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DEPARTMENT OF PHYSICS

EXOPLANETS AROUND BRIGHT STARS IN A FARAWAY ORBIT-USING TESS FOLLOW UP OBSERVATIONS

PROJECT REPORT

Submitted by,

Devika K R 210011023196

Under the guidance of

Dr. Manesh Michael
Assistant Professor, Department of Physics,
Bharata Mata College, Thrikkakara
Visiting Associate, IUCAA, Pune

Suman Saha
Post Doctoral Researcher,
Indian Institute of Astrophysics,
Bangalore

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CERTIFICATE

This is to certify that the project entitled ”EXOPLANETS AROUND BRIGHT STARS IN A FARAWAY ORBIT-USING TESS FOLLOW UP OBSERVATIONS” is a record of original work by DEVIKA K R (210011023196) who is a bonafied student of Bharata Mata College, Thrikkakara in partial fulfilment of the requirements for the award of the degree of Master of Science in Space Science of the Mahatma Gandhi University, Kottayam during the academic year 2021-2023. It is certified that all corrections marked for internal assessment have been included in the report deposited in the departmental library. The project report has been approved as it complies with the academic requirements in respect of project work approved by the institution for the said degree.

Signature of Internal Guide
Dr. Manesh Michael

Signature of External Guide
Suman Saha

Signature of HoD
Dr. Shibi Thomas

Signature of Principal
Dr.Johnson K M

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DECLARATION

I, Devika K R (210011023196), student of fourth semester MSc Space Science, Department of Physics, Bharata Mata College, Thrikkakara, hereby affirm that the project work titled "EXOPLANETS AROUND BRIGHT STARS IN A FARAWAY ORBIT-USING TESS FOLLOW UP OBSERVATIONS" has been carried out by me and submitted in partial fulfilment of fourth semester requirements in Master of Science at Mahatma Gandhi University, Kottayam Gandhi University, academic year 2021-2023.

I further declare that the context of this dissertation has not been formed the part of any other project work submitted for award of any degree or diploma to any other university.

I also declare that any intellectual property rights arising out of this project completed at IIA will be the property of Bharata Mata College, Thrikkakara, and I will be one of the authors of the same.

Place: Thrikkakara
Date:

Name Signature

Devika K R(210011023196)

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ABSTRACT

The habitable zone exoplanets are among the most fascinating of all exoplanet populations since they give us the opportunity to study the existence of life outside our solar system. A large number of exoplanets of various sizes have been discovered to date that fall in the habitable zones of their host stars. The larger exoplanets in the habitable zones might have potential rocky exomoons around them, while the smaller terrestrial exoplanets in the habitable zones of their host stars give a direct opportunity to study for their habitability, which also gives an equally interesting opportunity to study their habitability.

Gas giant exoplanets are not habitable as they do not have any surface, but their exomoons might be habitable since they are in a faraway orbit. This project aims at studying the gas giant exoplanets around bright stars in a faraway orbit through transit follow-up observations by the Transiting Exoplanet Survey Satellite (TESS). This study aims at studying the habitable zone exoplanets around the bright stars in the solar neighbourhood through transit photometric follow-up observations by the Transiting Exoplanet Survey Satellite (TESS). TESS is a space-based survey telescope to discover new exoplanets around the bright stars in the solar neighbourhood. Since it will cover a large portion of the sky ($\sim$75% of the sky) during this survey, the TESS is also an excellent instrument to conduct transit photometric follow-up studies of a large number of both existing and newly discovered exoplanets. Being a space-based instrument, the TESS observations are not affected by perturbations in the Earth's atmosphere. This allows us to obtain photometric observations with a very high signal-to-noise ratio (SNR) from TESS, especially for the bright stars. All the data files were accessed through the NASA Caltech and MAST portals. From the data obtained, light curves are formulated, and these light curves would then be modelled using the Markov-chain Monte-Carlo (MCMC) sampling technique to precisely estimate the physical properties of the target exoplanets. The estimated physical properties from this study are expected to be both more accurate and more precise compared to the previous studies and would shade more light on the dynamical properties of these exoplanets.

Contents

1 Introduction

1.1 Exoplanets

An exoplanet, or extrasolar planet, is a planetary body outside the solar system. The discovery of exoplanets posed a significant challenge due to the fact that the planets orbit stars that are several times brighter than the planets themselves. In 1995, the first exoplanet, 51 Pegasi b, which orbits a main sequence star, was discovered by Michel Mayor and Didier Queloz (Mayor and Queloz, 1995). Their discovery earned them the Nobel Prize in 2019. 51 Pegasi b is a gas giant with a mass similar to that of Jupiter, and it orbits the star in a very close in orbit.

The desire to categorize planets has grown as the frequency of exoplanet discoveries has increased. Exoplanets come in a varying range of masses, sizes, and compositions. Exoplanets can be categorized in a number of ways based on these.

- Hot Jupiters

  Hot Jupiters are gas giants that resemble Jupiter and Saturn, that orbit the host star with typical periods of only a few days. These planets are found around 1% of the sun-like stars and are under strong stellar irradiation. Gas giants are essentially composed of hydrogen and helium with minor additions from complicated molecules and heavier elements (Fortney et al., 2021)

- Super earth exoplanets

  Super Earths exoplanets (Haghighipour, 2013) are the planets slightly larger than Earth and smaller than mini-Neptunes. They are necessarily terrestrial exoplanets, means they have a solid surface. Super Earth had the capability to produce a magnetic field several times stronger than the geomagnetic field, and the magnetic field is an essential key for habitability.(Boujibar et al., 2020).

- Mini Neptunes

  The most prevalent type of exoplanet that has no solar system counterpart is called a mini-Neptune. Mini-Neptunes are planets that are smaller than Neptune in both mass and radius. These are intermediate objects with properties between rocky planets and ice giants. Mini-Neptunes are an optimal target for the study of habitable exoplanets (Piette and Madhusudhan, 2020)

The study of exoplanets also focuses on determining whether those worlds are habitable or not. The habitable zone refers to the region surrounding a star, where a planet's surface temperature can support the existence of liquid water.(Kite and Ford, 2018)

1.2 Discovery methods

Exoplanet discovery helps in advancing humanity's knowledge and comprehension of the universe. It makes it possible to learn more about planetary systems and how they were formed. The angular separation between the star and the orbiting planet is small, so direct detection is difficult (Jones, 2008).Therefore, several indirect methods are also developed: Radial velocity method, Transit method, Gravitational microlensing and Astrometry.

