Project Report on

ANALYSIS OF LIGHT CURVE OF EXOPLANET AND DETERMINATION

OF PHYSICAL PARAMETERS BY TRANSIT METHOD

Submitted by

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Submitted to

Department of Physics

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In partial fulfilment of the requirements for the award of the

Master of Science in **SPACE SCIENCE**

September 2022

ACKNOWLEDGEMENTS

DECLARATION

I, **ASWATHY SASI**, do hereby declare that the project report entitled "Analysis **of light curve of exoplanet and determination of physical parameters by Transit method**" is a bona-fide record of the work submitted to Mahatma Gandhi University in partial fulfilment of the requirement for the award of the degree of MSc in Space Science carried out by me under the guidance of Dr. Binukumar G, Post Doctoral Fellow, Indian Institute of Astrophysics, Bangalore.

Place: Thrikkakara   **ASWATHY SASI**

Date: 24/09/2022

ABSTRACT

This project report contains the analysis of the light curve obtained by the Transit method of exoplanet detection. The data collected by a dedicated exoplanet space probe known as Transiting Exoplanet Survey Satellite (TESS) is chosen for the study and analysis for this particular project. Different methods for the discovery of exoplanets are also discussed in detail. The physical parameters of the exoplanet such as the radius, orbital period, semi-major axis, transit impact parameter and orbital inclination of the planet are determined using transit data. Transit data from the data archive is presented in the form of 'Light Curves' and the data was analysed by a Python based programme. The above mentioned physical parameters of the exoplanets were obtained from the light curve and the results are presented here. In addition to that, future scope of such work with contemporary relevance in this emerging area of research is briefly discussed here.

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CHAPTER 1

INTRODUCTION

1.1   Exo-planets

The planets that are found outside the Solar System are called as exoplanets or extrasolar planets. Most exoplanets orbit any star but some free-floating planets orbit the galactic centre and they are called as rogue planets. They are untethered to any star.

Exoplanets are made of same elements as the planets in Solar System but their ratio may vary. Some planets may be dominated by water while others by iron or carbon. By measuring the size and mass of exoplanets, it's composition ranging from rocky to gaseous can be identified. The first exoplanets outside the solar system were identified in 1990s. Now more than 4000 exoplanets have been discovered through different detection methods.

Exoplanets are very faint light source as compared to their host star. Hence, scientists rather use indirect methods than direct imaging technique using telescope. (1)

1.2   Detection Methods of Exoplanets

There are mainly five methods used for detecting the exoplanets. They are mentioned below.

1.2.1   Radial Velocity method

In response to the planet's gravity a star will move in its own small orbit. This leads to variations in the radial velocity of the star with respect to the Earth. The radial velocity can be deduced from the displacement in spectral lines of the parent star due to Doppler Effect.

The star wobbles around its orbit due to the small gravitational effect of the planet. As the planet moves to and fro, the light waves get compressed and stretched out. This causes change in the colour of light we see.

Velocity variations greater than 3 m/s can be detected using modern spectrometers such as HARPS (High Accuracy Radial Velocity Planet Searcher). This method is one of the successful ways to find exoplanets. Often, the method of radial velocity is used to confirm the planets that are found by other detection methods. About 915 planets are discovered using this method.
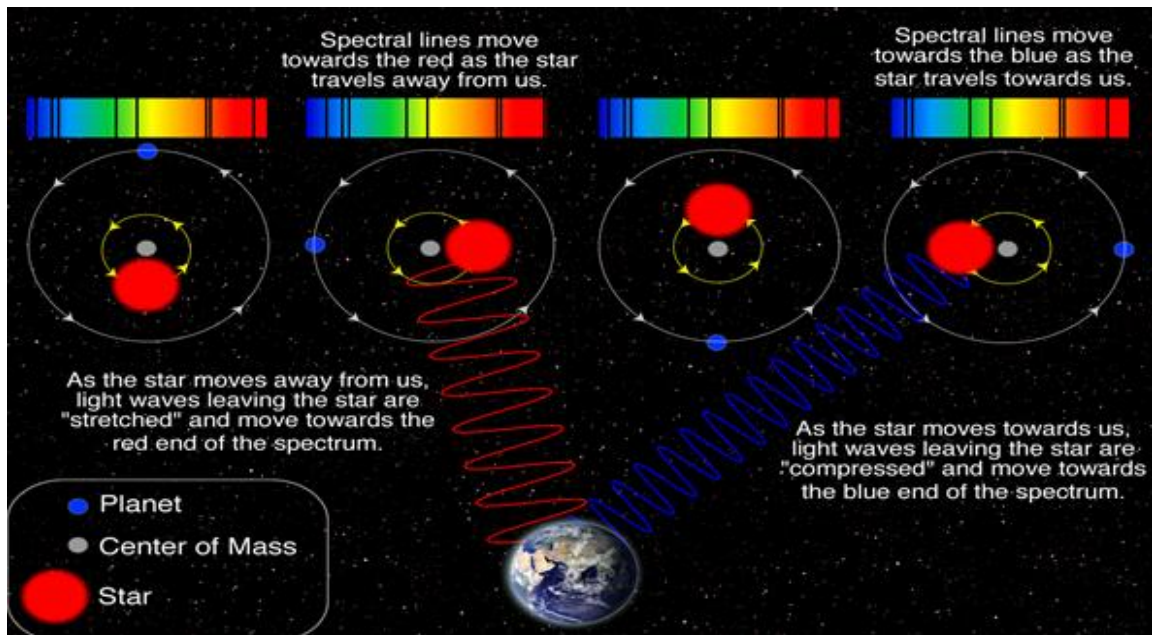
Figure 1. Radial velocity method

1.2.2 Transit Method

When a planet transits across the parent star's disk, the visual brightness observed of the star drops by small amount depending on the relative sizes of the planet and the star. The graph plotted is known as light curve. When the planet passes in front of its host star blocking some of its light, the light curve indicates the drop in brightness. Bigger planets block more light and they create deeper light curves. Also, the planets that are farther away take longer time to orbit and pass in front of its star.
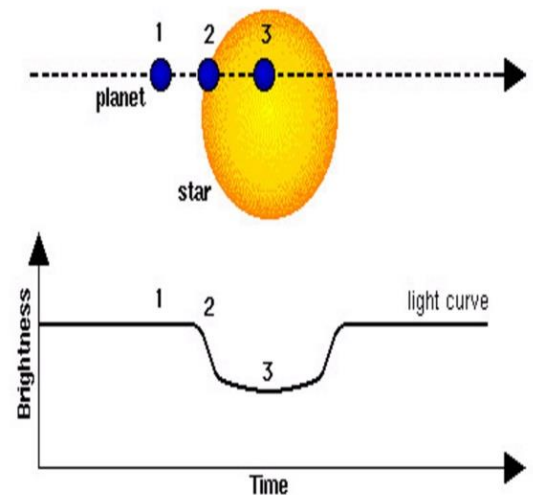
Figure 2. Transit Method

The transit method also gives the information about the composition of a planet's atmosphere or its temperature. By analysing the colours of the starlight passing through the atmosphere of the planet, scientists have found the presence of methane to water vapour on other planets. About 3780 planets are discovered by transit method.

1.2.3 Direct Imaging

In this method, the pictures of the exoplanets are taken by removing the overwhelming glare of the stars they orbit. Various techniques are used to block out the light of stars that the planets orbit. Once the glare of the star is reduced, the planets can be observed. There are two main methods that are used to block the light of stars.

a) *Coronography:* A device is used inside the telescope to block the light of the star before it reaches the telescope's detector.

b) *Starshade:* It is a device that is positioned to block the starlight before it enters the telescope. For a space-based telescope, the starshade would be a separate spacecraft, which is designed to position itself at right distance and angle to block the corresponding starlight.
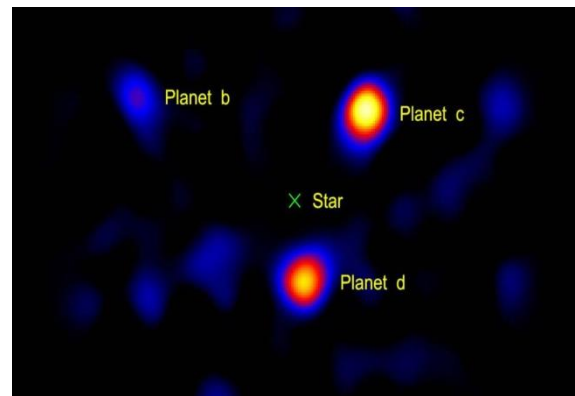
Figure 3. Direct imaging method

Direct imaging techniques help us to identify atmospheric patterns, oceans and landmasses on exoplanets. About 58 planets are discovered using this method.

