Hack an Exoplanet

Team Abyss Watchers

Contents

1 INTRODUCTION

The purpose of this protocol is to summarize the research conducted as a part of a competition titled "Hack an Exoplanet" by the team Abyss Watchers. The main focus of this protocol will be TOI-560c, also known as HD 73583c, but information regarding the whole solar system will be included in the document. General information will be provided in this section.

1.1 The Team

Abyss Watchers is a two-member team composed of Hugo Korcina and Vojtěch Mikeš, students of 1.SJG (translated as The First Private Language Grammar School) in Hradec Králové, Czechia. Both of us are in the second year of our studies and we both participated in last year's Astro Pi competition. Furthermore, we are more than keen on discovering new facts about physics, especially astrophysics, quantum physics and the theories of relativity.

We found out about this competition from Jan Spratek from Planetum Prague, thanks to whom we participated in a 24h hackathon in Prague. It was there where we learnt what an exoplanet is, how to work with data from telescopes and many more useful skills.

1.2 An exoplanet

An exoplanet is a celestial object orbiting a star outside of our solar system. It also has to satisfy these parameters:

1. It must be big enough to have enough gravity to force it into a spherical shape.
2. It's gravitational force must be strong enough to clear away any other object of a similar size near its orbit around the star.
3. Its mass and radius most not cross the threshold of being considered a brown dwarf.

1.2.1 Methods of discovering exoplanets

Firstly, the most commonly used method is the transit method, in which the decrease in luminosity of a star caused by the transiting planet is detected. Thousands of exoplanets have been discovered using this method. However, smaller planets and planets with significantly longer orbit times are very difficult to detect, as the decrease of luminosity of the star is close to none or the orbit time is too long for the planet to be verified (the orbit has to be confirmed three times in order for the planet to be verified). The size of the exoplanet, its orbit time and the semimajor axis can all be calculated using this method.

Secondly, the Doppler shift can also be utilised as method of discovering new exoplanets. Doppler shift is caused by the gravitational pull of an exoplanet, due to which the star moves closer to or further from us in certain moments, which creates a shift in the spectral lines of a star. If the star moves closer to us, we can witness a shift towards the ultraviolet light. On the other hand, if it moves further from us, the lines shift towards the infrared light. This is caused by either the wavelength shortening or lengthening. Insofar as this method allows us to detect pretty much any exoplanet orbiting around a star for which spectroscopy could be made , it is relatively slow compared to the transit method. Thanks to this method it is possible to calculate the mass of the planet, its orbit time and its semi major axis which closely corelates with its temperture therefore making it possible to be simulated.

Lastly, for certain planets an actual photo can be taken. However, for this method to work the planet must be both big and close enough for the photo to be taken as well as its inclination to be equal to or close to 90°. These requirements lower the possible amount of exoplanets found by this method drastically making it almost impossible to detect new planets at this moment of time. Due to these circumstances this method is mostly used for already discovered planets as a method of further research.

Despite more methods existing, we only decided to include these three thanks to the other methods being either unreliable or not as widely used.

1.3 CHEOPS

CHEOPS (CHaracterising ExOPlanets Satellite) is a space telescope from ESA with an objective to provide additional information on already detected expolanets. It launched on 18 December 2019 with a goal to be in function for atleast 5 years. Its targets are host stars with V-magnitude lower or equal to 12. V-magnitude is the magnitude of a star in a range of wavelengths for which human eye is sensitive, magnitude itself is a measure of the brightness of a star, the lower the number, the brighter the star. CHEOPS is sensible to wavelengths from 330 nm to 1100 nm.

1.4 TESS

TESS (Transiting Exoplanet Survey Satellite) is a space telescope from NASA with an objective to search for exoplanets using the transit method covering area 400 times larger than Kepler telescope (Kepler telescope is a telescope which detected more than 2600 exoplanets and has been in function since 2009). The telescope is sensitive to wavelegths from 600 nm to 1000 nm and has been in function since 7 August 2018 and at this moment is on its second extended mission ending in 2025.

