ANALYSIS AND RESULTS

A. Modeling based on the transit data of TOI-560c

Figures 2 and **3** display images showing the Allesfitter interface with the brightness data that were adjusted to find the best model. This data fitting process is performed using the statistical method called Markov Chain Monte Carlo. The calculation of the parameters took several minutes to complete, ultimately resulting in the model shown in **Figure 4**.

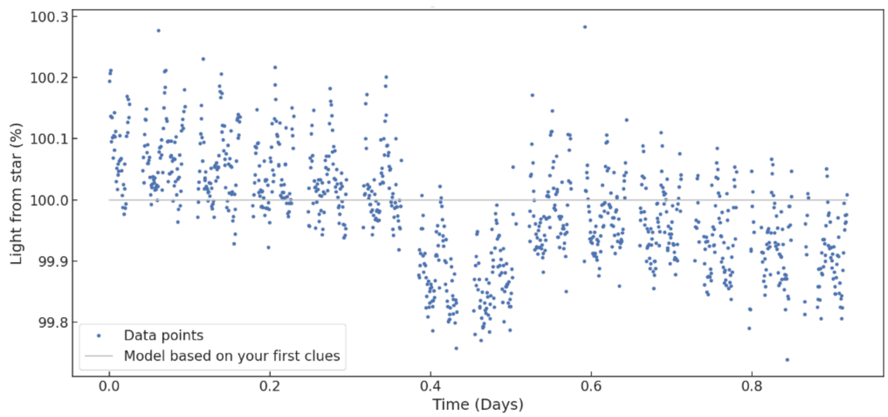

FIGURE 2. Allesfitter interface for fitting the light curve of the transit of TOI-560c.

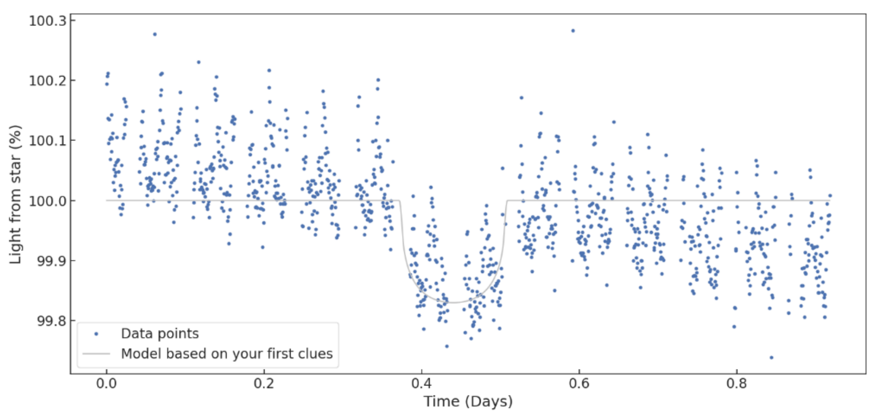

FIGURE 3. Allesfitter interface for fitting the light curve of the transit of TOI-560c.

In **Figure 4**, the light axis of the star is normalized to 100%. However, some outlier values appear above 100%, which may be related to stellar flares or stellar storms. Therefore, the asymmetry in the transit can be observed. This is because the transit of the exoplanet in front of its host star can be asymmetric in nature. Hence, these phenomena affect the shape of the exoplanet's transit curve, resulting in luminosity values exceeding 100%.