1.2.4 Gravitational Microlensing

Gravitational microlensing occurs only when two stars are almost exactly aligned. The gravitational field of a star acts like a lens thus magnifying the light of a distant star. That is, gravitational microlensing happens when a star or planet's gravity focuses the light of another more distant star in such a way that makes it seem brighter temporarily. Lensing events can last for weeks or days as the two stars and the Earth are all moving relative to each other. About 129 planets are discovered by gravitational microlensing. (2)
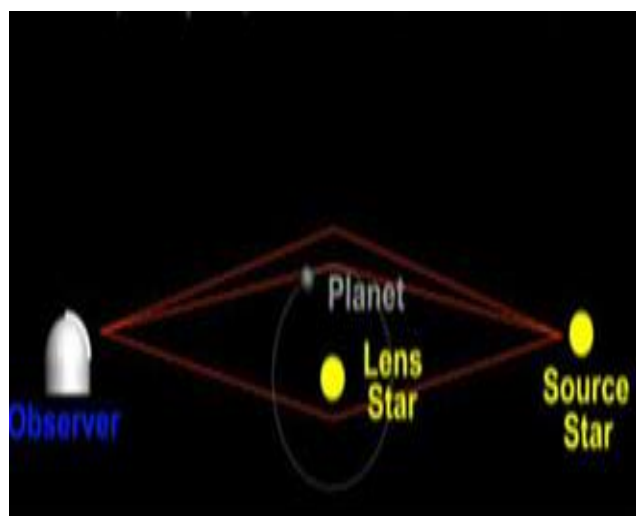
Figure 4. Gravitational microlensing

1.2.5 Astrometry

In this method, the precise position of the star in the sky is noted and the change in that position is measured with respect to other stars. If a star has a planet, the gravitational influence of the planet will cause the star to move in a small elliptical or circular orbit. Hence, the star and planet orbit around their mutual centre of mass called the Barycentre. The orbit of the star will be much smaller since it is more massive. It is easier to find the planets around low-mass stars like the brown dwarfs.

The orbit of a planet causes a star to wobble around in space with respect to the nearby stars. The apparent change in star's position can be detected. However, stars wobble very minute distance and it's very difficult to accurately detect the wobble from planets, especially small ones as the size of the Earth. A series of images of a star and some of the other that are near it in the sky are taken in order to track the movement of these stars. The distance between the reference stars and the star of interest is compared in each picture. Astronomers analyse the movements for signs of exoplanets.

Astrometry requires extremely precise optical devices and is difficult to do from the Earth's surface due to atmospheric refraction. 61 Cygni is the only planet discovered by the method of Astrometry. (3)

1.3 Ground based instruments for exoplanet search

1.3.1 The Anglo-Australian Planet Search

The Anglo-Australian Planet Search (AAPS) is a long-term astronomical survey which started in 1998. It is carried out by a 3.9 metre Anglo-Australian Telescope (AAT) of the Anglo-Australian observatory in Australia. The survey is done to catalogue planets around more than 240 nearby stars of the southern hemisphere. The survey uses the radial velocity method to detect the extrasolar planets. The target stars include F,G and K V-IV stars with V<7.5 and M V stars with v<11.5. The first observation is a 51 Peg-like planet around the star HD 179949 with M sin i =0.84 M_{JUP}. The second observation is a brown dwarf or a very low mass star companion to HD 164427, which is in an eccentric orbit with M sin i = 46 M_{JUP}.

Figure 5. Anglo-Australian Telescope

The star HD 179949 is an F8 V star which has had confirmatory observations. It has a moderate x-ray luminosity and is metal-rich than the majority of the disk main-sequence stars. The Hipparcos magnitude, colour index and parallax of HD 179949 suggest that it has a radius of about 1.24 $R_\odot$. Almost 23 observations are made about HD 179949.

HD 164427 is an inactive G0 V star. Recent work on the mass function of brown dwarfs in star clusters has failed to show that the star formation processes cannot form objects below 13 M_{JUP} deuterium burning limit. Only an understanding of formation mechanisms can allow us to determine whether objects in the 5-20 M_{JUP} range are planets or brown dwarfs. Since maximum mass of the companion of HD 164427 lies in a range unlikely to be due to planetary formation processes, it is clear that it is a brown dwarf or a star, not a planet.

The Anglo-Australian Planet Search is now the highest-precision Doppler Planet Search in the southern hemisphere. The survey has discovered more than 28 planetary objects including 3 multi-planet systems. The survey extends its sensitivity towards Jupiter-like planet regime. (4, 2001)

1.3.2 The High Accuracy Radial Velocity Planet Searcher

The High Accuracy Radial Velocity Planet Searcher (HARPS) is a fibre-red, cross-dispersed, high precision echelle spectrograph that became operational on 1st October 2003. Two fibres, an object and a reference fibre, feed the spectrograph with the light from the telescope as well as the calibration lamps. The spectrograph re-images the fibres on a mosaic of two 2K4 CCDs, where two echelle spectra of 72 orders are formed for each fibre. The resolution of the

spectrograph is given by the diameter of the fibre and has a value of about R = 115,000. Even at this resolution each spectral element is sampled by 3.2 CCD pixels.

HARPS is an ordinary spectrograph with outstanding efficiency, spectral resolution and mainly extraordinary stability. It uses the ThAr-reference technique to measure and correct the tiniest instrumental drifts. To avoid any kind of second-order instrumental errors, the spectrograph is operated in vacuum, where the temperature and pressure are strictly controlled. The operating pressure is always kept below 0.01 mbar and the air temperature to 17° C.

Figure 6. HARPS

HARPS has been optimised for radial-velocity efficiency. It can obtain the most precise radial-velocity measurement in the shortest possible exposure time. The short-term precision (1 night) of HARPS is below 1 m/s. Even in the time scale of a commissioning period (two weeks) it was able to measure standard stars which showed radial-velocity dispersions of 1 m/s including photon noise. Acoustic waves are generated in stars, by turbulent convections near their surfaces. Frequencies and amplitudes of these acoustic waves depend on the physical conditions of the layers crossed by the waves and provide a powerful seismological tool.

HARPS was able to detect an unambiguous oscillation signal of 31 m/s amplitude of the star α Centauri A. Several oscillation modes were separated and clearly identified using these measurements. Because of the limited duration of the tests, the measurements made on α Centauri B with HARPS have lower frequency resolution. However, the measurements obtained with HARPS have the advantages of high efficiency and high precision. The HARPS was also able to observe planets around faint stars like OGLE-TR-56 with visual

magnitude 16-6. From a hundred planets detected, only a few have masses less than that of Saturn. (5)

1.3.3 The WASP Project and the SuperWASP Cameras

The WASP or Wide Angle Search for Planets is an international consortium of several academic organisations, established in 2000, which is used for an ultra-wide angle search of exoplanets using transit photometry. The SuperWASP cameras are wide-field imaging systems situated at the Observatorio del Rogue de los Muchachos on the island of La Palma in the Canary Islands (SuperWASP-North), and at the Sutherland station of the South African Astronomical Observatory (SuperWASP-South). Each instrument has a field of view of about 482 days with an angular scale of 13.7″ pixel^{-1} and is capable of delivering photometry with accuracy better than 1% for objects that have V~$7.0 - 11.5$.

