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EVOLUTION STUDY OF SOLAR LIKE STAR τ CETI USING MESA PROGRAM

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Abstract

Tau (τ) Ceti is a G8V class star that has similarities to the sun and several comparable physical properties, although in general its value is smaller and not as active as the sun. Similarities also occur in the planetary system, which has been studied and confirmed to be terrestrial types, four of them were confirmed in the Habitable Zone. This paper aims to study the evolutionary traces of the star Ceti related to the initial studies of its influence on the planetary system through modelling experiments. Interior structure modelling and evolution were carried out with the MESA program. The study of stars belonging to population II begins with the determination of several fundamental parameters obtained from observations such as interferometry and spectroscopy from several references and calculations, which are then used as input in building the model. Static modeling has been carried out by the current condition of the star in the main sequence phase with an age of 9.5 Gyr producing various physical parameters and the division of the star's atmospheric zone. The evolutionary modelling was carried out up to the Asymptotic Giant Branch (AGB) stage, related to the initial studies of its relationship to the planetary system. Result shows that, without consideration of planetary tidal effect, three of the four planets are likely to be affected by the evolution of τ Ceti. Even though the simulation was only carried out up to the AGB stage, the end history of τ Ceti will be similar to a Solar-mass star, yet over a longer period of time than the Sun.

Keywords: τ *Ceti, solar-like star, stellar evolution, MESA.*

1. Introduction

Tau Ceti (HD 10700) is a metal-poor population II G spectral class star in the main sequence (G8V). Its apparent magnitude (V) is 3.50 ± 0.01, while its absolute magnitude (M_v) is 5.69 ± 0.01 (Tang & Gai 2011). The star is quite close to our Solar System at the distance of 3.65 ± 0.01 pc (Di Folco et al. 2014) and has an age of 10.0 ± 0.5 Gyr (Di Folco et al. 2004). This single star has a fainter close neighbor with only 10 arcseconds in angle separation and a magnitude of 13.1, but it does not significantly affect the measurements (Pijipers et al. 2003). Teixeira et al. (2009) suggest that τ Ceti's rotation period is 34 days long and almost unmodulated, so it is thought to be undergoing a phase like the Sun's Maunder minimum. The star also has a convective envelope that exhibits solar-like oscillations (Teixeira et. al., 2009). τCeti is well known for its similarity to the Sun, especially in its Hydrogen core (Pijpers et al. 2003). Other physical parameters of τ Ceti are listed in Table 1 in the Data and Methods section.

τCeti is one of the unique laboratories that can be used to study the long-scale dynamical evolution of planetary systems and become an alternative representation of the evolution of the Solar System (Di Folco et al. 2014). Another interesting feature of this yellow-orange star is the presence of a Super Earth in the planetary system, the discovery of which was detailed by Tuomi et al. (2013) and Feng et al. (2017). This planetary system has also been analyzed by Dietrich & Apai (2020).

Greaves et al. (2004) started the τ Ceti study by obtaining an image of a dusty disk around a τ Ceti star with a mass exceeding that of the Kuiper Belt. Then it continues to be observed down to the millimeter domain using ALMA by MacGregor et al. (2016). Tuomi et al. (2013) described τ Ceti was a 5-planets system, but recent observations by Feng et al. (2017) confirmed that it has four planets with some parameters known to a certain degree. The Radial Velocity (RV) technique is used to model wavelength-dependent noise in combination with a moving average model, hence the name 'differential radial velocity'. The model used by Feng et al. (2017) is used to improve HARPS (High Accuracy Radial Velocity Planet Searcher) measurements, which were previously analyzed by Tuomi et al. (2013) under the program name MT13.

