TOI-560 C: THE HABITABILITY OF EXOPLANET

KRYŠTOF VILGUS, PROKOP VILGUS, KRISTÝNA VILDOVÁ, KATEŘINA ERNÉE

Abstract

This work focuses on the exoplanet TOI-560 c (referred to as a mini-Neptune or super-Earth), one of the two exoplanets orbiting the K-type dwarf star TOI-560, which was observed using the transit method with the CHaracterising ExOPlanets Satellite (CHEOPS) space telescope. The objective of our research was to calculate the fundamental properties of this exoplanet, including its radius, mass, orbital distance, orbital period, density, and average temperature. Based on these findings, the work is aimed to determine whether this exoplanet satisfies the conditions necessary for the existence of life similar to life on Earth. Based on available informations, the existence of life similar to that on Earth on TOI-560 c is considered unlikely.

To calculate the radius of the exoplanet TOI-560 c, the transit method is utilized, which involves observing the planet's passage in front of its host star. The average radius of the planet in comparison to the radius of the Earth is determined. The mean orbital distance and orbital period were calculated using Kepler's laws. The density of the exoplanet TOI-560 c was obtained from the volume and mass values based on the estimated radius.

The results indicate that the exoplanet TOI-560 c has a radius approximately 2.37 times bigger than the radius of Earth, a mass approximately 9.7 times that of Earth, a mean orbital distance of about 0.124 AU, and an orbital period of approximately 18.88 days. The estimated density of the exoplanet is approximately 4.004 g/cm3, and the average temperature is estimated to be 225°C.

1. Introduction

TOI-560 c is one of the two exoplanets orbiting the K-type dwarf star TOI-560 at a distance of approximately 0.26 astronomical units (AU). An astronomical unit is the standard unit of measurement of distances within the solar system, representing the average distance between Earth and the Sun. With its estimated mass and radius, TOI-560 c is presumed to be a gas giant, resembling Neptune.

Exoplanet TOI-560 c was selected as the target of research within the Hack an Exoplanet competition organized by the European Space Agency (ESA). The objective of the research is to determine whether the properties of the exoplanet (such as distance from its star, temperature, density, orbital period, etc.) enable the existence of life similar to life on Earth.

The historical timeline of observing the planetary system of TOI-560 can be traced to recent breakthroughs in advanced methodologies and techniques that have facilitated the detection of remote exoplanetary worlds. The star TOI-560 itself first garnered scientific attention through the utilization of the Transiting Exoplanet Survey Satellite (TESS) mission. TESS, a space-based observatory, employs the method of transit photometry to unveil exoplanets.

2. Theory

Transit photometry

Transit photometry is a powerful and widely used method for exoplanetary research. This method enables the detection and characterization of these distant celestial objects. Transit photometry involves the measurement and analysis of periodic changes in the observed flux or brightness of a star caused by the passage of an exoplanet across its stellar disk, as viewed from the observer's line of sight.

The principle behind transit photometry lies in the detection of the small but discernible decrease in the star's apparent brightness during an exoplanet transit event. When an exoplanet orbits its host star, it periodically aligns in such a way that it partially blocks a portion of the stellar surface as it transits across it. This alignment leads to a decrease in the observed flux from the star, resulting in a characteristic light curve with a temporary decrease in brightness.

To carry out transit photometry observations, precise and high-precision photometric measurements are performed on the target star over an extended time period. This can be achieved using ground-based observatories, space telescopes, or dedicated exoplanet missions such as TESS.

Through rigorous analysis of the light curve, astronomers can extract valuable data about the exoplanet, including its radius, orbital period, orbital inclination, and the potential presence of additional bodies in the system. The depth and duration of the transit provide insights into the size and orbital parameters of the exoplanet, while the shape of the light curve can yield information about the planet's atmosphere, potential obliquity, or the presence of additional transiting objects.

Observations

The observations of the exoplanet TOI-560 c, along with other planetary objects in the system, have been conducted using a combination of ground-based and space-based observatories, including instruments such as the CHEOPS satellite. The data obtained from CHEOPS are essential in our research on TOI-560 c.

Within the scope of our research, the values of the mass and the radius of the host star, the exoplanet mass and its temperature were made available.

The available data from the CHEOPS telescope was accessible within the Allesfitter software. Allesfitter is a software tool that is designed for the purpose of fitting models to observational data, particularly in the field of astronomy and exoplanet research. It provides a framework for analyzing various types of astrophysical data. The primary goal of Allesfitter is to facilitate the comparison of theoretical models with observed data and to determine the best-fitting parameters for those models. By automating and streamlining the fitting process, Allesfitter simplifies the analysis of complex astrophysical systems and allows researchers to extract valuable information from observational data.