2 OUR CALCULATIONS

Herein will our course of action be provided in great detail, giving further insight into our thought process and calculations.

2.1 Transit Light Curve of TOI-560c

The satellite Cheops provided us with the initial information about TOI-56Oc and its star. We were supposed to guess the size of the exoplanet and its mid-transit time based on the provided data. This created a so called ”transit light curve” which served as an initial guess. This guess was then analyzed by Markov chain Monte Carlo (a statistical method), creating a much more precise transit light curve. The depth of the exoplanet transit is equivalent to the ratio of the area of the

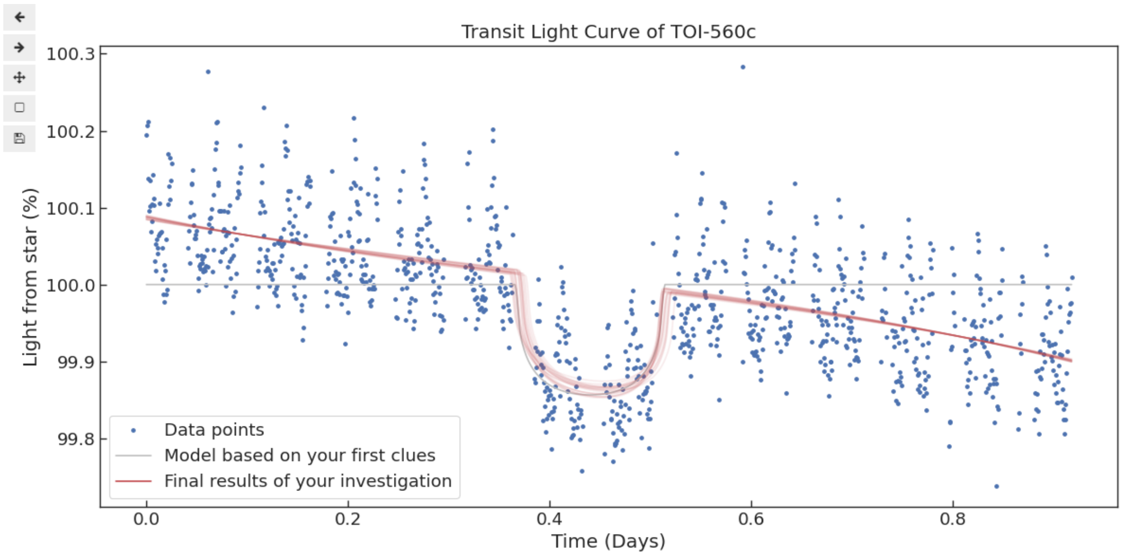

Figure 1: Transit Light Curve of TOI-560c

planet's disc and the area of the star's disc. By measuring the transit's depth from the transit light curve and knowing the stellar radius (Rs) we could determine the exoplanet's radius (Rp) using the following formula:

$$\text{Transit depth } (\%) = \frac{\pi \cdot R_p^2}{\pi \cdot R_s^2} \cdot 100. \tag{1}$$

Solving for R_p gives us

$$R_p = \frac{\sqrt{D \cdot R_s^2}}{10} \tag{2}$$

where D represents the Transit depth (%). Using the data given and considering the lower and upper errors, we calculated that the radius should be in between $R_{p1} = 16594$ km and $R_{p2} = 16697$ km. Albeit our correct calculations, the Allesfitter program provided a different answer, that is $15205km$. This could be explained by rounding up certain values during the calculation and perhaps using a different method of calculating the radius.

2.2 Orbital Period and Distance

From the archive of observations from Cheops, the orbital period of TOI-560c should be 18.8797 (in units of days). Using Kepler's Third Law

$$T^2 = (\frac{4\pi^2}{GM_s})d^3, \tag{3}$$

where G is the gravitational constant ($G = 6.6743 m^3 kg^{-1} s^{-2}$), T is the orbital period, d is distance from the home star and M_s is the mass of the home star. Solving for d gives us

$$d = \sqrt[3]{\frac{T^2 G M_s}{4\pi^2}}, \tag{4}$$

that is $1.86908 \cdot 10^{10}$ m. Converting this value to astronomical units (au) gives us 0.1249 au, which is a discrepancy of only 0.0007 au from the table value provided by Allesfitter.