The challenge of constraining the stellar inclination of τ Ceti arises from uncertainties in the observed radial velocities (RV). Korolik et al. (2023) have introduced new constraints on the inclination of the stellar rotation axis that carry significant implications for potential planets identified through RV observations. Korolik et al. (2023) utilized various observation methods to define and improve the understanding of inclination parameters and other parameters of the τ Ceti star. They revised the estimated inclination of τ Ceti's rotation axis to 7 ± 7°. Differences in the stellar inclination parameter have the potential to impact the interpretation of observational data concerning exoplanets in the τ Ceti system.

In light of the many research on this exoplanet, this paper aims to conduct a preliminary review of the influence of τ Ceti's evolution on its planetary systems. However, before looking at the exoplanets, the initial goal of this paper is to model the evolutionary tracks of τ Ceti stars. This evolutionary modelling research is a continuation of the static modelling. Previous static modelling has provided an understanding of the current interior structure of τ Ceti stars through the relationships between the physical parameters (Mumtahana 2020).

A preliminary study of the planetary system of τ Ceti was carried out with the basic idea of comparison with the Solar System. The sun, as a comparison star with τ Ceti, will undergo certain evolutionary stages that affect the planets as its radius increases. The sun is currently in the main-sequence phase with increasing luminosity. In the solar evolution model by Rybicki & Denis (2000), the sun will expand its radius by the time on the RGB stage, which can reach Mercury as the first expansion, then the sun will engulf Venus and Mars in the Asymptotic Giant Branch (AGB) stage as the second expansion. In these references, it is mentioned that the study of stellar evolutionary trajectories is an important input to models their influences on the planet, especially in the RGB and AGB stages. Thus, to achieve the goal of this study, evolutionary modelling was carried out up to the AGB stage because the radius will attain its maximum values.

2. Data & Methods

2.1. Physical Parameters

The study of this star begins with a literature study to determine several physical parameters obtained from observations such as interferometry and spectroscopy. Some parameters have also been validated by calculations, as these values will be adopted as inputs both in the static and evolution model. As shown in Table 2-1, the parameters are mostly taken from Teixeira et al. (2009) and Pagano et al. (2015).

Table 2-1: Fundamental parameters used in static modeling (Mumtahana 2020).

Parameter	Value	Reference
Mass [$M_\odot$]	0.783±0.012	Teixeira et al (2009)
Radius [$R_\odot$]	0.793±0.004	Teixeira et al (2009)
Luminosity [$L_\odot$]	0.488±0.010	Teixeira et al (2009)
T_{eff} [K]	5373±53 K	Pagano et al (2015)
Age [Gyr]	23.164	Di Folco et al (2004)
Log g [dex]	4.55±0.06	Pagano et al (2015)
[Fe/H]	-0.49±0.0.8	Pagano et al (2015)
Metallicity (Z)	0.00642	Calculations (Berteli et al, 1994)
V *sin* i [km/s]	2.4 ± 0.4	Pavlenko et al (2013)

The modelling of the previous interior structure and this evolution study was carried out with the MESA (Modules for Experiments in Stellar Astrophysics) program developed by Bill Paxton (Paxton et al., 2013). The Mesa r-10000 version was used in this study, which can be downloaded at https://sourceforge.net/projects/mesa/files/releases/. This program, which incorporates many numerical and physical modules in stellar evolution simulations, has the ability to model the structure and evolution of stars with a large mass range, from metal-poor to metal-rich stars (Paxton et al., 2013). Thus, it is suitable for τ Ceti that has small mass and low metal fraction.

Table 2-2: Parameters obtained from the static model for the evolution study.

Physical Parameter	Value
Mass [$M_\odot$]	0.775
Metal Fraction (Z)	0.00783
Scaling Factor (RGB, Reimers)	0.2
Scaling Factor (AGB, Blockers)	0.2

In the interior structure model, the main parameters used as input include mass and metallicity (Z) with a stopping condition of T_{eff} (Mumtahana et al., 2020). The main input parameters for the evolution model, including the mass and metallicity from the previous static modelling, are shown in Table 2-2. Other parameters can be added according to the stellar physical properties and modeling objectives. The scaling factors of 'Reimers' and 'Blockers' are used due to their relation to mass loss during evolution in the RGB and AGB stages.