Figure 7. The SuperWASP cameras

The SuperWASP cameras use eight wide-angle cameras to monitor the sky for planetary transit events simultaneously and also allow the monitoring of millions of stars simultaneously, enabling the detection of rare transmit events. The SuperWASP CCD cameras are back illuminated with a peak quantum efficiency of above 90%. It is manufactured by Andor Technology which uses a five-stage thermoelectric cooler to reach an operating temperature of -75℃. At this temperature the dark current is approximately 11 e pixel^{-1} hr^{-1}, which is comparable to cryogenically cooled devices. Since its exposure time is only 30s, it does not require this level of performance, hence the devices are cooled to -50℃, at which point the dark current is approximately 72 e pixel^{-1}hr^{-1}. Andor Technology also provides a 32 bit PCI controller card to control all CCD functions. As of the year 2016, the Extrasolar Planets Encyclopaedia data base consists of a total of 2,107 planets of which 118 were discovered by WASP. (6, 2006)

1.3.4 The HATNet and HATSouth projects (HAT)

The Hungarian Automated Telescope Network (HATNet) has been in operation since 2003, for an all-sky variability search of the northern hemisphere. It has the goal of discovery and accurate characterization of transiting extrasolar planets (TEPS) around bright stars. It is a small autonomous observatory that records the brightness of stars in the range of $I_c \approx$ 6-13 magnitude with a telephoto lens and its 9° x 9° field of view, yields a data rate of ~10^6 photometric measurements per night.

Figure 8. HATNet Observatory

Figure 9. HATSouth Observatory

The Hungarian Automated Telescope (HAT) hardware consists of an equatorial telescope mount, enclosure (dome), CCD, a telephoto lens and a PC. Several devices like as a rain detector, photo sensor and lens-heating and dome-flat lights are attached to the dome and telescope. The software system consists of an ordinary Linux OS with a Real-Time Linux kernel (RTLinux). RTLinux is a real-time, multitask operating system in which the kernel treats the real-time processes as independent "threads" with response times better than 15 μs. HAT uses the fast, reliable and open-source relational structured Query Language (MySQL) database for storing associated parameters of the station (setup of mount, telescope, CCD, scheduled tasks etc) and for keeping continuously accumulating logs of operations (parameters of archived images etc.) all of them arranged into tables.

The observatory as a whole is managed by a virtual observer that communicates with the access module and central database and executes (observer) programs. It is a Tel language-based simulation of near-perfect observer, which is modelled as a finite-state machine, which makes decisions or transitions depending on the circumstances.

During normal operations, the observer is in the "run" state, while if the weather is unfavourable, it passes to a "weather sleep" state, in which the CCD is kept cooled, the dome is closed and the system waits for clearing. If the weather permits, the HAT South network could make a round-the-clock observations of a 128 square are degree swath of the sky at any given time. HATSouth has discovered over 36 transiting exoplanets and both HATNet and HATSouth have discovered ~100 exoplanets of this kind. (7, 2002)

1.4   Space missions in search of exoplanets

1.4.1 The Kepler Mission

The Kepler Mission is designed to survey our region of the Milky Way galaxy to discover hundreds of Earth-size and smaller planets in or near the habitable zone and determine the fraction of the hundreds of billions of stars in our galaxy that might have such planets. The objective of the Kepler Mission is to explore the structure and diversity of planetary systems.

The mission does survey on a large sample of stars to ;

- Determine the percentage of terrestrial as well as larger planets that are in or near the habitable zone of a wide variety of stars.
- Determine the sizes and shapes of orbits of these planets.
- To find out how many planets are there in a multiple-star system.
- Determine the properties of the host stars that harbor the planetary systems.

Kepler uses transit method for detecting extrasolar planets. Since transits last only for a fraction of the day, all the stars must be monitored continuously.
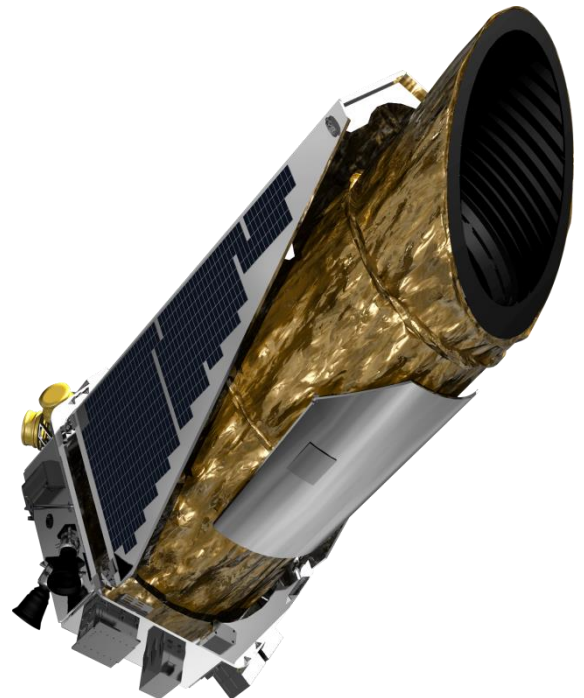
Figure 10. The Kepler Space Telescope

The brightness of stars must be measured atleast once every few hours. Hence the field of view (FOV) must never be blocked at any time during the year. To avoid the sun the FOV should be out of the ecliptic plane. Also, the FOV must the largest possible number of stars. Hence the region in the Cygnus and Lyra constellations is selected. During its 9.6 years in orbit, Kepler discovered more than 2,600 planets by observing more than half a million stars. (8)

1.4.2 The CHEOPS Mission

CHEOPS (Characterising Exoplanet Satellite is ESA's first mission to study the bright, nearby stars that are already known to host exoplanets, in order to make high-precision observations of the planets size as it passes in front of its host star. It was launched on 18 December 2019. It will focus on planets that have the size ranging from the Super-Earth to Neptune size.

Figure 11. CHEOPS space telescope

CHEOPS detects the transits of R V planets by photometric monitoring, if the geometric configuration results in a transit. CHEOPS will be able to improve the transit light curve for hot Neptune discovered from the ground, so that the radius can be determined precisely. High precision R V measurements are possible for all targets because of the host star's brightness. All planets observed in transit by CHEOPS will be validated as well as their masses will be known. (9) (10)

1.4.3 The CoRoT Mission

The Convection, Rotation and planetary Transits (CoRoT), launched on December 27, 2006 is a French satellite that studies the internal structure of stars and detects the extrasolar planets. The mission routinely provides high-precision photometric measurements of thousands of stars that have been continuously observed

Figure 12. CoRoT space telescope

for months. It aims in the discovery and characterization of the first very massive transiting planetary companion with a short orbital period. A series of 34 transits was detected in the CoRoT light curve of an F3 V star. The radius was accurately determined and mass derived for the new transiting by the combined analysis of the light curve and complementary ground-based observations, high precision radial velocity measurement on-off photometry and high signal-to-noise spectroscopic observations. (11) (12)

1.4.4 The JWST

The James Webb Space Telescope (JWST) is the most powerful space telescope launched on December 25, 2021 which is designed primarily to conduct infrared astronomy. Its greatly improved infrared resolution and sensitivity will allow it to view objects too old, distant and faint
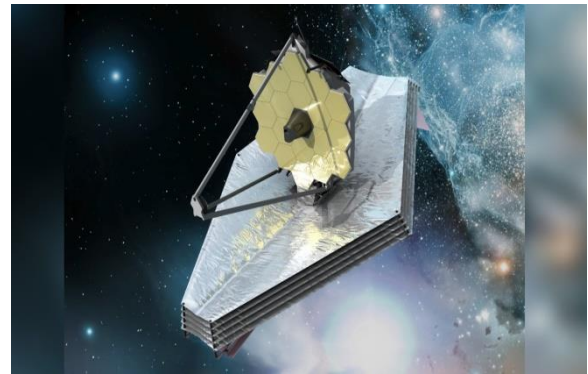
Figure 13 JWST

for the Hubble Space Telescope. The telescope is expected to enable a broad range of

investigation across the fields of astronomy and cosmology, such as observations of first stars and the formation of the first galaxies and detailed atmospheric characterization of potentially habitable exoplanets. (13)

1.5 Transiting Exoplanet Survey Satellite (TESS)

The transiting exoplanets survey satellite TESS is a mission for searching the transiting exoplanets revolving around the nearest and brightest stars. The primary objective is to discover the transiting planets that are smaller than Neptune whose parent stars are bright enough for spectroscopic experiments to measure planetary masses and atmospheric compositions.

Figure 14 TESS

1.5.1 History

The discussions regarding the concept of TESS began at the Massachusetts Institute of Technology (MIT) and the Smithsonian Astrophysical Observatory (SAO) in the late 2005. In 2006, a proposal for a Mission of Opportunity was submitted to NASA for using the optical camera of the High Energy Transient Explorer to perform a survey for transiting planets. This proposal was rejected.

