

A Search For the Possible Planetary Companions of Hot Jupiters

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Abstract: Regarding the origin of Hot Jupiters, a topic that remains mysterious for contemporary astronomers, current theories primarily diverge into two distinct hypotheses. The first posits disk-driven migration theory, while the second advocates for high-eccentricity migration theory. The former hypothesis suggests that Hot Jupiters are frequently accompanied by additional planetary companions, whereas the latter implies that systems with such configurations are comparatively rare. In this analysis, we meticulously examine four systems: TOI-1259, TOI-1130, TOI-2337, and XO-7, utilizing data collected by the Transiting Exoplanets Survey Satellite (TESS) over recent years. Each of these systems harbors at least one Hot Jupiter orbiting its host star (with some systems containing two stars). Our principal objective is to detect potential smaller planets with larger orbits, or planetary companions, by processing the raw data employing computational methods and Python programming. We retrieve data from TESS and select sectors with an exposure time of 120 seconds, subsequently coalescing them into a unified light curve. Subsequent to eliminating inferior data quality and isolating the transit dips attributable to the known Hot Jupiters, we exclude these dips to obtain a light curve unaffected by the presence of gas giants. Utilizing the Box-Least-Squares technique, we identify the period with the highest likelihood and seek a distinct peak within a relatively flat baseline in the graphical representation. Ultimately, we fold the light curve according to the calculated period, scanning for a conspicuous dip that would indicate the presence of an additional planet. By predicting whether these systems have planetary companions, we can measure the probability and obtain a guess that the high-eccentricity migration theory may be more likely.

Keywords: Hot Jupiter, high-eccentricity migration, disk-driven migration, exoplanets, transiting method, planetary companions, TESS

1. Introduction

Hot Jupiters, exoplanets resembling Jupiter in terms of size and composition, have garnered significant attention due to their close proximity to their parent stars. Astronomers have been captivated

by the distinct conditions and unique properties exhibited by these celestial bodies. With recent advancements in observational techniques and theoretical models, researchers continue to investigate this intriguing phenomenon with great interest.

Hot Jupiters are gas giant exoplanets that share physical similarities with Jupiter but have significantly shorter orbital periods spanning 0.36-11.8 Jupiter masses and 1.3-110 Earth days, with masses not exceeding 13.6 Jupiter masses. Their close proximity to their host stars and resulting high surface-atmosphere temperatures have led to the informal designation "hot Jupiters."

We meticulously examine four systems: TOI-1259, TOI-1130, TOI-2337, and XO-7:

TOI-1259 is officially classified as a "hot Jupiter," based on its attributes as a high-temperature gas giant exoplanet with a relatively short orbital period. TOI-1259Ab completes an orbit around its host star, TOI-1259A, every 3.47798 days, as depicted in the flux-time graph. It possesses a mass of approximately 0.441 Jupiter masses and a radius of about 1.022 Jupiter radii[1].

TOI-1130 is indeed a hot Jupiter. The system consists of two planets: TOI-1130 c, a hot Jupiter, and TOI-1130 b, a mini-Neptune. The uniqueness of TOI-1130 lies in the fact that it is one of the few known systems where a hot Jupiter has another planet, specifically a smaller one, within its orbit. This configuration is unusual because current models of planetary migration suggest that a hot Jupiter's movement towards its star would typically eject smaller planets from the system. TOI-1130. It is only the third star known to have a transiting giant planet with an orbital period shorter than 10 days as well as a second transiting planet. The host star is brighter than the host stars of the previously known systems, especially at infrared wavelengths, which should provide good opportunities to study this type of system in detail[2].

TOI-2337b, a gas giant exoplanet detected through NASA's Transiting Exoplanet Survey Satellite and the W.M. Keck Observatory, orbits its host star every 2.9943 days and belongs to a group of three planets in advanced stages of evolution. TOI-2337b is characterized by its close proximity to the host star and short orbital period, resulting in high temperatures and significant gaseous composition. Notably, TOI-2337b's extremely close orbit around an evolved star suggests it will be engulfed within a million years, making it one of the shortest-lived known planets in terms of orbital period before being consumed by its host star. The study of TOI-2337b and similar exoplanets provides valuable insights into planetary system evolution and interactions between planets and their aging host stars during the final stages of stellar life cycles[3].

XO-7 b is categorized as a Hot Jupiter due to its abbreviated orbital period and close proximity to its host star, resulting in elevated surface temperatures. Discovered in 2019 using the transit method, XO-7 b orbits its host star at a distance much closer than Mercury orbits the Sun, completing an orbit in just under three days. Its mass is 0.71 times that of Jupiter and its radius is 1.37 times that of Jupiter[4].