1.2.1 Radial velocity

The basic principle behind the radial velocity method is that an orbiting planet brings about a gravitational pull on the host star(Faria et al., 2018). It is observed as a periodic variation in the velocity of the star along the line of sight. Since the star has more mass than the planet, the centre of mass will be close to the star or within the star itself, and the star appears to wobble slightly as the planet revolves around it. By analysing the spectra of the star, the scientists can measure the radial velocity using the Doppler effect. According to Doppler effect, an object seems to be blue-shifted because its radiation frequency rises as it gets closer to the observer. Additionally, if it is moving away from the observer, it undergoes a redshift. If the shifts are regular, repeating themselves at fixed intervals of time, then there might be a body orbiting the star.

Radial velocity method has the ability to detect and measure the mass of potential Earth twins. Due to its ability to discover planets with far larger ranges of orbital periods than other detection approaches, the radial velocity method is essential to comprehending the planetary system demography. Additionally, since it is not necessary for the orbital plane to be oriented precisely, it can characterize planetary systems in which the planets have large mutual inclinations (Hara and Ford, 2023)

1.2.2 Transit method

Since the discovery of the first transiting exoplanet, HD 209458b, the transit method has been the most effective detection method (Deeg and Alonso, 2018). When the planet's orbit is nearly edge-on, it can be detected using the transit method. The method is similar to a solar eclipse, where the Moon blocks the sun's light. When the planet passes between the host star and the observer, it will occult the star's light. It results in a relatively periodic, slight decrease in the brightness of the star. This variation will be visible in the photometric measurement of the star, called a transit event. Here, the host star, observer, and planet are almost in a collinear state. Large planets block more light and thereby create a significant dip in the light curve.

From the analysis of the transit of a planet, the period of the planet and the density of the star can be obtained. Together with the radial velocity detection, it is also possible to determine the mass and density of the planet.(National Academies of Sciences et al., 2018).

1.2.3 Direct imaging

Direct imaging(Li et al., 2021) concerns capturing images of exoplanets directly using infrared wavelengths. At this wavelength, the star would likely be 1 million times brighter than the planet, whereas at the visual wavelength, it would be 1 billion times brighter. The method employs a number of techniques to block out the starlight. Once the glare of the star was reduced, a better look at the objects around the star that might be an exoplanet was obtained.Young, massive, self-luminous objects that are farther from their host star can be investigated using the direct imaging technique.The technique does not allow the observer to estimate a planet's mass directly, but instead uses the star's brightness and spectrum to determine the planet's surface temperature and diameter.Mostly used for detecting planets that were positioned face-on, that is, those that do not transit in front of the star.

1.2.4 Astrometry

The oldest method used to detect exoplanets is called Astrometry (Malbet and Sozzetti, 2018), which deals with the study of the positions, motions, and orbits of these planets. Astrometry involves the measurement of stellar positions in the sky for indirect planet detection. It is done by observing the small lateral displacement of the star when it is orbited by a planet. The astrometry technique is mostly applicable for planets with wider orbits since the amplitude of displacement of the center of mass increases with the orbital period.

1.2.5 Gravitational Microlensing

An indirect method for detecting exoplanets is referred to as Gravitational Microlensing. This phenomenon is an observational effect that was predicted by Einstein using his General Theory of Relativity. When one star passes in front of another, the gravitational influence of the foreground star causes the light rays of the background star to become bent. The foreground star essentially acts as a virtual magnifying lens, often called a ”lens star,” which magnifies the brightness of the background star.

In cases where the lens star hosts a planetary system, these planets can also act as additional lenses in the process. This results in a short and temporary deviation in the brightness of the background source. As a consequence, the presence of an exoplanet can be detected through this phenomenon. Gravitational microlensing offers a unique and valuable method for discovering exoplanets that might not be easily detectable using other observational techniques (Tsapras, 2018)

1.3 Discovery Surveys

After the first discovery of an exoplanet in the 1990s, there have been significant advancements in the field of exoplanet research, facilitated by sophisticated instruments and various observational techniques. Thousands of planets outside the solar system have been discovered over the past few decades. The detection of exoplanets has been made possible by both ground-based and space-based telescopes, each playing a crucial role in expanding our knowledge.

Among the notable ground-based surveys, The Hungarian-made Automated Telescope Network (HATNet) and the Wide-Angle Search for Planets (WASP) stand out for their contribution to the discovery of many transiting exoplanets. Simultaneously, several space-based survey satellites have made remarkable contributions, including the Kepler mission, the TESS mission, the Spitzer Space Telescope, the Hubble Space Telescope, and the James Webb Telescope. These space-based observatories have significantly increased the number of known exoplanets and have provided valuable insights into their characteristics and properties.

1.3.1 Ground Based Surveys

- HATNet

  The Hungarian made Automated Telescope Network exoplanet survey consists of HAT-North and HAT-South. HAT-North, located at the Fred Lawrence Whipple Observatory (FLWO) at Mount Hopkins in Arizona and at the Mauna Kea

Observatory in Hawaii, USA, is a network of seven telescopes for detecting transiting exoplanets around bright stars. It was started in 2003 using 11-cm-aperture fully automated telescopes with large-format CCD cameras. HAT-South, which began in 2009, contains six astrograph telescopes that are located over three continents: South America, Africa, and Australia. It uses slightly larger 18-cm-diameter optical tubes for exoplanet detection (Bakos, 2018)

- WASP

  WASP(Wide Angle Search for Planets) has made a significant contribution to finding transiting exoplanets. The two robotic observatories, one in del Roque de los Muchachos on La Palma (Northern hemisphere) and the other one in South African Astronomical Observatory (Southern hemisphere) are taking wide field images of the night sky from 2004 onwards. Each telescope has eight lenses Canon $200mm f/1.8$ lenses with 2048×2048 CCD (Street et al., 2002)

1.3.2 Space Based Surveys

- CoRot

  The CoRot was a high-precision photometric satellite developed with the aim of detecting exoplanets by the transit method. It was led by the French space agency CNES, with partners including several French laboratories and European countries. CoRot was launched in December 2006 at an altitude of 900 km (Bordé et al., 2003). The telescope has an effective diameter of 0.27m and comprises four cooled(-40°c) 2048×2048 CCD's. Originally intended to last 2.5 years, the mission was extended to June 24, 2013. CoRot observed more than 20 distinct star fields during its lifespan (Perryman, 2018)

- Kepler and K2 Missions

  NASA's Kepler space telescope, launched in 2009, was a revolutionary instrument in the field of exoplanet discovery. The concept for Kepler was put forward by William J. Borucki (Borucki et al., 2020), with its main objective being the search for habitable Earth-sized planets around sun-like stars. Kepler operated by observing the tiny dips in the brightness of a star as a planet passed between the star and the observer. It was able to measure these small decreases in brightness with great precision, covering a large area of the sky. The telescope had a 0.95-metre aperture and utilized CCDs (Charge-Coupled Devices) for data collection.

