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Using Python programs to determine the secondary eclipse depth of Kepler-12 b and its geometric albedo

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Abstract. The discovery of Hot Jupiter in 1995 marks the beginning of a new era in Astrophysics, and deep space observatory provides valuable data that helps us understand the evolution of the universe and extrasolar systems. This paper reports on the secondary eclipse depth and the geometric albedo of a hot Jupiter "Kepler-12 b" with a planet radius of $1.695 \pm 0.03 R_J$, and the use of Python programs helps derive the results. The Python programs also help draw the figures in this work with data from *Spitzer* IRAC, an infrared camera designed to detect near- and mid-infrared light. The conclusion drawn from the work is that the orbital period is 4.401 days and the geometric albedo $A_g = 0.17^{+0.08}_{-0.08}$. This work points out that the relatively low geometric albedo of Kepler-12b could imply that Kepler-12 b is a pM-class planet. The distinguishing factor between a hot Jupiter of pL-class and one of pM-class is the variation in their spectra and the temperature difference between their day and night sides.

Keywords: Kepler-12 b, Geometric Albedo, Secondary Eclipse, Python, Techniques, Spectroscopic.

1. Introduction

Kepler-12 b(KIC 11804465) is a hot Jupiter with a planet radius of $1.695 \pm 0.03 R_J$. Discovered in 2011, Kepler-12 b was confirmed through the transit method. Kepler-12b is orbiting the Kepler-12, a G0 host, with a 4.483-day period, this planet is the least irradiated within this largest-planet-radius group, which has important implications in Astrophysics [1]. Kepler-12 b has an eccentricity of less than 0.021, which means that its orbit is almost a perfect circle [2]. Table 1 shows the parameters of Kepler-12 b.

A secondary eclipse(occultation) happens when the planet's thermal radiation and reflected light from the planet disappear and reappear because the main star blocks the vision of the telescope. The detection of occultation could provide us with information such as the light emitted or scattered by the planet's atmosphere, which could give the planet's dayside temperature structure. At the same time, the occultation light curve could be used to analyze four parameters: i. R_{Day}, the contrast ratio between the planet dayside flux and the stellar flux; ii. $F_{\frac{N}{D}}$, the ratio of nightside to dayside flux; iii. the flux of the star; iv. The geometric albedo of the planet. These parameters are crucial when determining the class(pM or pL) of a hot Jupiter. Figure 1 are the light curves of Kepler 12-b.

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2. Data Analysis

For the analysis of the data of Kepler-12 b, this work used the Lightkurve package to get the normalized transit light curve and the phase-folded transit light curve of Kepler-12 b in the seventh quarter with an exposure time of 1800 seconds. The corresponding normalized flux curve and the folded transit curve are shown in Figure 1. Then the work uses the Lightkurve package to make the period gram fit the orbital period of Kepler-12 b. The Kepler Telescope could observe the change of light of an exoplanet and its frequency in a given exposure time. The Kepler data that the paper studied in a certain duration is not a continuous set of observations, but a discrete set of observations due to the various kinds of variability caused by rotation, activity, and the motion of the telescope itself [3]. To tell the frequency of these oscillations, we need to find the Discrete Fourier Transform of the equation of Kepler-12 b's changing brightness to receive the frequency of the periodic signals [4]. The in-built function used by Lightkurve is the Lomb-Scargle periodogram, a well-known algorithm for detecting and characterizing periodicity in unevenly-sampled time series. The detailed introductions of the Lomb-Scargle periodogram could be found in Vanderplas (2017). The Lomb-Scargle periodogram allows the computation of the estimated Fourier-like Power spectrum of the unevenly-distributed data, the graph is shown in Figure 2. The power spectrum gives us an approximate orbital period of Kepler-12 b of 4.401 days. Figure 3 uses the identical data in Figure 2 and folds over the detected 4.401-day to show the coherent periodic variability.