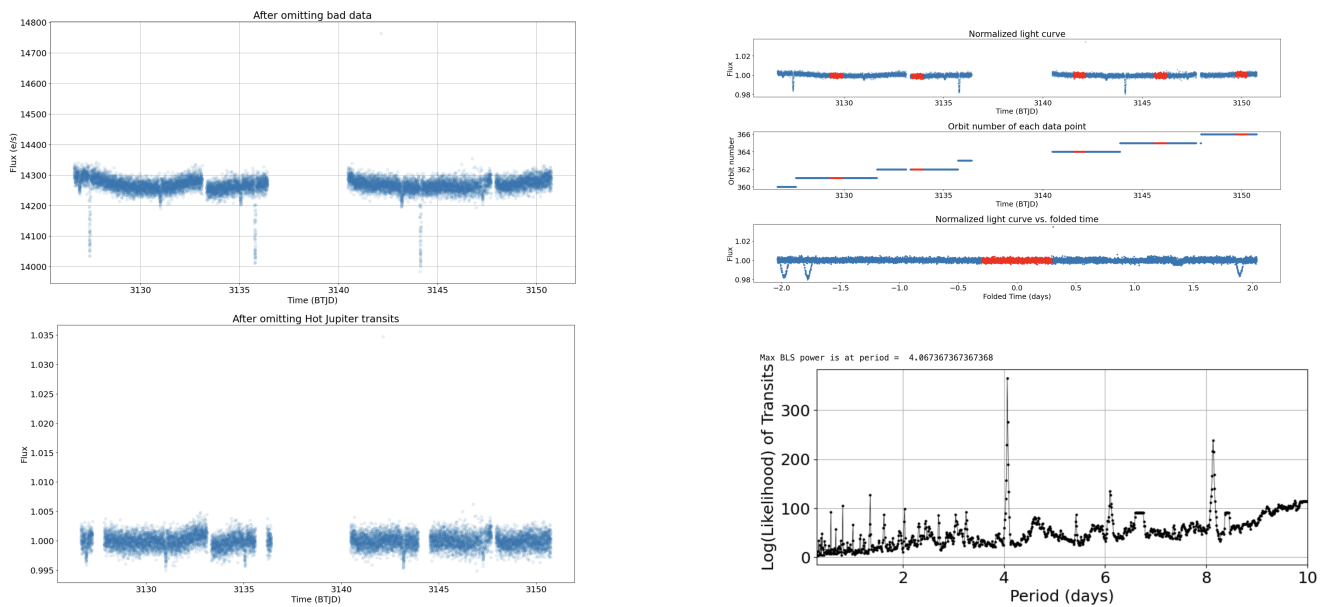


Figure 1: This is an example of TOI-1259. The upper diagram is the transits caused by the known Hot Jupiter picked out according to its searched period, time of conjunction and the transit duration and labeled as red. The middle one is the orbit number of each data point. The last diagram is the normalized light curve with the transits in red and other parts in blue already folded so that the red part can be easily removed.

2. Observations

In our study, we reviewed and analyzed 53 hot Jupiters, and we chose 4 planets that possess relatively special features among all the candidates. They are TOI-1259 A, TOI-1130, TOI-2337, and XO-7. Our analysis of these objects is according to data provided by the Transiting Exoplanets Survey Satellite (TESS) and the thesis published by past authors.

The TESS spacecraft is designed to discover exoplanets by observing transits, where planets pass in front of their host stars, causing temporary dips in brightness. TESS has four wide-field cameras, each with a $24^\circ \times 24^\circ$ field of view, using 2048×2048 pixel CCD sensors. It observes one sector of the sky for 27 days before moving to the next, completing a two-year mission to cover nearly the entire sky.

TOI-1259 A is the host star in the TOI-1259 system. Its Mass in units of Jupiter's mass is 0.411 ± 0.448 , the radius in units of Jupiter is 1.022 ± 0.0285 , the Orbit period is 3.4779780 ± 0.000018 days, and the Eccentricity of *TOI-1259 A* is 0[1]. *TOI-1259 A b* is a gas giant planet with 1.0R in unit of the radius of Jupiter. It transit with 0.71R K-dwarf in TOI-1259 system on the orbit which is 3.48 d[1].

TOI-1130 is the host star in TOI-1130 system with a lot of data recorded. Its mass in units of solar mass is 1.405 ± 0.059 , and its radius is 1.480 ± 0.022 in units of Jupiter's radius[2]. *TOI-1130 b* is a hot Jupiter in this system, 2458658.7405 ± 0.0013 Its time of conjunction is 8.350231 ± 0.000098 days and radius is 3.56 ± 0.13 in units of solar radius, period is 4.07445 ± 0.00046 . *TOI-1130 c* is another hot Jupiter. The period of it is 8.350231 ± 0.000098 days, radius is 0.175 in units of Jupiter, and its time of conjunction is $2458657.90322 \pm 0.00030$ days[2].

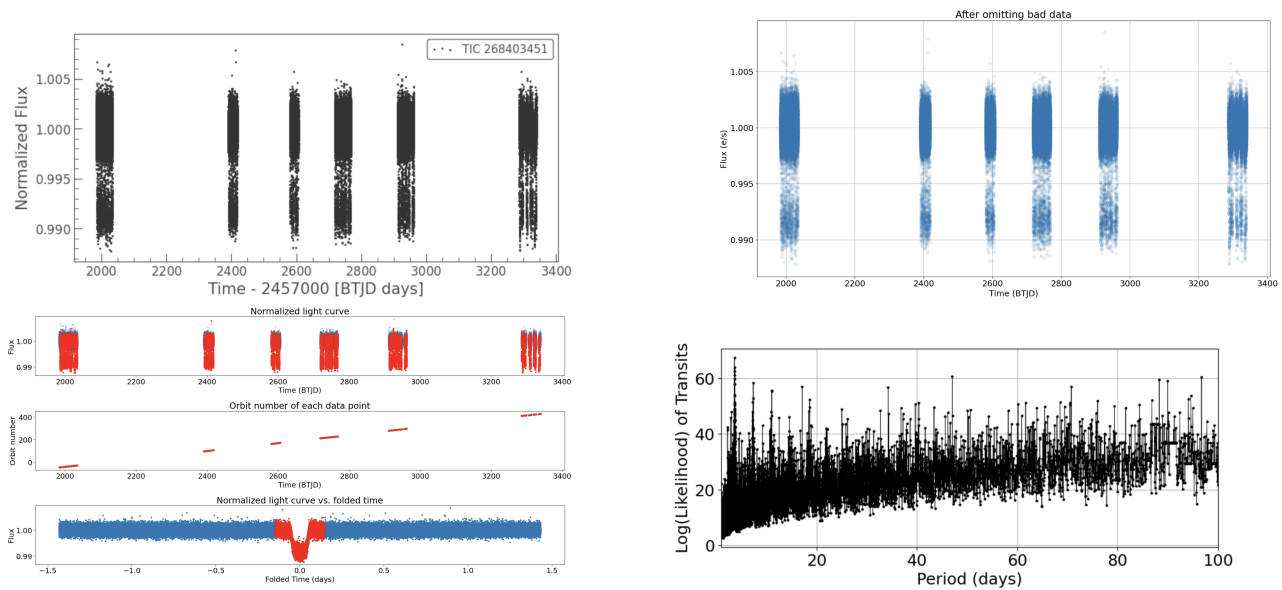


Figure 2: This is the BLS diagram of XO-7 as an example. The highest peak at probably 3.7 has the highest likelihood so there is a chance that there is a small planet existing with the period of 3.6942694269426943 days, calculated by the computer in this case.

TOI-2337's mass in units of Jupiter's mass is 10.284 ± 0.022 . It's radius in previous unit is 3.220 ± 0.062 , mass is 1.325 ± 0.118 in solar mass unit. It is the host star in *TOI-2337* system. Its radius in units of solar radius is 3.220 ± 0.062 , and mass is 1.325 ± 0.118 in previous unit[3]. *TOI-2337 b* is the only hot Jupiter in this system that has been observed by transit. Its time of conjunction is 2458793.828 ± 0.003 days and radius is 0.9 ± 0.1 in units of Jupiter radius. The period of it is 2.99432 ± 0.00008 days[3].