2.2. Planetary System Overview

In studying the influence of a host star on a planetary system, at least two fundamental pieces of information are required: a stellar evolution model and a planetary evolution model. The evolutionary tracks of the τ Ceti star, which have been modeled up to the AGB stage, are then used to estimate the evolution timing and stages that will affect the planets. Rybicki & Denis (2000) studied the case of the Solar System with two assumptions, by considering the mass loss rate of the star and also by considering the tidal effects of planets.

This study only uses stellar evolution models that account for the mass loss rate. To model its evolution up to the AGB stage, experiments using both the Reimers and Blocker scale factor values were conducted, which turned out to have a significant effect on τ Ceti stars with a scale factor value of 0.2. Table 2-2 gives results that are quite suitable for the character of τ Ceti stars.

Table 2-3: τ Ceti Planetary System Parameters.

Planet	P (day)	A (au)	$R_\odot$
τ Ceti g	20.00	0.133	28.58
τ Ceti h	49.41	0.243	52.25
τ Ceti e	162.87	0.538	115.64
τ Ceti f	636.13	1.334	288.69

The τ Ceti star system has been widely studied, and the recent reference by Feng et al. (2017) provides more accurate information. Some of the information required for this study is given in Table 2-3. The corrected distances for planets orbiting τ Ceti stars named g, h, e, and f are obtained from Feng et al. (2017) and converted from au to $R_\odot$.

3. Result and Analysis

3.1. Evolution Model Analysis

The results of the evolution modelling are shown in the Hertzsprung-Russel diagram in Figure 3-1. The evolution model obtained is carried out for low-mass stars, starting from the Pre-Main Sequence (PMS) phase to the AGB. In Figure 3-1, points A to I are given to trace the evolution of each stage. The parameters of each point are given in Table 3-1.

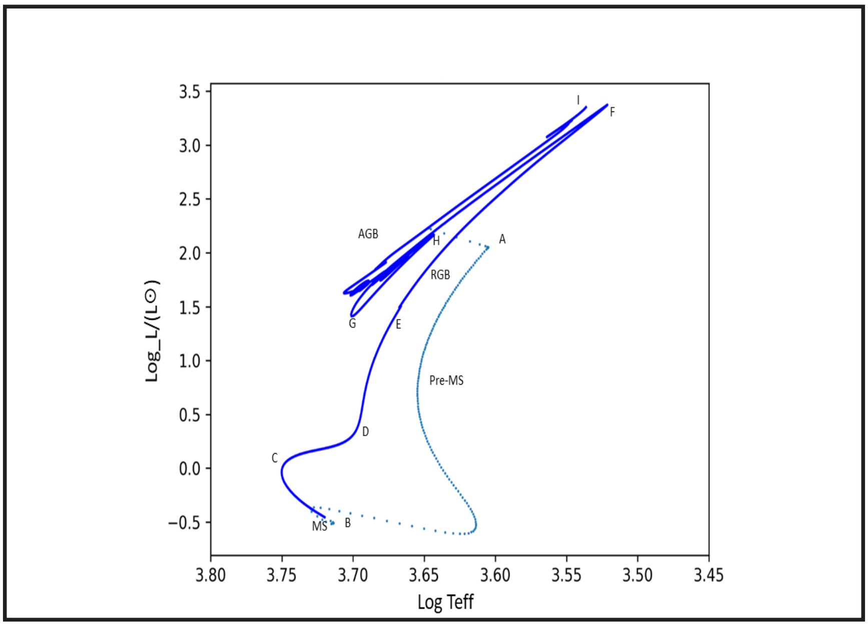

Figure 3-1: Evolution track of τ Ceti on HR Diagram from Pre Main-Sequence (dotted-line) to AGB stage.

Table 3-1: MESA modelling results for the τ Ceti evolution track.