  Kepler operated successfully until May 2013, when two of its reaction wheels malfunctioned, and a minimum of three were required for optimal functionality. However, NASA introduced a new mission called K2 in 2014, utilizing the remaining two reaction wheels. K2 was designed to balance the effect of solar pressure on the solar panels and studied specific regions of the sky for up to 83 days at a time. In 2018, K2 ran out of fuel and was officially decommissioned by NASA. Both Kepler and K2 made significant contributions to the detection of exoplanets, and the results obtained were later confirmed through further analysis of the collected data.

- TESS

  TESS (Transiting Exoplanet Survey Satellite) is a NASA Astrophysics Explorer mission led by the Massachusetts Institute of Technology, the Harvard-Smithsonian Centre for Astrophysics, and the NASA Ames Research Centre. Additional TESS scientific partners included Las Cumbres Observatory Global Telescope, Lowell Observatory, the NASA Goddard Space Flight Centre, the Infrared Processing and Analysis Centre at the California Institute of Technology, the Geneva Observatory (Switzerland), the Tokyo Institute of Technology (Japan), and the Institut Supérieur de l'Aéronautique et de l'Espace (France) (Ricker et al., 2010).

  Launched on April 18, 2018, aboard a SpaceX Falcon 9 rocket, the mission was focused on detecting small, Earth-sized planets transiting around bright stars. TESS was based on the transit method, which looked for tiny dips in the light curve of stars when a planet passed in front of them. The operational orbit of the moon was a highly eccentric, elliptical orbit called P/2, which was exactly half the moon's orbital period. That is, TESS orbited Earth every 13.7 days. Its closest point of approach to Earth was around 108,000km, and when it reached this point, it downlinked information to the ground station. TESS had four identical cameras with a combined field of view of 24×96 degrees. TESS divided the entire sky into 26 sectors with a 27.4-day observing period for each segment. The observations were made in the wavelength range of 600 to 1000nm.

  It was primarily designed to find small exoplanets, but it discovered many exoplanets, like Earth-sized exoplanets, potentially habitable ones, rocky planets, Jupiter-like exoplanets, etc., and astronomers are working to confirm the results. This particular project's work is entirely based on TESS data from the NASA Exoplanet Archive and MAST portal.

The other space-based telescopes, such as Hubble Space Telescope, James Webb Space Telescope, and Spitzer Space Telescope, were not specifically meant for exoplanet detection; instead, they were used for follow-up studies.

2 DETAILS OF OBSERVATIONAL DATA

2.1 Target selection

I have selected data from theNASA Exoplanet Archive (Akeson et al., 2013) for the study of gas giants in faraway orbits. The TESS follow-up observational data were used because all of the planets chosen for this work were transiting ones. The NASA Exoplanet Archive contained more than 5000 exoplanets, of which only a few were opted for this study. Several filters were made here to extract those planets, which include surface temperature, planet radius, visual magnitude.

The planets with a surface temperature less than 373K were classified as lying in the habitable zone(Seager, 2013). Since we have been dealing with gas giant exoplanets, there is no possibility of life on them. They did not have a surface; instead, a swirling gas atmosphere was present. But the exo-moons might be habitable. The habitable zone was the region around a star where the surface temperature was sufficient for the existence of liquid water. Above 373K, water wouldn't exist in liquid form. As a result, the temperature filter was specified as $\leq$373 K.

Another filter given was the planet's radius. The planet radii were selected so that $R_{\rm p}$ $\geq$ 2AU because this work concentrated on gas giant exoplanets and this large radii made it more likely to be detected. These planets were all in faraway orbits.

I have selected $V_{\rm mag}$ as less than 16, which is the measure of the brightness of the star. Since V magnitude is a logarithmic scale, as the value increases, the star appears fainter. Hence, a lower magnitude has been selected to get accurate information about the celestial object.

The ratio of planet radius $R_{\rm p}$ to star radius R_* had been chosen above a particular value, say 0.02. As the planet revolved around the star, the brightness of the host star decreased, causing a noticable dip in the transit curve. The depth of the transit signal had been proportional to $R_{\rm p}/R_*$. Hence, a larger value was required to observe a significant dip, thereby making the detection easier.

In Table 3.1, I have included the planet radius$R_{\rm p}$, equilibrium temperature, and $V_{\rm mag}$ for each of the 31 target exoplanets obtained from the NASA Archive.

