PAPER NAME

Transit Photometric.pdf

AUTHOR

Krishnapriya P.R.

WORD COUNT

6570 Words

CHARACTER COUNT

33411 Characters

PAGE COUNT

31 Pages

FILE SIZE

5.6MB

SUBMISSION DATE

Jul 31, 2023 3:18 PM GMT+5:30

REPORT DATE

Jul 31, 2023 3:18 PM GMT+5:30

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DEPARTMENT OF PHYSICS

TRANSIT PHOTOMETRIC FOLLOW-UP STUDY OF SUPER-EARTHS AROUND BRIGHT STARS USING TESS

PROJECT REPORT

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CERTIFICATE

This is the certification for the project work ”TRANSIT PHOTOMETRIC FOLLOW-UP STUDY OF SUPER-EARTHS AROUND BRIGHT STARS USING TESS” completed by Ms. Krishnapriya P R (210011023200), a bonafide student of Bharata Mata College, Thrikkakara, in partial fulfillment for the award of the Degree of Master of Science in Space Science of Mahatma Gandhi University, Kottayam, in the academic year 2021-2023. It is authorized that all modifications identified for Internal Assessment have been integrated with the report and given over to the departmental library. The project report has been accepted as it satisfies the academic standards for project work set by the institution for the forenamed 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, Krishnapriya P R (210011023200), student of fourth-semester M.Sc. Space Science, Department of Physics, Bharata Mata College, Thrikkakara, hereby declare that the project titled ”TRANSIT PHOTOMETRIC FOLLOW-UP STUDY OF SUPER-EARTHS AROUND BRIGHT STARS USING TESS” has been completed by me and submitted in partial fulfillment of fourth-semester requirements in Master of Science in Space Science from Mahatma Gandhi University, Kottayam during the academic year 2021-2023.

I further declare that no one else has ever submitted this project for the award of a degree or diploma to any other university.

I also declare that I shall be one of the authors of any Intellectual Property Rights generated by this project and that they will belong to Bharata Mata College, Thrikkakara.

Place: Thrikkakara
Date:

Name Signature

Krishnapriya P R (210011023200)

ACKNOWLEDGEMENT

Any success, whether academic or otherwise, depends not only on the individual's efforts but also on the advice, support, and collaboration of intellectuals, elders, and friends. Several people have contributed to the success of this project in various ways. At this point, I'd like to express my gratitude to everyone.

I sincerely thank my external project guide Suman Saha, Postdoctoral Researcher, Indian Institute of Astrophysics, Bangalore, and my internal project advisor Dr. Manesh Michael, Assistant professor, Department of Physics, Bharata Mata College, Thrikkakara, for their expert guidance, constant sources of inspiration, and assistance throughout this project.

I would like to express my gratitude to Dr.Shibi Thomas, HoD, Department of Physics, Bharata Mata College, Thrikkakara, for her helpful suggestions and persistent help.

I also want to express my gratitude to Dr. Johnson K. M., Principal of Bharata Mata College, Thrikkakara, for providing moral support in the completion of this project.

I admire my parents' constant support and encouragement as well as that of the entire Physics Department faculty at Bharata Mata College, Thrikkakara, and the Indian Institute of Astrophysics, Bangalore. Last but not least, I want to thank our friends and peers who offered me helpful advice throughout the course of this project.

ABSTRACT

The Transiting Exoplanet Survey Satellite (TESS) is a space-based survey telescope to discover new exoplanets around the bright stars in the solar neighborhood. Since it will cover a large portion of the sky (~75%) 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. While there are thousands of exoplanets discovered till date, the smaller terrestrial exoplanets of a size similar to or a little bigger than the Earth, also known as the super-Earths, are of particular interest. Studying the super-Earth population can reveal important understandings about the formation and evolution of terrestrial exoplanets and the criteria for the existence of life.

This project aims at studying the super-Earths around the bright stars in the solar neighborhood through transit photometric follow-up observations by TESS. 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 portal. From the data obtained, light curves are formulated. This lightcurves would then be modeled 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

Exoplanets are planets that orbit other stars. Exoplanet research is a relatively recent area of study in astronomy. The first true exoplanet that revolves around a real star wasn't found until 1995. Since then, both technology and the rate of newly found exoplanets have grown quickly. Since the planets are far fainter than their stars, it is quite difficult to directly detect them. In 1995, Mayor and Queloz(Mayor and Queloz, 1995) discovered 51 Pegasi b, the first exoplanet, orbiting a sun-like star. They were awarded the 2019 Nobel Prize in Physics for their remarkable discovery. 51 Pegasi b was the first known "hot Jupiter", a gas giant planet orbiting very close to its star. Its mass is about half of Jupiter's mass.

Exoplanets can be divided into several types.

- Hot Jupiters

  Hot jupiters resembles Jupiter in size and composition. They are gas giants that are located closer to their stars. Due to their close proximity to their host star, they have high surface temperatures. It is made of hydrogen and helium. Hot Jupiters were the first exoplanets discovered (Dawson and Johnson, 2018) orbiting around a main sequence star.

- Mini-Neptunes

  Mini-Neptunes are primarily made of solid rock and ice. It possesses a substantial primordial atmosphere accreted from the protoplanetary nebula and a composition that is generally identical to that of the Sun (Bean et al., 2011).

- super-Earths

  Super-Earths are a class of planets with masses greater than Earth but lighter than ice giants like Neptune and Uranus.They have a size similar to or a little bigger than the Earth.Super Earths could form with CO2 concentrations (Von Bloh et al., 2007)that are higher or lower than those of the Earth's.

1.2 DISCOVERY METHODS

Since the first discovery of exoplanets through a precise radial velocity (RV) approach, the number of confirmed exoplanets has increased rapidly. Extrasolar planets are extremely difficult to directly detect since they are far fainter than the stars they orbit. There are several techniques that have identified exoplanets.

- Radial velocity method
- Transit photometry
- Direct imaging method
- Gravitational microlensing
- Astrometry

1.2.1 Radial velocity method

The first exoplanet was discovered in 1995 (Mayor and Queloz, 1995)using the radial velocity technique. It is a technique in which variations in the distance of an object are measured with respect to a reference point. In astronomy, the Earth is considered the reference point, and the radial variations of celestial objects are measured with respect to it. The fundamental theory of the radial velocity technique is based on Doppler theory. According to Doppler theory, the frequency of radiation emitted from an object decreases as it recedes from the reference point. A star travelling towards an observer appears blue-shifted, and a star travelling away from an observer appears red-shifted. Radial velocity (RV)(Reiners et al., 2010) has the key advantages of measuring planetary mass and orbital eccentricities. However, for the true mass to be measured, the inclination angle, i, is needed, which can be obtained from transit observations if the planet transits its host star.

1.2.2 Transit method

When the star, planet, and observer are in alignment, exoplanets can be found using the transit method(Moutou and Pont, 2006). The transit method then enables the estimation of a planet's mass, radius, and density when coupled with radial velocity observations. With the observation of the transit of the HD 209458 in 1999, the transit method achieved its first success. The transit approach involves spotting the slight dip in a star's light curve that occurs when a planet rotates in front of its host star.The transit occurs on a periodic basis, with a period that corresponds to the planet's revolution.

1.2.3 Direct imaging method

Direct imaging (Brande et al., 2019) is an effective method for finding exoplanets. It is challenging to find planets with large orbital separations using time-series techniques like transit photometry and radial velocity measurements. Direct imaging can find planets with suitable brightness and orbital separations faster than other techniques. However, this procedure is exceedingly difficult because it requires extremely high contrast imaging capabilities.