Based on the available data from the CHEOPS telescope, the following data were made available. The mass of the star TOI-560 (M_S) is equal to 0.73 ± 0.02 solar masses (M_{Sun}), and its radius (R_S) was equal to 0.65 ± 0.02 solar radii (R_{Sun}). The mass of the planet itself (M_P) is amounted to $9.70^{+1.80}_{-1.70}$ Earth masses (M_{Earth}), as well as its orbital period around the star (18.8797 days). The last known information was the planet's average temperature, reaching 225±15°C (for comparison, the average temperature on Earth is 17° C).

Name	Median value	Lower error	Upper error	Case note
Radius of the star (in units of Solar radii)	0.653	0.018	0.016	Cheops observations
Mid-transit time (in units of days)	0.4416	0.0058	0.0050	Cheops observations
Orbital period (in units of days)	18.8797			Other observations from the archive

Figure 1: Data from CHEOPS [ ]

3. Data analysis

The aim of the analysis is to determine the radius of the exoplanet TOI-560 c, its orbital period, distance from its star, and its density. The methods of calculations are given in the following sections.

3.1. The radius of TOI-560 c

To determine the radius of the planet, it was necessary to know the depth of the transit (i.e., the percentage decrease in the brightness of the star TOI-560 when the planet TOI-560 c was located between the observer and its star). In our calculations, this was estimated to be 0.2%.

Subsequently, the analysis is proceeded with the formula:

$$Transit = \frac{\pi \times Rp^2}{\pi \times Rs^2 \times 100} \quad (3.1)$$

R stands for radius; *p* stands for the exoplanet (TOI-560 c) and *s* stands for its star (TOI-560).

The following is modification of the formula for calculating the radius:

$$Rp^2 = \frac{\pi \times Rs^2 \times Transit}{\pi \times 100} \quad (3.2)$$

$$Rp^2 = \frac{Rs^2 \times Transit}{100}$$

$$Rp = \sqrt{\frac{Rs^2 \times Transit}{100}}$$

The known values are substituted into the formula (3.2.):

$$Rp = \sqrt{\frac{0.65^2 \times 0.2}{100}} \quad (3.3)$$

Calculations of radius follows.

$$Rp = 0.029\ Rs$$

$$Rp = 0.029\ \times\ 109$$

$$Rp = 3.16\ REarth$$

Due to the imprecise estimation of the percentage transit depth, however, our result Due to the imprecise estimation of the percentage transit depth, our result turned out slightly higher than it actually was. Referring to the values obtained in the Allesfitter program, we adjusted our result to $Rp = 2.378$ R_{Earth}, and this value is used as the basis for further calculations.

