DETERMINING THE WEATHER ON AN EXTRASOLAR PLANET

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Abstract

Transit photometry data from the Kepler Space Telescope was used to construct light curves for exoplanets Kepler-7b and HAT-P-7b in order to determine the bond albedo and effective temperature of each planet. Other values calculated include exoplanet radius, orbital radius, geometric albedo, phase integral and luminosity of the host star. The light curve constructed of Kepler-7b had too much noise, so the remainder of the experiment used only HAT-P-7b. The albedo was found to be 0.003124 ± 0.00074, which was consistent with values found in other publications. The effective temperature was found to be $2149.22 \pm 128.77K$, which was similar to published values but not an exact match. Ultimately it was concluded that not enough information on the weather and cloud cover could be found from just the albedo, however the high temperatures on the planet would most likely rule out HAT-P-7b as a habitable planet regardless. It was also found the that the orbital inclination was very high, $83.5 \pm 7.93 degrees$, meaning the transit method used may not be the most accurate method in the case of HAT-P-7b, and another exoplanet may have been more suitable if one with a deeper secondary transit could have been found.

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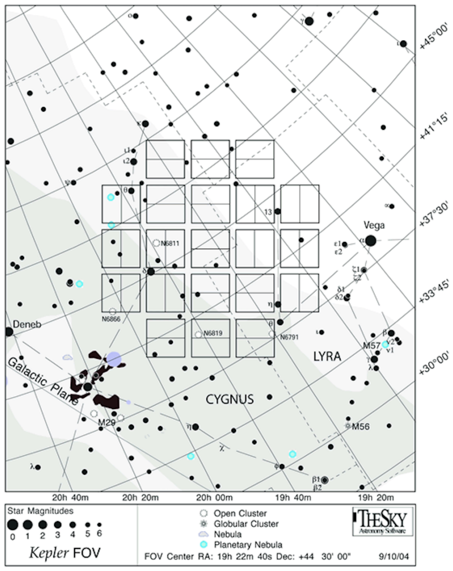

Figure 1: Kepler Field of View of 116 square degrees, for the K1 Kepler Mission[7].

1 Introduction

Extrasolar planets, or exoplanets, have long been a topic of discussion among astrophysicists. An exoplanet is a planet orbiting a star outside of our own solar system. The first confirmed exoplanet detection was in 1992[15]. As of the 18th March 2019, there have been 4,011 confirmed exoplanet discoveries from all observatories[12]. The Kepler Space Telescope (Kepler) is responsible for over half of these with the current number of confirmed exoplanets detected by Kepler being 2,338[10]. The aim was not necessarily to find detailed information about individual exoplanets, but rather to gather information on as may exoplanets as possible in order to gain greater knowledge of planets outside our solar system as a whole. The telescope was operational for almost 10 years, from 2009 to 2018, and used the transit photometry method to detect exoplanets by measuring the intensity of light from stars[8]. In this report, Kepler data will be used to investigate the secondary transits of exoplanets in order to calculate the albedo of the planet. The albedo, representing the reflective-ness of the planet, could offer insights into the weather on the planet such as cloud cover, as a planet with high cloud cover will be more reflective. The more information gathered about exoplanets, such as weather and atmospheric conditions, the more prepared future generations can be if they are ever to travel to planets outside of the Solar System.

2 Background Theory

The Kepler Space Telescope used a photometer comprising of 21 CCD modules in order to measure the intensity of light incident on the telescope from its field of view[7]. As can be seen in Figure 1, Kepler had a fixed field of view which covered the area of sky around the Cygnus and Lyra constellations. By measuring the intensity of light coming from this region, light curves could be created for individual stars in the region. A light curve shows the intensity of light from a star with respect to time, and when a planet crosses between the star and the observer, a dip intensity is seen on the graph. This dip is known as a primary transit, and occurs due to the planet partially blocking the light incident on the telescope. The primary transit is visible on the light curve shown in Figure 2, at 0 orbital phase.

However there is also a second dip in intensity observed, the secondary transit. The secondary

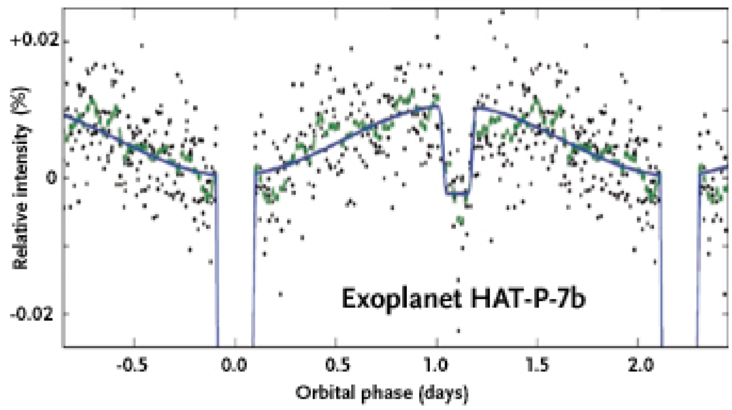

Figure 2: Light curve for Kepler-HAT-P-7b from test data taken over 10 days, plotted to show full depth of transit. Blue line represents a simple fit. Both primary and secondary transits visible[2].