1.2.4 Gravitational microlensing

Gravitational microlensing(Seager and Lissauer, 2010) occurs when a foreground star passes very close to the observer's line of sight to a more distant background star. By acting as a lens, the foreground star magnifies the background source star as a function of time by a factor that depends on the angular separation between the lens star and source star. If a planet orbits the lens star, the lightcurve may be further disrupted, providing a distinctive, short-lived signature of an exoplanet and the planet's mass planet-star physical separation.The most distant and tiny planets can be detected using this method. The discovery of planets the size of Earth may result from this microlensing. The main drawback of the microlensing technology is the fact that the lensing occurs only once and never again.

1.2.5 Astrometry

The instrumentation on the ground or in space can be used for the astrometric detection of extrasolar planets. The angular position of a star as determined by a specific instrument in its local frame of reference is often referred to as the astrometric observable. Astrometric measurements can be made in wide-angle mode both on the ground and in space (SOzzETTI, 2005). Astrometry is the measuring of a star's position in relation to the sky's background. Because the amplitude of the center of mass shift grows with orbital period, astrometry is most sensitive to wider orbits (Malbet and Sozzetti, 2018).

1.3 EXOPLANET DISCOVERY MISSIONS

The exploration of exoplanets has been revolutionized by the collective efforts of space and ground-based surveys. They have played a major role in discovering a wide range of exoplanet systems using various detection methods. Ground-based surveys have made a remarkable contribution to exoplanet study by various discovery methods. Space-based missions provide many benefits, including access to a large spectral range and highly accurate data for exoplanet discovery.

Two major ground-based surveys are the Hungarian-made Automated Telescope Network (HATNet) and the Wide Angle Search for Planets (WASP). TESS, Kepler, the James Webb Space Telescope, Spitzer, and the Hubble Space Telescope are some of the major space-based surveys.

1.3.1 Ground based surveys

- HATNet

  Hungarian-made Automated Telescope Network (HATNet) (Bakos, 2018), a ground-based observatory project for detecting transiting exoplanets, consists of two observatories: HATNet-North and HATNet-south.HATNet-North started in 2003, is located at the Fred Lawrence Whipple Observatory (FLWO) at Mount Hopkins in Arizona, USA, and at the Mauna Kea Observatory in Hawaii, USA. It consists of a network of small telescopes that continuously monitor the sky, looking for exoplanets. HATNet-South, started in 2009, is located at Las Campanas Observatory (LCO) in Chile. It has a network of telescopes to observe the southern skies. The HATNet project has contributed to the discovery of numerous exoplanets.

- WASP

  Wide Angle Search for Planets (WASP) (Pollacco et al., 2006), launched in 2004, can cover both hemispheres of the sky with the help of two robotic observatories that operate continuously. On the island of La Palma, SuperWASP-North is situated, and SuperWASP-South is situated at the South African Astronomical Observatory. Eight wide-angle cameras are used in each to concurrently scan the sky for planetary transit occurrences. Exoplanets of all sizes, including hot Jupiters, Neptunes, and super-Earth-sized planets, have been successfully found by WASP.

1.3.2 Space based surveys

- CoRoT

  The CoRoT space mission, which was launched on December 27, 2006, has been developed and controlled by CNES (Léger et al., 2009). CoRoT was the very first space mission assigned to the detection of exoplanets. The mission operated between 2008 and 2012, covering 24 fields with pointings ranging in length from 24 to 153 days (Klagyivik et al., 2021). Observations were initially planned for a duration of 2.5 years. Although operations were extended until 2013, a computer breakdown on November 2, 2012, resulted in mission termination on June 24, 2013. CoRoT has confirmed the discovery of several planets.

- Kepler and K2

  Kepler, a space telescope (Howell, 2020), was invented with the aim of searching for exoplanets. It was launched by the National Aeronautics and Space Administration (NASA) on March 6, 2009. The Kepler mission uses the transit method to look for terrestrial exoplanets. It searches for little decreases in the star's brightness as a sign of planets. It can calculate the star's mass and the planet's orbital radius using Kepler's Third Law of Planetary Motion. 2012 saw the failure of one of the spacecraft's four reaction wheels. The data collection was halted in May 2013 when another wheel failed. To address this deficiency, the K2 mission was initiated in May 2014 and ran until October 2018. Scientists developed an innovative approach that used solar radiation pressure with the remaining two reaction wheels to keep the spacecraft pointed at the same spot for 83 days at a time. The satellite would then be directed at a new area of the sky once the telescope received some sunlight. The K2 mission ended in October 2018 due to the spacecraft running out of fuel. The K2 mission offers long-term, high-precision optical research that is superior to what is feasible with ground-based telescopes. Its observations include young open clusters, galaxies, supernovae, and bright stars.

- TESS

  The NASA-launched Transiting Exoplanet Survey Satellite (TESS), an MIT-led (Ricker et al., 2015) space-based observatory, employs the transit technique to find exoplanets.TESS has proven immensely successful in its mission to find exoplanets. It will observe 85% of the whole sky, tracking and discovering planets transiting bright stars. These are suitable for further studies using photometric and radial velocity measurements and also for analysis of their atmospheres with ground-based and space-based telescopes. The primary aim of this mission is to identify small planets and determine their mass with follow-up spectroscopy. Even though many transiting exoplanets have been found, only a few of them orbit bright stars, which enable measurements of planet masses and atmospheres. So, an objective of TESS is to monitor bright stars. In addition to a data handling unit (DHU), the TESS payload comprises four identical cameras. Each camera consists of a lens assembly with seven optical elements, a detection assembly with four CCDs, and associated electronics. Numerous planets smaller than Neptune are anticipated to be found by TESS. Along with this, a number of false positives originating from background eclipsing binaries will also be detected.TESS data from the Mikulski Archive for Space Telescopes (MAST) was used in this study to analyse exoplanets using the transit technique.

The James Webb Space Telescope, Spitzer Space Telescope, and Hubble Space Telescope are not intended to detect exoplanets. Instead, they are used in follow-up investigations.

2 DETAILS OF OBSERVATIONAL DATA

2.0.1 TARGET SELECTION

For this study, I have selected those transiting exoplanets from the NASA Exoplanet Archive that have TESS follow-up observational data. Out of the 5470 confirmed exoplanets discovered by NASA Caltech, only some planets have been chosen for study.

Since our project aims at studying super-Earths around bright stars, we have chosen a planet radius that is similar to an earth's radius. Here we have chosen the planets with a radius,,R_{p} $\leq$2.5. Smaller planets have a higher chance of being habitable since they are more likely to be within their star's habitable zone. Since super-Earths are terrestrial exoplanets, there is a chance of finding life on them.

The visual magnitude of a star, which is the measure of its brightness as observed from the earth, is another parameter. A lower V magnitude indicates a brighter object, while a higher V magnitude indicates a dimmer object. So it has set a limit of $V_{\mathrm{mag}}\leq$ 15. The solar radius is taken to have a maximum value of 0.6.

The Rp/Rstar criteria are applied by looking for periodic brightness dips that indicate a planet passing in front of its host star. This criteria involves setting a threshold value for the ratio. Here it is set to R_{p}/R_{*} $\geq$0.02.

2.0.2 FINAL SELECTION OF PLANETS

All of the planets listed in the table 3.1 cannot be investigated since they include multi planetary systems.Multiplanetary systems (Wright et al., 2009)are stars with at least two confirmed planets, so they are a little more complex to solve. In table 3.1, multiplanetary systems are avoided.