This work has measured the approximated orbital period of Kepler-12 b, the next step would be the measurement of the occultation depth of Kepler-12 b. For the analysis of the occultation depth of Kepler-12 b, this paper uses the Pylightcurve package to get the approximate occultation depth and eclipse light curve. Pylightcurve, a Python package developed by Angelos Tsiaras, helps scientists analyze exoplanet light curves. This package includes data from *Spitzer* IRAC, the Infrared Array Camera on the telescope that is designed to detect light with lengths between 3.6 μm to 8.0μm, which is near- and mid-infrared light. IRAC could provide a more sophisticated filter that helps me determine the occultation depth of Kepler-12 b [5]. The occultation of Kepler-12 b was measured by Warm-Spitzer/IRAC four times between August 2010 and January 2011 in 4.5 μm channels and 3.6 μm channels respectively [6]. An occultation depth of 0.0935% is measured in the work with Spitzer IRAC 4.5 μm channel. In Figure 4 there is the corresponding phase-folded occultation light curve generated by the Pylightcurve with the best-fit model superimposed, the detrended phase-folded occultation light curve with the best-fit model superimposed, and the residual phase-folded occultation light curve with best-fit model superimposed [7].

Furthermore, this work uses the planet's radius $R_P = 1.695^{+0.028}_{-0.032} R_J$ and mass $M_P = 0.433^{+0.041}_{-0.04} M_J$ from Table 1(visit *exoplanetarchive.ipac.caltech.edu* for more details), and the orbital period of 4.041 days, which is explained previously. Then, I determine the major long axis a= $0.054^{+0.028}_{-0.027}$au by using the following equation [8].

$$P^2 = \frac{4\pi^2}{G(M_* + M_P)} a^3 \tag{1}$$

And that gives a geometric albedo A_g = $0.17^{+0.08}_{-0.08}$ with the below equation, where $\frac{F_p}{F_*}$ the occultation depth, an orbital semi-major axis, and R_p the planetary radius [6].

$$\frac{F_p}{F_*} = A_g \left(\frac{{R_p}^2}{a} \right) \tag{2}$$

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Table 1. Parameters of Kepler-12 b [2].

Source	Bonomo et al. 2017
M_P	$0.433^{+0.041}_{-0.04}$
M_*	138^{+13}_{-13}
R_P	$1.695^{+0.028}_{-0.032}$
R_*	$0.433^{+0.042}_{-0.04}$