transit occurs midway through the period, half a phase after the primary transit when the star is directly between the exoplanet and the observer. This is visible on the light curve as a dip in intensity, as shown in Figure 2, due to the albedo of the exoplanet. An exoplanet that is reflective will reflect light from the star towards the observer. This means that light from the back of the star that would not normally reach the telescope will be observed. The amount of extra light reflected by the exoplanet depends on the phase of the planet. When the exoplanet is on the near side of its orbit around the star, it does not reflect any light towards the observer. When the exoplanet is on the far side of its orbit around the star, it reflects light from the far side of the star. This variation in reflected light means the total intensity measured by the telescope oscillates with phase, shown as a sinusoidal relation on the light curve. The reflection means the measured intensity of the star is higher than the actual intensity. When the exoplanet transits behind the star, there is no reflection, and a dip in intensity is visible. The intensity value of the dip is the true intensity of the star without any contribution from reflection. A plethora of information can be calculated from just the light curve alongside a small number of values taken from literature, such as exoplanet radius, orbital radius, albedo of the planet, and effective temperature of the planet. There are two types of albedo; geometric and bond. Both albedos are effectively a ratio of the light reflected off a surface to the light incident on that surface. The geometric albedo can be calculated most simply, using information on the star that can be taken from literature alongside radius of the exoplanet and orbital radius. Geometric albedo represents the ratio of the real measured brightness of the planet, to the brightness of the exoplanet if it were a idealised disk at zero phase angle. The bond albedo takes into account the fact that the exoplanet is spherical, and reflects light from different areas and sizes of area on the surface depending on the phase angle. Calculating the bond albedo is more difficult and requires the calculation of a phase integral, as explained in Methodology.

As well as calculating the average albedo for an exoplanet, it may also be possible to calculate the albedo for smaller time increments across the measurement period. This could allow us to see how albedo changes over time, which could suggest weather patterns such as cloud movements, giving yet more information on the weather conditions of the planet.

3 Methodology

Before any calculations can be made, the raw data must first be processed. To do this, the Python Package LightKurve[1] was used. The code automatically pulls the data from the Mikulski Archive for Space Telescopes (MAST)[14], which provides Flexible Image Transport System (FITS) files for each Kepler observation made. Within the list of FITS files in the archive, there are two types of cadence used for the observations; Long Cadence (LC), and Short Cadence (SC). The data used by LightKurve is LC only, which used an observation period of around half an hour, rather than the SC data which used an observation period of around a minute. This is because the longer observation period results in a higher signal-to-noise ratio.

The data available to LightKurve is from the prime Kepler mission, that is the period of operation before part of the telescope was damaged, requiring the field of view to be altered. The data is split into 15 quarters of observations. In order to reduce the noise and plot a more accurate light curve, the data from each LC quarter was combined by importing the data using LightKurve, and then appending the data to include all quarters before using LightKurve to plot it. The LightKurve module de-trends and normalises the data, as during different quarters, the intensity of light is offset from the true value due to other factors such as temperature of the telescope.

Once the intensity had been normalised, the LightKurve module was used to plot a periodogram of the data set. Periodograms are often used for uneven data sets such as telescope observations, for example Kepler which has data missing at certain times, for example due to breaks in observation due to the telescope communicating with stations on Earth. By plotting a periodogram, the dominant period throughout the data can be identified. The periodogram uses a similar process to a Fourier Transform, and identifies possible frequencies of the series. The resulting graph portrays the importance of each frequency in the data using a scale of Power Spectral Density, whereby a higher value represents a more important frequency. The period is found by taking the inverse of the frequency where the Power Spectral Density is at maximum value. Having calculated the period and fed it back into the LightKurve module, the data can be phase folded to produce a graph of normalised intensity against phase angle. This graph is the light curve, on which the primary and secondary transits can be seen, and their depths measured.

Due to the nature of the code and the use of the LightKurve module, the period of orbit is calculated without an error, as the module uses a periodogram to calculate the period. These can be used alongside characteristics of the host star taken from literature to calculate exoplanet radius, orbital radius, geometric albedo, bond albedo, luminosity of the star, and blackbody temperature of the exoplanet. The calculations used in the experiment are laid out below.