During the late 2006 and early 2007, TESS was reframed as a stand-alone mission that would be privately funded by the Kavli Foundation, Google and MIT. But they could not raise funds for the full mission. In 2008, the concept of TESS as a Small Explorer Mission (SMEX) was proposed to a NASA program with a cost cap of $100m. This concept was funded for a phase A study during 2008-2009, but was not chosen to phase B. In 2011, a refined concept of TESS was submitted to the NASA Explorer program. There were several key improvements like the use of a high-Earth elliptical orbit that provides a more stable platform for precise photometry than the low-Earth orbit. In the late 2011, TESS was selected by NASA as an Explorer mission for phase A study and proceeded to phase B in April 2013.

Features

    (a)   *Sky coverage:*   The prime objective of TESS is to monitor bright stars. Since the brightest stars are evenly distributed over the entire sky, TESS is designed for an all-sky survey.

(b)   *Period sensitivity:*   If the maximum period P_{max} is chosen as short as 10 days, habitable zone planets around sun-like stars can be detected. Also, it is possible to

find habitable zone planets M stars, if a portion of the sky is observed for atleast 40 days. In account of these considerations, P_{max} is chosen as $\cong$ 10 days in general and $P_{max} \geq$ 40 days for as large as an area surrounding the ecliptic poles.

(c) *Types of stars monitored:* TESS mainly concentrate on main sequence dwarfs with spectral types F5 to M5. Since the evolved stars and early-types dwarfs are large, the detection of small planets is difficult. Dwarfs with spectral type earlier than F5 rotate rapidly leading to the broadening of their spectral lines that prevents the precise radial-velocity monitoring. About three-quarters of the stars near the Solar System are M0-M5 dwarfs and M dwarfs are common in the Milky Way. Stars with spectral lines later than M5 are rarer and optically faint.

(d) *Detector and bandpass:* Silicon charge- coupled devices (CCDs) are the best astronomical detectors in the optical band. They have excellent linearity and dynamic range for bright objects, and a long spaceflight heritage. A wide bandpass is chosen in order to reduce the photon counting noise. Also, small planets are more easily detected around small stars, which are cool and red; hence an enhanced sensitivity to red wavelengths is required. TESS has chosen a 600-1000 nm bandpass.

(e) *Number of stars monitored:* TESS is designed to monitor atleast 500 stars for each super-Earth detection. Therefore, in order to find hundreds of such planets, TESS is required to monitor more than 10^5 stars. TESS monitors about 2 x 10^5 stars according to transit detectability rather than strictly on apparent magnitude. This leads to the limiting apparent magnitude of $I_c \leq$ 10-13 depending on the spectral type. The brightest 10^5 dwarf stars have a limiting apparent magnitude of $I_c \approx$ 10. Hence, the faint M stars can be searched for small planets even though they have small sizes.

(f) *Aperture size:* In order to detect planetary transits, the stars must be monitored with sufficient photometric precision. The transit depth (d) varies with the radii of the star (R_*) and planet (R_p)

$$d = (337 \text{ ppm}) (R_p/2R_\oplus)^2 (R_*/R_\odot)^{-2}$$

The transit duration (T) depends on the stellar mean density (ρ_*), the orbital period (P) and the dimensionless transit impact parameter(b)

$$T = (3.91 \text{ hr}) (\rho_*/\rho_\odot)^{-1/3} (P/10 \text{ days})^{1/3} \sqrt{(1 - b^2)}$$

The results indicated that an effective collecting area of 50 cm or an effective aperture diameter D ≈ 10 cm is sufficient to detect hundreds of super-Earths.

(g) *Time sampling:* The typical transit durations are measured in hours, hence the time sampling of the photometric observations should be less than an hour. For planets smaller than Neptune the time scale of the partial transit phases is several minutes. To avoid excessive smearing of the partial transit signals, a time sampling of less than a few minutes is preferred. For TESS, the brightness measurements of the preselected stars will be recorded every two minutes.

(h) *Orbit:* An elliptical orbit around the Earth is chosen, with approximate perigee and apogee distance of 17 and 59 $R_\oplus$ and a period of 13.7 days, since the requirements for the TESS spacecraft were continuous observations lasting for weeks and stability to perturbations. Also, it required a low-radiation environment and a stable thermal environment. Again, to make data transfer easier the spacecraft should be close to the Earth during atleast a portion of the orbit.

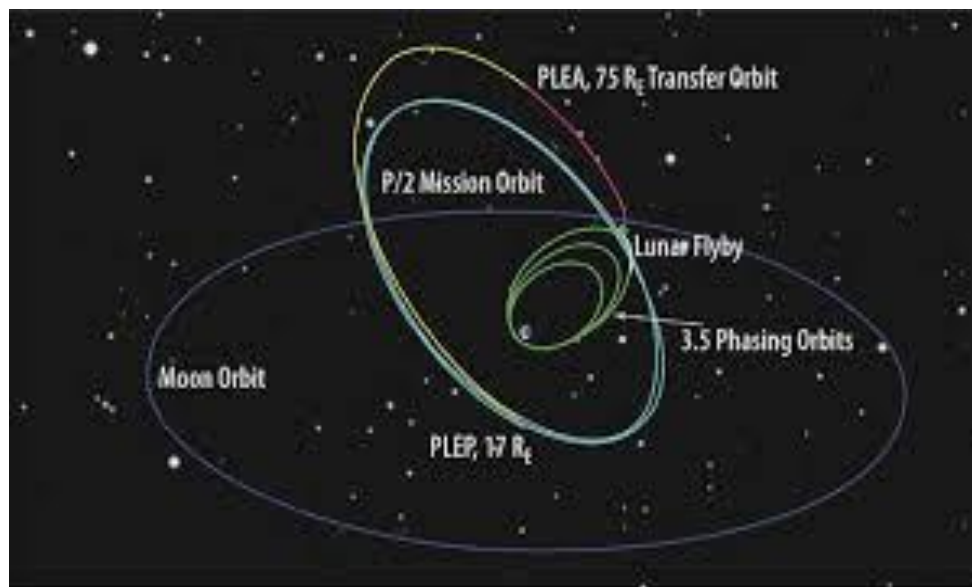Figure 15 TESS orbit

1.5.2 Payloads

The payload consists of four identical cameras and a Data Handling Unit (DHU). Each camera consists of a lens assembly that has seven optical elements and a detector assembly with four CCDs. Each of the TESS lenses is an f/1.4 custom design with an entrance pupil diameter of 10.5 cm. A 24° x24° unvignetted image is formed on the four CCD mosaic in

the focal plane of the lens. In order to reduce the effects of scattered light from the Earth and Moon, the lens is equipped with a lenshood.

The Data Handling Unit (DHU) is a Space Micro Image Processing Computer (IPC-7000). It consists of five boards which are given below.

i)   *The Image Processing Computer (IPC):*   It contains two Virtex-7 field-programmable gate arrays (FPGAs) that are interfaces to the four cameras. They perform high speed data processing.

ii)   *The Proton 400k computer:* It does the work of commanding, communicating with spacecraft master avionics unit, and interfacing with the Ka-band transmitter.

iii)   *A 192 GB solid-state buffer (SSB)* used for mass data storage.

iv)   *An analog I/O power switches board* to control instrument power.

1.5.3 Power supply board for the DHU

Continuous streams of images are produced by the CCDs with extraction time of 2 seconds. FPGAs receive these images on the IPC and sum into consecutive groups of 60. This gives an effective exposure time of two minutes. Full frame images are stacked every 30 minutes and stored in the SSB. Data from the SSB are downloaded every 13.7 days at the perigee.

1.5.4 Spacecraft

TESS uses the Orbital LEOStar-2/750 bus which has a three-axis controlled, zero-momentum altitude control system and two deployed solar array wings. The bus is equipped with a Ka-band transmitter and a monopropellant (hydrazine) propulsion system.

The spacecraft uses four reaction wheels and high-precision quaternions that are produced by the science cameras, in order to achieve fine point.

To downlink the science data at an interval of four hours at each perigee, the transmitter has a body-fixed high-gain antenna which has a diameter of 0.7m, a power of 2 W and a data rate of 100 MB/s.

