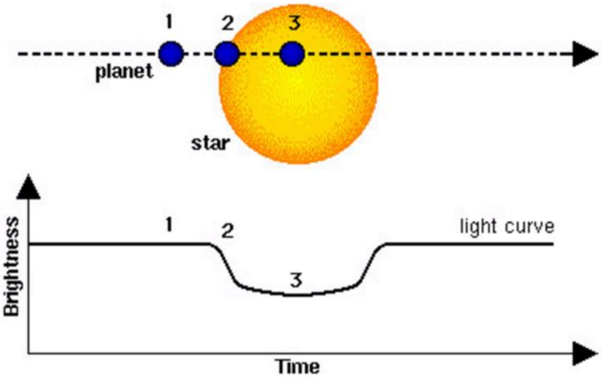


Fig. 1 Light curve of a transit.

While having all the data from the Kepler telescope, the Kepler light curve could be drawn in Fig. 2, which is basically the same thing with the light curve mentioned in the section above. From the graph, we could know the period (T) of the exoplanet by calculating the distance between the lowest point of two transits. Then, the Kepler's third law could be usen to calculate the semi-major axis a:

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

$$a = \sqrt[3]{\frac{GMT^2}{4\pi^2}} \tag{2}$$

In addition, the equation of the area ratio of the star covered by the planet to the star equals to the luminosity ratio could be usen to calculate the radius of the exoplanet:

$$\left(\frac{R_{planet}}{R_{star}}\right)^2 = Depth \tag{3}$$

$$R_{planet} = R_{star}\sqrt{Depth} \tag{4}$$

While having the radius of the exoplanet, the size of the exoplanet could be known.

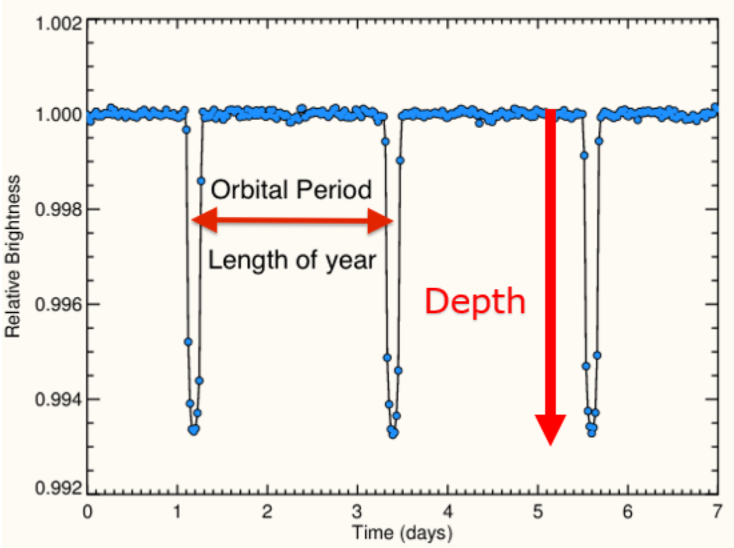


Fig. 2 Kepler light curve of a planet.

3. Results & Discussion

3.1. Calculations for HAT-P-56 b

Fig. 3 shows the light curve of HAT-P-56 plotted using Plotly (a website). It shows Barycentric Julian Day on the abscissa and star brightness on the ordinate. The ninth transit point inside the orange circle is clearly not at the depth of the luminosity ratio that this planet should have for a transit. This is lack of sample as the actual depth of the transit could not be seen in the figure, so this point will be deleted. From the figure, the time difference between the transit points (lowest point) and the depth of the lowest point for each transit could be measured. The measurements are listed in Table 3.

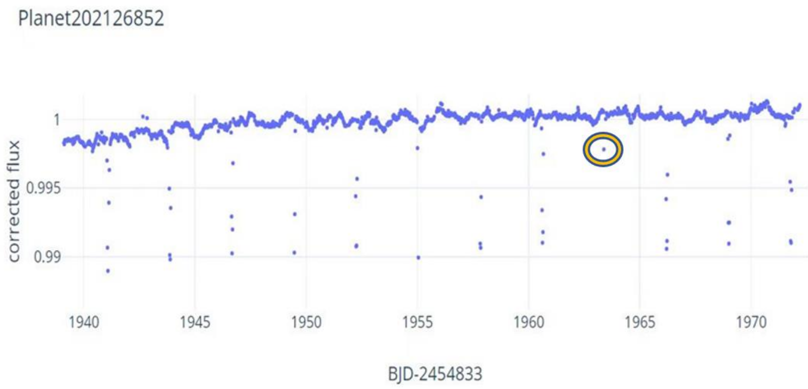


Fig. 3 Kepler light curve of HAT-P-56 b.