3.1 Exoplanet Radius

The radius of the exoplanet can be calculated using the relation

$$\Delta F = \left(\frac{R_P}{R_*}\right)^2, \tag{1}$$

where ΔF is the normalised primary transit depth, as measured from the normalised light curve, R_P is the radius of the exoplanet, and R_* is the radius of the star. In this experiment, $\Delta F = 1 - f_1$ where f_1 is the value of normalised flux at the time of primary transit. By rearranging, the radius of the exoplanet can be calculated. The value for radius of the star will be taken from literature, although if there were a need for not using data from other sources the stellar radius could be calculated from luminosity observations of the star. It is worth noting that Equation 1 assumes the star is a disk of uniform brightness, meaning it does not take into account limb darkening, which could potentially affect the results. The error on the exoplanet radius is calculated using Equation 2.

$$\delta R_P = R_P \sqrt{\left(\frac{\delta R_*}{R_*}\right)^2 + \left(\frac{1}{2}\frac{\delta(\Delta F)}{\Delta F}\right)^2} \tag{2}$$

The exoplanet radius along with its error can be checked against prior calculations from literature to ensure the method is accurate, and will be used in later albedo calculations.

3.2 Orbital Radius

The orbital radius, a, of the exoplanet is required for albedo calculations, and can be found by rearranging Kepler's Third Law. Therefore orbital radius can be expressed as

$$a = \sqrt[3]{\frac{GM_*T^2}{4\pi^2}}, \tag{3}$$

where G is the gravitational constant, M_* is the mass of the star, and T is the period of orbit. Values that cannot be calculated from the light curve will be taken from literature. The uncertainty on the orbital radius will be found using Equation 4.

$$\delta a = a\sqrt{\left(\frac{1}{3}\frac{\delta M_*}{M_*}\right)^2 + \left(\frac{2}{3}\frac{\delta T}{T}\right)^2 + \left(\frac{1}{3}\frac{\delta G}{G}\right)^2} \tag{4}$$

3.3 Geometric Albedo

In order to calculate the bond albedo of the exoplanet, the geometric albedo must first be calculated. The geometric albedo, A_g is given by Equation 5[13].

$$\frac{F_P}{F_*} = A_g\left(\frac{R_P}{a}\right)^2, \tag{5}$$

where F_P is the flux measured from the exoplanet, F_* is the flux measured from the star, R_P is the radius of the exoplanet, and a is the orbital radius. In the case of this experiment, the light curve has been normalised, meaning the ratio $\frac{F_P}{F_*}$ is equal to simply the flux value measured at the point of secondary transit; f_2. Once Equation 5 is rearranged for geometric albedo, the uncertainty on geometric albedo can be found to be

$$\delta A_g = A_g\sqrt{\left(\frac{\delta f_2}{f_2}\right)^2 + \left(2\frac{\delta a}{a}\right)^2 + \left(2\frac{\delta R_P}{R_P}\right)^2}. \tag{6}$$

3.4 Phase Integral and Bond Albedo

The geometric albedo, once calculated, can be used to calculate the bond albedo using the expression

$$A_b = pA_g, \tag{7}$$

where A_b is the bond albedo, p is the phase integral, and A_g is the geometric albedo. The phase integral, p is defined as

$$p = 2\int_0^{\pi} \frac{I(\alpha)}{I(0)}\sin(\alpha)d\alpha, \tag{8}$$

where $I(\alpha)$ is the intensity of the light at a phase angle of α, and $I(0)$ is the intensity of light at a phase angle of zero, being when the star is between the exoplanet and the observer meaning there is no reflection detected at the observer. When calculating the phase integral, it was found that the simplest way to calculate this using the code was to approximate the phase integral as

$$p \approx \sum_{\alpha=0}^{\pi} I(\alpha)sin(\alpha). \tag{9}$$

To calculate this, the time between primary and secondary transit was converted to angles from 0 to π radians. At small increments between these 2 points, the intensity is calculated for each angle. The sine function of each angle is taken, and the phase angle is therefore approximated as the sum of the products of the intensity and sine function at each angle. The error on the phase integral can be calculated using Equation 10.

$$\delta p = \sqrt{\sum_{\alpha=0}^{\pi} \delta I(\alpha)^2} \tag{10}$$

The resulting phase angle can then be used to calculate the bond albedo. This can be checked against values in literature to ensure the value is correct.

3.5 Luminosity of Star

The bond albedo is the primary characteristic that will be used to estimate the weather conditions on the planet, however there are in fact other characteristics that can be calculated to find more about the planet's weather. One such characteristic is the blackbody temperature of the exoplanet, which can be calculated from bond albedo, luminosity of the star, and orbital radius of the star. The luminosity, L of the star is given by

$$L = \Big(\frac{D_*}{D_v} L_v\Big) 10^{-\frac{M}{2.5}}, \tag{11}$$

where D_* is the distance to the star, D_v is the distance to star Vega, L_v is the luminosity of Vega, and M is the apparent magnitude of the star.