Table 2.1: Table1

Planet name	Planet radius	Equilibrium temperature	Vmag
TOI-1468 c	$2.064^{0.044}_{-0.044}$	$337.5^{3.7}_{-3.4}$	$12.5^{0.2}_{-0.2}$
K2-286 b	$2.1^{0.2}_{-0.2}$	347^{21}_{-11}	$12.881^{0.13}_{-0.13}$
K2-323 b	$2.1^{0.09}_{-0.11}$	318^{24}_{-43}	$14.935^{0.114}_{-.114}$
Kepler-61 b	$2.15^{0.13}_{-0.13}$	273^{13}_{-13}	$15.227^{0.069}_{-0.069}$
Kepler-1653 b	$2.17^{0.16}_{-0.23}$	284^{25}_{-21}	$15.864^{0.172}_{-0.172}$
TOI-2257 b	$2.194^{0.113}_{-0.111}$	256^{61}_{-17}	$15.211^{0.034}_{-0.034}$
K2-332 b	$2.2^{0.19}_{-0.15}$	266^{5}_{-8}	
K2-9 b	$2.25^{0.53}_{-0.96}$	314^{67}_{-64}	$15.86^{0.195}_{-0.195}$
K2-152 b	$2.29^{0.25}_{-0.24}$	337^{3}_{-3}	$13.728^{0.019}_{-0.019}$
LTT 3780 c	$2.3^{0.16}_{-0.15}$	353^{18}_{-18}	$13.14^{0.035}_{-0.035}$
LP 791-18 c	$2.31^{0.25}_{-0.25}$	$370^{30}-30$	$16.91^{0.2}_{-0.2}$
K2 18 b	$2.37^{0.22}_{-0.22}$	284^{15}_{-15}	$13.477^{0.042}_{-0.042}$
Kepler-22 b	$2.38^{0.13}_{-0.13}$	262	$11.751^{0.057}_{-0.057}$
TOI-712 d	$2.474^{0.092}_{-0.082}$	$313.6^{2.9}_{-2.8}$	$10.838^{0.021}_{-0.021}$
K2-264 c	$2.668^{0.201}_{-0.194}$	331^{7}_{-7}	$16.701^{0.0462}_{-0.0462}$
EPIC 212737443 c	$2.69^{0.146}_{-0.146}$	316^{10}_{-10}	$14.81^{0.137}_{-0.137}$
TOI-712 c	$2.701^{0.092}_{-0.082}$	$369.9^{3.4}_{-3.4}$	$10.838^{0.021}_{-0.021}$
K2-123 b	$2.76^{0.16}_{-0.16}$	338^{5}_{-5}	$14.781^{0.034}_{-0.034}$
TOI-1231 b	$3.65^{0.16}_{-0.15}$	$329.6^{3.8}_{-3.7}$	$12.36^{0.2}_{-0.2}$
Kepler-1661 b	$3.87^{0.06}_{-0.06}$	243	$14.357^{0.092}_{-0.092}$
Kepler-421 b	$4.16^{0.19}_{-0.16}$	$184.8^{8.6}_{-4.8}$	$13.611^{0.08}_{-0.08}$
Kepler-1654 b	$9.18^{0.21}_{-0.19}$	$206^{3.7}_{-3.5}$	$13.497^{0.103}_{-0.103}$
PH2 b	$10.12^{0.56}_{-0.56}$	281^{7}_{-7}	$12.645^{0.046}_{-0.046}$
Kepler-167 e	$10.16^{0.42}_{-0.42}$	134.4^{4}_{-4}	$14.284^{0.126}_{-0.126}$
WD 1856+534 b	10.4^{1}_{-1}	163^{14}_{-18}	$17.244^{0.046}_{-0.046}$
KOI-3680 b	$11.1^{0.7}_{-0.8}$	347^{12}_{-12}	$14.616^{0.103}_{-0.103}$
TOI-2180 b	$11.32^{0.25}_{-0.21}$	$348^{3.3}_{-3.6}$	$9.162^{0.002}_{-0.002}$
Kepler-1704 b	$11.95^{0.49}_{-0.47}$	$253.8^{3.7}_{-4.1}$	$13.392^{0.137}_{-0.137}$
EPIC 248847494 b	$12.4^{0.8}_{-0.8}$	183^{25}_{18}	$12.353^{0.08}_{-0.08}$
TOI-4562 b	$12.53^{0.15}_{-0.15}$	318^{4}_{-4}	$12.14^{0.217}_{-0.217}$
TOI-1899 b	$12.9^{0.4}_{-0.6}$	362^{7}_{-7}	$14.88^{0.2}_{-0.2}$

2.2 Final selection

Only a few of the planets mentioned above were chosen for further research. All the multi planetary systems, which have more than one planet rotating around the same star, were disregarded. It is challenging to analyse these planets because they have intricate gravitational interactions. The list also contained a white dwarf, which had also been avoided in the study.The list also contained a white dwarf WD 1856+534 b and a circumbinary planet Kepler-1661 b, which have also been avoided in the study.

For the remaining planets, I have searched for TESS data in the MAST. If the TESS light curves for each of the sectors were available, then that particular planet had been selected.The Mikulski Archive for Space Telescopes (MAST) is an astronomical data archive, funded by NASA, that contains information from the near infrared, ultraviolet, and visible wave length ranges. MAST has a number of filters. The first filter, mission has been selected as TESS since this project focuses on Transit follow-up investigations. The provenance name being preferred as SPOC, the Science Processing Operations Center (SPOC) developed at NASA Ames Research Center based on the Kepler science pipeline would have provided calibrated pixels, light curves, and also searched for periodic transit occurrence. Its main objective has been to process and store the data for TESS mission(Jenkins et al., 2016). The transit approach was based on the examination of the star's periodic variation in brightness, therefore the product type was regarded as a time series. The amount of time an astronomy equipment is exposed to light is referred to its exposure length. More precise data were gathered during that observational period as a result of longer exposure durations suggesting higher signal-to-noise ratios. I have selected a standard of 120 seconds for the observation. Only those observations were analysed that exactly matched the searched coordinates, as indicated by the choice of a 0 arcsec angle between the searched coordinates and the centre of observation.

The final list has once again been reduced after applying the MAST filters. I have selected only a few planets for further studies that have TESS data available. The final planet list include :TOI-2257 b,K2-332 b,K2-9 b,K2-152 b,K2 18 b,K2-123 b,TOI-2180 b,TOI-4562 b,TOI-1899 b.

3 ANALYSIS AND MODELING

3.1 Data extraction using fv fits editor

For a single exoplanet, there have been multiple data files. From MAST, the raw data for each of the chosen planets were retrieved. The downloaded files were in zip file format, which needed to be extracted. After the extraction part, raw data was accessed using the FITS editor software called fv.

In astronomy, a FITS file (Flexible Image Transport System) is a standard data format that has been used for storing and transmitting scientific data, such as pictures, spectra, and tables. The High Energy Astrophysics Science Archive Research Centre (HEASARC) at NASA/GSFC developed the fv FITS file viewer and editor. It is an easy-to-use graphical programme that can run on Linux, macOS, and Windows as well (Pence and Chai, 2012). FV was a general software package that could be used for viewing, plotting, and editing FITS format data files (Pence et al., 1997). It included numerous spreadsheet-like features for sorting tables, adding or removing rows and columns, and recalculating the values in it.

Each data file was inspected using FV, and the pdcsap flux error was chosen as the y-error when plotting the data with time on the x-axis and pdcsap flux on the y-axis. There are several null values in the table that need to be eliminated. The data file with the null values removed has been stored into a separate file.