XO-7 Its mass in units of Jupiter's mass is 9.557 ± 0.024 in *XO-7* system. It's same that it also contain only one hot Jupiter that has been confirmed in this system, which is *XO-7 b*. Its time of conjunction is $2457917.47503 \pm 0.00045$ days and radius is 1.373 ± 0.026 in units of Jupiter. The period of it is 2.8641424 ± 0.0000043 days[4].

We analyzed all the data that content the characteristics of the data is mission = TESS, exposure time = 120, of four systems above. During the research, we drew their light curves, Flux graph after omitting bad data, the graph after omitting hot Jupiter, The BLS power plots, and folding graph.

3. Methods

To be short, we pick out the suitable data—from TESS, SPOC and with the exposure time of 120—from the existing database.[5] After then, we plot the light curve according to the data collected, removing bad data, and what we see is some obvious dips caused by the known Hot Jupiters, which can be omitted according to their observed period and time of conjunction. Ultimately, we use the BLS technique to calculate the most possible period for a potential smaller planet, and substituting the value of the period into a code, the light curve is folded and if there is still an obvious dip, the smaller planet exists with the calculated period.

In detail, for the first step, after the installation of pip and miniconda on the computer, we import numpy¹, which is a package that contains a lot of numerical functions and can operate complex

¹ numpy

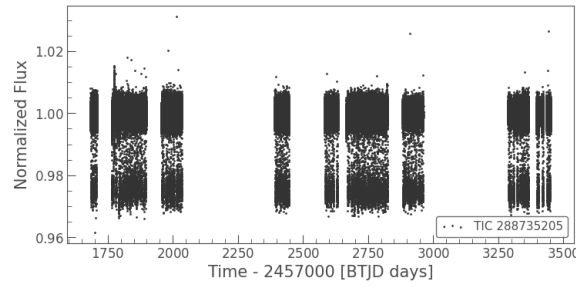


Figure 3: This is the graph with the y-axis labeled as flux of TOI-1259 after normalized and the x-axis labeled as the time in BTJD days, combining all the TESS data into one light curve so that the precision is significantly improved and all the transits caused by the known Hot Jupiter can be collected clearly.

calculations in a easier way. In the same way, we import matplotlib.pyplot² module to effortlessly plot countless graphs and manage with the data picked out and visualise them, followed by the import of lightkurve³, which is a package that can be applied to generate the light curves, for which as says in his essay: "The light curves, i.e. the time series plot of star's brightness, can provide information about the several stellar types, allowing even the detection of exoplanets via the planetary transit method[6], whose signature is revealed by periodic dips in the target star's brightness caused by the passage of the planet in the front of the host star." Afterwards, the most importantly, we import BoxLeastSquares (BLS)[6,7]⁴ to simulate the system model and obtain a possible value for the period of the potential planets by implicated calculations and numerous attempts.

For the next step, we define our parameters which are the time of conjunction "tc", the limb-darkening coefficient "u", the defined parameter "b"⁵, the orbital radius "a", the ratio between the radius of planet and the radius of the star "k"—they are all necessary for the demonstration of the planet's ideal orbit—by the method of diction using the command of params⁶. Also, we define the flux out of the transit and the rate of change of it per day, and what we do is to establish a relationship between them to calculate the actual flux considering the effect of limb-darkening. To have a better understanding of the location of the potential planet, we also create a three-dimension coordinate system, symbolized as x, y and z. As the formulae in the astronomy show:

$$x = a \cdot \sin(\phi) \quad (2)$$

$$y = b \cdot \sin(\phi) \quad (3)$$

$$z = \sqrt{a^2 - b^2} \cdot \cos(\phi) \quad (4)$$

$$s = \sqrt{x^2 + y^2} \quad (5)$$

where x is the x-coordinate, y is the y-coordinate, z is the z-coordinate and s is the the distance between the planet and the star, the location is expressed with the parameters stated above. Besides,

² matplotlib.pyplot

³ lightkurve

⁴ BoxLeastSquares

⁵ b is defined as

$$b = a \cdot \cos(I) \quad (1)$$

where a is the orbital radius and I is the angle of inclination.

⁶ params

we define the residuals⁷ using the formula:

$$res = \frac{f - tlc(params, t)}{f_unc} \quad (6)$$

and then it's the end of our definitions.

In the third step, we need to search for the data in the mission of TESS about our celestial object with the exposure time of 120 and the author of SPOC (Scientific Physical and Operational Characterisation)⁸, followed by the command of collecting all the searched dataset into a table with the headers of "order", "mission", "year", "author" and "exposure time". After downloading all the selected data, we put all the light curves into one graph named lcs 0 and plot it out with the y-axis labeled as flux in the unit of e/s and the x-axis labeled as time in BTJD days⁹. Next, we combine and integrate these separated light curves together with a code called stitch¹⁰ to make them as a whole, like Figure 1 shows, scattering the single light curve out with the only change that the y-axis is turned into the normalised flux and the name of the figure is given by the command of title. To make the y-axis more detailed and clearer, we can change the upper limit and the lower limit on the graph to zoom in, and it's the same with the x-axis[7].

Fourthly, we again define the command of removing the data within a certain time interval by setting a time interval where there are some bad data that should be removed to get rid of their negative effect. Then, we import the values (eg. from 3224 to 3227) shown on the graph as the bad time intervals and setting the alpha for a value, successfully removing the bad data.

Afterwards, we search on a website <https://nexsci.caltech.edu/> which is called NASA Exoplanet Science Institute, to obtain the information about the known Hot Jupiter about its time of conjunction in BTJD days, the orbiting period in days and the transiting duration in hours. Substituting the values into the params of tc, period and t_{14} ¹¹ in the definitions above after the definition of the command of folding the time where we generate an equation to express the time folded as:

$$t_{fold} = t_{fold} - 0.5 \cdot period_ref \quad (7)$$

we obtain a light curve with the transiting dips folded together caused by the Hot Jupiter and label them in red while the other parts in blue so that all the dips are gathered which gives convenience to the following part of omitting.

In the next step, we flatten the light curve with the definition of it as the fitting of a polynomial functions of time into the light curve to filter out the slow variations. Then we remove the data near the transits that are labelled in red referring to the time and the normalised flux to get rid of the effect of Hot Jupiter[8].