I have looked into the availability of TESS data in MAST for the remaining planets. The MAST Data Discovery Portal allows users to search for, explore, and download data products from most MAST missions and other collections. The TESS lightcurves

Table 2.1: LIST OF PLANETS

Planet name	Planet radius	Solar radius	V magnitude
HD 260655 b	$1.24^{0.023}_{-0.023}$	$0.439^{0.003}_{-0.003}$	$9.63^{0.1}_{-0.1}$
HD 260655 c	$1.533^{0.051}_{-0.046}$	$0.439^{0.003}_{-0.003}$	$9.63^{0.1}_{-0.1}$
GJ 367 b	$0.718^{0.054}_{-0.054}$	$0.457^{0.013}_{-0.013}$	$10.053^{0.044}_{-0.044}$
LTT 1445 A b	$1.305^{0.066}_{-0.061}$	$0.265^{0.011}_{-0.01}$	$10.59^{0.046}_{-0.046}$
LTT 1445 A c	$1.147^{0.055}_{-0.054}$	$0.265^{0.011}_{-0.01}$	$10.59^{0.046}_{-0.046}$
GJ 357 b	$1.217^{0.084}_{-0.083}$	$0.337^{0.015}_{-0.015}$	$10.91^{0.1}_{-0.1}$
GJ 3090 b	$2.13^{0.11}_{-0.11}$	$0.516^{0.016}_{-0.016}$	$11.403^{0.026}_{-0.026}$
TOI-776 b	$1.85^{0.13}_{-0.13}$	$0.516^{0.016}_{-0.016}$	$11.536^{0.041}_{-0.041}$
TOI-776 c	$2.02^{0.14}_{-0.14}$	$0.538^{0.024}_{-0.024}$	$11.536^{0.041}_{-0.041}$
L 98-59 b	$0.85^{0.061}_{-0.047}$	$0.303^{0.026}_{-0.023}$	$11.685^{0.017}_{-0.017}$
L 98-59 c	$1.385^{0.095}_{-0.0758}$	$0.303^{0.026}_{-0.023}$	$11.685^{0.017}_{-0.017}$
L 98-59 d	$1.521^{0.119}_{-0.098}$	$0.303^{0.026}_{-0.023}$	$11.685^{0.017}_{-0.017}$
LHS 1815 b	$1.088^{0.064}_{-0.064}$	$0.501^{0.03}_{-0.03}$	$12.167^{0.047}_{-0.047}$
TOI-1201 b	$2.415^{0.091}_{-0.09}$	$0.508^{0.016}_{-0.016}$	$12.26^{0.2}_{-0.2}$
TOI-1468 b	$1.28^{0.038}_{-0.039}$	$0.344^{0.005}_{-0.005}$	$12.5^{0.2}_{-0.2}$
TOI-1468 c	$2.064^{0.044}_{-0.044}$	$0.344^{0.005}_{-0.005}$	$12.5^{0.2}_{-0.2}$
K2-391 b	$1.371^{0.284}_{-0.188}$	$0.566^{0.112}_{-0.076}$	$12.527^{0.08}_{-0.08}$
LHS 1678 b	$0.696^{0.044}_{-0.044}$	$0.329^{0.01}_{-0.01}$	$12.6^{0.02}_{-0.02}$
LHS 1678 c	$0.982^{0.064}_{-0.063}$	$0.329^{0.01}_{-0.01}$	$12.6^{0.02}_{-0.02}$
TOI-270 b	$1.206^{0.039}_{-0.039}$	$0.378^{0.011}_{-0.011}$	$12.603^{0.039}_{-0.039}$
TOI-270 c	$2.355^{0.064}_{-0.064}$	$0.378^{0.011}_{-0.011}$	$12.603^{0.039}_{-0.039}$
TOI-270 d	$2.133^{0.058}_{-0.058}$	$0.378^{0.011}_{-0.011}$	$12.603^{0.039}_{-0.039}$
TOI-1075 b	$1.791^{0.116}_{-0.081}$	$0.581^{0.024}_{-0.024}$	$12.615^{0.069}_{-0.069}$
GJ 3929 b	$1.09^{0.04}_{-0.04}$	$0.32^{0.01}_{-0.01}$	$12.675^{0.069}_{-0.069}$
GJ 1252 b	$1.18^{0.078}_{-0.078}$	$0.391^{0.02}_{-0.02}$	$12.68^{0.2}_{-0.2}$
K2-155 b	$1.8^{0.2}_{-0.1}$	$0.58^{0.06}_{-0.03}$	$12.773^{0.114}_{-0.114}$
K2-155 d	$1.9^{0.7}_{-0.2}$	$0.58^{0.06}_{-0.03}$	$12.773^{0.114}_{-0.114}$
TOI-1266 b	$2.37^{0.16}_{-0.12}$	$0.42^{0.02}_{-0.02}$	$12.941^{0.049}_{-0.049}$
TOI-1266 C	$1.56^{0.15}_{-0.13}$	$0.42^{0.02}_{-0.02}$	$12.941^{0.049}_{-0.049}$
TOI-1693 b	$1.41^{0.1}_{-0.1}$	$0.46^{0.01}_{-0.01}$	$12.962^{0.069}_{-0.069}$
TOI-1695 b	$1.9^{0.16}_{-0.14}$	$0.515^{0.015}_{-0.015}$	$12.989^{0.081}_{-0.081}$

produced from MAST for each target from each sector cover a period of about 27 days. MAST has certain filters that can be used to research a target based on our requirements.Since this study is based on Transit photometric follow-up studies, TESS was the first filter I applied.

The next filter I applied was SPOC. ”TESS Science Processing Operations Center” is referred to as SPOC on the site. It is in charge of processing the raw data that the TESS spacecraft gathered during its observations(Jenkins et al., 2016). It carries out a number of operations, including calibrating the pixel data, producing light curves, and looking for periodic transit events brought on by exoplanets passing in front of their home stars.

The amount of time a camera sensor on a space telescope is exposed to light while making an observation is referred to as exposure length. Only data sets with a 120-second exposure were included in our selection.

Timeseries has been chosen as the product type. The angular separation between the searched coordinate and the center of observation, which is the distance, is set to zero. Several planets with short periods are not used for research because it would be challenging to detect a transit. Since the TESS data for some planets is not available on the MAST website, it cannot be used for study.

By considering all these criteria, the planet list has been updated as GJ 357 b, GJ 3090 b, TOI-776 b, TOI-1201 b, TOI-1695 b, TOI-1468 b, K2-391 b, TOI-1266 b, G 9-40 b, TOI-2136 b, and LTT 1445 A b.

3 ANALYSIS AND MODELING

3.1 DATA EXTRACTION USING FV TOOLS

Data products were downloaded from MAST as zip files and extracted as the initial stage in the data extraction process. A single planet has several data files. Using the fv fits editor, these raw data have been accessed.

FV is a FITS file viewer and editor created by NASA's High Energy Astrophysics Science Archive Research Center (HEASARC). It is a general software that could be used to examine, plot, and edit data files in the FITS format. Image data or tabular data are the two types of data recorded in FITS files(Muna, 2017). The standard astronomical data format authorized by both NASA and the IAU is called FITS, which stands for "Flexible Image Transport System."

Using the fv fits editor, each set of data has been plotted with time on the x axis, pdcsap flux on the y axis, and pdcsap flux error on the y error axis. The data has been exported to a text file with three columns: time, flux, and flux error. There are null values in the data that need to be eliminated. The null-removed data has been saved and used for further studies.