2.3 Mass, Volume and Density

Unfortunately, we cannot calculate the planet's mass using the transit method, but other methods, like the radial velocity method, can. Taking this value from the table, we get the value of $9.7 M_\oplus$ ($5.9730243 \cdot 10^{25} kg$). To calculate the volume of the exoplanet, we can assume it has a perfectly spherical shape, thus allowing us to use the formula

$$V = \frac{4}{3}\pi r^3 \tag{5}$$

where r is the radius of the planet. This gives us the value of $1.47247 \cdot 10^{22} m^3$. If both the mass and radius of the planet are known, we can calculate its density using

$$\rho = \frac{m}{V}. \tag{6}$$

In this case specifically (and taking into account lower and upper errors), we estimate the planet's density to be in the range of $3.244 g \cdot cm^{-3}$ and $4.664 g \cdot cm^{-3}$.

2.4 Orbital Velocity

In order to calculate the velocity of TOI-560c, we first needed to calculate the angular velocity. This was done using the formula

$$\omega = \frac{2\pi}{T} \tag{7}$$

where ω is the angular velocity and T is the orbit time. The result was $\omega = 3.8519 \cdot 10^{-6} rad \cdot s^{-1}$. With this, we could easily calculate the actual velocity, simply by multiplying this value by the distance of TOI-560c from its home star:

$$v = \omega d. \tag{8}$$

This then gave us the final result of $v = 71.994 km \cdot s^{-1}$.

2.5 Summary

To sum up this section, we would like to talk about why certain values might differ from table values. The main reason for these discrepancies is indisputably the source of data used for calculations. The agencies' values were different from ours mainly due to the fact that they had first-rate access to their own research and data, while we had to work with the data provided and the error of rounding up definitely played its part.

Despite these factors influencing the final results, the discrepancies between our and the agencies' values were not too significant and some were even little to none.

3 ADDITIONAL INFORMATION

Despite our calculations being interesting, we decided to dig deeper and find more compelling information not only about TOI-560c, but the whole solar system of TOI-560 (HD 73583). After looking at more data from different telescopes and reading professional articles we want to present our own opinions and interesting facts found about the TOI-560 solar system.

3.1 General information about the solar system

TOI-560 was observed by TESS 1.4 from February 2 2019 to February 28 2019. The system is approximately 103 lyr away and so far 2 planets have been discovered (TOI-560b and TOI-560c) by TESS 2. TOI-560b was verified by 3 visible transits. On the other hand TOI-560c was verified