⁷ residuals

⁸ SPOC, a navigation monitoring computer used by NASA in a 1983 mission, was a modification of a commercial computer called GRiD Compass

⁹ BTJD days is the abbreviation of the Baricentric Julian Date, which

¹⁰ stitch

¹¹ t_{14} is the transiting duration which is the time interval between the ingress and egress during the transiting

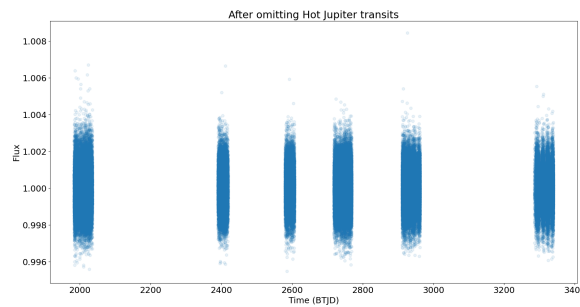


Figure 4: This is an example of XO-7 and the diagram is after omitting the transits caused by the Hot Jupiter XO-7 b, leaving only the blue parts where there may be some other transits caused by the potential planetary companions.

The last step is the BLS search,

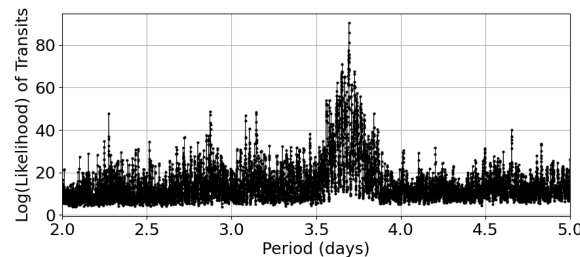


Figure 5: This is the BLS diagram of XO-7 as an example. The highest peak at probably 3.7 has the highest likelihood so there is a chance that there is a small planet existing with the period of 3.6942694269426943 days, calculated by the computer in this case.

for which we set a range for the possible values of the periods and the transits durations the potential planet can have for the attempts to match the best results using a bulk of calculations. Commanding the computer to plot out the periodogram with the x-axis labeled as “period” in days and the y-axis labeled as “Log (likelihood) of Transits”, we set the peak of the graph, which means that the highest likelihood, as the period of the planetary companion. What we are looking for is a diagram that is relatively flat with small variations and a significant peak suddenly appearing in the middle. If so, it’s a sign of the planetary companions and after folding the light curve again with the value of the calculated period, we see if there is a sharp dip within the line, deciding whether we discover a new planetary companion of a Hot Jupiter.[9,10]

4. Results

Our overall result is that for the most systems with Hot Jupiters, the probability to have one or more planetary companions is nearly 0, based on our researches for more than 50 systems observed by TESS using coding and python. Since the probability is nearly 0, this definitely increases the probability that the high-eccentricity migration can be the correct hypothesis explaining the origin of Hot Jupiters rather than the disk-driven migration, since the former one proves that there should rarely exist companions for Hot Jupiters while the latter one is quite the opposite. Therefore, our conclusion is there would be a higher likelihood for high-eccentricity migration theory. Here, we pick out mainly

4 systems to be representatives from our more than 50 samples since they either are weird, have a lot of data or have the rare planetary companions.

4.1. Results for TOI-1130

In the system of TOI-1130, which is a unique and weird star system with two companion stars TOI-1130b and TOI-1130c, both of them were discovered using transit methods, where the planets pass in front of their host star from our perspective causing a slight dimming of the star's light that can be detected by TESS. TOI-1130 c is a Hot Jupiter with the period of 8.350231 days, the radius of $1.188 R_{Jup}$ and an orbital semi-major axis of 0.07191 au. Besides, TOI-1130b is a gas giant planet, larger than Neptune, and orbits really close to star, completing an orbit in just a few days, so it's a so-called "Inner Neptune". For the details about this system, suggested in the paper published in 2020, "the host star, TOI-1130, is an eleventh magnitude K-dwarf in Gaia G-band. It has two transiting planets: a Neptune-sized planet ($3.65 \pm 0.10 R_{oplus}$) with a 4.1 days period, and a hot Jupiter ($1.50-0.22+0.27 R_{Jup}$) with an 8.4 days period. Precise radial-velocity observations show that the mass of the hot Jupiter is $0.974-0.044+0.043 M_{Jup}$. For the inner Neptune, the data provide only an upper limit on the mass of $0.17 M_{Jup}$ " We use the figure in TESS:

3 TESS Sector 67 2023 SPOC 120

the figure of BLS in TOI-1130b is really special:

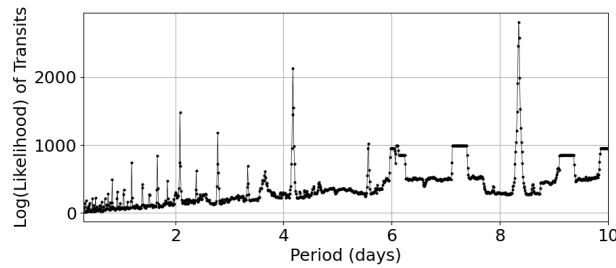


Figure 6: Max BLS power is at period = 8.34934934934935 days

5 which have the max period is 8.34934934934935. The planet's substantial size and relatively short orbital period have led some to colloquially refer to it as a "warm Neptune" Besides we also find a "Hot Jupiter" is TOI-1130c

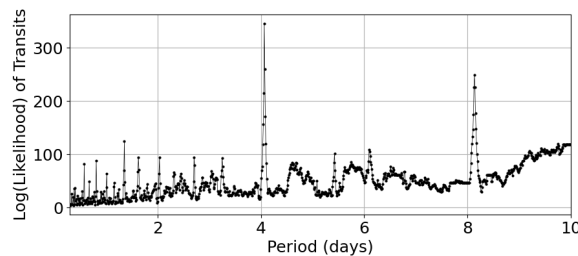


Figure 7: Max BLS power is at period = 4.067367367367368

The most prominent one is TOI-1130c, with a maximum period of BLS at 4.067367367367368, falling within the "Hot Jupiter" range.