3.2 Identification of the Transit

The null-removed time and flux have been plotted. In the obtained Figure 3.1, the transit dips have been checked. A single plot may have contained multiple transits. The regions are noted. The values lying on the premises of the transit event are only taken into consideration, and the other values are removed by slicing.

preconfigured programmes based on the work of Mandel and Agol (2002) and Carter et al. (2008) were used to model the respective data sets. One of the codes, occultquad, was used to model the light curve of a source that is quadratically limb-darkened during the occultation by the planet or star. The model, also known as the MA02

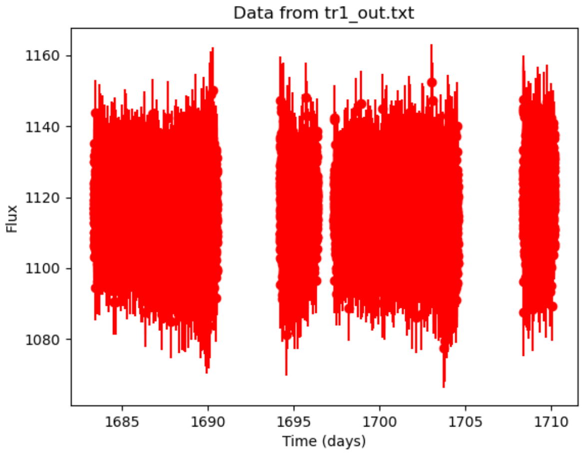

Figure 3.1: plot of null removed data of the TOI-1899

model, shows how the brightness of the star varies from its centre to limb during a transit event.

3.2.1 Transit parameters

There are several parameters for describing the light curve's shape during transit in order to model it, which include mid transit time t_c, impact parameter b, ratio of stellar radius to semi major axis R_*/a, ratio of planet radius to stellar radius R_p/R_*, flux f, linear limb darkening coefficient C1, quadratic limb darkening coefficient C2. Among these seven parameters, the mid-transit time and flux are roughly estimated from the plot obtained after slicing.

Mid-transit time occurs when the planet's centre lines up with the star's centre, causing a dip in the star's brightness. The time is expressed in Barycentric Julian date (BJD), a modification of Julian date, which began counting on January 1, 4713 BC. It was was taken as the time standard for astronomical events (Eastman et al., 2010).

The impact parameter b is the projected distance in units of stellar radius R_* between the star and planet centres during mid Transits . Changes in transit duration or shape will have a significant influence on transits with large impact parameters (Perryman, 2018). b is physically meaningful only on a transiting system for values 0¡ b ¡ 1+p, where p is the planet-to-star radius ratio whose value lies between 0 and 1 (Espinoza, 2018). It has an impact on the planet's orbital inclination, transit duration, transit dimensions, and transit light curve form.

The size of the host star in relation to the planet's orbit is indicated by the parameter R_*/a. The semi-major axis (a) in a system of transiting exoplanets measures the average separation between the star's center and the exoplanet's orbital center. If Rstar/a has a high value, the star must be considerably massive in relation to the planet's orbit. As a result, the transit's duration and depth will be relatively reduced.

The ratio of the planet's size to that of the host star is expressed as R_p/R_*, which describes the relative size of the planet to the size of the host star. It is a measure of how large the planet is compared to the star. The square of the R_p/R_* determines how much light is occulted during a transit event. Therefore, a high value results in a deeper transit, showing that the planet blocks a larger percentage of the star's light.

The amount of light emitted by the star is referred to as flux. When a planet moves in front of a star during a transit, it occults the star's light and reduces the observable flux. As a result, the transit-light curve dips, and the depth of the dip will be directly related to the size of the planet passing by.

Limb darkening is essential in determining shape of the transit light curve. It refers to the decrease in intensity of a star moving from the centre to its limb. It is the outcome of the combined effect of optical depth with the decreasing star density and temperature with radius. It is usually represented as the functions of $\cos\theta$, where θ is the angle between line of sight to the observer and normal to a given point of the stellar surface. For planet transits, the effect is very significant and results in a little change in colour with wavelength, it decreases with increasing wavelength (Perryman, 2018). There are several limb darkening models and the corresponding limb darkening coefficients including linear, quadratic and non linear coefficients. In this study two limb darkening coefficients, linear and quadratic were used. In linear limb darkening model the star's light is assumed to dim linearly from its centre to limb. The quadratic model is more accurate than the other, where the intensity varies quadratically. Both the values lies between 0 and 1.

Using these 7 parameters, the light curve can be modeled.

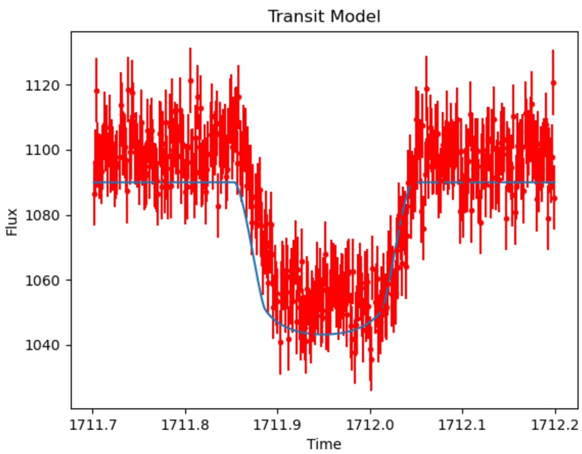

Figure 3.2: modeled light curve of the planet TOI-1899

The values for b, R_*/a ,and R_p/R_* were taken directly from NASA Exoplanet Archive

. They weren't particularly precise or accurate. Markov Chain Monte Carlo fitting was utilised to obtain values that were more accurate than those from previous studies.

3.3 Modeling using MCMC

The light curves would then be modeled using the Markov-chain Monte-Carlo(MCMC) sampling technique to precisely estimate the physical properties of the target exoplanets. MCMC is a method to fit the model light curve to the data available. Here, one creates a Markov chain by randomly creating the next sample value using the previous sample values(Carlo, 2004). With the help of a Markov process, the chain is built so that each subsequent parameter value depends on the previous one. This ensures that the chain will eventually converge to the posterior distribution of the parameters. Here Metropolis–Hastings algorithm has been used for the generation of model. A comparison of the likelihood function and the prior distribution is called the posterior distribution. It comes about as a result of updating the prior probability with the information summarised by the likelihood. The likelihood function can be calculated as:

$$lnP\left(\{y_n\}|\{\,t_n\},\{\,\sigma_n^2\},\theta\right) = \frac{-1}{2}\sum_{n=1}^{N}\frac{[y_n - f_\theta(t_n)]^2}{\sigma_n^2} + A$$

where A is independent of θ so can be neglected here. f_θ(t) is the model function, y_{n} is the observed data and σ is the observed error bar

3.3.1 Algorithm

Metropolis-Hastings algorithm for MCMC sampling technique is:

step 1 : Define the likelihood function, which measures the probability of observing the data, and the model function, which explains the relationship between the parameters and the observed data

step 2 : For each parameter, select the prior distribution.

step 3 : Initialise the chain by randomly selecting parameter value from the prior distribution.

step 4 : Propose a new parameter value at each of chain by drawing the parameter values from proposal distribution.

step 5 : Calculate the acceptance probability for the proposed new parameter values. It is the ratio of likelihood of proposed new parameter values to the likelihood of current parameter values.

step 6 : If acceptance probability is greater than or equal to 1 accept the proposal. Otherwise continue with the previous one.

step 7 : Repeat the steps 4 to 6 until it generates enough samples from the posterior distribution.

step 8 : To estimate the parameter values and associated uncertainty, analyze the posterior distribution of each parameter.

step 9 : Verify that the chain has converged to the posterior distribution.

step 10 : Refine the model and iterate the method until a satisfactory fit is achieved if the posterior distribution suggests that the model is not a good fit for the data.