The error on the luminosity is given by Equation 12.

$$\delta L = L\sqrt{\left(\frac{\delta D_*}{D_*}\right)^2 + \left(\frac{\delta D_v}{D_v}\right)^2 + \left(\frac{\delta L_v}{L_v}\right)^2 + \left(\frac{\delta M}{M}\right)^2} \tag{12}$$

Unfortunately, the data being used for this experiment does not have the information required to calculate all these parameters, so all of these must be taken from literature.

Despite none of the parameters for this equation being calculated from this experiment, it was felt it can still be included as it provides supplementary information that will be relevant and necessary to make a fair conclusion about an exoplanet, and it is required for the next calculation which uses data from this experiment.

3.6 Temperature of the Exoplanet

The blackbody temperature, or the effective temperature, is the temperature of the exoplanet taking into account just the host star as it's sole source of heat. It does not include other factors such as greenhouse gases in the planet's own atmosphere. Therefore, as it is only an approximation of exoplanet temperature it is straight forward to calculate. The effective temperature, T_{eff}, is given by

$$T_{eff} = \left(\frac{L(1-A_b)}{4\pi\sigma a^2}\right)^{\frac{1}{4}}, \tag{13}$$

where L is the luminosity of the star, A_b is the bond albedo of the exoplanet, σ is the Stefan-Boltzmann constant, and a is the orbital radius of the exoplanet. The error on the effective temperature is given by Equation 14.

$$\delta T_{eff} = T_eff\sqrt{\left(\frac{1}{4}\frac{\delta L}{L}\right)^2 + \left(\frac{1}{4}\frac{\delta A_b}{A_b}\right)^2 + \left(\frac{1}{4}\frac{\delta \sigma}{\sigma}\right)^2 + \left(\frac{2}{4}\frac{\delta a}{a}\right)^2}. \tag{14}$$

It is important to note that this assumes a lack of greenhouse gases in the atmosphere. If future generations intend to use the results of experiments such as this to find a planet to inhabit,

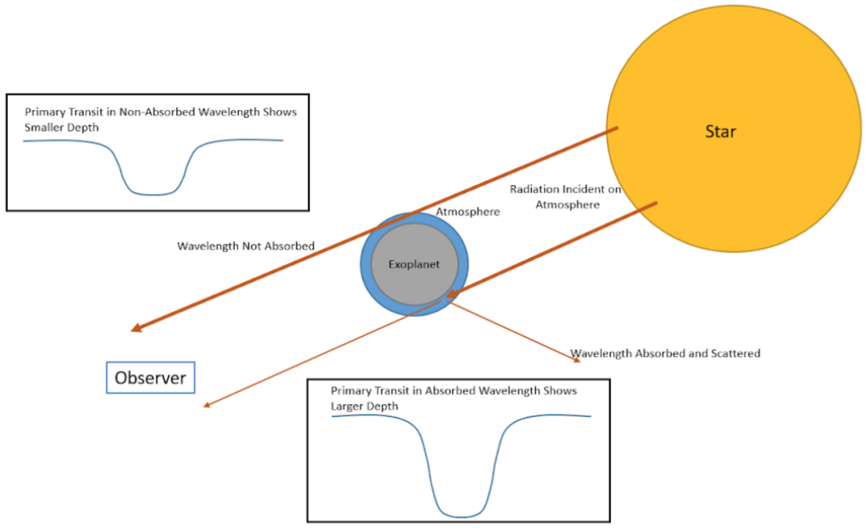

Figure 3: Diagram portraying the difference in primary transit depth for different wavelengths of infra-red radiation due to atmospheric absorption.

effective temperature alone would not be enough information, as the surface temperature they would have to survive in could be vastly different due to the greenhouse effect and other factors. However, there is other data that could be utilised to more accurately predict the temperature of an exoplanet; data from the Spitzer Space Telescope (SST).

SST is a space telescope that was launched in 2003 and is still operating in 2019, which measures the intensity of infra-red radiation at specific wavelengths[9]. This means that with SST data it is possible to produce light curves of the exoplanet for a range of wavelengths of infra-red radiation. Depending on the atmospheric composition of the exoplanet, the depth of the primary transit will be different for each light curve due to absorption in the atmosphere, as shown in Figure 3. The primary transit occurs when the exoplanet is directly between the observer and the star, meaning some of the light from the star passes through the exoplanet's atmosphere before reaching the observer. Wavelengths of light from the star that are absorbed by the atmosphere will be scattered at different angles, meaning less light of that wavelength will reach the observer, so the depth of the primary transit will be larger. Light that is not absorbed will pass through as normal, and a higher intensity of that wavelength of light will reach the observer. This will correspond to a smaller primary transit depth. By analysing SSC light curves, it can be determined which wavelengths of light are being absorbed by the atmosphere. By comparing these with absorption spectra of greenhouse gases, it can be determined which greenhouse gases are likely to be found in the atmosphere. This could be useful for potential extrasolar settlers, as if an exoplanet had an ideal effective temperature, but a high proportion of greenhouse gases in its atmosphere, this could suggest that the surface temperature of the planet would be higher than first thought, and that the planet may not be as suitable as the effective temperature suggested.