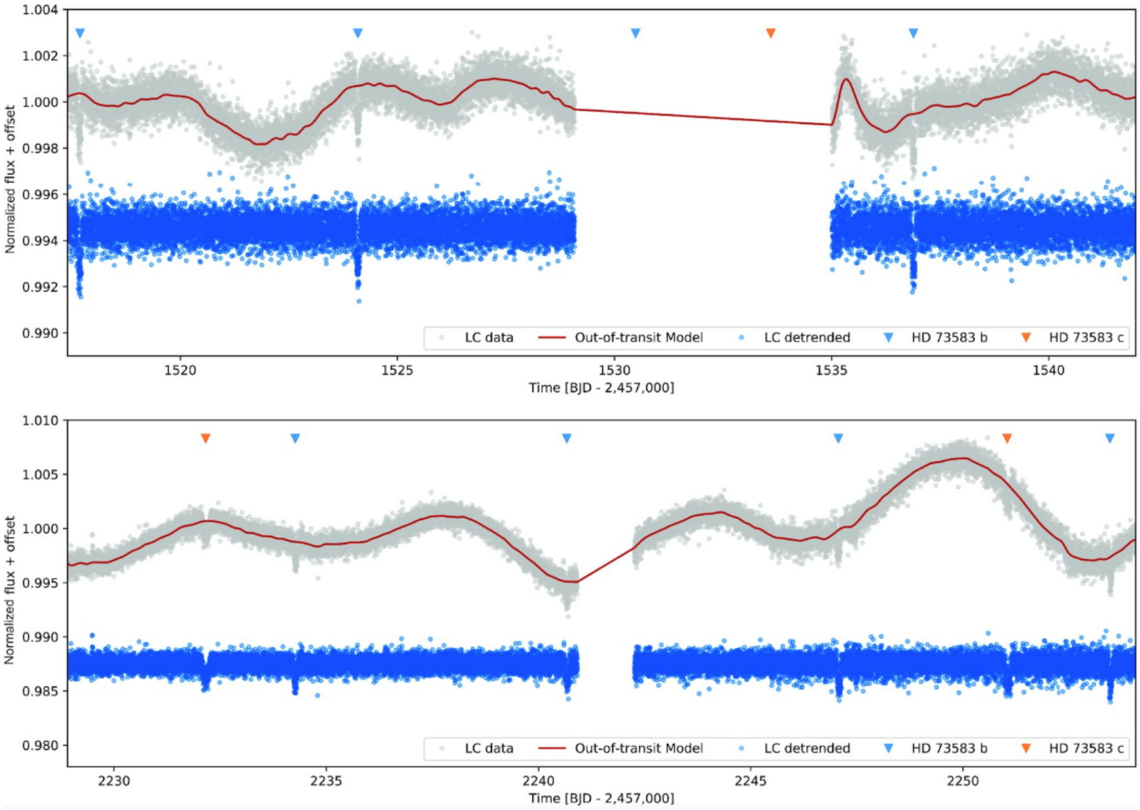

Figure 2: TESS's observation of TOI-560c and TOI-560b [1]

by doppler's shift consistent with its period. CHEOPS afterwards provided photometry of TOI-560b with relatively high efficency. Further observations and follow up measurements have been conducted on TOI-560 afterwards. Furthermore it is unlikely that both TOI-560c and TOI-560b have been formed in a high-eccentricity migration but rather in situ [1]. [1] [2]

Information on the star and planets The star of TOI-560 solar system is a young 500 Myr old bright K Dwarf 3.4.1 with a mass radius of approximately 0.73 R_S. Its precise type is K4V which indicates its effective temperature to be around 4600 K.

TOI-560b is both bigger and closer to the star than TOI-560c. Its orbital period is 6.4 days with semimajor axis of only 0.06 au. Being 10 M_E and 2.79 R_E and density of 2.58gcm^{-3}. Information on TOI-560c are in 2. [1] [2]

[1] situ basically means they were formed by fragments in the area and not caught by the star while flying nearby

3.2 Strange orbital period resonance

The orbital period resonance of TOI-560b and TOI-560c is near 1:3. This may seem normal at first sight but is actually quite rare among other exoplanet systems where 2:3 or 1:2 orbital period resonances are in common. Such orbital period resonance raises an interesting possibility of another, 3rd, this time nontransiting [2], exoplanet in TOI-560 system with and orbital period of aproximately 12 days. If this theory is true it would make the orbital period resonance to be 1:2:3 making it more common. [2]

3.3 Planetary composition

Although we cannot be entirely sure about the elemental composition of TOI-560c, there is plenty of leads that give us a hint as to what it could be. For example, the dependency of the planet's radius on its mass suggests that the planet is below pure water composition. There are therefore two most probable outcomes. Either the planet is mostly composed of water ice and silicates or it has Earth-like interior and volatile hydrogen envelope with helium being present as well.