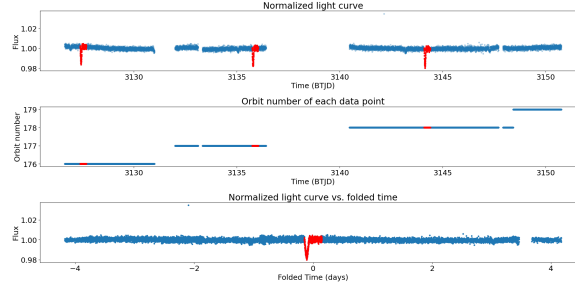


Figure 8: Enter Caption

The top graph displays the data after the removal of outliers, specifically capturing dips attributed to the known Hot Jupiter based on period, time of conjunction, and transiting duration, which are highlighted in red. The middle graph illustrates the orbit number associated with each data point. Lastly, the bottom graph represents a folded compilation of all red segments, effectively isolating and eliminating dips caused by TOI-1130 b for easy and complete removal.

4.2. Results for TOI-1259

As for the system of TOI-1259, which is a binary system with a known Hot Jupiter orbiting around one of them called TOI-1259A, although we have tried a lot, there is probably no other small planets orbiting in that system. To introduce this system first, TOI-1259 is a system with TOI-1259 B, a white dwarf, and TOI-1259 A, a K-type star, being orbited by a known Hot Jupiter TOI-1259 A b, which has a radius of $1.022 R_{Jup}$, a mass of $0.441 M_{Jup}$ and an orbit's semi-major axis of 0.04070 au. As says in his essay, "We present TOI-1259Ab, a $1.0 R_{Jup}$ gas giant planet transiting a $0.71 R_{Sun}$ K-dwarf on a 3.48 d orbit. The system also contains a bound white dwarf companion TOI-1259B with a projected distance of 1600 au from the planet host."

TESS has already targeted this system since 2019, obtaining data separated different sectors, with the exposure time of 20, 120 and 200 respectively. However, since the exposure time of 20 can't collect enough data for a more precise analysis, causing a greater impact from noise and instrument error, we don't choose the dataset observed with the exposure time of 20. For the exposure time of 200, since there are too many data being collected, although the precision can be improved, these data may have more errors and noise being accumulated, causing trouble, either, for which as a reason, we don't use 200 as well. Table 1 is part of our dataset from TESS, selected with the condition that the data is from the author of SPOC and the exposure time is 120.

Table 1: Selected TESS Dataset

order	mission	year	author
0	TESS Sector 25	2020	SPOC
1	TESS Sector 47	2021	SPOC
2	TESS Sector 58	2022	SPOC
3	TESS Sector 73	2023	SPOC
4	TESS Sector 78	2024	SPOC

After sorting out the useful data, totally 27 sets of data, we plot out their light curves and combine all of them into one single light curve, with the y-axis labelled as “normalised Flux” with the lower limit of 0.96 and the upper limit of 1.03 after the normalisation, and the x-axis as the time between 1720+2457000 BTJD days and 3500+2457000 BTJD days.¹²

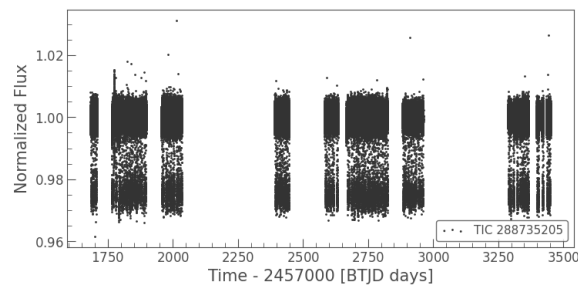


Figure 9: This is the graph plotted out according to the raw data collected by the SPOC in TESS. The y-axis is labelled as “normalized flux”, being normalized within the range between 0.96 and 1.04 so that the values can be comparable and clear. The x-axis is labelled as “Time - 2457000” in the unit of BTJD days.

¹³Later, we change the data graph into dot graph, symboling the data as points in blue. We find that the data between the time interval from 1720 to 1750 is too little that there can be some significant negative effects on the precision of the research, so we remove those data. What’s more, since the graph is varied a lot in the vertical direction, we decide to remove the data that have fluxes larger than 1.01, avoiding the bad impacts.

¹² As said before, BTJD day can be seen as a standard unit for the measure of time in the field of astronomy

¹³ The minus of 2457000 is for a easy calculation since the numbers become shorter and briefer than before

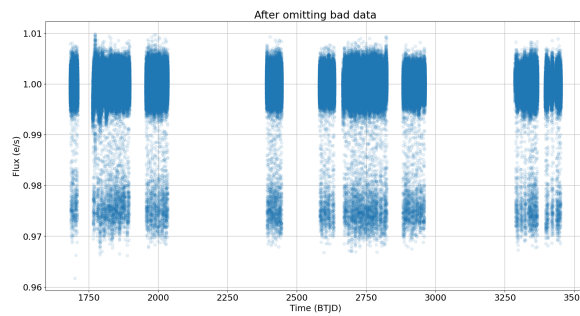


Figure 10: This is the graph after removing the bad data, plotted in the form of points. The data between the time of 1720 and 1750 is not much enough to support high precision and reliability so it's removed. Also, the data above 1.01 is too scattered and weird, so to get rid of its negative effects on the variations of the whole dataset, we omit these values.

Afterwards, we search out that the time of conjunction for TOI-1259 A b (the known Hot Jupiter) is 2458996.240605 BJD days, the period is 3.47797910 days and the transit duration is 2.4754 hours. Typing these values into the code, we plot out the graph with the transits labelling in red, and again we fold the graph to make all the red transits gather together so that we can easily remove these dips.

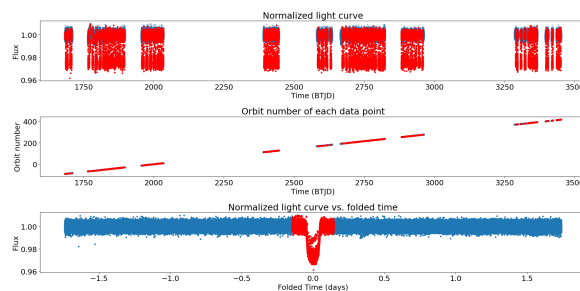


Figure 11: The graph on the top is the graph in which dips caused by the known Hot Jupiter are picked out according to the planet's period, transiting duration and the time of conjunction and are labelled in red. The graph in the middle is the graph showing the orbit number of each data point. The one at the bottom is the graph after folding all the red parts together, gathering all the dips caused by the known transiting so that they can be removed easily and completely.