Table 3. All the transit point of HAT-P-56 b in Fig3

number	BJD (day)	Brightness(%)
1	1941.091	0.988969
2	1943.89	0.989807
3	1946.669	0.990246
4	1949.468	0.990294
5	1952.247	0.990752
6	1955.046	0.989936
7	1957.845	0.990652
8	1960.624	0.991016
10	1966.202	0.990573
11	1969.001	0.990952
12	1971.8	0.991011

Table 4. All the periods between each transit in Table3

$T_{12} = 2.799$	$T_{23} = 2.779$
$T_{34} = 2.799$	$T_{45} = 2.799$
$T_{56} = 2.799$	$T_{67} = 2.799$
$T_{78} = 2.779$	$T_{1011} = 2.799$
$T_{1112} = 2.799$	

While having all the transit point here in Table 3, the period of each transit could be determined by using the equation:

$$T = \left|x_{transit(n)} - x_{transit(n+1)}\right|(day) \tag{5}$$

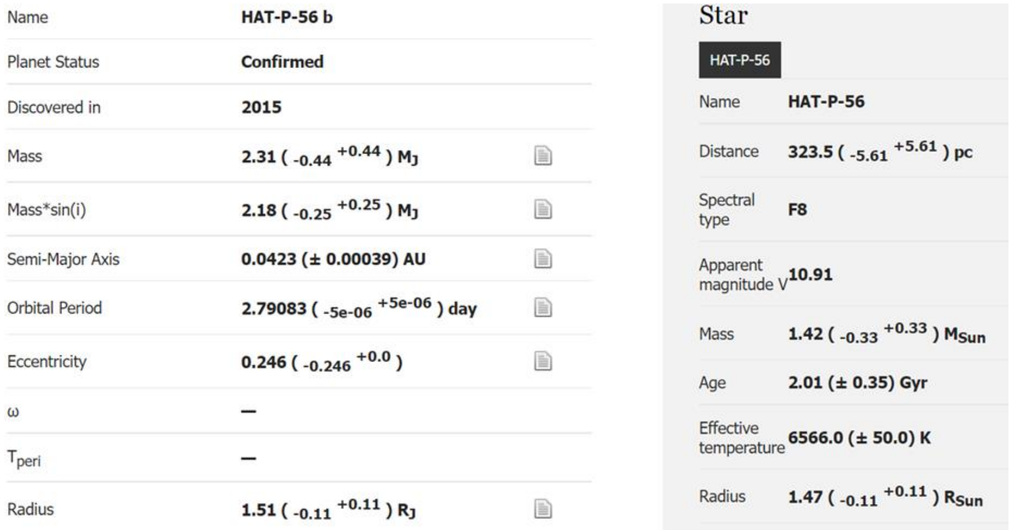
Here, the periods between each transit could be calculated as listed in Table 4. While having all the periods in Table 4, one could get the average period of the exoplanet by using averaging method:

$$T_{average} = \frac{(T_1 + T_2 + \cdots + T_n)}{n} = 2.79233\ days \tag{6}$$

The mass of the HAT-P-56 is 1.3 times the mass of the sun. Knowing the average period and the mass of the star, the Kepler's third law could be usen, Equation (1) and Equation (2), to compute the semi-major axis of the exoplanet which is $0.042353\ AU$.

Table 5. All the depth and radius of HAT-P-56 b for each transit

Depth(%)	Radius(km)
0.009742	100636
0.009627	100069
0.009616	100012
0.00967	100293
0.009314	98429.2
0.010556	102939
0.009876	101355
0.009325	98487.3
0,009821	101073
0.009504	99428.1
0.009693	100412



Name	HAT-P-56 b
Planet Status	Confirmed
Discovered in	2015
Mass	2.31 ($_{-0.44}$ $^{+0.44}$) M_J
Mass*sin(i)	2.18 ($_{-0.25}$ $^{+0.25}$) M_J
Semi-Major Axis	0.0423 (± 0.00039) AU
Orbital Period	2.79083 ($_{-5e-06}$ $^{+5e-06}$) day
Eccentricity	0.246 ($_{-0.246}$ $^{+0.0}$)
ω	—
T_{peri}	—
Radius	1.51 ($_{-0.11}$ $^{+0.11}$) R_J

Star

HAT-P-56

Name	HAT-P-56
Distance	323.5 ($_{-5.61}$ $^{+5.61}$) pc
Spectral type	F8
Apparent magnitude V	10.91
Mass	1.42 ($_{-0.33}$ $^{+0.33}$) M_{Sun}
Age	2.01 (± 0.35) Gyr
Effective temperature	6566.0 (± 50.0) K
Radius	1.47 ($_{-0.11}$ $^{+0.11}$) R_{Sun}

Fig. 4 Online data of HAT-P-56 b from exoplanet.eu.