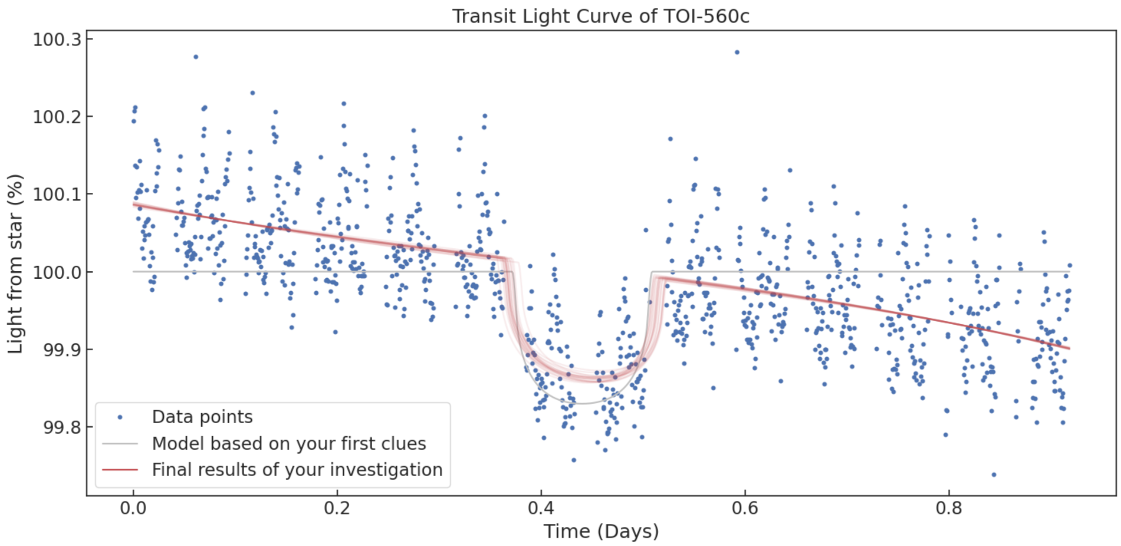

FIGURE 4. Transit light curve fitting for TOI-560c.

On the other hand, **Figure 5** displays a statistical probability histogram of the estimated parameters of the transit of the exoplanet TOI-560c, providing a visual representation of the probability distribution of the data. This is useful for analyzing centrality, dispersion, the shape of the distribution, and detecting outliers. This knowledge is crucial for statistical analysis and interpretation of results in exoplanet research.

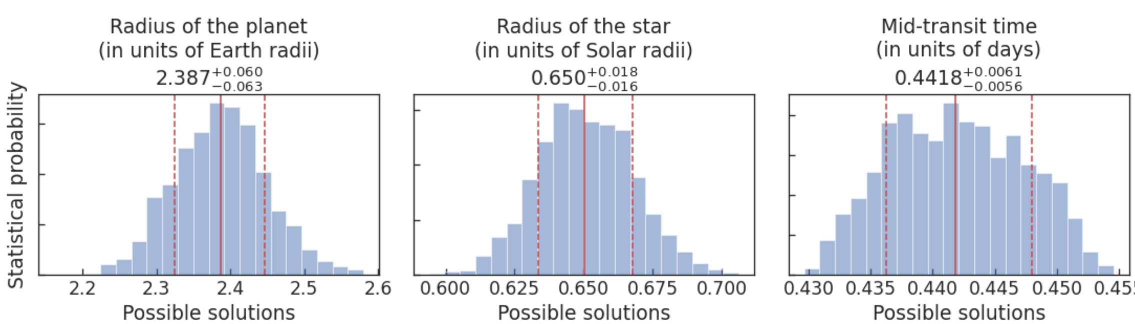

FIGURE 5. Probability histogram of values and parameters for TOI-560c

Finally, the estimated data by the Allesfitter software are shown in **Table 2**. This version of the tool already has the loaded data sets and only allows the exploration of specific parameters: planet radius, star radius, semi-major axis of the orbit, and mean transit time.

TABLE 2. Fitting data for the exoplanet estimated by Allesfitter

Name	Median value	Lower error	Upper error	Case note	Target
Radius of the planet (in units of Earth radii)	2.387	0.063	0.060	Cheops observations	TOI-560c
Radius of the star (in units of Solar radii)	0.65	0.016	0.018	Cheops observations	TOI-560c
Mid-transit time (in units of days)	0.4418	0.0056	0.0061	Cheops observations	TOI-560c
Orbital period (in units of days)	18.8797			Other observations from the archive	TOI-560c
Orbital semi-major axis (in units of AU)	0.1242			Other observations from the archive	TOI-560c

B. Calculation of Orbital Distance

The ESA's Cheops satellite observed TOI-560c on January 23, 2023, at 13:12 CET, using transit photometry. The estimated radius of the star TOI-560 (HD 73583) was determined to be $0.65R_{\odot}$. Consequently, through the analysis of the data, we can measure the transit depth of the exoplanet to be approximately 0.12%, as shown in **Figure 6.**