3.2 IDENTIFICATION OF THE TRANSIT

The null removed datas are plotted with time, flux and flux error.From the plot 3.2.1,transit dips have been identified and noted. Transit dips on the plot have been identified and noted. Only values that are relatively near the transit dip's position are taken into account. By slicing, additional values are eliminated from the whole data.

A predefined algorithm is applied for modeling the light curve. It provides a way to look at the effects of limb-darkening light curves observed during occultation events and is based on published research articles Mandel and Agol (2002) and Carter et al. (2008). This algorithm can be useful in modeling and analyzing the light curves of exoplanetary transits in astronomical research. The modeling of a light curve can be done by inputting several parameters. The parameters include mid-transit time t_c , impact parameter b, ratio of stellar radius to semi major axis R_*/a, ratio of planet radius

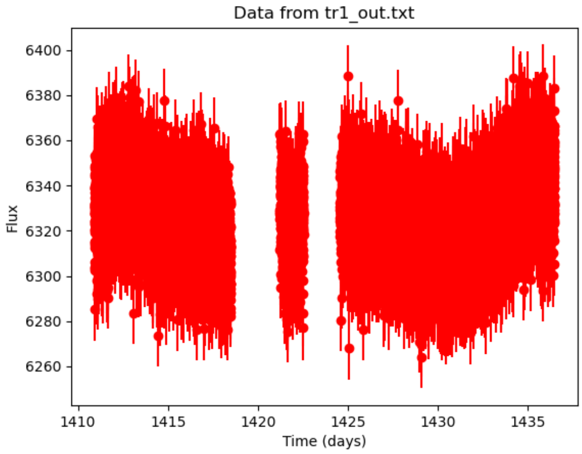

Figure 3.1: Null removed plot of TOI-776b

to stellar radius R_p/R_*, flux F, linear limb darkening coefficient C1, and quadratic limb darkening coefficient C2. In this mid-transit time and flux are roughly estimated from the plot.

3.2.1 Transit parameters

The mid-transit time of a planet is the time when it is directly in front of its star as observed from Earth. This is the point in the planet's orbit where it blocks the most light from the star, causing the brightness of the star to decrease. Time is expressed in Barycentric Julian Date (BJD). It is the most practical absolute time stamp for extraterrestrial events, but it is ultimately limited by the target system's properties(Eastman, 2012).

The impact parameter (Perryman, 2018) is the projected distance in units of R_* between the planet and star centers during mid-transit. It is the shortest projected distance between the centers of the two objects at mid-eclipse. Both the shape and depth of the transit light curve are influenced by the impact parameter. A small impact parameter planet will generate a deeper and more prominent dip in the light curve, whereas a big impact parameter planet will cause a shallower and less intense dip.

The parameter R_*/a is the ratio of the star radius to the semimajor axis. It is a measure of how large a star is in comparison to the average distance between the star and its planet. This parameter could be used to calculate the temperature of the planet. One of the primary parameters determining a planet's temperature is the quantity of light it gets from its star. As a result, a planet with a high R_*/a value will be hotter than one with a low R_*/a value.

R_p/R_* is the ratio of planet radius to stellar radius. It is a measure of a planet's size relative to its host star and it is an important parameter in transit modeling since it indicates the depth of the transit event. The transit depth, which measures how much light an exoplanet blocks during transit, is proportional to the square of R_p/R_*. A deeper transit is produced by a bigger R_p/R_*, and a shorter transit is produced by a smaller R_p/R_*.

The flux is the quantity of light released by the star that reaches the exoplanet's surface. When a planet transits its host star, it temporarily reduces the star's flux when viewed from Earth. The decrease in flux offers significant data that may be used to calculate the size and orbital period.

Limb darkening is the decline in intensity in a stellar image as it moves from its center to its limb. It is the outcome of the interaction of optical depth with decreasing stellar density and temperature with radius. It is commonly represented by functions of cosθ, where θ is the angle between the normal to the stellar surface and the observer's line-of-sight. More specifically, a transit light curve is caused by the planet's atmosphere and its own attenuation of the stellar photosphere, which causes the planet's limb to darken(Perryman, 2018). A mathematical function called a limb darkening model depicts how a star's disk gets dimmer as it gets closer to its edge. The models are linear limb darkening, quadratic limb darkening and non-linear limb darkening. Here we use two limb darkening coefficients C1 and C2.

Light curve modeling has been done using these parameters.

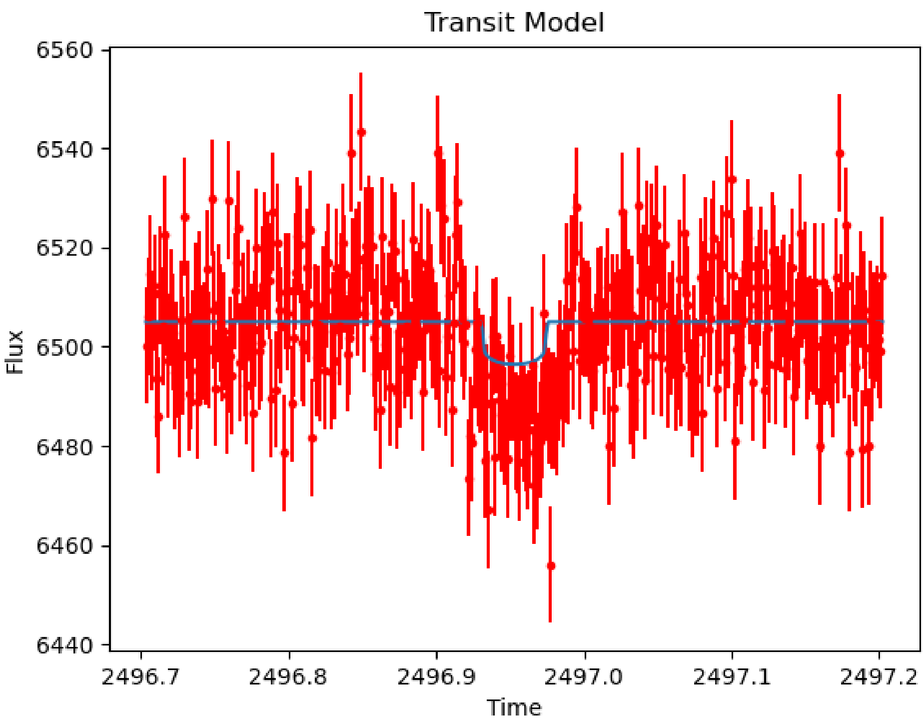

Figure 3.2: Modeled light curve of TOI-1468b

The values for b, R_*/a, R_p/R_* that were taken directly from NASA Exoplanet Archive are not very precise. The Markov-chain Monte-Carlo (MCMC) sampling technique has been used to model and obtain more accurate values than in previous studies.

3.3 MODELING USING MCMC

A statistical approach for modeling data is called Markov chain Monte Carlo (MCMC) fitting. It is an effective tool for fitting models to data.Monte-Carlo and Markov chain are two characteristics combined in the acronym MCMC. Monte-Carlo is a technique for analyzing random samples from a distribution in order to estimate its properties. The Markov chain property of MCMC refers to the concept that a special sequential procedure is used to create random samples(Van Ravenzwaaij et al., 2018). Here, the modeling has been done using the Metropolis Hastigs algorithm. By sampling from the posterior distribution of the model parameters, it can be used to fit models to data. The estimation of likelihood function is given by the equation

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

A is independent of θ, so it can be neglected.Here y_n is the observed data, $f_\theta(t)$ model function and σ_n is the 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.