1.6 Working

1.6.1 Star selection

A catalog of stars that are preselected are monitored at an interval of 2 minutes. The catalog includes almost 200,000 main sequence FGKM stars that are bright and small enough to enable the detection of transiting planets smaller than Neptune.

1.6.2 Scanning structures

The cameras act as a 1 x 4 array and provide a combined FOV of 24° x 96°. These partially overlapping sectors extend from ecliptic latitude of 6° to the ecliptic pole. Each sector is observed continuously for two spacecraft orbits. After 2 orbits the FOV shifts eastward in ecliptic longitude of about 27° and next sector is observed. It takes one year to observe an entire hemisphere.

1.6.3 Data downlink and housekeeping operations

At perigee, the science operations are interrupted after 16 hours, then the antenna is pointed towards the Earth, downlink data and then resume observing. A nominal 4 hour period for Ka-band science data is downlinked using NASA's Deep Space Network.

1.6.4 Ground-based data analysis and follow-up

The TESS data is processed with a data reduction pipeline based on software which was developed for the Kepler mission. The selected stars will be characterized with ground based imaging and spectroscopy once the data are processed and the transits are identified. Using these observations, reliable stellar parameters are established, the existence of the exoplanets is confirmed and their sizes and masses are determined.

1.7 Transit detections

TESS is expected to find thousands of planets that are smaller than Neptune. This may include hundreds of super-Earths and tens of planets that are comparable in the size of the Earth. There are equal probabilities of false positives. Some of the false positives are identified by the TESS data, based on the detection of secondary eclipses, ellipsoidal flux modulation, or transit-specific image motion, while others are identified in the ground based observations by checking for composite spectra, large radial-velocity variations, colour dependent transit depths and resolved companions that are indicative of false positives.

1.7.1 *Π* Men C

Π Men C is the first transiting planet discovered by the TESS, it is a super-Earth transiting the naked-eye G0 v star Π Mensae (Π Men). It was previously known to host a sub-stellar object (Π Men b) on a long period.

Using TESS time series photometry combined with Gaia data, published UCLES at AAT Doppler measurements, and archival HARPS at ESO-3.6 m radial velocities, it is found that

Π Men C is a close-in planet with an orbital period of 6.27 days, a mass of 4.52 ± 0.81 $M_\oplus$ and a radius of 2.06 ± 0.03 $R_\oplus$.

Figure 16. Planet Π Men C

It is also found that Π Men C is a super-Earth located at, or close to the radius gap based on the planet's orbital period. From its mass and bulk density it is thought that it may have a significant atmosphere. Since the host star is highly bright, the system is suitable for a wide range of studies to characterize the planetary atmosphere and dynamical properties. (14)

1.8   Conclusion

Kepler has revealed the existence of a large number of small planets in the galaxy. TESS is designed to find them around the stars in the local neighbourhood which will be easier to study using the current instruments, including the JWST.

After its launch, TESS serves as the "People's Telescope", since it release data to the public every four months. The Precise Radial Velocity (PRV) monitoring is one of the most scientifically productive and challenging types of follow-up observations. PRV monitoring is used to confirm the planetary nature of TESS detections. It provides constraints on planetary densities and their interior compositions and informs the interpretation of planetary atmosphere studies with JWST and other instruments. The TESS legacy is the catalogue of the nearest and brightest stars that host the transiting planets

CHAPTER 2

EXOPLANET DATA AND DATA ANALYSIS

2.1 Databases

A set of related data and the way it is organized is referred to as a database. This data is accessed by a Database Management System (DBMS) which consists of an integrated set of computer software that allows users to interact with one or more databases and provides access to all the data in the database. The DBMS provides various functions that are used for the entry, storage and retrieval of large quantities of information and also provides ways to manage how that information is organized. Databases and DBMSs are categorized according to the database model that they support, the types of computer they run on, the query languages used to access the database and their internal engineering which affects performance, scalability and security. (15)

2.1.1 NASA Exoplanet Archive

The NASA Exoplanet Archive is an online astronomical exoplanets and stellar catalog which consists of the data service that collates and cross-correlates astronomical data and information on exoplanets and their host stars. It also provides tools to work with these data. The database includes interactive tables containing properties of all published exoplanets, Kepler planet candidates, threshold-crossing events, data validation reports and target stellar parameters. It also consists of light curves from the Kepler and CoRoT missions and from several ground-based surveys, and spectra and radial velocity measurements from the literature along with the tools to work with these data that include a transit ephemeris predictor, both for single planets and for observing locations, light curve viewing and normalization utilities, and a periodogram and phased light curve service.

Tools to Work with Exoplanets Data

The NASA Exoplanet Archive contains several tools for working with exoplanets and stellar host data.

- **Interactive tables for planet parameters**: The interactive tables display the data for various data sets, which includes the Planetary Systems, Kepler Objects of interests, Threshold-Crossing Events and target stellar data. The users can filter, sort and download or export to other Exoplanet Archive Services like the light curve visualization for the Kepler stars.

- **Table Access Protocol (TAP) Service** : The Table Access Protocol Service allows a user to programmatically access and retrieved data from the Planetary System (PS), Planetary Systems Composite Parameters (PSComPars), Kepler Names, and K2 Names tables as an alternative to the interactive web interface.

- **Application Program Interface (API) :** The Application program Interface is the original query-based service of the archive that allows a user to access the contents of various data tables via a URL or command-line-based query. Though some tables are accessible through the original API service, the archives data tables are slowly being transitional to the newer TAP service.

- **Transit and Ephemeris Service** : The Transit and Ephemeris Service for Kepler Objects of Interest and Planetary Systems is a service that returns an ephemeris of the time of transit of the exoplanets across its host star. It can also tabulate the times of transit at a particular location and can calculate the time for secondary transits or other phase points in the orbit for a given latitude and longitude.

- **Periodogram Service :** The Periodogram Service calculates the periodogram of the time series data from the archive or a file which is uploaded by the user. It supports three algorithms which are Lomb-Scargle, Box-fitting Least Squares (BLS) and Plavchan.

- **EXOFAST :** EXOFAST is a fitting tool that accepts the transit light curves and/or radial velocity data and various other inputs to create models of planet systems.

- **Predicted Observables for Exoplanets (POE)** : The Predicted Observables for Exoplanets is an observational planning tool that provides the estimates of the Habitable Zone parameters and predicted planet signatures for stars known to host

exoplanets or KOIs, mission stars, or hypothetical stars. It is applied to individual stars or to catalogs of stars from the archive.

- **Inventory Service/ Search for Archive Holdings:** The Inventory Service/ Search for Archive Holdings is a search tool which provides a list of all data in the Exoplanet Archive that corresponds to a user-specified object or location.

- **Plotting and Histogram tool**: The Plotting and Histogram tool is used to create scatter plots and histograms from planetary systems table data.

- **Pre-generated Exoplanet Plots:** The Pre-generated Exoplanet Plots are presentation-ready plots that are generated daily with the most current information available in the Exoplanet Service.

Transit Survey Data in the Exoplanet Archive

The Exoplanet Archive serves the photometric time-series data from surveys that aim to discover transiting exoplanets like the Kepler Mission or CoRoT. The database provides access to more than 107 million light curves from space and ground-based exoplanets transit survey programs which include:

- List of planet candidates from TESS
- List of planet candidates from K2
- Kepler public survey data
- K2 public survey data
- UKIRT microlensing survey data
- SuperWASP light curves
- CoRoT Exoplanet Survey data
- CoRoT Asteroseismology data
- HATNet survey data
- X0 survey data
- TrES survey data
- KELT Praesepe survey data
- KELT time series (16)

2.1.2 **ESO Archive**

The European Southern Observatory (ESO) is an intergovernmental organization which is established in 1962 and supported by 16 Member States with host country Chile and strategic partners. All the telescopes of ESO are currently located in the Chilean Atacama Desert. ESO operates in three observation sites in Chile namely La Silla, Paranal and Chajnantor.

Contents of the ESO Archive

➢ All the raw observations which are performed at the LA Silla Paranal observatory on the NTT, MPG-ESO 2.2m, ESO 3.6m, VLT/VLTI and APEX telescopes.

➢ It also includes the raw data from the UKIRI Infrared Deep Sky Survey (UKIDSS) taken with the Wide Field Infrared Camera (WFCAM).