In MCMC sampling, 30 walkers were used, and 5000 iterations were performed for each walker. Such a large sampling was done in order to obtain highly accurate and precise data. The algorithm was initially developed for a planet with a single transit; later, it was updated for multiple transits. The first 2000 iterations were neglected as burn-in iterations, and a new set of parameters was obtained. The modeling was then performed using these new set of parameters.

3.3.2 Derived parameters

The parameters obtained from the MCMC sampling can be used to derive some other parameters, which include transit duration T_{14}, inclination angle of the planetary orbit i, and the equilibrium temperature T_{eq} (Saha et al., 2021)

The transit duration is the time it takes for a planet to pass in front of its host star during a transit event.

$$T_{14} = \frac{p}{\pi}\sin^{-1}\left[\frac{\sqrt{1+(R_p/R_*)^2 - b^2}}{\sqrt{(a/R*)^2 - b^2}}\right]$$

The angle between the planet's orbital plane and the observer's line of sight from the observer is known as the inclination angle (i) of the planetary orbit. In other words, it refers to the tilt of the planet's orbit with respect to the plane of the sky.

$$i = cos^{-1}\left[\frac{bR_*}{a}\right]$$

and the equilibrium temperature of the planet could be estimated as

$$T_{eq} = T_{eff}\sqrt{\frac{R_*}{2a}}$$

4 RESULTS

I have changed the parameter set and range values multiple times until a saturated figure is obtained. The parameter that moderately saturates the plot is taken as the final value. These are the plots obtained after running MCMC code multiple times for the planet TOI-1899, and the corresponding values are tabulated in the Table 4.1