5000 iterations have been chosen for each of the 30 independent walkers in the MCMC sampling technique. In order to get more precise values, a large number of sampling is done. We have updated the algorithm to account for multiple transits. The first 20,000 iterations have been discarded to obtain posterior distributions.

3.3.2 DERIVED PARAMETERS

The posterior distribution of transit parameters from the MCMC sampling technique has been adopted to estimate physical properties (Saha et al., 2021)

We have estimated transit duration T_{14}

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

The equilibrium temperature Teq is estimated by the relation

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

Inclination angle of the planetary orbit i is estimated using the relation

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

4 RESULTS

I have changed the parameter values and ranges multiple times in order to get a saturated plot. After repeating it several times, the following saturated plots are obtained. These values are chosen as a new set of parameters.The obtained parameters are tabulated in table 4.1.

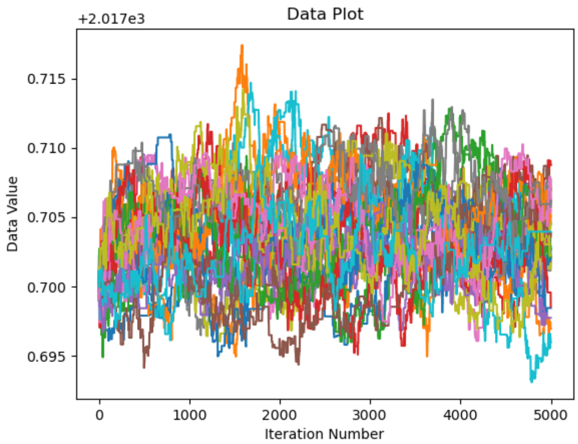

Figure 4.1: mid-transit time1

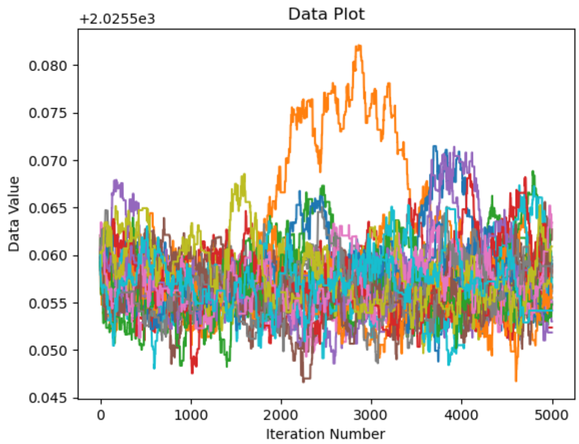

Figure 4.2: mid-transit time2