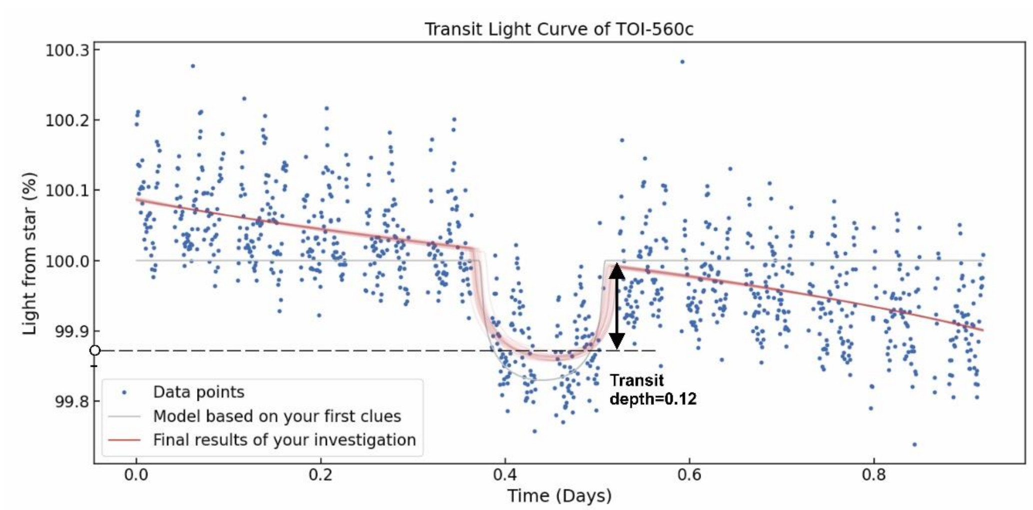

FIGURE 6. Transit light curve depth for TOI-560c.

Esta profundidad está relacionada de forma directa con el radio de la estrella (R_s) y el radio del planeta (R_p), como se muestra en la **Ecuación 1**. Donde R_p es el radio del planeta, R_s radio del a estrella, obtentiendo el porcentaje de la profundidad del transito.

This depth is directly related to the radius of the star (Rs) and the radius of the planet (Rp), as shown in **Equation 1**, where Rp represents the planet's radius, Rs represents the star's radius, and the transit depth is expressed as a percentage.

$$transit\ depth\ (\%) \approx \frac{\pi {R_p}^2}{\pi {R_s}^2} \times 100 \qquad (1)$$

Calculus:

$$R_p = \sqrt{{R_s}^2 \times \frac{trasit\ depth}{100}}$$

$$R_p = \sqrt{{R_s}^2 \times \frac{trasit\ depth}{100}} = \sqrt{0.65\ {R_\odot}^2 \times \frac{0.12}{100}} = 0.022 R_\odot$$

In order to compare with the radius of Earth, a unit conversion is performed.

$$R_p = 0.022 \cancel{R_\odot} \times \frac{109 R_\oplus}{\cancel{1 R_\odot}} = \mathbf{2,45} \boldsymbol{R_\oplus}$$

In light of this result of $2.45R_\oplus$, the radius obtained from the Allesfitter fit is $2.387R\oplus$. It can be observed that they are close and this result can be compared with some known planets in the solar system. The planet that is most similar, albeit smaller in size, is Neptune with a radius of $3.88R\oplus$. It is well known that Neptune is a gas giant, as described in the specialized literature, and its formation was primarily based on processes occurring in protoplanetary disks, which are byproducts of the stellar formation process. [[i]]

To further study TOI-560c, the calculation of the orbital period (d) must be done by applying Kepler's third law, as shown in **Equation 2**.

$$T^2 = \left(\frac{4\pi^2}{GM_s}\right) d^3 \qquad (2)$$

Where G is the gravitational constant, Ms is the mass of the star, d is the mean orbital distance, and T is the orbital period. Note that the mass of the star, as shown in **Table 2**, is $0.73M_\odot$. Additionally, for the calculations, unit conversion to SI units is performed, resulting in 1.45×10^30 kg for the mass of the star. The orbital period of 18.8797 days, obtained from the fitting data in the Allesfitter software (**Table 2**), is also converted to seconds.

Calculus:

$$d = \sqrt[3]{\frac{GM_s}{4\pi^2} T^2} = \sqrt[3]{\frac{(6.674 \times 10^{-11}) \times 1.452 \times 10^{30}}{4\pi^2} \times 1631206\ ^2} = 18.69 \times 10^9\ m$$

In order to compare the calculated distance with other reference data, it is necessary to convert the units into astronomical units (AU). The mean distance between the exoplanet and its host star is 0.124 AU. Below, in **Table 3**, a comparison can be made between the orbital period and the mean orbital distance with some planets in our solar system, as well as another studied exoplanet, Kelt-3b.

Table 3. Comparison of the period and mean orbital distance of TOI-560c and the planets of the Solar System.