Point	Stages	Age (year)	T_{eff} (K)	M /M⊙	L/L⊙	Tc (K) (10^7)	R/R⊙	Pc (dyne/cm²)
A	Pre-MS	17.44	4029.93	0.775	111.872	0.0302	21.726	3.8×10^{10}
B	ZAMS	5.855×10^8	5178.168	0.775	0.315	1.15	0.2777	1.39×10^{17}
B-C	MS	9.5×10^9	5401.321	0.775	0.455	1.34	0.766	2.23×10^{17}
C-D	SGB	1.895×10^{10}	5624.321	0.774	0.915	1.65	1.008	9.93×10^{17}
D-F	RGB	2.295×10^{10}	5016.785	0.773	1.999	2.42	1.874	9.03×10^{19}
E	Dredge up 1	2.309×10^{10}	4640.876	0.770	31.908	3.52	8.729	1.95×10^{21}
F	Helium Flash	2.318×10^{10}	3318.945	0.659	2349.633	3.33	146.521	3.13×10^{21}
G-H	AGB	2.318×10^{10}	3810.658	0.659	641.032	2.60	51.942	1.66×10^{21}
I	Thermal Pulsation	2.329×10^{10}	3437.954	0.594	2243	9.89	133.659	4.23×10^{22}

Pre-Main Sequence Evolution (A-B)

The pre-main sequence evolution shown at point A starts from the Hayashi track with a vertically decreasing feature until the star reaches the beginning of the main sequence phase or Zero Age Main Sequence (ZAMS) at point B. In this phase, the proto-star has a convective structure with low temperature values but high luminosity. τ Ceti stars have an effective temperature of 4029 K and a central temperature (Tc) of only 3.02×10^5 K. At this stage, the star's energy source comes from gravitational contraction, which causes its luminosity to decrease with a slight increase in temperature. However, as the energy production continues to increase, the luminosity increases again along with the temperature, while the radius becomes smaller. After passing this stage, a radiative core begins to form as the temperature in the core increases until it is hot enough for nuclear fusion to begin. The star then begins a hydrogen burning reaction in the core as its main source of energy and enters the ZAMS stage, which starts at an age of 5.855×10^8 years.

Main Sequence Evolution (B-C)

In the main sequence phase, stars can spend a very long time, up to 90%, of their lifetime. By the end of the main sequence stage, a low-mass star like τ Ceti will have spent 13 Gyr before moving on to the next stage of its evolution. However, the change in position is very slow, with the temperature and luminosity increasing slightly over time as the star burns hydrogen to helium in the dominant proton-proton reaction. As a result of this reaction, at the end of this sequence phase, helium will accumulate in the center of the star, while the remaining hydrogen will accumulate in the core envelope. This changes the interior structure of the star as the temperature and luminosity increase, although the radius does not increase as significantly as it would for a high-mass star going through this stage. Although the hydrogen in the center begins to burn out and helium is abundant in the core, the helium burning process will not yet occur. This is because the core is not hot enough (only 1.34×10^7 K) and has not yet reached a degenerative state.

Post-Main Sequence: SGB – RGB – TP AGB (C-I)

Although the temperature at the center is not yet sufficient to generate energy from helium nuclear reactions, the helium deposits at this stage cause the core of the star to contract and heat up, allowing hydrogen combustion to occur in the shell surrounding the helium core. This process causes a doubling of the star's luminosity at the beginning of the phase. However, not all of the energy generated from the hydrogen shell is channeled to the surface, as some of the energy is used to expand the hydrogen envelope. Therefore, in the middle of the phase, the temperature decreases but the radius increases. To maintain equilibrium, the helium-rich core must not expand beyond the Schonberg-Chandrasekar limit.