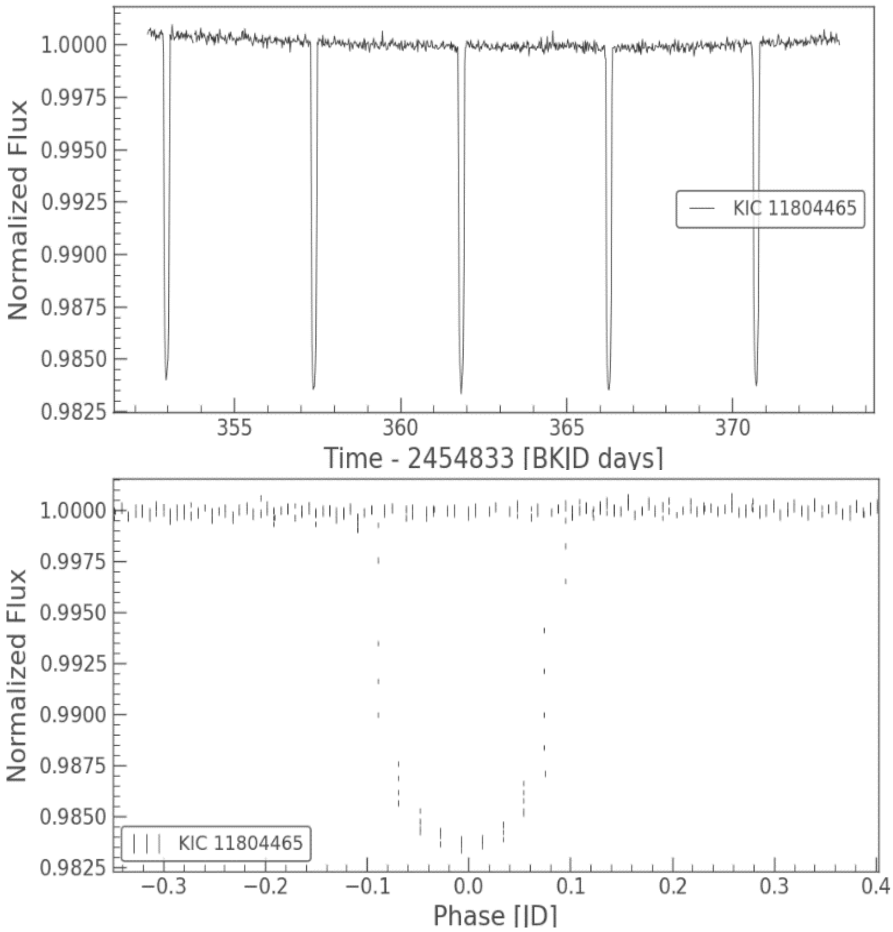

Figure 1. Top: Kepler-12 b transit light curve computed and drawn by the lightkurve program. Bottom: Kepler-12 b phase-folded transit light curve computed and drawn by the lightkurve program.

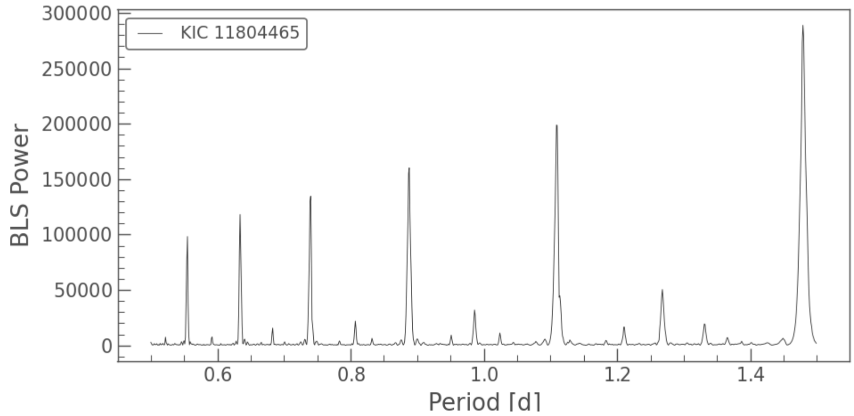

Figure 2. The Lomb-Scargle periodogram computed from the data in Figure 2.

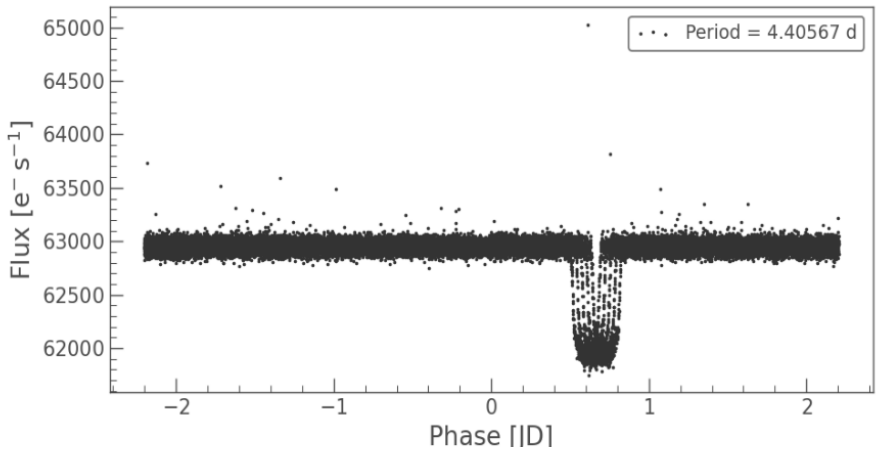

Figure 3. The input data in Figure 2, folded in phase and tells the period of 4.40567 days.