Planet	Period (days)	Mean orbital distance (ua)
Kelt-3b	2.70339	0.048
TOI-560c*	**18.8797**	**0.124**
Mercury	87.97	0.4
Earth	365.25	1
Neptuno	60266.25	30

C. Habitability of TOI-560c

An important factor to consider when assessing the habitability of a planet is its temperature. This can be studied by taking into account the distance to its host star, where water remains in a liquid state on the planet's surface, known as the habitable zone. Water is a vital component for the development of life as we know it. If the planet is too far from its host star, water remains in a solid state due to freezing, and if it is too close, water could be in a gaseous state. In this particular context, TOI-560c has a shorter orbital period than Mercury, which is the closest planet to the sun. As stated by Zhu [[ii]], planets with radii between 1 and $4R_{\oplus}$ are frequently found in close orbits around Sun-like stars. It is unlikely that TOI-560c can support life, as it is very close to its host star. This proximity results in high levels of radiation. As a consequence, the temperature of TOI-560c is 225± 15 °C, which is extremely high and would have significant implications for the development of life as we know it. Other authors, such as Barragán et al [6], propose temperatures of 498±15 °C for this exoplanet, which, in the context of this study, still represent inhospitable conditions for an extraterrestrial world.

1. In summary, due to the extreme conditions such as high temperature and lack of liquid water, it would be highly unlikely for carbon-based life and organic compounds to exist on the exoplanet TOI 560c. At such high temperatures, the planet would present:
2. Inhospitable environments: High temperatures would create an extremely inhospitable environment for most known forms of life.
3. Water evaporation: Liquid water would quickly evaporate. Water vapor would rise into the atmosphere and could have a significant impact on the climate and atmospheric composition of the planet.
4. Chemical anomalies: Many chemical compounds would decompose or react differently at high temperatures. Therefore, the surface chemistry and atmospheric composition could change dramatically.
5. Detrimental effects on the atmosphere: The high temperature could affect the stability of the planet's atmosphere. Intense atmospheric movements, such as extremely strong winds or violent storms, could occur.

These factors collectively suggest that TOI 560c is highly unfavorable for the development and sustainability of life as we know it.

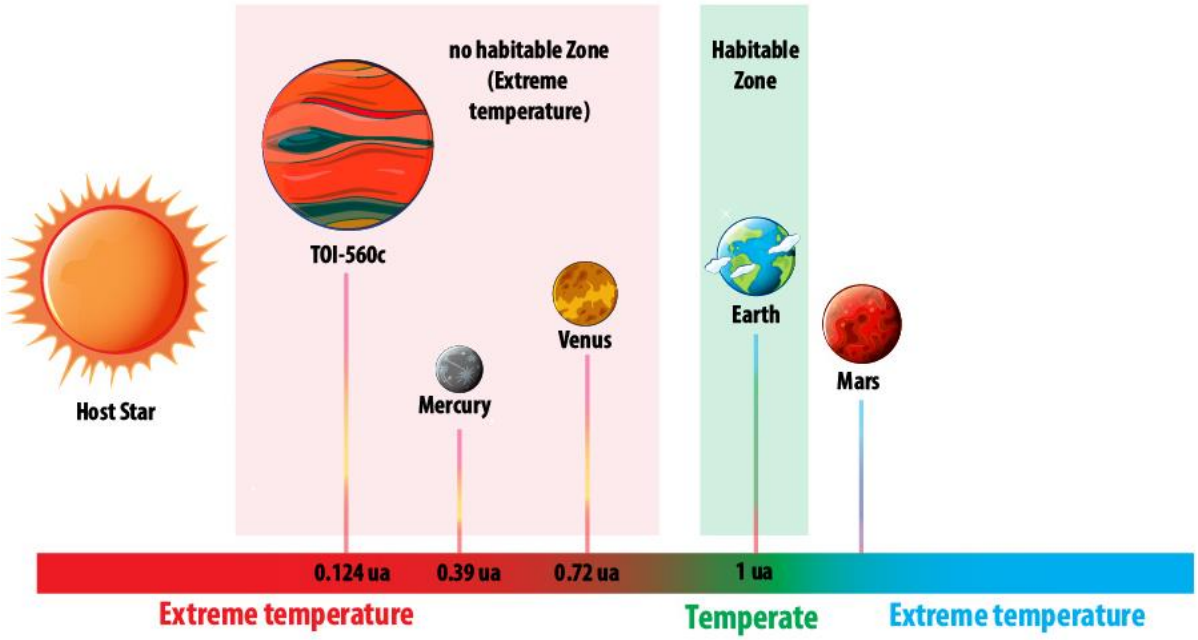

FIGURA 7. Illustrative diagram presenting the size and temperature of planets relative to their distance from their host star.