When it reaches its limit, the helium nucleus collapses, heats up, and releases energy. The reaction then continues until the core is in a degenerative state. In τ Ceti star, the Sub Giant Branch (SGB) stage is characterized by a horizontal line to the right (points C-D), indicating a cooling temperature. The cooling of the outer layers results in the formation of a convective envelope, and the star finally reaches the RGB or red giant branch, at point D. In this phase, the convective envelope expands so that a mixture of material that has been partially processed in the nuclear core is carried to the surface, including a small amount of helium. This event is called the first dredge-up, where the star's radius and luminosity then increase significantly, as well as the temperature and pressure at the center.

In these small-mass, low-metallicity stars, the first dredge-up is characterized by an enlarged E-point profile (Figure 3-2). The stirring of the material causes the convection layer of the star to thicken. As the radius expands and the temperature decreases, the HR diagram shows a rightward shift of the star's position during the RGB stage (points D-F).

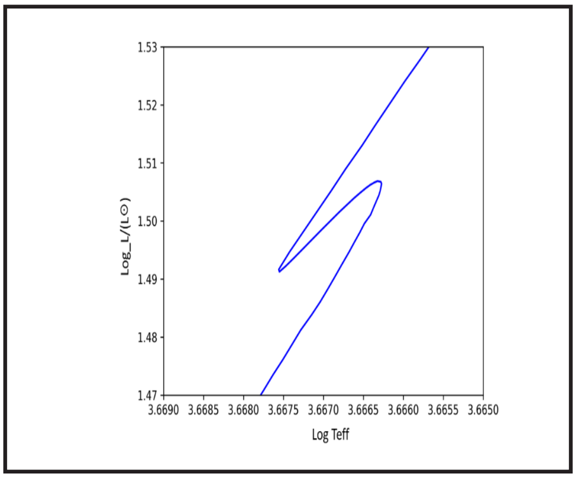

Figure 3-2: The first dredge-up during RGB phase, which occurred at the age of 2.309×10^{10} year.

Towards this final stage of the RGB, the size of the helium core continues to contract and heat up until the temperature is high enough to start the helium-burning reaction. The burning occurs within the shell, in the helium-rich core of the star. The material then degenerates and results in a helium flash (Point F) as the initiation of the helium-burning process in the core. This event occurred when τ Ceti's age reached 2.13 x 10^{10} years with a very high luminosity of 2349.633 $L_\odot$ and a radius of 146.521 $R_\odot$. After this event, the star enters the ZAHB (Zero Age Horizontal Branch) phase, where helium burning in the core starts to produce carbon and oxygen.

At a later point, the Helium at the center is depleted, and the star enters the AGB stage. As in the RGB stage, this phase again sees the mixing of surface convective material with material inside the star as a second dredge-up event. At this stage, the star has an inert core composed of carbon and oxygen, which burns the helium shell and the hydrogen shell located much further out. In this phase, the helium and hydrogen burning shells alternate as the energy sources of the AGB star as a result of thermal instability. However, the excess energy generated from the burning helium shell cannot be transported to the surface because it is blocked by the burning hydrogen shell, increasing pressure from both regions. As a result, the outer layers of the star expand but also contract again due to gravity under unstable and repetitive conditions. This phase is called the AGB thermal pulsation, characterized by the up and down graph (G-H-G-I) on the HR diagram.

3.2. A Preliminary Look at the Effects of Evolution on Planetary Systems

Based on the evolutionary parameters previously shown in Table 3-1, we can obtain information on the relationship with the planets' parameters summarized in Table 3-2. The planets around the star τ Ceti are named g, h, e, and f according to the reference Feng et al. (2017).

Table 3-2: Parameter results for planets g, h, e, and f.

Star parameter	g	h	e	f
Radius ($R_\odot$)	28.973	52.480	116.412	-
Mass ($M_\odot$)	0.760	0.747	0.698	-
Luminosity	208.106	558.72	3394.77	-
T_{eff} (K)	4115.92	3819.73	3394.77	-
Age (Gyr)	23.164	23.174	23.180	-
Stage	RGB	RGB	RGB	-

In Table 3-2, it can be seen that 3 of the four planets with well-known parameters are likely to be affected by the evolution of τ Ceti since the RGB stage. Assuming without considering tidal effects, when the expanding solar radius reaches planet g, the star is 23.16 billion years old, and the luminosity is 208.106 $L_\odot$. When the star reaches 23.174 and 23.180 billion years old, the radius of the star can engulf the planets h and e with increasingly larger luminosities of 558.72 $L_\odot$ and 3394.77 $L_\odot$. The effect of the radius evolution is shown in Figure 3-3, focused on the RGB and AGB stages.