Using the command of removing, we remove the data with the Hot Jupiter transits, leaving the blue parts which may have some signs of dips caused by potential small planetary companions. Most importantly, we carry out the BLS technique to calculate the most possible period for the potential planet, at first setting the range for the accessible periods from 0.3 days to 10 days and the available transiting durations from 0.25 hours to 4 hours—the reason is that most known planetary companions of Hot Jupiters are within these two ranges. The result is shown on the figure below, with the calculating value of 3.6110110110110107 days as the period with highest likelihood.

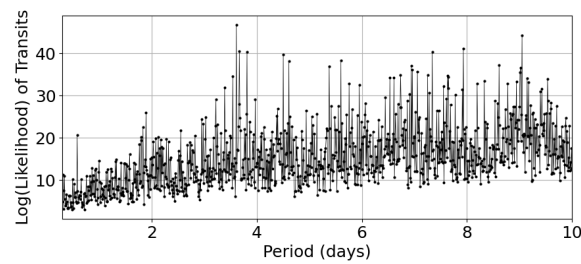


Figure 12: This is the BLS diagram for the system of TOI-1259 and as it shown, the most possible period for the potential planetary companion is at the peak of the graph, which occurs in this occasion when the period is 3.6110110110110107 days, so we have the highest likelihood to have a small planet with the period of 3.611011 days.

After then, we fold the light curve again according to the calculated period, looking for any signs that there is some dips to indicate the transits caused by the potential planetary companion. However, pitifully, our curve is flat and there is no dips at all, so our result is that there is probably no planets with the periods between 0.3 days and 10 days.

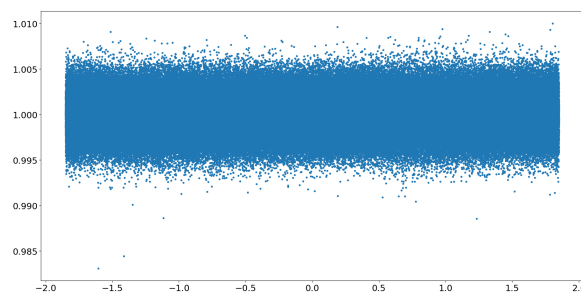


Figure 13: This is the graph after the second folding according to the period obtained in the BLS diagram above which is 3.6110110110110107 days. The graph shows no obvious or even visible dips caused by transiting of an unknown planet, so the possible result is that there is no planetary companion for the Hot Jupiter TOI-1259 b in the system of TOI-1259.

Trying our best, we repeat the step of BLS technique but with the only change that the period range expands to the position between 0.2 days and 100 days to enlarge our scope of search. This time, the calculated period is 98.60140140140139 days and after repeating the process of folding, our light curve is still flat without any obvious dips caused by the transits.

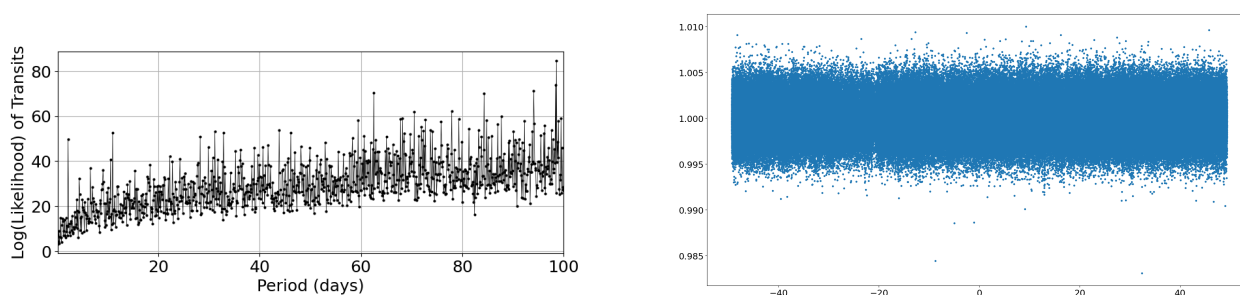


Figure 14: The top graph is another BLS diagram when increasing the scale of research to the range of the periods from 0.2 days to 100 days, obtaining a result with the highest possibilities: 98.60140140140139 days. The diagram at the bottom is the one after folding according to the results obtained before and the conclusion is the same: there is probably no planetary companion for the Hot Jupiter in the system of TOI-1259.

Therefore, our conclusion for this system is that there is probably no planetary companions that can be observed by the method of transit, but other methods like Doppler effects. Even if there is a planetary companion, we suppose there are two possibilities: one is that the planet's orbit may not cross the surface of TOI-1259 A in the eye of us Earth observers; the other one is that the planet is too small that it can't create a significant dip on the light curve, beyond the precision of our calculations.

4.3. Results for TOI-2337

In the system of TOI-2337, which have a hot jupiter orbiting called TOI-2337b, although we have tried a lot, there is probably no other small planets orbiting in that system. TOI-2337 is a red giant star, which means it is in a late stage of its evolution, having expanded and cooled after exhausting the hydrogen in its core. The exoplanet orbiting TOI-2337 was discovered using data from NASA's Transiting Exoplanet Survey Satellite (TESS). The planet was identified through the transit method.

TESS has already targeted this system since 2019, obtaining data across different sectors, with exposure times of 20, 120, and 200 seconds, respectively. However, since the exposure time of 20 seconds can't collect enough data for more precise analysis, resulting in a greater impact from noise and instrument error, we don't choose the dataset observed with the exposure time of 20 seconds. For the exposure time of 200 seconds, although the precision can be improved due to the higher data collection, these data may accumulate more errors and noise, causing trouble as well. Therefore, we don't use the data from the 200-second exposure time either. Table 1 is part of our dataset from TESS, selected under the condition that the data is from the author of SPOC and the exposure time is 120 seconds.

After sorting out the useful data, totaling 27 sets of data, we plot out their light curves and combine all of them into one single light curve, with the y-axis labeled as "normalized flux" within the range of 0.97 to 1.04 after normalization, and the x-axis as the time between 2400+2457000 BTJD days and 3450+2457000 BTJD days.

Afterward, we determined that the time of conjunction for TOI-2337 A b (the known Hot Jupiter) is 2458793.828 BJD days, with a period of 2.99432 days and a transit duration of 2.3125 hours. Entering these values into our code, we plotted the graph with the transits labeled in red and then folded the graph to gather all the red transits together, making it easier to remove these dips. Using the remove command, we removed the data corresponding to the Hot Jupiter transits, leaving only the blue parts, which might contain some signs of dips caused by potential small planetary companions.