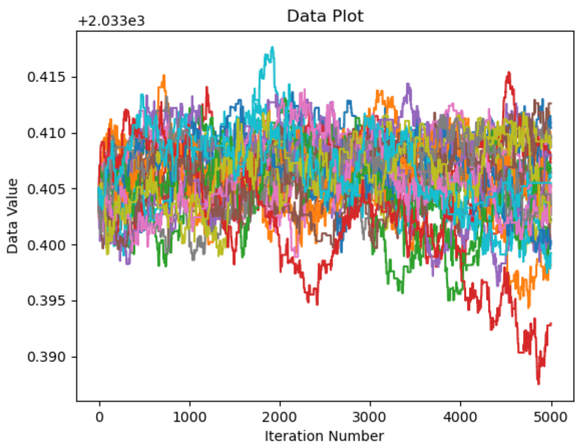

Figure 4.3: mid-transit time3

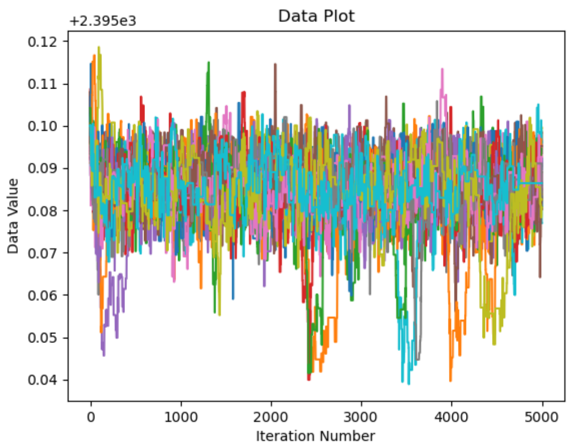

Figure 4.4: mid-transit time4

Figure 4.5: mid-transit time5

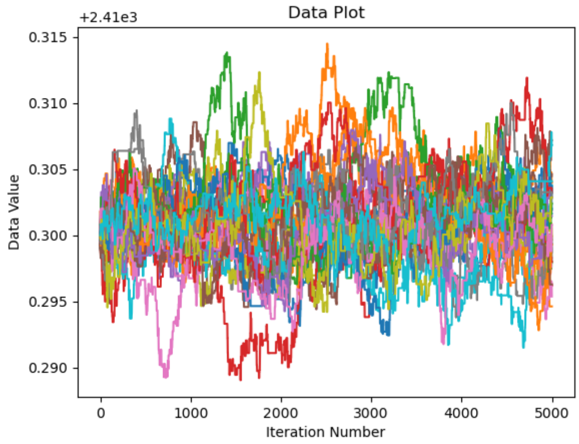

Figure 4.6: mid-transit time6

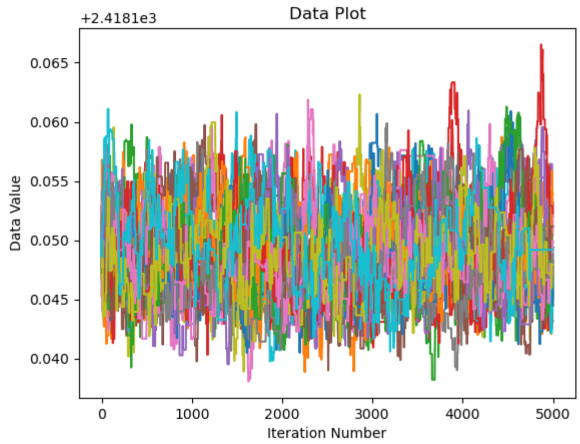

Figure 4.7: mid-transit time7

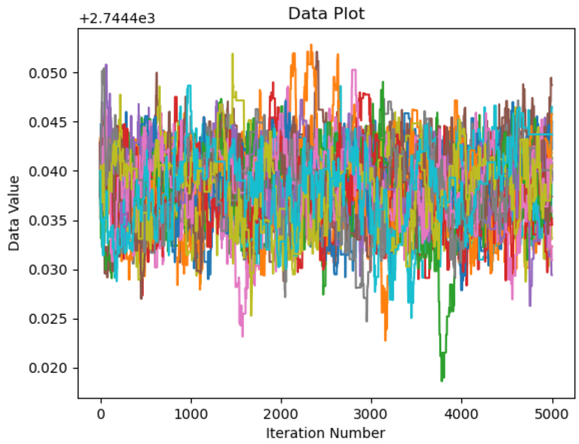

Figure 4.8: mid-transit time8

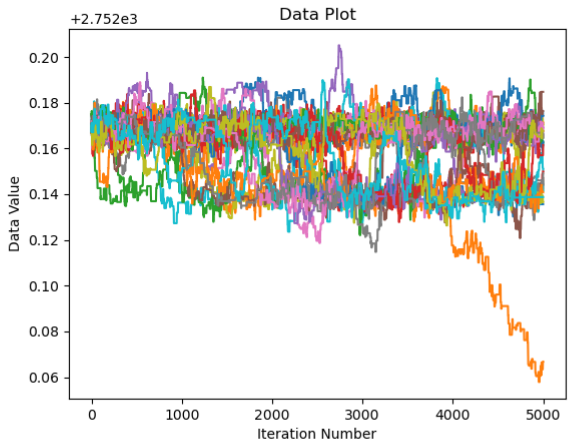

Figure 4.9: mid-transit time9

Figure 4.10: mid-transit time10

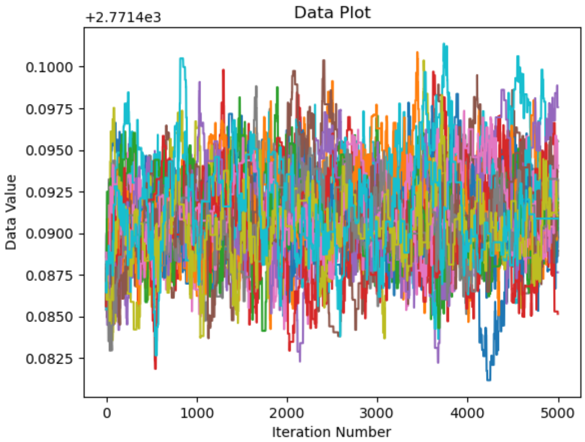

Figure 4.11: mid-transit time11

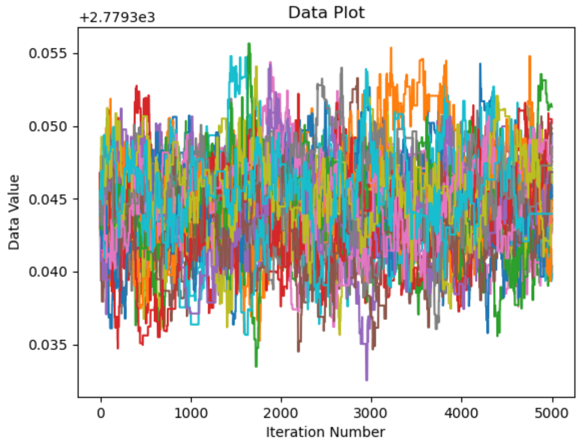

Figure 4.12: mid-transit time12

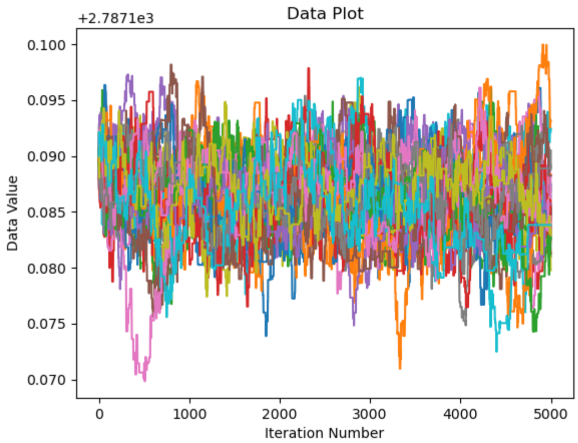

Figure 4.13: mid-transit time13

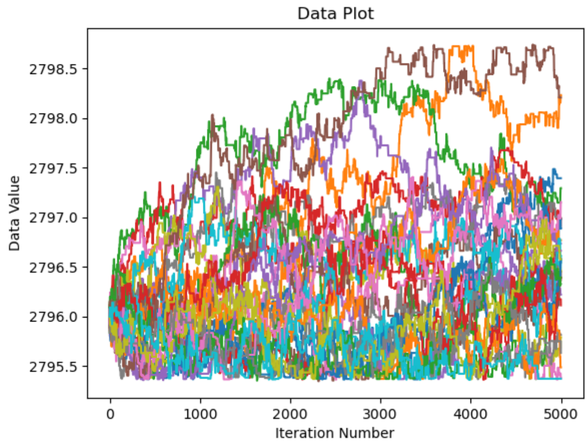

Figure 4.14: mid-transit time14

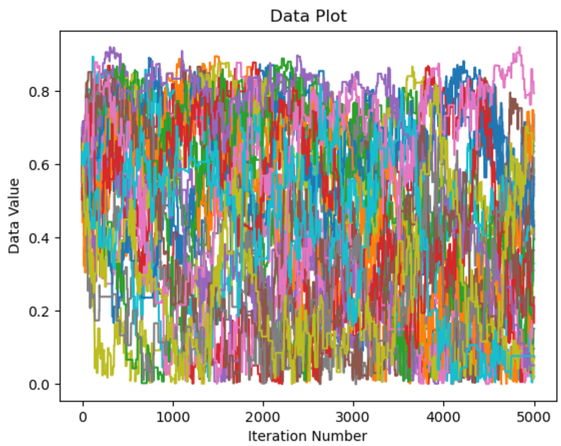

Figure 4.15: b

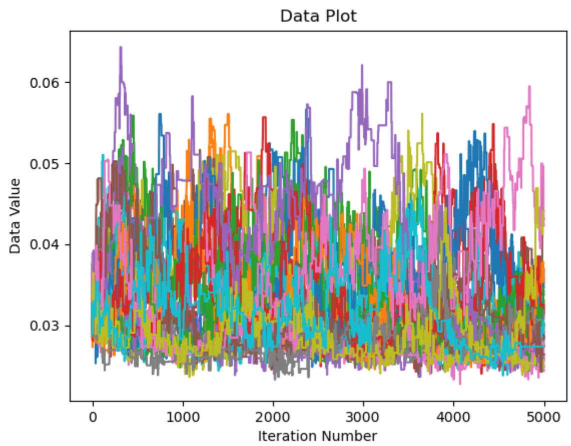

Figure 4.16: R_*/a

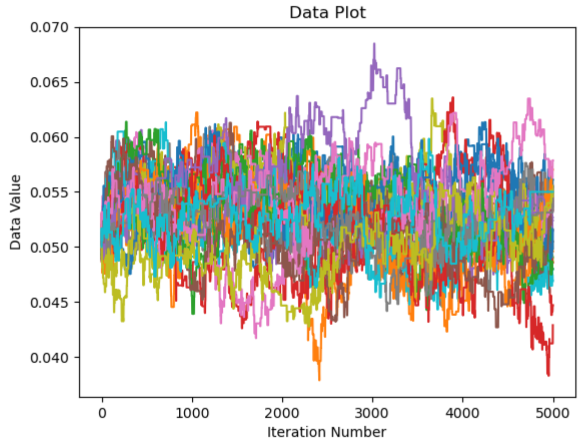

Figure 4.17: R_p/R_*

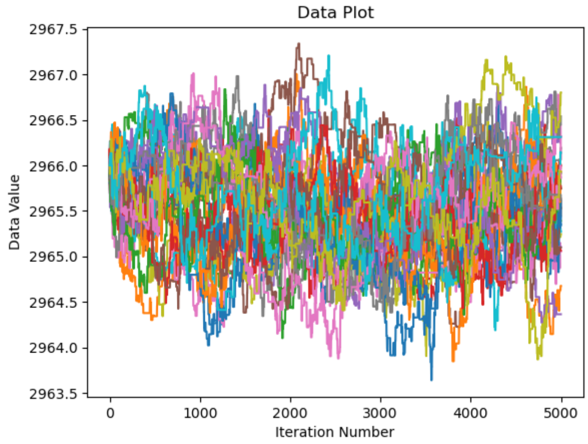

Figure 4.18: flux1

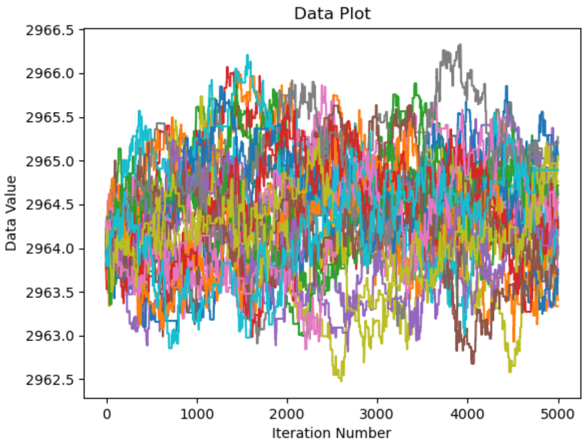

Figure 4.19: flux2

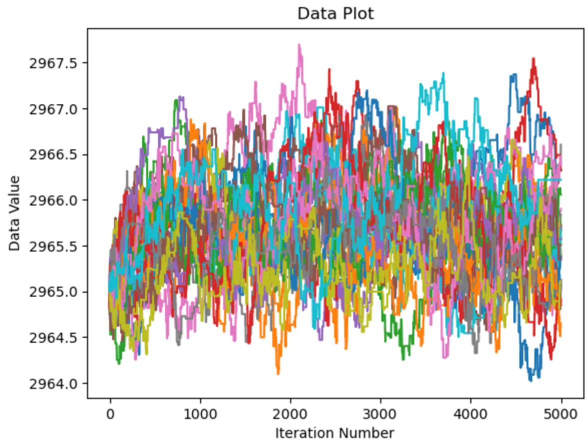

Figure 4.20: flux3

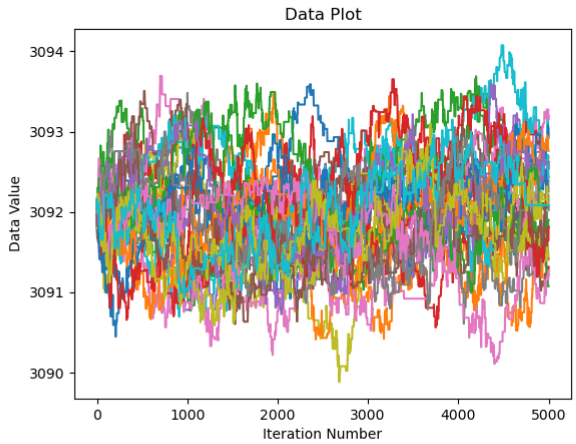

Figure 4.21: flux4

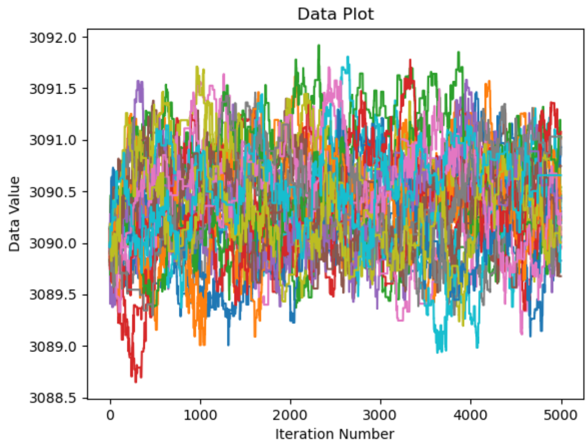