3.7 Orbital Inclination

The calculations being made in this experiment all rely on the transit method, however the transit method only works well if the planet crosses the star directly across the middle with respect to the observer, however the line of sight of the observer is not always in the orbital plane of the exoplanet. If the planet only transits across the star at the edge, then less light will be blocked during the transit, and the primary transit depth will be lower. This is due to limb darkening, where the outer edges of the star are less bright then the center. By calculating the orbital inclination; the angle between the orbital plane and the line of sight of the observer; it can be determined whether or not the transit method can be reliably used. The angle of orbital inclination is given by the equation

$$b = \frac{acos(i)}{R_*}, \tag{15}$$

where b is the impact parameter, a is the orbital radius, i is the angle of inclination, and R_* is the radius of the star. In order to calculate angle of inclination, the impact parameter must first be calculated. The impact parameter describes the perceived distance between the centre of the star and the centre of the planet during transit. The impact parameter can be calculated from known values about the star from literature and characteristics of the planet calculated using the light curve. The impact parameter can be calculated using the expression

$$\tau = \frac{T}{\pi} sin^{-1}(\frac{\sqrt{(R_* + R_P)^2 - (bR_*)^2}}{a}, \tag{16}$$

where τ is the time for the exoplanet to transit the star, T is the orbital period, R_* and R_P are the radii of the star and exoplanet, b is the impact parameter, and a is the orbital radius. Using these two equations, the angle of inclination can be found and used as a guide to whether the planet transits centrally enough across the star to use the transit method.

3.8 Modelling A Light Curve

Using the methods presented here, the albedo and temperature of exoplanets can be found using data from the Kepler Space Telescope, and a selection of values taken from literature. When beginning the experiment and writing the first section of code, the exoplanet chosen was Kepler-7b. This was because its original detection was made using the transit method, suggesting that the secondary transit would be large enough to be visible in the data. However when plotting the light curve of Kepler-7b, it was found that the secondary transit was not prominent enough for its depth to be measured, so the calculations necessary could not be done. It was therefore decided to switch to HAT-P-7b, an exoplanet orbiting star HAT-P-7, which had a very low albedo, corresponding to high reflective-ness, and was featured in a study by W.J. Borucki[2]. HAT-P-7b's light curve showed a much more prominent secondary dip, meaning the depth could be measured and used in calculations, the results of which can be found in Results.

When plotting more light curves for other potential experiment subjects, no more were found with measurable secondary transits, meaning it was difficult to investigate further planets. Instead of plotting further light curves that would not yield results, code was constructed to model an expected light curve based on already known parameters of the exoplanet. The code was constructed to model a normalised light curve in separate parts, modelling the primary and secondary transits separately. As the light curve would be normalised, the regions in between the 2 transits would just be zero. The primary transit model used 4 parameters; planetary radius, radius of the star, average intensity of the star, and inclination angle. The model for the secondary transit used these parameters alongside intensity of reflected light from the planet, and the albedo. When modelling the secondary transit The model was not able to work as hoped to produce light curves for planets with too small to measure secondary transits due to the fact that it requires the light reflected from the planet and the albedo, which must be calculated from the secondary transit depth. However, the model can be used to produce a more accurate light curve fit, and can be useful if the secondary transit of an exoplanet is too small to be accurately measured, but visible enough to be approximated. The curve fitting code then uses the estimates for the parameters along with the intensity of the star to produce an expected light curve model.

4 Results

The following figures show the plots constructed for HAT-P-7b, that were produced using the methods outlined in Methodology. As aforementioned, the raw data collected by the KST is not consistent across quarters, and the intensity in each quarters is offset by varying amounts, shown in Figure 4.

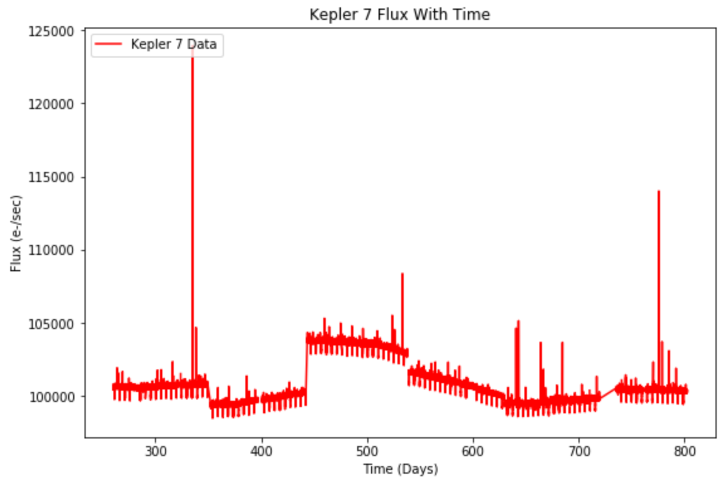

Figure 4: Raw data for HAT-P-7b from the Kepler Space Telescope, before normalisation.