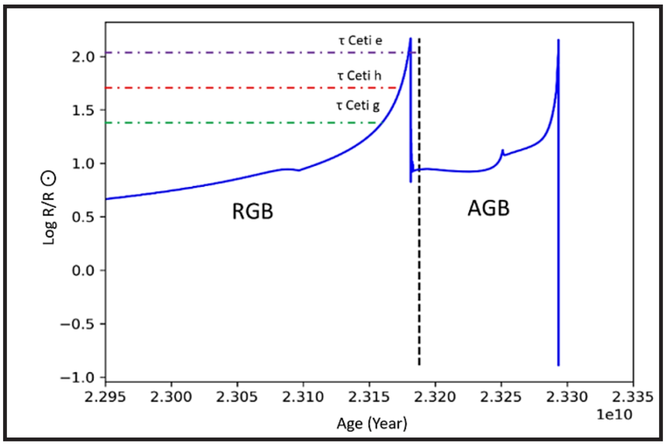

Figure 3-3: Evolution of the stellar radius with age and distance of the planets τ Ceti g, h, and e, uncorrected for mass loss and tidal effects.

In Figure 3-3, the position of the planet τ Ceti g is shown on the green dashed line, planet h in red, and planet e in purple. The vertical black lines are the boundaries of the RGB and AGB stages. The positions of these planets have not been corrected for changes in distance due to mass loss when they enter the AGB stage. The calculation of mass loss from the evolutionary results of τ Ceti stars yields a value of 3.8 x 10^{-13} $M_\odot$/yr in the early RGB stage and a slightly larger 4.5 x 10^{-9} $M_\odot$/yr in the early AGB stage, which can be used as a recommended value to build a linkage model for the planets.

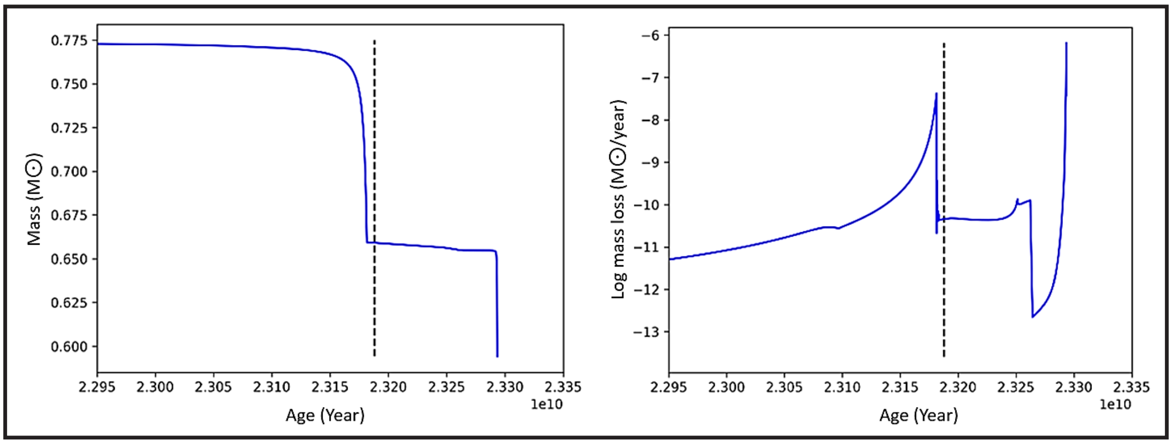

Figure 3-4: The mass change of the star (left) and the amount of mass loss per year (right) during τ Ceti in the RGB and AGB stages, separated by black vertical dashed lines.