Figure 4.22: flux5

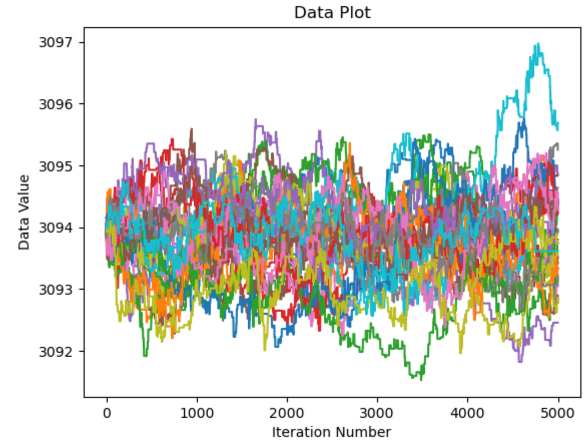

Figure 4.23: flux6

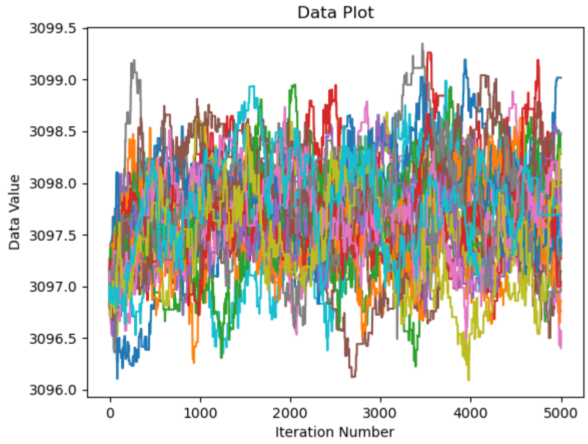

Figure 4.24: flux7

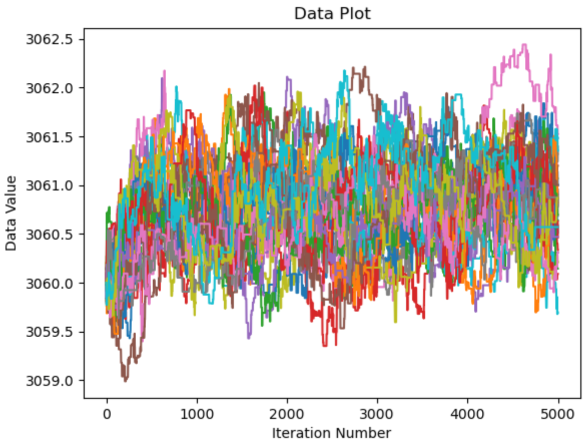

Figure 4.25: flux8

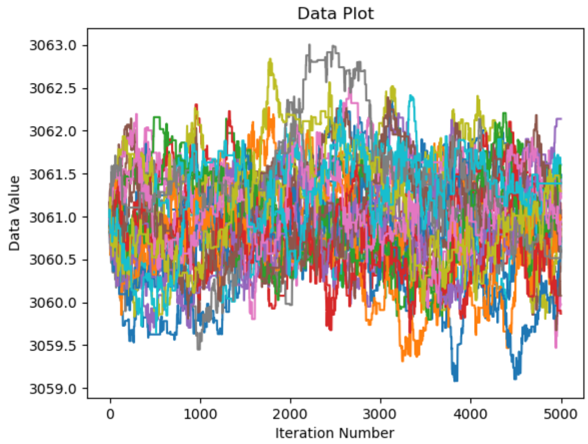

Figure 4.26: flux9

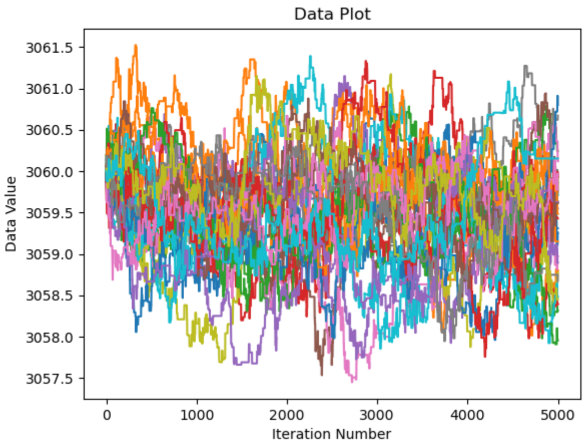

Figure 4.27: flux10

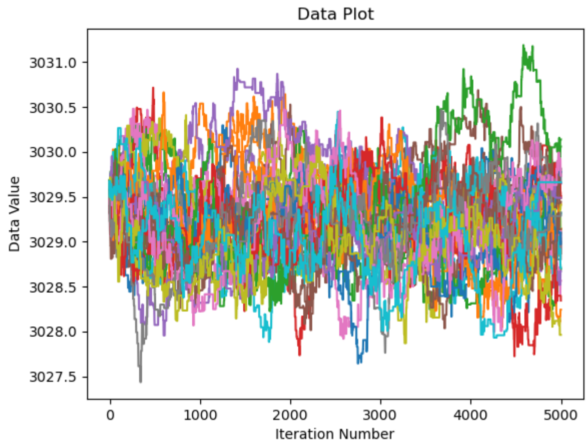

Figure 4.28: flux11

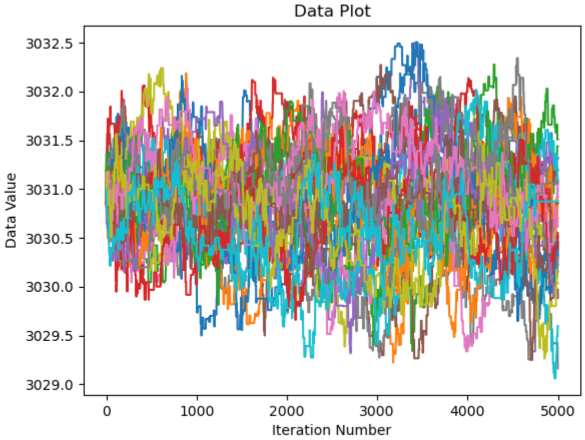

Figure 4.29: flux12

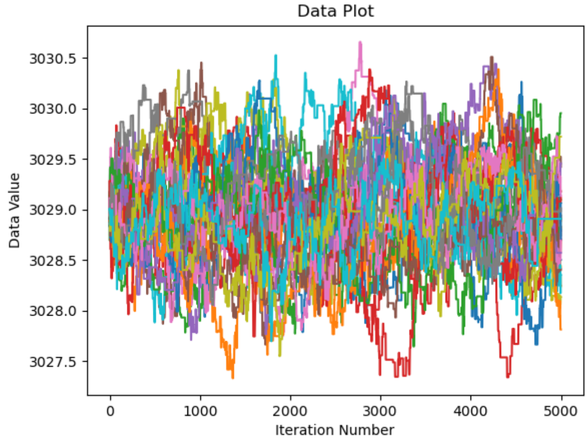

Figure 4.30: flux13

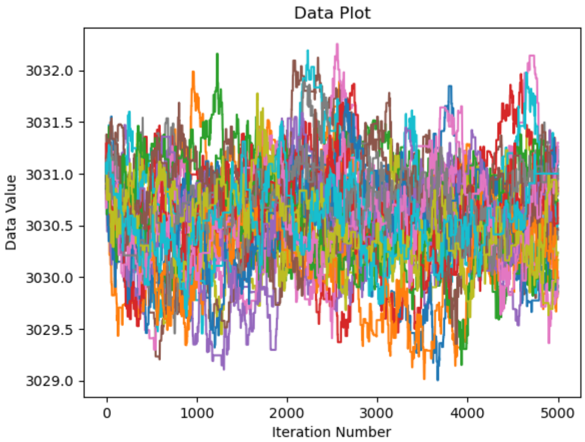

Figure 4.31: flux14

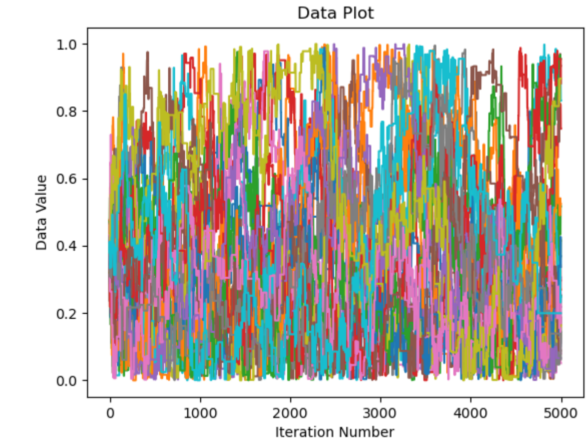

Figure 4.32: C1

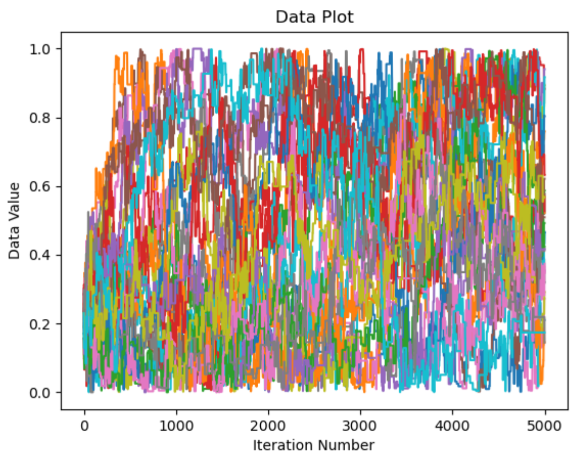

Figure 4.33: C2

Table 4.1: Comparison between observed parameters and previously observed parameters of TOI-2136 b

Parameters	Observation	(Gan et al., 2022)	(Beard et al., 2022)	(Kawauchi et al., 2022)
b	$0.375^{+0.281}_{-0.168}$	$0.35^{+0.20}_{-0.18}$	$0.41^{+0.10}_{-0.10}$	$0.462^{+0.067}_{-0.078}$
a/R_*	$33.557^{+0.006}_{-0.001}$	$35.75^{+1.98}_{-2.01}$	$35^{+1.3}_{-1.3}$	$33.35^{+0.67}_{-0.71}$
R_p/R_*	$0.052^{+0.002}_{-0.001}$	$0.059^{+0.001}_{-0.0009}$	$0.058^{+0.001}_{-0.001}$	$0.0588^{0.0006}_{-0.0006}$
T_{14}	$1.623^{+0.104}_{-0.057}$		$1.66 + 0.02 - 0.02$	
i	$89.363^{+0.427}_{-0.367}$	$89.4^{+0.3}_{-0.4}$	$88.441^{+0.003}_{-0.003}$	$89.20^{+0.12}_{-0.09}$
T_{eq}	$408.14^{+41.82}_{-12.922}$	395^{+24}_{-22}	403^{+5}_{-5}	378^{+13}_{-13}
C1	$0.311^{+0.277}_{-0.129}$			
C2	$0.484^{+0.293}_{-0.181}$			

TOI-2136 b

5 CONCLUSION

In this work, I have analyzed already discovered super-Earth exoplanets. This project includes data collected by the TESS mission, which were available in the Mikulski Archive for Space Telescopes and NASA Caltech. With the use of the MCMC sampling technique, modeling of the light curves was done with the available data.

With the aim of obtaining a saturated plot, the ranges and the parameters have been changed multiple times. The set of values that give a saturated plot has been chosen as the final result. The results have been compared with previous studies. Some of the parameters were more accurate and precise than in the previous studies, but some of them were not. By executing this procedure a few more times, I will be able to achieve the required accuracy.

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ACKNOWLEDGEMENTAny

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this project.I would like to express my gratitude to Dr

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