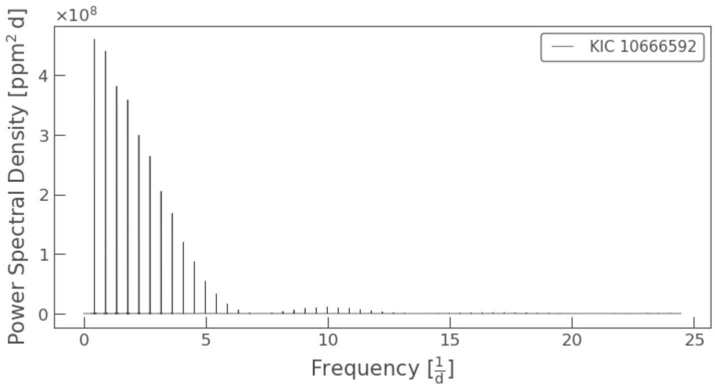

Figure 5: Periodogram of HAT-P-7b, produced using the LightKurve module. The x-axis represents the frequency of sequences in the data from which period is calculated.

The periodogram for this data is shown in Figure 5.From Figure 5, it was possible to calculate the period of the orbit for HAT-P-7b. The resulting light curve constructed by the LightKurve module is shown in Figure 6. Table 1 shows the data that was calculated directly from the light curve. In the Methodology it was noted that certain values would be taken from literature as they could not be calculated from the light curve. Values taken from literature are shown in Table 2. Using the values in Tables 1 and 2, the calculations outlined in the Methodology could be performed. The results are shown in Table 3. Unfortunately, the Spitzer data aspect of the experiment outlined in the Methodology could not be done due to problems with coding the Spitzer data, meaning the true surface temperature of the planet could not be estimated.

The final part of the investigation into HAT-P-7b involved trying to model a light curve. The results of this are shown in Figures 8 and 9.

Table 1: Data Extracted Directly from HAT-P-7b Light Curve

Data	Calculated Value
Orbital Period	2.2047096 days
Normalised Primary Transit Depth	0.99325 $\pm(3 \times 10^{-5})$
Normalised Secondary Transit Depth	$(4.9 \pm 1.04 \times 10^{-5})$

Table 2: Values Taken From Literature

Parameter	Value
Solar Radius, $R_\odot$	$6.957 \times 10^8 \pm 1.4 \times 10^5 m$[4]
Solar Mass, $M_\odot$	$1.9884 \times 10^30 \pm 2 \times 10^{26} kg$[5]
HAT-P-7 Radius, R_*	$(1.84 \pm 0.23) R_\odot$ [3]
HAT-P-7 Mass, M_*	$(1.47 \pm 0.8) M_\odot$ [3]
Gravitational Constant, G	$(6.674 \pm 0.00031) \times 10^{-11} m^3 kg^{-1} s^{-2}$[11]
Distance to HAT-P-7, D_*	1,100 ly [3]
Distance to Vega, D_v	25.04 ± 0.07 ly [3]
Luminosity of Vega, L_v	$(1.547 \pm 0.017) \times 10^{28}$[3]
HAT-P-7 Apparent Magnitude, M	10.48 ± 0.05 [3]
Stefan Boltzmann Constant, σ	$(5.670 \pm 0.000013) \times 10^{-8} W m^{-2} K^{-4}$[11]

Table 3: HAT-P-7b Results

Parameter	Result
Radius, R_P	$(11.29 \pm 0.062) \times 10^7 m$
Orbital Radius, a	$(5.631 \pm 0.00137) \times 10^9 m$
Geometric Albedo, A_g	0.0149 ± 0.0069
Bond Albedo, A_b	0.003124 ± 0.00074
HAT-P-7 Luminosity, L	$(1.9402 \pm 0.699) \times 10^{26} W$
Effective Temperature, T_{eff}	$2149.22 \pm 128.77 K$
Orbital Inclination, i	83.5 ± 7.93 *degrees*

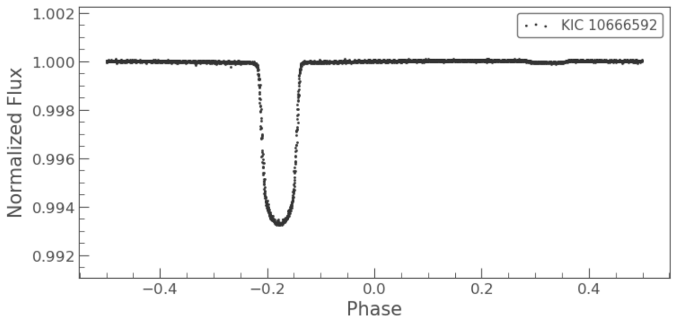

Figure 6: Light curve for HAT-P-7b, with both primary and secondary transits visible.