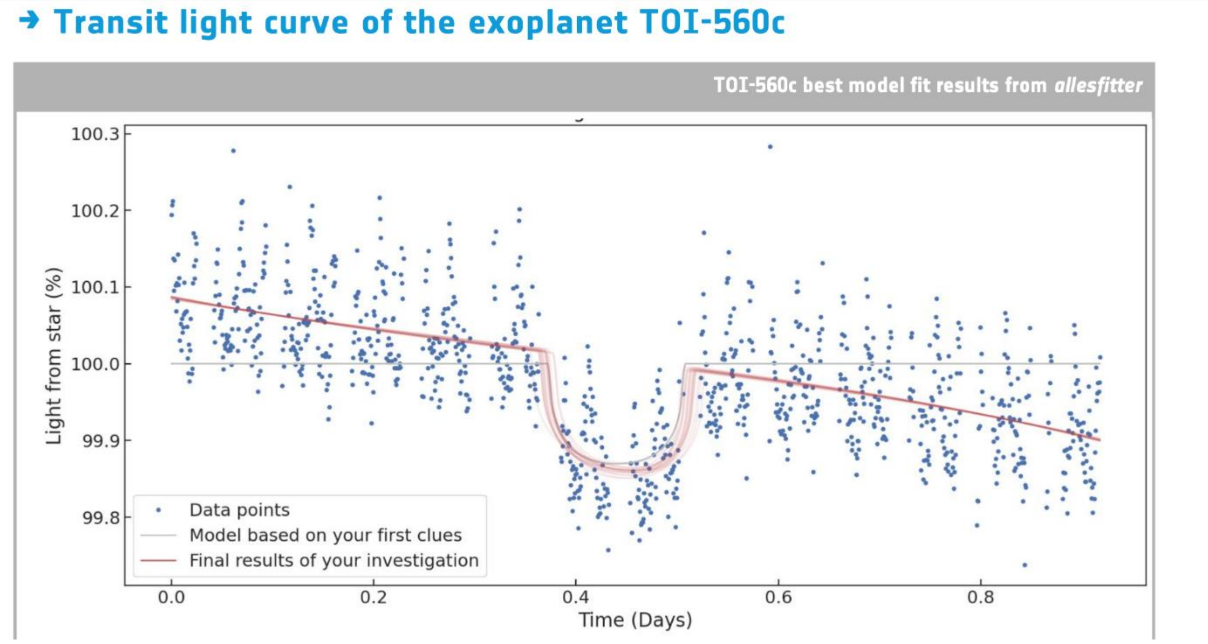

Figure 2: Transit light curve of the TOI-560 c [1]

3.2. Orbital period

In the calculation of the orbital period, it was necessary to know the gravitational constant (G) and the mass of the Sun (M_S).

We found both values on the Hack an Exoplanet website[1]. The values we worked with are as follows:

$$G = 6.6743 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2} \qquad (3.4)$$

$$Ms = 1{,}9554 \times 10^{30}\ kg \times 0.73 \qquad (3.5)$$

$$Ms = 1.451532 \times 10^{30}\ kg$$

From the values obtained from the Allesfitter program, the orbital period of TOI-560 c (18.8797 days) was determined. For further calculations, this value to seconds (1631206.082 s) is converted.

These values were then used in the formula

1 https://hackanexoplanet.esa.int/wp-content/uploads/2023/04/Hack_an_exoplanet_challenges_Czech.pdf

$$T^2 = \left(\frac{4 \times \pi^2}{G \times Ms}\right) \times d^3, \tag{3.6}$$

where *d* represents the orbital distance.

The work with the formula proceeded as follows:

$$T^2 = \left(\frac{4 \times \pi^2}{G \times Ms}\right) \times d^3 \tag{3.7}$$

$$d = \sqrt[3]{\frac{G \times Ms}{4 \times \pi^2} \times T^2} \tag{3.8}$$

$$d = \sqrt[3]{\frac{6.6743 \times 10^{-11} \times 1{,}451532 \times 10^{30}}{4 \times 3.14^2} \times 1631206.08^2} \tag{3.9}$$

$$d = 1.869721425 \times 10^{-11}\, m \tag{3.10}$$
$$d = 0.124\, AU$$

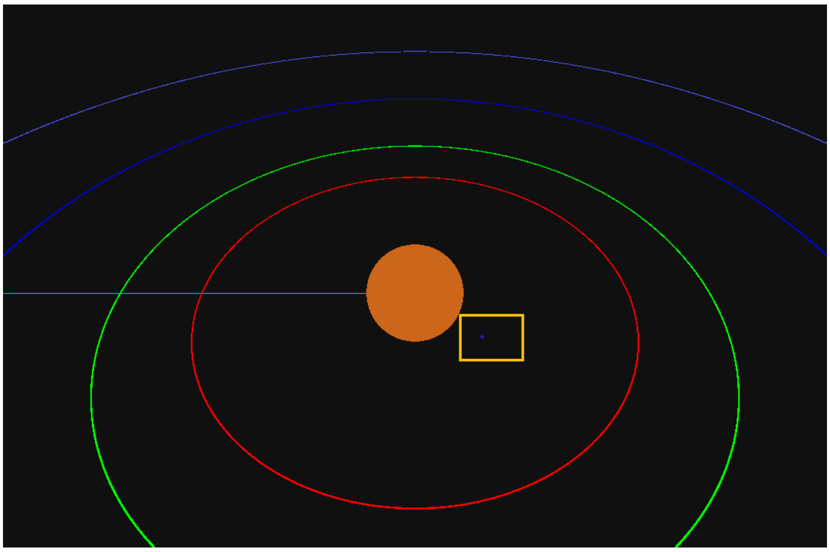

Figure 3: The model of the orbit of TOI-560 c around the star TOI-560 (the blue dot in the yellow rectangle represents TOI-560 c) [1]

From the calculations, a result of 0.124 AU, which is a shorter distance compared to the Earth's distance from the Sun (1 AU). The comparison of values related to TOI-560 c with those related to planets in the Solar System will be addressed in a later part of the study. At this point, it is appropriate to mention that based on the orbital period and the distance from the host star, it can be inferred that TOI-560 c is very close to its star and is not located within the habitable zone (Figure 3).