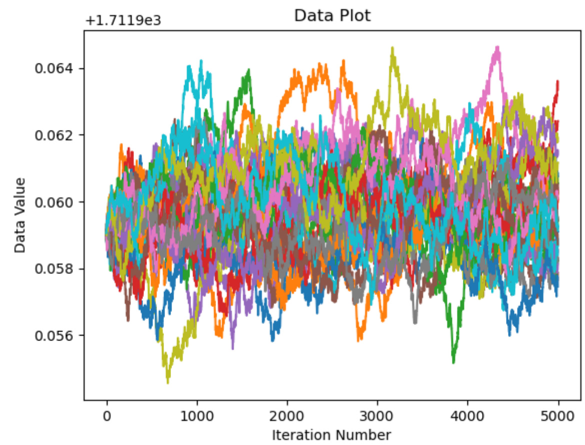

Figure 4.1: mid-transit time1

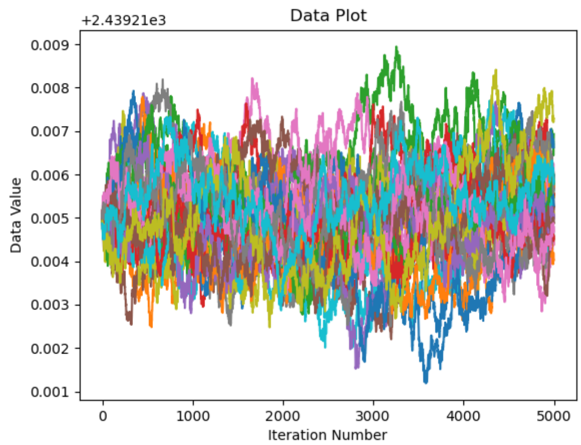

Figure 4.2: mid-transit time2

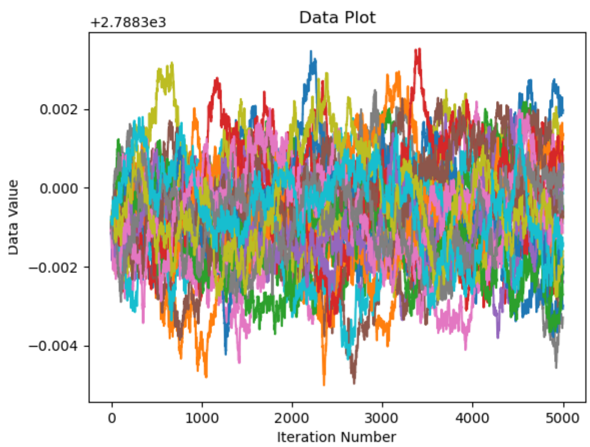

Figure 4.3: mid-transit time3

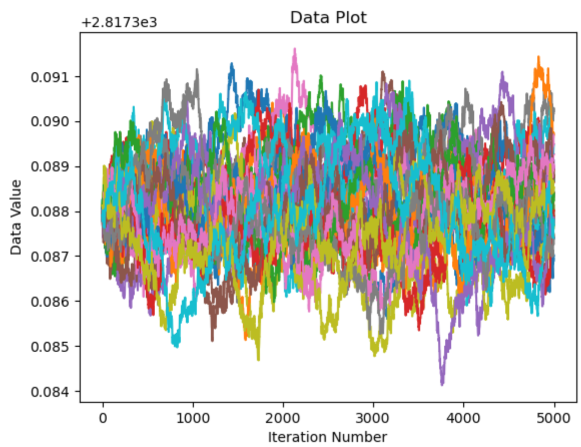

Figure 4.4: mid-transit time4

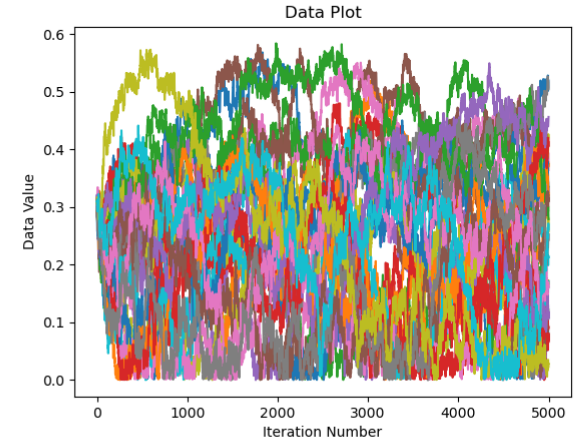

Figure 4.5: impact parameter

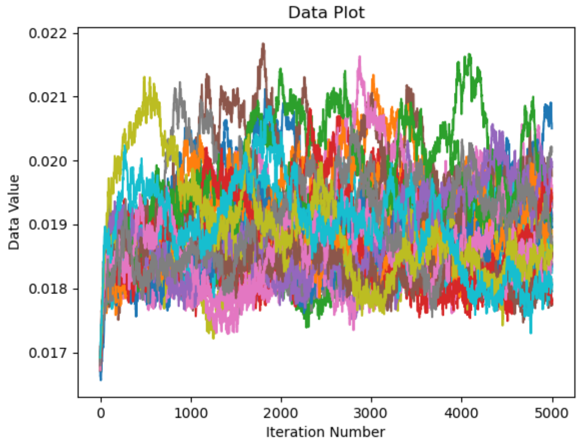

Figure 4.6: R_*/a

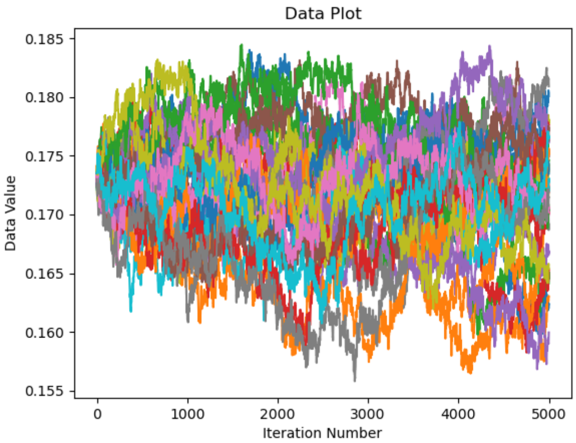

Figure 4.7: R_P/R_*

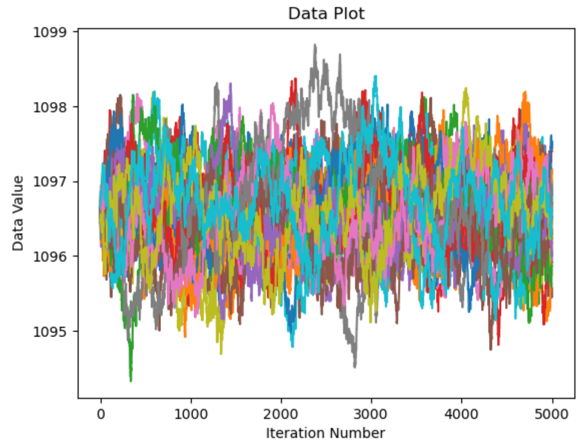

Figure 4.8: Flux1

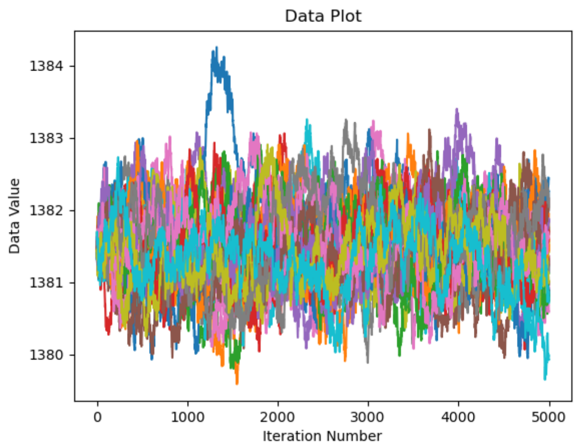

Figure 4.9: Flux2

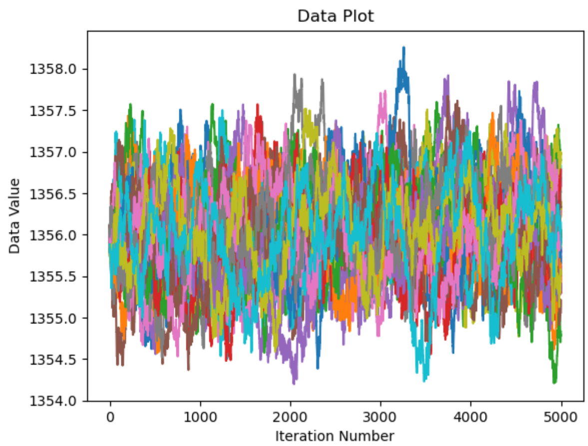

Figure 4.10: Flux3

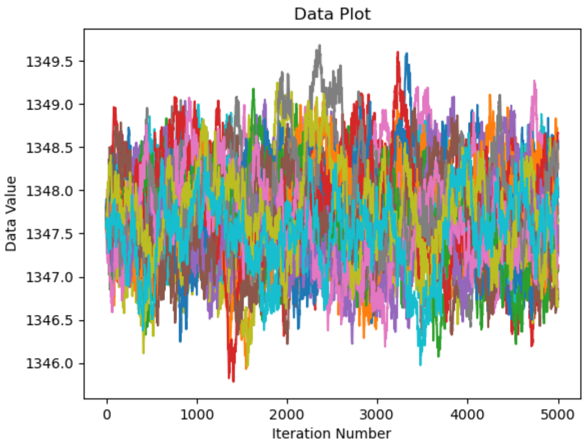

Figure 4.11: Flux4

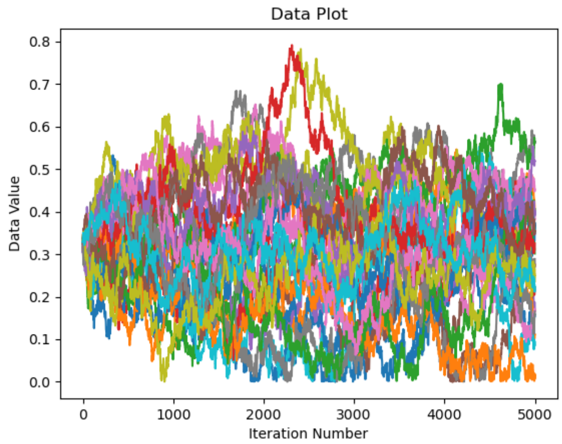

Figure 4.12: C1

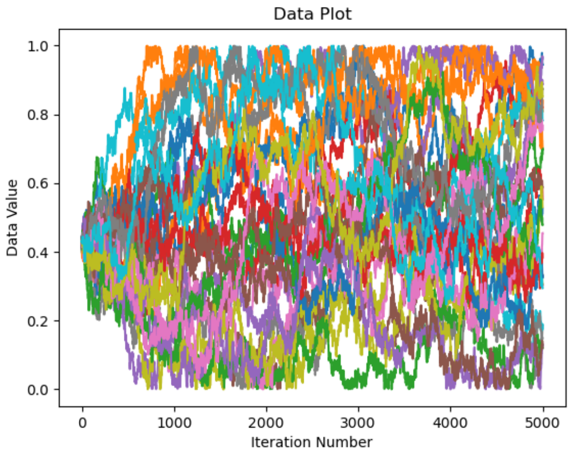

Figure 4.13: C2

TOI-1899

Parameters	Observation	(Cañas et al., 2020)
b	$0.2509^{+0.1335}_{-0.1022}$	$0.22^{+0.15}_{-0.14}$
a/R_*	$52.9717^{+0.000669}_{-0.00041}$	$56.22^{+1.59}_{-1.66}$
R_p/R_*	$0.1718^{+0.00377}_{-0.0025}$	$0.194^{+0.004}_{-0.005}$
t_{14}	$4.0662^{+0.09400}_{-0.0447}$	$4.67^{+0.12}_{-0.10}$
i	$89.7300^{+0.1632}_{-0.1008}$	$89.77^{+0.15}_{-0.14}$
t_{eq}	373.177^{+54}_{-45}	362^{+7}_{-7}
C1	$0.3194^{+0.1251}_{-0.8369}$	
C2	$0.5056^{+0.3062}_{-0.1400}$	

Table 4.1: comparison between observed parameters and previously obtained parameters for the planet TOI-1899