Most importantly, we performed the BLS technique to calculate the most likely period for the potential planet, we set the range for accessible periods from 0 days to 100 days and the result is shown in the figure below, with a calculated value of 73.85617956292602 days as the period with the highest likelihood.

Next, we folded the light curve again according to the calculated period, searching for any signs of dips indicating transits caused by the potential planetary companion. Unfortunately, the light curve remained flat without any dips, suggesting no other planet. Therefore, our conclusion for this system is that there are probably no planetary companions detectable by the transit method. However, other methods like Doppler spectroscopy might still reveal something. If there is a planetary companion, we propose two possibilities: either the planet's orbit does not cross the surface of TOI-2337 A from our vantage point on Earth, or the planet is too small to create a significant dip in the light curve, beyond the precision of our calculations.

4.4. Results for XO-7

In the last system, XO-7, it's a normal system with one star being orbited by a normal Hot Jupiter XO-7 b which has a radius of $1.373 R_{Jup}$, a semi-major axis for the orbit of 0.04421 au and an orbiting period of 2.8641424 days. To be more specific and detailed, as Nicolas's description in his paper in 2020 about XO-7 b shown, "We conducted photometric and radial velocity follow-up with a team of amateur and professional astronomers. XO-7 b has a period of 2.8641424 ± 0.0000043 days, a mass of $0.709 \pm 0.034 M_J$, a radius of $1.373 \pm 0.026 R_J$, a density of $0.340 \pm 0.027 \text{ g/cm}^3$, and an equilibrium temperature of $1743 \pm 23 \text{ K}$." The host star is a sun-like star with the radius of $1.48 R_{Sun}$ and the stellar effective temperature of 6250 K.

TESS has already targeted that system for further observations and researches since 2020, obtaining totally 16 datasets, all of the author of SPOC. But we still select the data with the exposure time of 120 seconds, so the number of dataset we decide to use is 10, observed by 10 sectors—the reason why we use the exposure time of 120 seconds is stated in the results of TOI-1259. The specific content of these data is neglected (the example in the system TOI-1259 can be a reference).

After picking out the suitable data, we plot it on our graph with different color to label the years and sectors with the x-axis of time, in the unit of BTJD and the y-axis of flux, in the unit of e per second. Next, we combine all the data so that they are not separated anymore but integrated, using the command of "stitch" to pursue a higher precision and accuracy at the same time when the reliability can be improved.

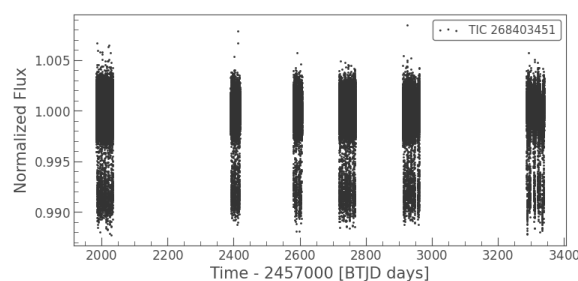


Figure 15: This is the graph plotted out according to the combined raw data collected by the SPOC in TESS from 10 different sectors. The y-axis is labelled as "normalized flux", being normalized within the range between 0.96 and 1.04 so that the values can be comparable and clear. The x-axis is labelled as "Time - 2457000" in the unit of BTJD days.

After that, changing the graph into the dot-plotted graph, we enlarge the y-axis ranging from 0.99 to 1.01 with the same range of x-axis. However, the data is too varied in the vertical direction, so what we do is choosing the data with the flux value greater than 1.01 to be removed. Afterwards, clearly, there are some obvious dips in the graph, so we type in the values of some information about the Hot Jupiter causing the large dips—the period of the planet is 2.8641356 days, the time of conjunction is 2459111.81975 years and the transiting duration is 2.772 hours (here, we need to change 2.772 hours into 0.1155 days). Then, these dips are all searched out and labeled in red so that they can be gathered together to be removed after folding together.

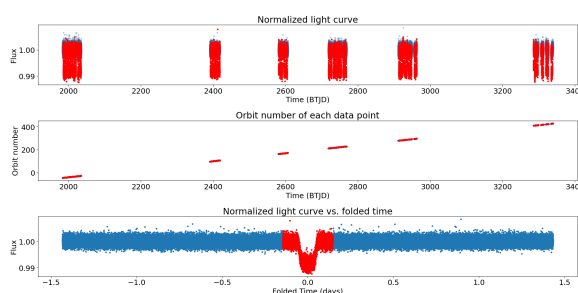


Figure 16: The graph at the top is the graph after removing the bad data in which the dips caused by the known Hot Jupiter are collected out according to the period, the time of conjunction and the transiting duration and are labelled in red. The graph in the middle is the graph showing the orbit number of each data point. The one at the bottom is the graph after folding all the red parts together, gathering all the dips caused by XO-7 b so that they can be removed easily and completely.

Now, the graph we obtain is the graph after omitting the effect of the known Hot Jupiter, so we now fold the graph, searching for any possible result that there are some signs that the potential planet is existing with the BLS technique, setting the range of the possible period from 2 days to 5 days.

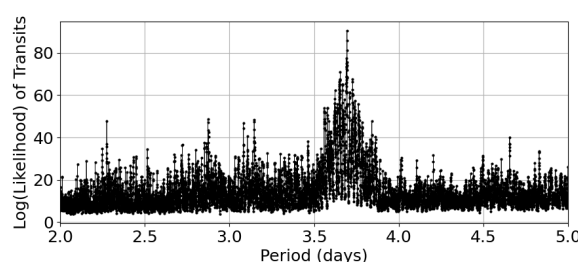


Figure 17: This is the BLS diagram for the system of XO-7 and as it shown, the most possible period for the potential planetary companion is at the peak of the graph, which occurs in this occasion when the period is 3.6942694269426943 days, so we have the highest likelihood to have a small planet with the period of 3.69427 days.

Showing on the BLS diagram, the period that the potential planetary companion has the highest possibilities to exist at is 3.6942694269426943 days, so we then type in the value of this period to fold the diagram so that we can see if there is a visible dip caused by the possible planet. Regretful, we find no any signs regarding to that potential dips, but only an extremely straight line.