3.3. Temperature

The average temperature on TOI-560 c was determined from the available data obtained by the CHEOPS telescope, as provided on the Hack an Exoplanet website [2]. The average temperature on TOI-560 c is approximately 225°C. This significantly surpasses the temperatures of nearly all the planets in the Solar System, with the possible exception of Venus, where the average temperature reaches values around 565°C. The temperature of TOI-560 c is close to the temperature of Mercury, where the average temperature reaches up to 167°C. Such a temperature is inhospitable for life similar to that on Earth, as the average temperature on Earth hovers around 17°C. Additionally, the temperature we have determined for TOI-560 c exceeds the boiling point of water (125°C). One crucial factor is the atmospheric pressure. The boiling point of a substance depends not only on its temperature but also on the pressure exerted on it. On Earth, at sea level, the atmospheric pressure is approximately 1 atmosphere, which allows water to boil at 100°C. On TOI-560 c, however, the atmospheric conditions and composition are substantially different. If the atmospheric pressure is significantly higher than on Earth, water would require a higher temperature to reach its boiling point. The boiling point of a substance is the temperature at which its vapor pressure equals the external pressure acting on it. If the external pressure is higher, as might be the case on TOI-560 c, the boiling point of water would be correspondingly higher.

This poses a significant challenge for the emergence of life akin to that on Earth.

Nevertheless, this conclusion is not entirely definitive or conclusive. Despite the inhospitable conditions on the planet's surface, there is a possibility of liquid water existing in the form of subsurface oceans or deep reservoirs. The high density (see *3.4. Density*) of TOI-560 c could indicate the presence of a significant amount of water locked beneath its rocky surface.

[2] https://hackanexoplanet.esa.int/wp-content/uploads/2023/04/Hack_an_exoplanet_challenges_Czech.pdf

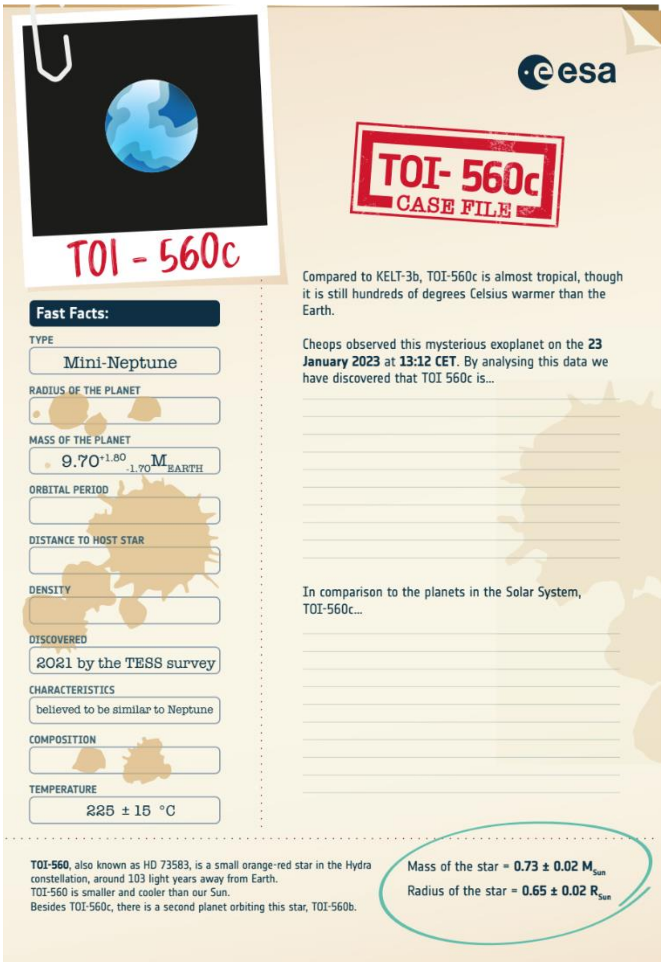

Figure 4: Data (temperature) from the Hack an exoplanet website [1]

3.4. Density

To calculate the density of the planet, it was necessary to determine its volume. The volume is calculated using the formula

$$Vp = \frac{4}{3} \times \pi \times Rp^2 \ , \tag{3.11}$$

where R_P represents the radius of TOI-560 c.