➢ Various data products include :

- Data from the commissioning and science verification or demonstration process.

- Data from ESO Imaging Survey and other projects.

- Phase3 Data Products (ESO public surveys, ESO pipeline- reduced products, large programs like GOODS, ZCOSMOS).

- Other Advanced Data Products like 30 Doradus, CoRoT, GaBoDs etc.

The science data are stored in the archive along with the calibration and auxiliary data.

ESO Archive Browsers

ESO allows the use of the following archive browsers to search and retrieve ESO data:

- ➢ **Raw data query form:** This is unified and observatory-oriented access to the ESO collection of raw data for astronomers who have no previous experience with ESO instruments.
- ➢ **Instrument specific query forms**: This is used for raw data only. It includes several instrument specific and technically-oriented access points to the ESO archive for astronomers who are already well familiar with the ESO instrument setups and observing strategies.
- ➢ **Reduced data query form**: This is a unified and science-oriented access to the ESO collection of historical advanced data products.
- ➢ **Science Portal**: This offers improved capabilities regarding visualization of the science data products which includes facets, previews, footprints etc.
- ➢ **Programmatic Access**: It offers direct access to database and offers scripting capabilities to query and access the raw data, science data products and ambient conditions. Also it gives access to the scientific catalogs generated by the principal investigators of various ESO observing programmes. This layer is based on the VO protocols to guarantee and facilitate interoperability. (17)

2.1.3 MAST

The Mikulski Archive for Space Telescopes (MAST) introduces a new way to explore the archives exoplanets data: exo.MAST. The exo.MAST is a new tool for navigating exoplanets data. The web interface brings together planetary parameters for confirmed planets and planet candidates with a filterable list of data products which are held by MAST and visualizations of those data. The user can start with a single search bar which autocompletes to the confirmed exoplanets, Kepler Object of Interest, or TESS threshold crossing event as the user types.
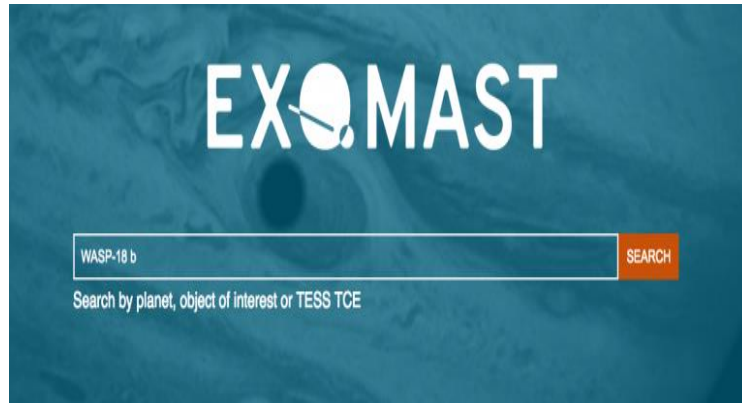
Figure 17. Window of EXOMAST

The result is a targeted cone search of data of the MAST at the coordinates of the planet's host star along with star, planet and their orbital properties and various data visualizations.
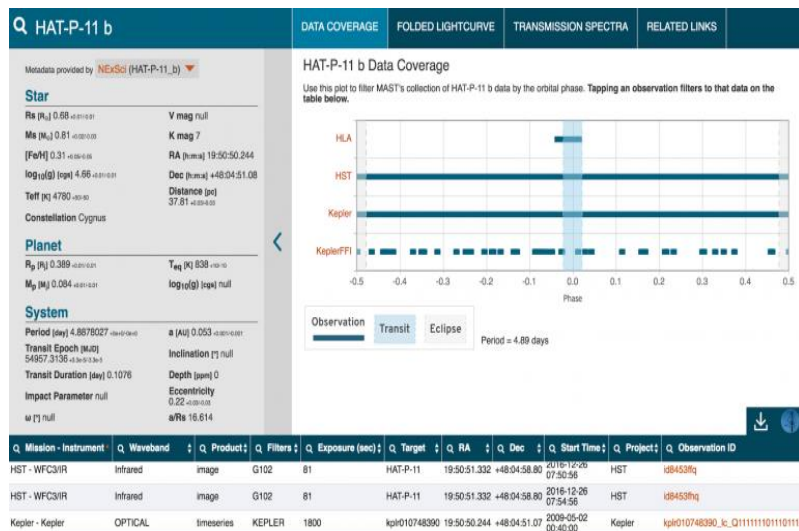

Figure 18. Data coverage window

MAST is the archive for Kepler, K2 and Transiting Exoplanet Survey Satellite. For all the transit signals that are found by the TESS or Kepler pipeline, the mission provides a detrended light curve and a fit to the transit signal. Exo.MAST takes these data to give scalable and zoomable plots of the most recent detrended light curve and transit model.

For exoplanets that have atmospheric characterization measurements, exo.MAST gives the access to the Space Telescope Archive of Transiting Exoplanet Spectra (STATES). The STATES is a database of published transmission and emission spectra started by Dr. Hannah Wakeford. The measurements done by the STATES are

linked to the source paper and to the observations that are hosted within the archive so that users can directly download and analyse the data themselves. (18)
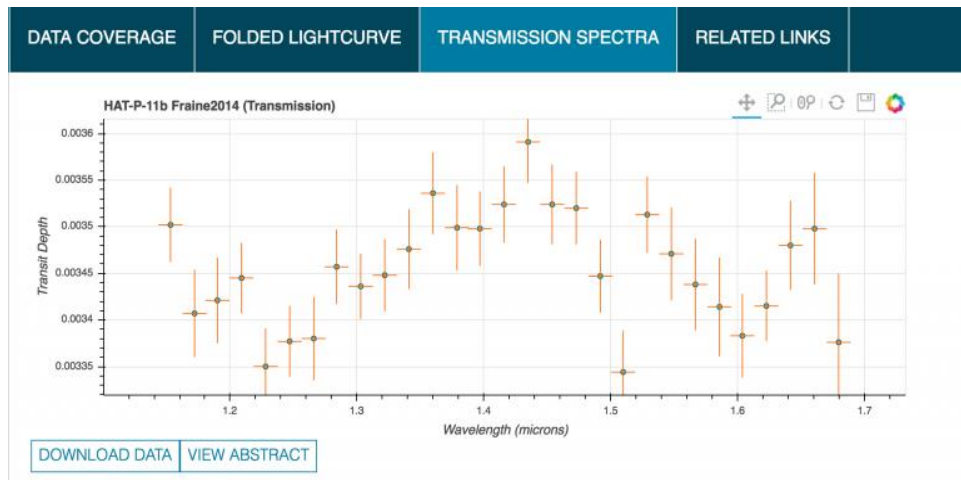

Figure 19. Transmission spectra

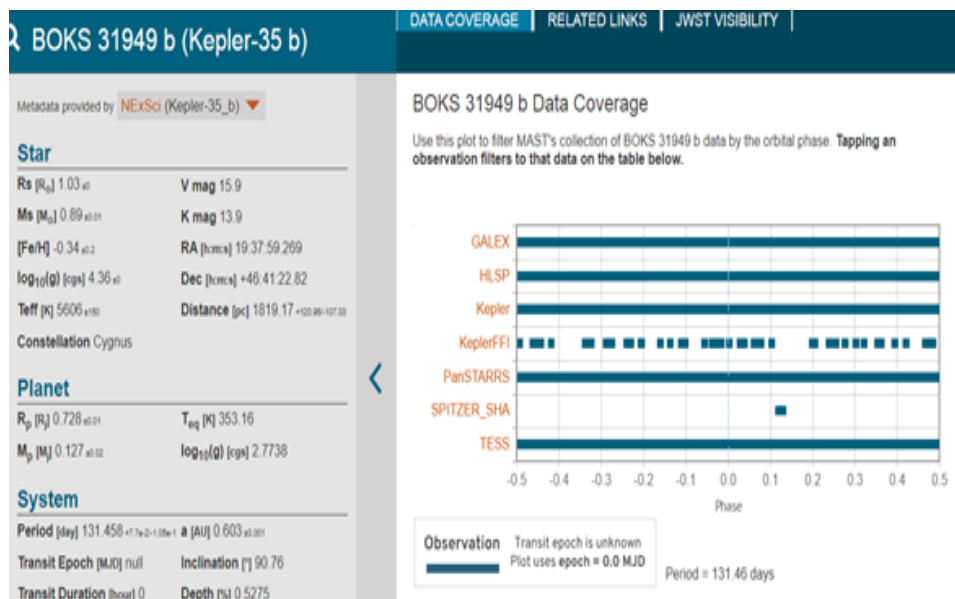As an example we take the data of the exoplanet BOKS 31949b.