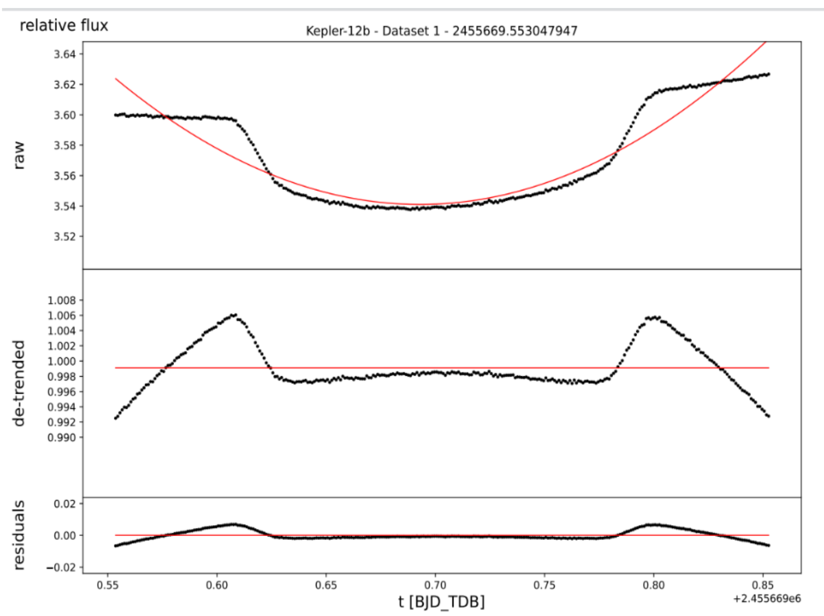

Figure 4. Top: Occultation light curve of Kepler-12 b with best-fit model superimposed. Middle: Occultation light curve of Kepler-12 detrended. Bottom: residuals are displayed in flux scale.

3. Conclusions

This paper reports the secondary eclipse depth and the geometric albedo of Kepler-12 b from occultation observations by *Kepler* and *Spitzer*. The relatively low albedo of the planet could imply that Kepler-12 b is a pM-class planet. A secondary eclipse is important because it tells us the chemical position and temperature structure of an exoplanet by providing a low-resolution spectrum of the atmosphere of the targeted planet. Geometric albedo, on the other hand, helps us determine the class of a hot Jupiter.

The geometric albedo of a celestial body eases the ratio of its actual brightness at zero phase angle (i.e. as seen from the light source) to that of an idealized flat, fully reflecting, diffusively scattering disk with the same cross-section [9]. There are plentiful pieces of evidence showing that the different amount of incident stellar flux of hot Jupiters leads to two distinct classes that describe their atmospheres. The difference between a pL-class hot Jupiter and a pM-class hot Jupiter lies in their spectra and dayside-nightside temperature [10]. In a pM-class planet, the condensation of titanium- and vanadium-bearing compounds is prevented by the warm atmosphere. Consequently, the thermal conversion caused by the warm atmosphere could prevent the redistribution of heat from dayside to nightside, resulting in large dayside-nightside temperature contrasts. A pL-class planet, on the contrary, absorbs incident stellar flux deeper in the atmosphere that renders the redistribution of energy easier, which leads to a weak thermal inversion and exhibits less contrast in dayside-nightside temperature. More irradiated planets such as HD 149026b, and HD 209458b are pM-class planets, while the less irradiated hot Jupiter such as HD 189733b is a pL-class planet1 [1]. Since the level of irradiation is one of the most important factors in considering the atmospheric properties of these planets, it is crucial to determine the classes of a hot Jupiter when studying it. Geometric albedo and redistribution fraction are two parameters that could help us make the model of a planet and find its best-fitted class. However, the class of Kepler-12 b remains uncertain since more calculations and graphing should be conducted to draw a valid conclusion.

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