We multiplied $R_P = 2.37$ by $R_{Earth} = 6378\ km$ to convert it to base units. From this, we obtained the value of R_p.

$$Rp = 2.37 \cdot 6378 = \ 15116000\, m^3 \tag{3.12}$$

We substituted this value into the aforementioned formula (3.11),

$$Vp = \frac{4}{3} \times \pi \times Rp^2. \tag{3.13}$$

The formula then looked as follows:

$$Vp = \frac{4}{3} \times 3.14 \times 15116000^2 \qquad (3.14)$$
$$Vp = 1.446724017$$

The value of volume was then substituted into the formula for calculating the density,

$$\rho = \frac{Mp}{Vp} \qquad (3.15)$$

where ρ represents the density, M represents the mass, V represents the volume and p represents the exoplanet (TOI-560 c).

The calculation proceeded according the (3.15) as follows:

$$\rho = \frac{9.70}{1.446724017 \times 10^{22}} \qquad (3.16)$$

$$\rho = 4004\ kg/m^3 \qquad (3.17)$$
$$\rho = 4.004\ g/cm^3$$

3.1. Results

Table 1: Results of the study

Name	TOI-560 c
Radius	2.378 R_{Earth}
Orbital distance	0.124 AU
Orbital period	18.8797 days
Density	4.004 g/cm3
Average temperature	225 degrees Celsius

Based on the provided information about exoplanet TOI-560 c, hypothesis could be proposed regarding its appearance and potential habitability.

- **Hypothesis 1:** Given the average temperature of 225 degrees Celsius, it is likely that TOI-560 c has a hostile environment with extreme heat. The high temperatures suggest the absence of an Earth-like atmosphere capable of sustaining life as we know it. Instead, it may have a predominantly thick and dense atmosphere composed of greenhouse gases, leading to a significant greenhouse effect. This could result in a runaway greenhouse effect, causing the surface temperatures to rise to uninhabitable levels.
- **Hypothesis 2:** The density of TOI-560 c, estimated at 4.004 g/cm3, suggests a high concentration of heavy elements or rocky materials. It is possible that the exoplanet has a rocky composition similar to terrestrial planets in our Solar System. The surface may be characterized by rugged terrain, rocky formations, and potentially active geological

processes. However, the extreme temperatures make it unlikely that liquid water exists on the planet's surface.

- **Hypothesis 3:** Despite the inhospitable conditions on the planet's surface, there is a possibility of liquid water existing in the form of subsurface oceans or deep reservoirs. The high density of TOI-560 c could indicate the presence of a significant amount of water locked beneath its rocky surface. It is conceivable that, if certain conditions are met, such as geothermal activity and insulation, these subsurface oceans could provide a potential habitat for microbial lifeforms adapted to extreme environments. These organisms might thrive in environments akin to Earth's deep-sea hydrothermal vents or subsurface habitats.

4. Conclusion

Based on the provided information, the following conclusions are obtained:

1. The exoplanet TOI-560 c has a radius of 2.378 times larger than the radius of Earth *(R_{Earth})*. This suggests that TOI-560 c is larger in size compared to Earth. That is also the reason why TOI-560 c is sometimes referred to as a *"Super-Earth"*. However, the radius of TOI-560 c is much closer to the radius of Neptune *(3.88 R_{Earth})*. That is also why we do not object to the designation *"Mini-Neptune"* in our study group.

2. TOI-560 c is situated at an average distance of *0.124* astronomical units *(AU)* from its host star. This indicates that it orbits relatively close to its star within the planetary system. For reference, TOI-560 c has a similar orbital distance to Mercury *(0.39 AU)* or Venus *(0.72 AU)*. Therefore, we can confidently state that it is not located in the habitable zone, considering both the properties of its host star.

3. Density: With a density of *4.004* (g/cm3), TOI-560 c possesses a relatively high density. This suggests that the exoplanet is likely composed of dense materials, possibly including heavy elements.

4. Average temperature: The average temperature on TOI-560 c is approximately 225 °C. This temperature is significantly higher than the average temperature on Earth.

Based on the provided data, the values of the radius, volume, density, temperature, orbital distance and period were provided for exoplanet TOI-560 c. It appears to be a hostile environment with extreme temperatures and an inhospitable surface. However, the presence of subsurface water reservoirs or oceans cannot be ruled out entirely, potentially providing a niche for extremophilic lifeforms. Further scientific investigation, including observations and measurements, would be necessary to validate these hypotheses and determine the actual habitability of TOI-560 c.