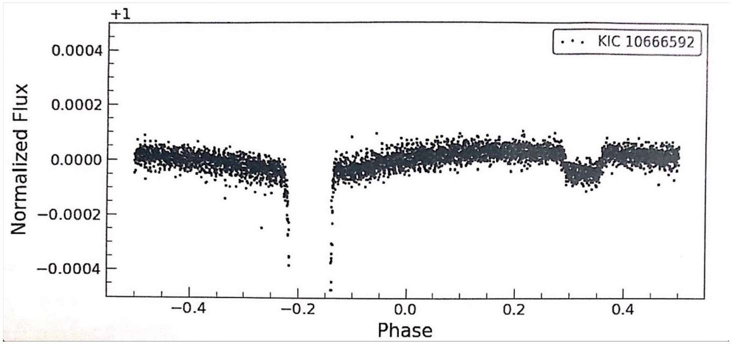

Figure 7: Light curve for HAT-P-7b, zoomed in on the y-axis to show the Secondary Transit more clearly.

5 Discussion of Results

Due to the time it took to complete the investigations laid out in this report, results were found for only one exoplanet; HAT-P-7b. This means the findings cannot be compared with other exoplanets. However, the values calculated in this experiment have already been found and published in literature, meaning it is possible to check the accuracy of the findings.

The values published in literature corresponding to the values calculated in this investigation can be found in Table 4. All values in Table 4 are taken from The Extrasolar Planets Encyclopaedia [12], unless otherwise stated. One of the first values calculated in this experiment was orbital period, calculated using a periodogram. Despite having to manually read off the most commonly occurring frequency of patterns in the data and using that value to find the corresponding period, the value is very accurate, with the calculated value matching the accepted value to 4 significant figures. Radius of the planet is slightly less accurate, and even with taking the most lenient error bounds, the value does not fit within the error bounds of the accepted value. However is only a difference of $0.09 \times 10^7 m$, which is a small error relative to the radius.

Table 4: HAT-P-7b Values From Literature

Parameter	Result
Period, T	$2.204 \pm (2.4 \times 10^{-6}) days$
Radius, R_P	$(9.744 \pm 1.394) \times 10^7 m$
Orbital Radius, a	$(5.7042 \pm 0.053) \times 10^9 m$
Bond Albedo, A_b	A_b<0.03 [6]
Effective Temperature, T_{eff}	2120
Orbital Inclination, i	84.1 ± 2 *degrees*

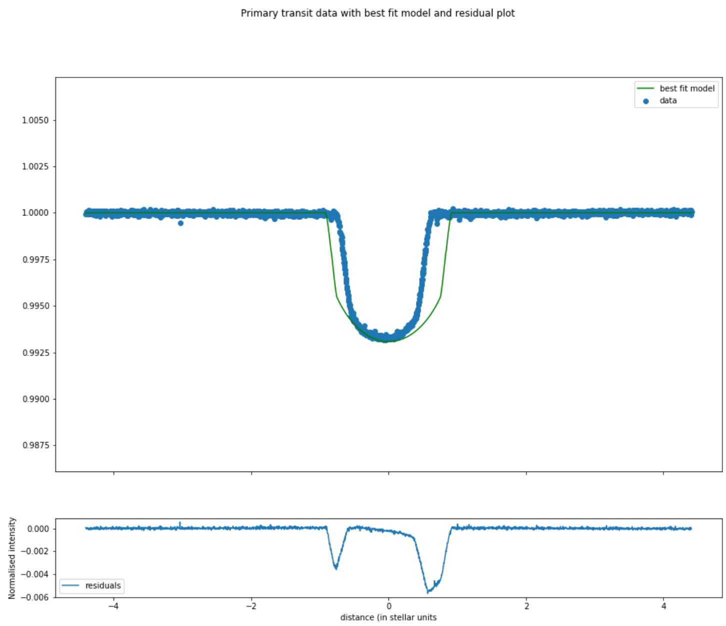

Figure 8: Model primary transit, plotted together with HAT-P-7b actual primary transit with residuals.