Another way to look at this problem is shown on graph 3. As we can see, TOI-560c (being

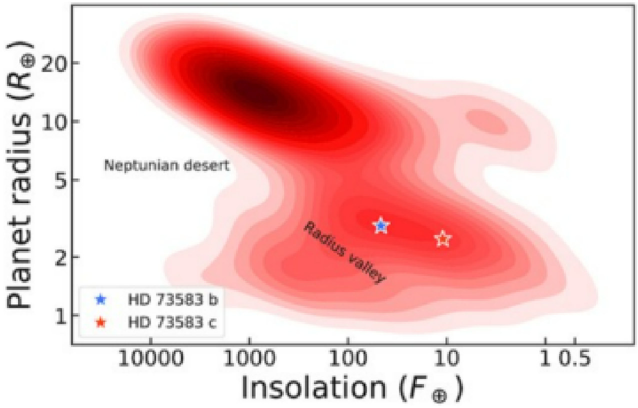

Figure 3: Radius of the planet and its insolation [1]

HD 73583 c) is way above the so called "radius valley". This supports the idea that the planet possesses a volatile envelope.

In terms of TOI-560b, it most likely has a similar composition. The reason for this statement is that the mass of the two planets is similar and both have a hydrogen envelope. However, there is one issue with that. The difference between the planets' temperature suggests that TOI-560b should have a larger radius. Despite this being true, the difference of 200K does not explain such a large difference of radii, suggesting that TOI-560b most likely possesses an extra hydrogen content. [1]

3.4 Explanations

3.4.1 Orange dwarf star

Also known as K type main sequence star [3]. K stands for it's type in Morgan-Keenan system classifying stars based on their effective temperature [4] into 7 categories O, B, A, F, G, K and M with O being the hottest and M being the coolest. K class is then split into 10 individual categories from K0V being the hottest to K9V being the coolest with effective tempertures ranging from 3930 K to 5270 K. [3]

[2] nontransiting meaning we cannot detect its transit thanks to its orbit being out of our viewpoint
[3] main sequence stars are also known as dwarfs, brown dwarfs are not included in the main sequence
[4] effective temperature is equal to temperature of a black body that would emit the same amount of radiation as the star

3.4.2 Mini-Neptune

Mini-Neptune is a planet less massive than Neptune but has simmilar structure that is thick hydrogen-helium atmosphere, deep layers of ice and rock (usually from water, ammonia or heavier metals). Thanks to its thick atmosphere the radies is usually between 1.7 and 3.9 Earth radii. No mini-Neptune type planet exists in the solar system. [4]

3.4.3 Super-Earth

Super-Earth is a planet which is more massive than Earth but substantially lower than Neptune or Uranus. Albeit the term mentioning Earth it does not mean that Super-Earth type planet has simmilar structure to Earth. Therefore these planets are quite often mini-Neptunes 3.4.2 but can also have an Earth-like character. [5]

3.4.4 Aproximation of temperature

While calculating the mass, radius or semimajor axis of an exoplanet is relatively easy task with enough information given. Aproximating the surface temperature is a different story, considering the lack of spectroscopy therefore knowledge of atmospheric composition.

In order to aproximate the temperature simulation must be conducted. Taking into account the stellar irradiance [5] it is possible to simulate the temperature of a dark body with the same size and semimajor axis. Counting with different emisivity [6] of the object we could aproximate the temperature on the surface. Unfortunately without the knowledge of the atmospheric composition we cannot take into account any greenhouse effect.

[5] stellar irradiance is the power per unit area recieved from the star on the surface of a planet

[6] emisivity is the ratio of the thermal radiation from an ideal black body and real black body, it varies from 0 to 1 with 1 being the emissivity of an ideal black body therefore making it impossible to achieve

4 CONCLUSION

To conclude, the information provided by CHEOPS allowed us to create the transit light curve of TOI-560c, deduce its orbital period and distance from its home star, calculate its mass, volume, density and orbital velocity. In spite of successfully describing the basic characteristics of TOI-560c, we wanted to dig deeper not only into information about this planet specifically, but also into information about its home star and the system in general. We would highly encourage conducting further spectroscopy on both (possibly all three) exoplanets of TOI-560 system as more research could be conducted afterwards.

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