Using the equation of the area ratio of the star covered by the planet to the star equals to the luminosity ratio, Equation (3) and Equation (4), radius of the exoplanet could be got. While knowing the radius of the star which is 1.466 times the size of the sun and the radius of the sun is 695700km, each depth and radius of the exoplanet could be listed in the Table 5. While having all the radius in Table 5, the average radius of the exoplanet could be known by using averaging method, here the radius of Jupiter is 71492km:

$$R_{average} = \frac{R_1 + R_2 + \cdots + R_n}{n} = 100456\ km\ (1.40514R_J) \tag{7}$$

According to all the result, the average period, average radius and the semi-major axis are here: $T_{average} = 2.79233$ days;$R_{average} = 100456$ km$(1.40514R_J)$;$a = 0.0423553\ AU$. In comparing with the data online in Fig. 4, the period in this research is a bit bigger and other values are within normal limits [13]. The large radius ($R_{average} = 100456\ km(1.40514R_J)$) and short orbital period ($T_{average} = 2.79233\ days$) of HAT-P-56 b match the criteria of a hot Jupiter. Therefore, it is concluded that HAT-P-56 b is a Hot Jupiter.

3.2. Calculations for HATS-36 b

Figure 5 shows the Kepler light curve of the HAT-P-56 b plotted by using Plotly(a website). This graph shows Barycentric Julian Day on the abscissa and star brightness on the ordinate. The measurements are listed in Table 6.

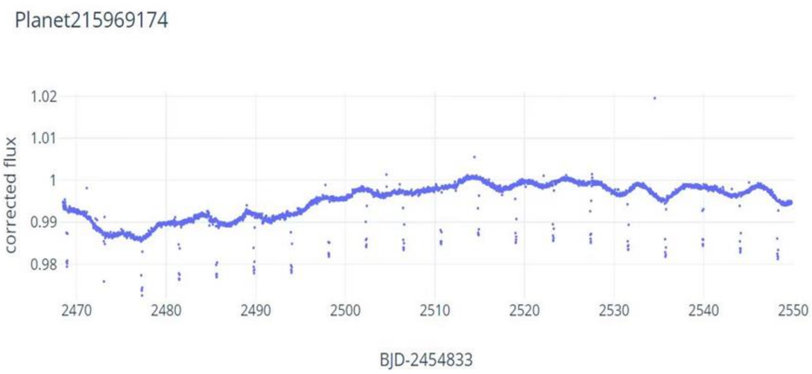


Fig. 5 The Kepler light curve of HATS-36 b

Table 6. All the transit of HATS-36 b in Fig. 5.

number	BJD(day)	Brightness(%)
1	2468.936	0.979378
2	2473.064	0.9758427
3	2477.313	0.9724941
4	2481.461	0.9762694
5	2485.65	0.9768693
6	2489.818	0.977771
7	2493.986	0.977917
8	2498.174	0.981746
9	2502.343	0.984046
10	2506.511	0.983367
11	2510.699	0.984741
12	2514.867	0.986902
13	2519.015	0.985073
14	2523.203	0.985528
15	2527.392	0.985033
16	2531.58	0.98338
17	2535.728	0.981735
18	2539.916	0.984351
19	2544.084	0.982764
20	2548.273	0.981179

While having all the transit point here in table6, each period of the transits could be known by using the equation (5). The periods are calculated as given in Table. 7. While having all the periods in Table. 7, the average period of the exoplanet could be calculated by using averaging method, in Equation (6), which is $T_{average} = 4.17563\ days$.

The mass of the HATS-36 is 1.1 times the mass of the sun. Knowing the average period and the mass of the star, while using the Kepler's third law, Equation(1) and Equation(2), the Semi-major axis of the exoplanet is $0.052385\ AU$.

In addition, the equation of the area ratio of the star covered by the planet to the star equals to the luminosity ratio could be usen, Equation(3) and Equation(4), to calculate the radius of the exoplanet. While selecting the radius of the star, the data from different websites are varied, in EPIC the radius is about 1.352 times the size of the sun and in NASA the radius is about 1.1 times the size of the sun. Since the radius of the star will affect the calculation of the radius of the planet, 1.1 times the radius of the sun has been choosen for this research, while it has been used by more researchers. While knowing the radius of the star which is 1.1 times the size of the sun and the radius of the sun id 695700km, each depth and radius of the exoplanet could be listed in the Table8:

Table 7. All the periods between each transit in Table6

$T_1 = 4.128$	$T_2 = 4.249$
$T_3 = 4.148$	$T_4 = 4.189$
$T_5 = 4.168$	$T_6 = 4.168$
$T_7 = 4.188$	$T_8 = 4.169$
$T_9 = 4.168$	$T_{10} = 4.188$
$T_{11} = 4.168$	$T_{12} = 4.148$
$T_{13} = 4.188$	$T_{14} = 4.189$
$T_{15} = 4.188$	$T_{16} = 4.148$
$T_{17} = 4.188$	$T_{18} = 4.168$
$T_{19} = 4.189$	

Table 8. All the depth and radius of HATS-36 b for each transit

Depth(%)	Radius(km)
0.01287	86816.8
0.010452	78237.4
0.012845	86732.5
0.012516	85614.5
0.011916	83537.2
0.01191	83516.2
0.012664	86037.6
0.012584	85846.8
0.011673	82681
0.012921	86988.7
0.012321	84945
0.011006	80284.1
0.012653	86081.8
0.012456	85409.1
0.013119	87652.7
0.012738	86370.5
0.012914	86965.1
0.012096	84165.8
0.011559	82276.3
0.012184	84471.4

While having all the radius in Table 8 and the radius of Jupiter is 71492km, the average radius of the exoplanet could be determined by using averaging method, in Equation(7), which is $R_{average} = 84731.5\ km\ (1.18519R_J)$. According to all the result, the average period, average radius and the semi-major axis are known here: $T_{average} = 4.17563$ days; $R_{average} = 84731.5$ km$(1.18519R_J)$; $a = 0.052385\ AU$. In comparing with the data online in Fig. 6, the period calculated in this research is a bit bigger and other values are within normal limits [13]. The large radius ($R_{average} = 84731.5$ km$(1.18519R_J)$) and short orbital period ($T_{average} = 4.17563$ days) of HATS-36b match the criteria of a hot Jupiter. Therefore, it is conclude that HATS-36 b is a Hot Jupiter.

Name	HATS-36 b
Planet Status	Confirmed
Discovered in	2018
Mass	2.79 ($_{-0.4}^{+0.4}$) M_J
Mass*sin(i)	–
Semi-Major Axis	0.0523 ($_{-0.0006}^{+0.0006}$) AU
Orbital Period	4.175186 ($_{-3.3e-05}^{+3.3e-05}$) day
Eccentricity	0.294 ($_{-0.294}^{+0.0}$)
ω	–
T_{peri}	–
Radius	1.153 ($_{-0.034}^{+0.034}$) R_J

Star

HATS-36

Name	HATS-36
Distance	878.65 ($_{-21.43}^{+21.43}$) pc
Spectral type	G0 V
Apparent magnitude V	14.386
Mass	1.1 ($_{-0.04}^{+0.04}$) M_{Sun}
Age	3.4 ($_{-1.4}^{+1.9}$) Gyr
Effective temperature	5950.0 ($_{-83.0}^{+83.0}$) K
Radius	1.1 ($_{-0.03}^{+0.03}$) R_{Sun}

Fig. 6 online data of HATS-36 b from exoplanet.eu.

3.3. Limitaton

Finally, the period of both planets, HATS-36b and HAT-P-56 b, are a bit bigger than the more precise measurements from Exoplanet.eu [13]. The reason is probably the lowest point read from the figures is not necessarily the lowest transit point of the planet. The point in the figure is not necessarily correspond to the same transit phase. Therefore, the accuracy of the measurement will be affected, which may also affect the calculations of the planet's period and radius. The error of the data measured by this method will be large. In future research, it is hoped that researchers can fit all the data with a planetary transit model and get more accurate measurements and more information, e.g., the eccentricity of the planet's orbit. In this way, based on the new methods, more planetary systems could be studied in the future.

4. Conclusion

In summary, this paper investigates HAT-P-56 b and HATS-36 b based on transit method. Using transit method, according to the analysis, one obtains the radius, period and semi-major axis of both HAT-P-56 b and HATS-36 b. For HAT-P-56 b, the period is $T_{average} = 2.79233$ days, the radius is $R_{average} = 1.40514\mathrm{R_J}$ and the semi-major axis is $a = 0.0423553$ AU. For HATS-36 b, the period is $T_{average} = 4.17563$ days, the radius is $R_{average} = 1.18519\mathrm{R_J}$ and the semi-major axis is $a = 0.052385$ AU. These measurements suggest that both the HAT-P-56 b and HATS-36 b are Hot Jupiters. Comparing with the pervious researchers, the periods of both exoplanets are a bit bigger and other values are within the normal range. Nevertheless, it is hard to get the actual transit points in the processed figure, so the calculation of exoplanet's radius and period would be affected. In the future, hoping researchers could fit all the data into a planetary transit model and obtain more accurate measurements and more information. These results offer a guideline for exploring the characteristic of Hot Jupiter and the exoplanets around the two host stars, HAT-P-56 and HATS-36.

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