Figure 20. Data coverage of BOKS 31949b

2.2 Time Series Data Analysis

Time series analysis is a specific method of analysing a sequence of data points that are collected over an interval of time. The data points are recorded at consistent intervals over a set period of time rather than just recording the data points intermittently or randomly. The analysis is not just the act of collecting data over time.

Time series data differ from other data because of its ability to show how variables change over time. Time is a crucial variable in time series data analysis because it shows how the data adjusts over the course of the data points and the final results. It also provides an additional source of information and a set order of dependences between the data.

Time series analysis requires a large number of data points in order to ensure consistency and reliability. An extensive data set ensures that there is a representative sample size and that analysis can cut through noisy data. The analysis also ensures that any trends or patterns discovered are not outliers and can account for seasonal variance. Time series data can be used for predicting the future data based on historical data.

The Interactive Time Series Viewer is a dynamic interface which allows the users to view and interact with all of the Kepler light curves that are currently available in the Exoplanet Archive. (19)

2.2.1 Light curve

A light curve is a graph of light intensity of a celestial object or a region as a function of time. The light will be usually in a particular frequency interval or band. Light curves are periodic in the case of eclipsing binaries, Cepheid variables, other periodic variables and transiting extrasolar planets. They are aperiodic in the case of the light curve of a nova, a cataclysmic variable star, a supernova, or a microlensing event or binary as observed during occultation events. The study of the light curve, along with other observations yields considerable information about the physical process that produces it or constrains physical theories about it.

In planetary science, the light curve is used to derive the rotation period of a minor planet, moon or comet nucleus. From the Earth, a small object in the Solar System cannot be resolved even with the most powerful telescopes, because the apparent angular size of the object is smaller than one pixel in the detector. Hence, the amount of light produced by the object as a function of time (light curve) is measured. The time separation of peaks in the light curve will give an estimate of rotational period of the object. The amplitude of the light curve is due to the shape of the object or due to bright and dark areas on its surface. (20)

2.2.2 Lightkurve

Lightkurve is python package that offers a user-friendly way to analyse time series data on the brightness of planets, stars, galaxies. The lightkurve package is used to analyse the light curves obtained by any telescopes including NASA's Kepler and TESS space telescopes. The package offers tools and tutorials for the people who are unfamiliar to it. (21)

2.3 Obtaining physical information from transit data

Transit data consist of a lot of information. The size or radius of the planet can be determined by measuring the depth of the dip in brightness and knowing the size of the star. When an exoplanet passes in front of its host star a portion of the starlight is blocked and a decrease in the flux of photons is measured. A light curve is created by measuring the change in flux over time. Various characteristics such as orbital motions and atmospheric composition can be extracted by fitting models to the light curve. The decrease in the flux during the transit is determined by the size of both the host star and the planet. Due to the enormous distance from Earth, the transit depth is not affected by the orbital distance between the exoplanets and its host star.

2.3.1 Obtaining the planet radius from light curve

It is possible to infer the relative sizes of the star and planet, the orbital inclination, stellar limb darkening function with precise measurements of the amount of light blocked by the planet as a function of time. Along with the measurements of the time-variable Doppler

shift of the star and an estimate of the stellar mass, the planetary mass and the stellar radius can be determined.

To determine the radius of the planet, the drop in the brightness of the parent star which occurs during a planetary transit is measured. This brightness drop is directly related to the ratio of the planet's radius to that of its parent star. Stefan-Boltzmann Law can be used to determine the radius of the parent star.
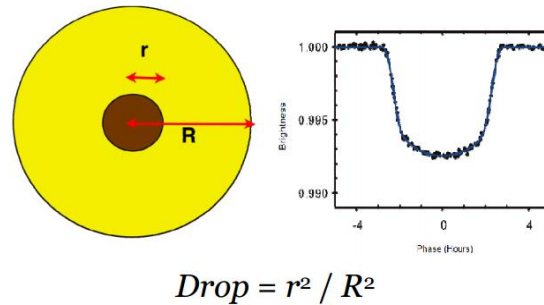

$$Drop = r^2 / R^2$$

Figure 21. Obtaining planet radius from light curve

The Stefan-Boltzmann law is a relation between the star's size and its temperature and luminosity. Mathematically, the law states the luminosity L is proportional to the star's surface area and fourth power of its surface temperature.

$$L = 4\Pi R^2 \sigma T^4$$

R is the radius of the star in meters,

T is the temperature in Kelvin,

L is the luminosity in Watts, and

σ is a constant known as Stefan-Boltzmann constant.

$\sigma = 5.67 \times 10^{-8}$

Rearranging,

$$R = [L/4\Pi R^2 \sigma T^4]^{1/2}$$

The drop in the brightness is given by,

$$Drop = r^2 / R^2$$

R is the radius of parent star , and

r is the radius of the planet.

2.3.2 Obtaining planet's orbital period from light curve

The amount of time that an astronomical object takes to complete one orbit around another object is called its orbital period. The orbital period of an exoplanets can be determined by measuring the time elapsed between the transits.
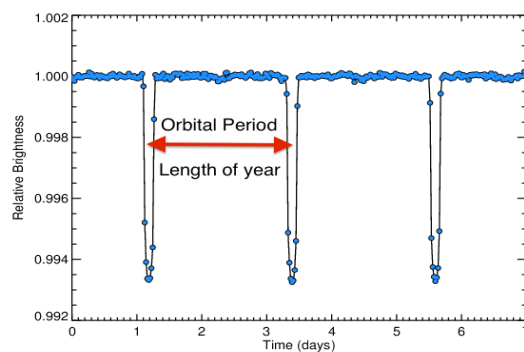

Figure 22. Obtaining orbital period from light curve

2.3.3 Obtaining the planet's orbital semi-major axis

The orbital semi-major axis in Astronomical unit gives the transit duration. The total transit duration, T_{dur} , is defined as the time during which any part of the planet obscures the disc of the star. It depends on how the planet is transiting its host star. If the exoplanets crosses the center of the stellar disc with impact parameter $b = 0$, the transit duration is the longest. $b \neq 0$ represents a shorter transit duration.
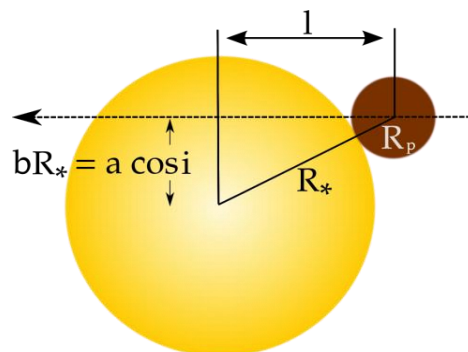

Figure 23. Obtaining planet's semimajor axis from light curve

From the figure, the length the planet has to travel across the disc of the star is given by,

$$2l = 2 \left[(R_* + R_p)^2 - (bR_*)^2 \right]^{1/2}$$

R_P is the radius of the planet and R_* that of the star.

The exoplanet moves from a point A to another point B around its orbit, creating an angle α with respect to the center of the host star.
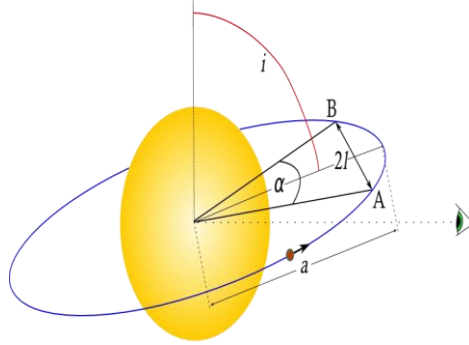

Figure 24. Planet inclination

We assume that the orbit is circular. The distance around an entire orbit is taken as $2\Pi a$, where a is the radius of the orbit. αa is the arclength between the points A and B. The distance along a straight line between A and B is 2l.