In this application context, the concept of habitability, as proposed by Charnonnel et al., does not solely depend on the effective temperature of the host star. Other variables, such as the relative position within the habitable zone, direct influence of intrinsic interstellar parameters, tidal, magnetic, and atmospheric interactions, also play a role. However, for life as we know it based on carbon, the primary factor of inhabitability is high radiation associated with high temperature. Compared to other planets in the solar system, as depicted in Figure 7 (a visual representation of size and distance), the radiation from the star and other forms of electromagnetic radiation could be much more intense, considering that known life is based on water and carbon.

D. The composition of TOI-560c

Once the radius of the exoplanet is calculated, assuming it is a perfect sphere, Equation 3 is applied, which is known for mass density, taking the mass of the Earth as 6 × 10^24 kg and the radius of the Earth as 6.37 × 10^6 m. By calculating the average density of an exoplanet, it is possible to get an idea of its composition.

$$\rho = \frac{M}{V} \quad (3)$$

$$V = \frac{4}{3}\pi {R_p}^3 \quad (4)$$

Where M is the mass of the exoplanet, V is the volume of the exoplanet, and ρ is the mass density with dimensions $[\rho] = ML^{-3}$.

Calculus:

$$R_p = \mathbf{2,45}\boldsymbol{R_\oplus} = \mathbf{1.56 \times 10^9}\ \boldsymbol{cm}$$

$$M_p = 9.70\boldsymbol{M}_{\oplus} = \mathbf{5.82 \times 10^{28} g}$$

$$V_p = \frac{4}{3}\pi(1.56 \times 10^{9}\ cm)^3 = 1.59 \times 10^{28}\ cm^3$$

$$\rho_p = \frac{M_p}{V_p} = 3.65\ gcm^{-3}$$

Although average density can provide some clues about the composition of a planet, additional information and a more detailed analysis are required to obtain a comprehensive and accurate understanding of its composition. However, for the purpose of this study, we can infer that if the average density of the planet is similar to the density of rocky materials, it may be primarily composed of silicate rocks such as basalt or granite. If the average density is higher, it could indicate the presence of denser metals such as iron or nickel in its core. An average density of 3.65 g/cm³ could indicate a composition within the density range of some common materials.

Table 2 presents a list of solid materials in the range of 3 to 4 gcm^{-3}. It is likely that TOI-560c is composed of silicates, specifically some iron-rich silicate minerals such as olivine or pyroxene, which have densities ranging from 3.2 to 4.5 gcm^{-3}. If the planet contains a significant amount of these minerals, its average density could fall within that range. Additionally, it could contain metallic alloys indicating the presence of alloys like bronze or brass, which have similar densities.

Table 2. Materials with densities in the range of 3 to 4 g/cm³

Material	Density (gcm^{-3})
Basalt	2.7 - 3.3
Granite	2.63 - 2.75
Pyrite	3.2 - 4.5
Olivine	3.2 - 4.5

In summary, **Table 3** presents a summary of the estimated properties for TOI-560c (HD 73583 c). It has a mass of 9.7 Earth masses (9.7 M⊕), a volume of 1.59×10^28 cm³, resulting in an apparent density of 3.65 g/cm³. The exoplanet TOI-560c is consistent with a planet composed of a Earth-like interior, which is why some authors refer to it as a "super-Earth." It is also surrounded by a hydrogen envelope that may represent 1% of its mass. Through the completion of this outreach work and experimental research, it was possible to reproduce physical information reported in the specialized literature for this exoplanet. [iii]

TABLA 3. Summary of an estimation of TOI-560c properties

PARAMETER	ESTIMATION
Planet type	Mini-Neptuno
Radio ($\boldsymbol{R}_{\oplus}$)	2,39 (Allesfiter) 2,45 (transit depth)
Mass ($\boldsymbol{M}_{\oplus}$)	9.70
Volumen (cm^3)	$1.59 \times 10^{28}\ cm^3$
Orbital period (days)	18.8797
Mean orbital distance (au)	0.124
Density (gcm^{-3})	3.65
Mean temperature (°C)	225 ±15

[i] Boss, A. P. (2002). Formation of gas and ice giant planets. *Earth and Planetary Science Letters*, *202*(3-4), 513-523.

[ii] Zhu, W., & Dong, S. (2021). Exoplanet statistics and theoretical implications. *Annual Review of Astronomy and Astrophysics*, *59*, 291-336.

[iii] Barragán, O., Armstrong, D. J., Gandolfi, D., Carleo, I., Vidotto, A. A., Villarreal D'Angelo, C., ... & Ziegler, C. (2022). The young HD 73583 (TOI-560) planetary system: two 10-M⊕ mini-Neptunes transiting a 500-Myr-old, bright, and active K dwarf. *Monthly Notices of the Royal Astronomical Society*, *514*(2), 1606-1627.