MODEL LIGHT CURVES

Using the new set of parameters the light curve can be modeled as:

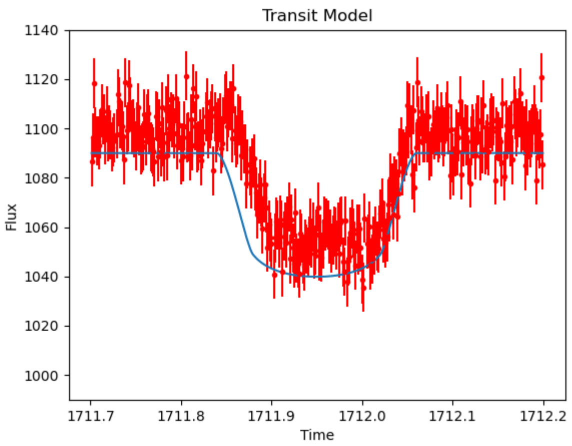

Figure 4.14: Model light curve of first transit

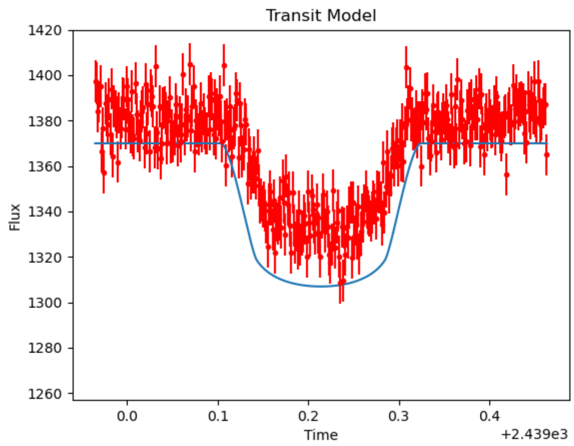

Figure 4.15: Model light curve of second transit

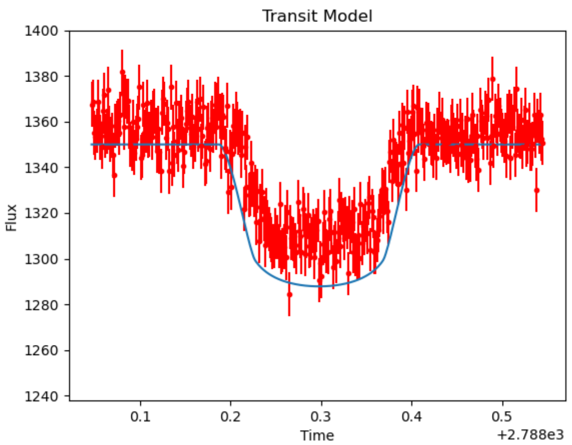

Figure 4.16: Model light curve of third transit

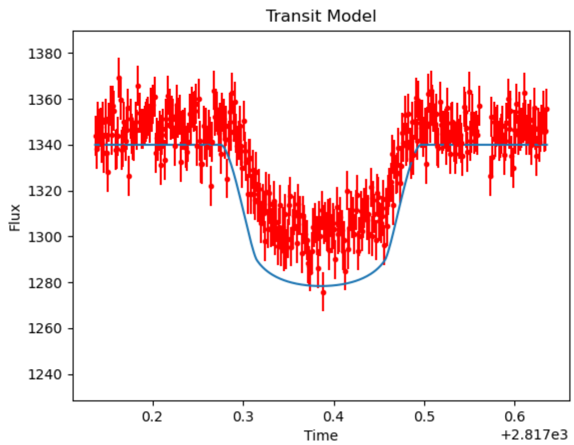

Figure 4.17: Model light curve of fourth transit

5 Conclusion

In this work, I have analyzed the TESS transit photometric data of the already discovered gas giant exoplanets. All the data for this paper was collected by the TESS mission, which were publicly available from the Mikulski Archive for Space Telescopes. From the data obtained, light curves were formulated, and these light curves have been modeled using the Markov-chain Monte-Carlo (MCMC) sampling technique. The parameters and ranges were changed until a saturated plot was obtained. The values which moderately saturated the graph were chosen as the final result. I have compared my estimated parameter values with those from the previous studies.

Some of the parameters show more accurate and precise results than the already existing studies, while others do not.By executing this procedure a few more times, I will be able to achieve the required accuracy.

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