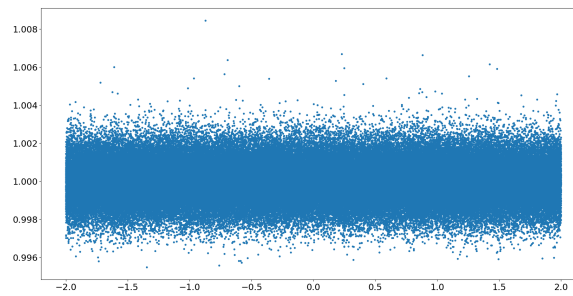


Figure 18: This is the graph after the second folding according to the period obtained in the BLS diagram above which is 3.6942694269426943 days. The graph shows no obvious or even visible dips caused by transiting of an unknown planet, so the possible result is that there is no planetary companion for the Hot Jupiter XO-7 b in the system of XO-7.

So we try other values appearing on the peaks in the BLS diagram, folding the graph to ensure the high reliability and precision. We change the range of the period from the range of 2 5 days to the range of 0.2 25 days to increase the scale of searching. Here is the BLS diagram:

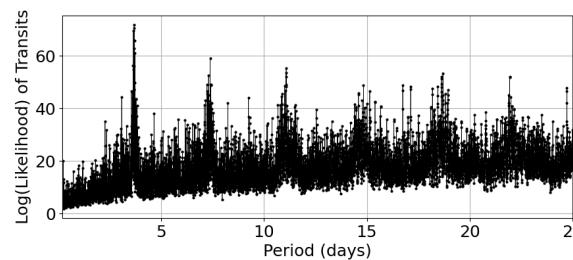


Figure 19: This is another BLS diagram but with the only change that the range is expanded from the original one within 2 and 5 days to the range from 0.2 days to 25 days so that the scale of searching can be increased. The period with the highest likelihood for the potential planet shown on the graph is 3.6897089708970903 days.

On the BLS diagram, the most likely period of the possible planetary companion is 3.6897089708970903 days, approximately the same as the results above from the first attempt. As expected, after typing in the new value and folding the graph again, there is no any obvious dip that is looked like it is caused by the transiting. Changing the range again to a range from 0.2 to 50 days, the result is changed to the 3.6897089708970903 days, still similar to the results before, and sure enough, there is no sign of a possible planetary companion for the Hot Jupiter XO-7 b.

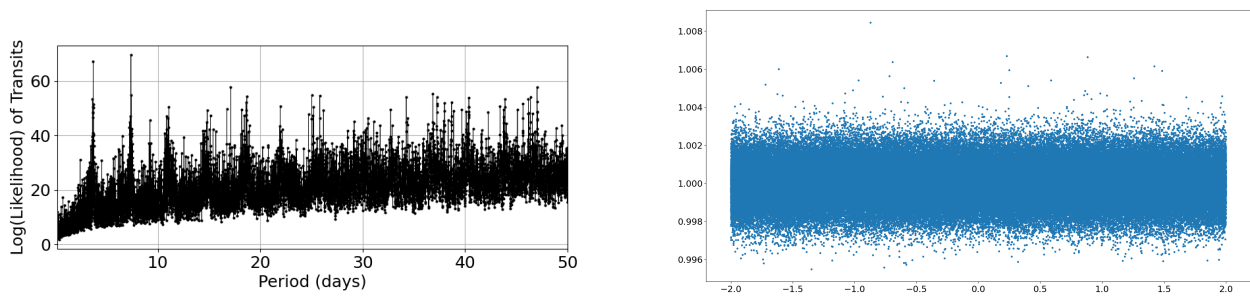


Figure 20: The top graph is another BLS diagram when increasing the scale of research to the range of the periods from 0.2 days to 50 days, obtaining a result with the highest possibilities: 3.6897089708970903 days. The diagram at the bottom is the one after folding according to the results obtained before and the conclusion is the same: there is probably no planetary companion for the Hot Jupiter in the system of XO-7.

As a result, to reach a summary, there is probably no planetary companions for the Hot Jupiter in the system of XO-7. Even if there are, we have two possible reasons to explain our failure: one is that the potential planets are too small that our computer can't reach a precision that high so we can't discover those planets; the other reason is that the orbits of those potential planets aren't cross the surface of the host star in the eye of the observers on the Earth so that there is no any transiting occurring in the Earth reference system.

5. Conclusion

After our research, we didn't discover any new companies of hot Jupiters and figured out that the companies of hot Jpiters are few by downloading and studying the light curves and BLS plots. It seems like the result is more confirmed with the theory of high-eccentricity migration which is one of the possible formations hypothesized for hot Jupiters, since it claims that the companies of hot Jupiters are rare. This theory supports that the planet that formed in a huger radius is triggered to high eccentricity by a type of mechanism, then migrated to its current orbit caused by occurring near perihelion tidal dissipation. See previous section 4.

The result of our research confirmed that 53 hot Jupiters don't have any companies, but there still countless planets in the universe. In this case the origin of the hot Jupiters is unknowing to human and the accuracy of previous two theories is also unsubstantiated. see Section 1. for the introduction.

In the future, the study of determine whether there are more cases of hot Jupiters with companions than without should be done more in order to find the process of the origin of the hot Jupiters.

6. Statement of work

Before the writing of the paper, FAN BAOYI is responsible for the listing of the stars and the brief checking and research of these stars. LI MINGYU, LIU ZHANGZE and ZHANG HAOCHEN are responsible for the performance of the code and python for some certain targeted systems. As for the writing of the paper, FAN BAOYI writes the abstract part, key words. LI MINGYU writes the introduction part, ZHANG HAOCHEN writes the observation part and FAN BAOYI writes the methods part. The results part is divided into four parts: LI MINGYU is responsible for the results of the system TOI-1130, FAN BAOYI is responsible for the results of TOI-1259 and the results of XO-7, and ZHANG HAOCHEN is responsible for the results of TOI-2337. The discussion part is written

mainly due to the contribution from LIU ZHANGZE and ZHANG HAOCHEN. The statement of work is written by FAN BAOYI. All pictures and data in the paper (except the data coming from the websites and TESS) are provided by these four members, especially ZHANG HAOCHEN and LI MINGYU, obtaining with their programming on the computers. After the writing of the paper, ZHANG HAOCHEN is responsible for the final version of the paper and the compiling of the paper on the overleaf, and for the polish and duplicate checking.

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