Consider the triangle formed by A, B and the centre of the star. Then,

$$\sin \alpha/2 = l/a$$

Thus ,

$$T_{dur} = p\alpha/2\Pi$$

$$T_{dur} = p/\Pi \ \sin^{-1}(l/a)$$

$$= p/\Pi \sin^{-1} \left\{ \left[(R_* + R_p)^2 - (bR_*)^2 \right]^{1/2} /a \right\}$$

is the expression for a full transit duration.

2.3.4 Determining the transit impact parameter

The impact parameter b is defined as the sky-projected distance between the center of the stellar disc and the center of the planetary disc at the point in the orbit where both the

planet and the star are most closely aligned. The transit duration is heavily dependent on the impact parameter.

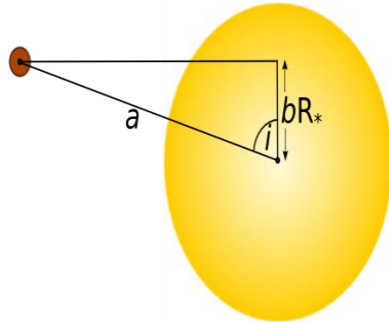The impact parameter of a circular orbit is given by,

$b = a \cos i / R_*$

Figure 25. Obtaining impact parameter from light curve

2.3.5 Determining the orbital inclination

The orbital inclination i has to be measured to constrain the actual mass of an exoplanets. This can be done by fitting an analytical transit light curve to the data using the transit equation. A transiting exoplanets that has an impact parameter $b \neq 0$ or $i < 90$, will have a shorter transit duration, a shallower transit depth and longer ingress and egress times. (22, 2006)
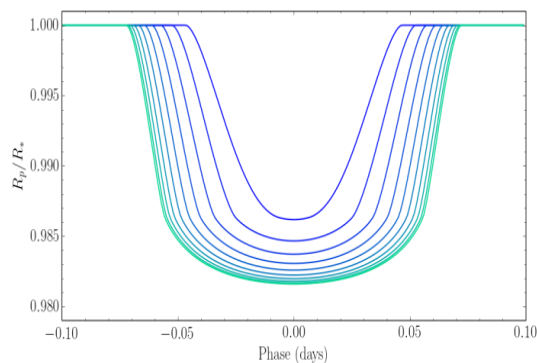
The figure shows the effects of varying I from 90° to 80°.

Figure 26. Obtaining orbital inclination from light curve

2.4 Conclusion

Exoplanet data and databases are accessed by the users with the help of a Database Management System. The databases commonly used are:

(i) NASA Exoplanet Archive

(ii) ESO Archive

(iii) MAST

The light curve of the exoplanets can be plotted by using the lightkurve tool. It helps us to analyse the time series data on the brightness of planets, stars or galaxies.

The physical information of the exoplanet like radius, orbital period, orbital semi-major axis, transit impact parameter and orbital inclination can be obtained from the light curve plotted from the transit data.

CHAPTER 3

RESULTS AND FUTURE SCOPES

3.1 HD 108236 b

HD 108236 b is an exoplanet which was discovered by TESS through transit method and was confirmed in 2020. The planet orbits a G-type star named as HD 108236 and is a super Earth exoplanet. The host star has an apparent magnitude of 9.2 and absolute magnitude of 5.1. It is 0.9 times massive and bigger than the Sun. The planet has a mass of about 3.24 Earth and takes 3.8 days complete a revolution around its star.
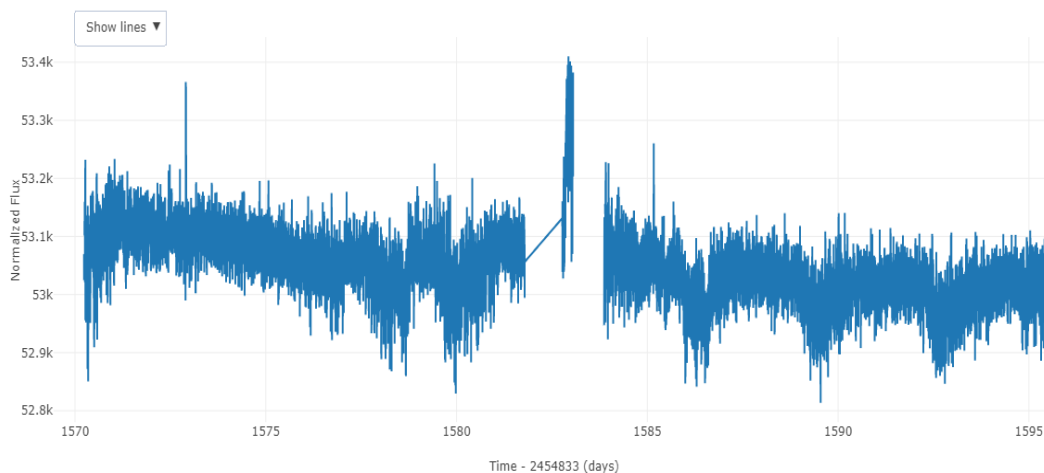
Figure 27. Light curve of exoplanet HD108236 b

The light curve of the exoplanet HD 108236 b is studied. The following observations are obtained.

- The planet radius is about 1.6 Earth radius.
- The impact parameter is 0.452 + 0.071 or 0.452-0.096 .
- The semi-major axis is estimated to be 0.04527 au.
- The transit duration is about 2.384 $\pm$ 0.093 hours.
- The orbital inclination is found to be 87.59 + 0.47 or 87.59 -0.35 degrees. (23)

3.2 Future Of Exoplanet Research

There is a constant rise in the number of exoplanets detected. Hence there are a lot to be learned about it. New areas of research is yet to be developed when we move from the era of detecting exoplanets to characterising them. There must be moons around the exoplanets like our Solar Sytem. Also this can be in the Golden Zone , that is it may have habitats that support life.

3.2.1 TESS

TESS was launched by NASA in 2018. TESS was designed to do an all-sky survey to find small transiting planets around bright stars. The stars surveyed by TESS are 30-100 times brighter tyhan those surveyed by the Kepler satellites. TESS observations provide precise measurements of planet's masses, sizes, densities and atmospheric properties.

3.2.2 CHEOPS

CHEOPS was launched by Europe in a partnership with ESA and Switzerland in December 2019. It studies the known exoplanets that are smaller than smaller than Saturn and orbiting close to bright stars using a technique called high precision transit photometry. In order to understand the nature of planets we need to know about the mass, radius and atmospheric properties of the exoplanets accurately. CHEOPS are able to determine the physical extent of the atmospheres of the planets and hence it can find Earth-like planets which can support life.CHEOPS can provide unique targets for JWST and future large telescopes.

3.2.3 JWST

The James Webb Space Telescope was launched by NASA, ESA and CSA in 2021. It is the largest optical telescope that is primarily designed to conduct infrared astronomy. JWST is able to characterise the atmospheres of exoplanet by recording the absorption, reflection and emission spectra at infrared wavelengths. It can also directly image some young and massive exoplanets that are orbiting at larger distances from their parent star.

3.2.4 PLATO

The Planetary Transits and Oscillations of stars(PLATO) mission is scheduled to launch in 2026 by ESA. PLATO is designed to find and determine the properties of planets that orbit in the habitable zone os stars that are similar to the Sun. The diversity of planets that exists and the constraints on the formation of planets can be found by accurate measurements of the radii of planets determined by PLATO combined with planetary masses determined from ground-based observations. PLATO also help scientists to determine the ages of the planets. Hence the changes undergone by planets in time and to find the conditions for habitability to evolve. PLATO can be a pathfinder for later missions that look for the possibility of life.

3.2.5 ARIEL

The Atmosphere Remote –Sensing Infrared Exoplanet Large-Survey (ARIEL) mission is scheduled to launch in 2029 by ESA. The ARIEL aims to study exoplanets both as individuals and as populations through simultaneous observations across a range of infrared and visible wavelengths. It is designed to provide the details of the chemical nature of the exoplanets studied and to make a catalolgue of planetary spectra, characterise the molecular abundances, chemical gradients, structure of atmosphere, seasonal and diurnal variation clouds and albedo measurements.
With the help of these telescopes we will be able to get closer to the task of finding Earth-like planets that are habitable. (24)

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