The subsequent graphs presented in Figure 3-5 provide information on additional parameters, such as luminosity, effective temperature, surface gravity, and core temperature at the RGB and AGB stages, that can be seen when the radius reaches the planets.

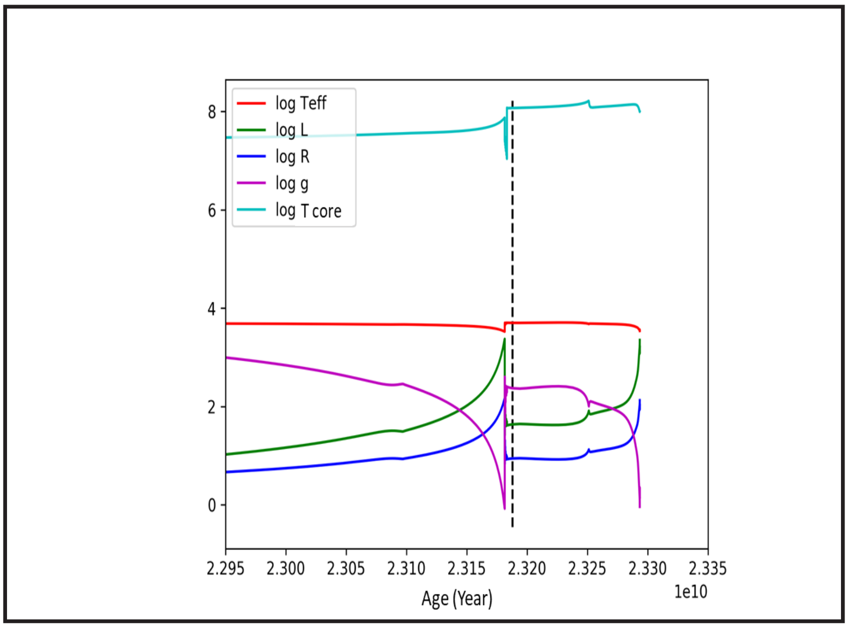

Figure 3-5: Some profiles of changes in the stellar parameter τ Ceti during its evolution in the RGB and AGB stages, separated by black vertical dashed lines.

4. Discussion and Summary

We have studied the evolutionary track of τ Ceti related to the initial analysis of its influence on the planetary system through modelling experiments with the MESA. The study began with by determining several fundamental parameters obtained from observations, such as interferometry and spectroscopy from several references and calculations, which are then used as input in building the interior model. Earlier studies of static modelling used the current condition of the star in the main sequence phase with an age of 9.5 Gyr.

Then, by using the parameters obtained from the static model, the evolutionary modelling was carried out up to the Asymptotic Giant Branch (AGB) stage, related to the initial studies of its relationship to the planetary system.

The result shows that 3 of the four planets with well-known parameters are likely to be affected by the evolution of τ Ceti since the RGB stage. Assuming without considering tidal effects, when the expanding solar radius swallows planet g, h, and f, the star reaches the age of 23.16, 23.174, and 23.180 billion years old, respectively.

In this study, modelling the evolution of a low-mass, low-metallicity star like τ Ceti is more appropriate using a lower solar wind scale factor of 0.2. Although the modeling was only conducted up to the AGB stage, the final history of this star will be similar to that of a Sun-mass star, in which it becomes a planetary nebula and then ends up as a white dwarf, but over a longer period of time than the Sun. The study of the relationship between stellar evolution and its effect on the planetary system is not simple, but reviewing the evolution and obtaining some of its parameters, especially up to the AGB stage, can be a significant first step in addition to modelling the planets themselves.

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Contributorship Statement

FM as the main contributor and conceptualized the research idea. MZN developed the simulation graphs and computations. GPP and AZ verified the references and prepared the manuscript. All authors discussed the results and contributed to the final manuscript.

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