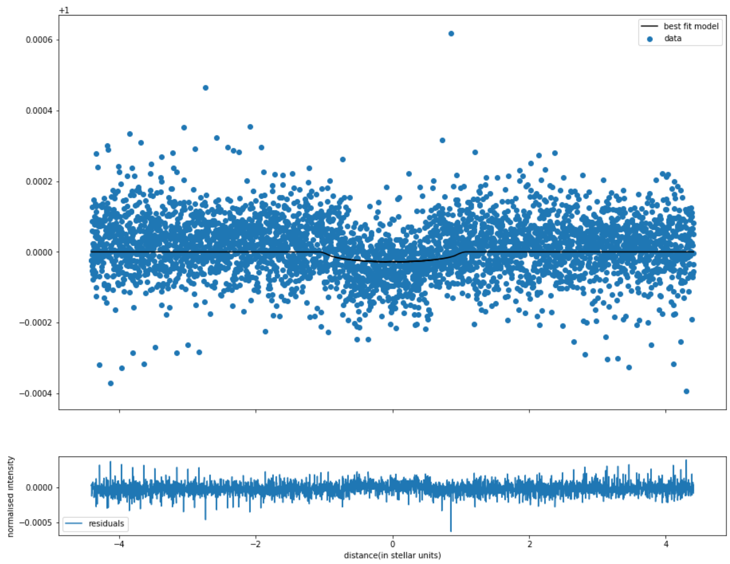

Figure 9: Model secondary transit, plotted together with HAT-P-7b actual secondary transit with residuals.

The same can be said for orbital radius, with the calculated and accepted values not matching even with the most lenient error bounds, but still being very close. The only published values for bond albedo found in literature state that the bond albedo should be less than 0.03, and with the value calculated in this report being 0.003, this criteria has been easily met. The effective temperature of the planet found in literature did not give an error, however the value is still well within the error bounds for the calculated value, meaning the value found in this investigation was accurate. Finally, the orbital inclination was calculated to match up with the value found in literature as well. The angle of inclination was found to be $83.5 \pm 7.93 degrees$, which is incredibly high at almost 90 degrees. This means that the exoplanet was not transiting directly across the centre of the planet, making the transit method less accurate than it ideally would be. This could have had an affect on the depth of mainly the primary transit, however could also have affected the secondary transit depth. Unfortunately it is difficult to estimate how much of an affect the angle of inclination would have had. Ideally, an exoplanet would be investigated with a angle of inclination as close to zero as possible, in order to minimise the affects of limb darkening. If this experiment were to be improved or lengthened, the main task would be to find a planet with minimal orbital inclination as well as a measurable secondary transit, however due to time constraints, HAT-P-7b was the best option.

The models fitted for the primary and secondary transits did well in resembling rough transits, however the secondary transit model was far less accurate, simply due to the noise on the data. Furthermore, modelling the data in this way is only of use if a value can already be estimated for transit depth, so is only of use when there is at least a partially visible secondary transit. This means for exoplanets without visible secondary transits on the light curve, the albedo could most likely not be calculated even with use of the model.

Overall, the results found in this report are accurate when compared with accepted results that have been published. There are a few inaccuracies such as radius and orbital radius. The error could likely be due to the fact that they were the first calculations made, and relied most heavily on the transit depths and period which were taken directly from the light curve. This means that small discrepancies in reading off the light curve would have a bigger impact on radius and orbital radius that it would on other calculations where the biggest contributing values were from other sources. Unfortunately due to the nature of the measurement and having used Kepler Space Telescope data, we are limited with how accurate the readings from the light curve can be. An improvement that could be made in future experiments could be to spend more time reducing the noise in the data, in order to have more accurate values to begin calculations with.

6 Conclusion

The aim of this experiment was to construct light curves of exoplanets and use them to determine more about the weather conditions, specifically the albedo, on the planet. Although only one exoplanet was investigated due to time constraints and difficulty finding data with deep enough secondary transits, a large number of values were calculated for HAT-P-7b. The first value of note calculated was the bond albedo, of 0.003124 ± 0.00074. This value corresponds to high amounts of reflection, as bond albedo values lie between 0 and 1, with 0 corresponding to full reflection of all incident light. The low albedo could have a number of connotations. For example, it could mean there is high cloud cover on the planet, which could mean large storms or even just still cloud. To find out if one of these is the case it would have been useful to plot a graph of changing albedo with time to look for cloud patterns. Unfortunately attempts to do this did not yield any results. A low albedo could also mean an icy surface, or snow, however the high effective temperature of $2149.22 \pm 128.77 K$ makes this unlikely. It could also be due to the surface of the planet itself that is causes the high reflection, for example if the planet was made out a metallic substance, which could be investigated in further investigations. Unfortunately the exact cause of the low albedo cannot be determined so easily, meaning much more research would have to be done in order to learn anything about the cloud cover. Regardless of the weather and the cloud cover, the effective temperature shows that the climate would not be suitable for humans to live in anyway. This rules out the possibility for HAT-P-7b to be a potentially habitable world, unless further advancements are made in the area of materials and designing a habitation environment that could withstand such high temperatures. For now, there is not much more information that can be found about exoplanets such as HAT-P-7b, until further advancements are made in observation and understanding of exoplanets. However, until then, small outcomes such as these still give a lot of information. Even if the information about individual exoplanets is not currently useful, data on all known exoplanets can be combined to learn more about our galaxy as a whole, and how common certain types of planets are. If needed, this experiment could be extended to research more planets, and contribute to the project of finding more about the distribution and characteristic about planets in our galaxy.

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