The Physical Parameters and Atmospheric Model of \( \alpha \) Tau at AGB Evolutionary Stage

R Darma\(^1\) and H L Malasan\(^2,3\)

\(^1\)Graduate Program in Astronomy, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Bandung, Indonesia
\(^2\)Astronomy Division and Bosscha Observatory, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Bandung, Indonesia
\(^3\)ITERA Astronomical Observatory, Institut Teknologi Sumatera, Bandar Lampung, Indonesia

E-mail: darmarendy@gmail.com

Abstract. \( \alpha \) Tau is an interesting Red Giant Branch (RGB) star with spectral type K5, yet not well studied. Helium core contraction and hydrogen burning in the shell are occurring in this star. Stars like \( \alpha \) Tau are interesting to be investigated in order to learn and understand how their evolution processes at the next stage, i.e. Asymptotic Giant Branch (AGB) stage. At AGB stage, a star will suffer stronger oscillations with larger radius than RGB stage. This stage is important because it will be the key-factor on most recent observational data, and Modules for Experiments in Stellar Astrophysics (MESA) and SPECTRUM packages to compute accurate physical parameters and atmospheric models of \( \alpha \) Tau at AGB stage.

Our computational results show that \( \alpha \) Tau will be an AGB star with \( M = (1.52 \pm 0.07) \) M\(_\odot\), \( T_{\text{eff}} = (4545 \pm 18) \) K, and \( \log L = (1.98 \pm 0.07) \) L\(_\odot\) at age \( (2.11 \pm 0.27) \) Gyr. Its radius at this stage is determined to be \( \log R = (1.20 \pm 0.92) \) R\(_\odot\). Mass loss at the initial of this stage is still small, i.e. \( (2.07 \pm 0.09) \times 10^{-10} \) M\(_\odot\)/yr and it will increase during this stage. The core at this stage contains carbon and oxygen with \( C/O \sim 0.26 \) which shows that \( \alpha \) Tau will be type M-AGB. Atmospheric model of \( \alpha \) Tau at AGB stage shows that this star will have higher effective temperature and gas pressure than at RGB stage. These conditions will cause the increasing of electron density and Rosseland absorption coefficient in its atmosphere. The hotter atmosphere of AGB stage causes its peak of continuum shifts toward smaller wavelength and yields in three times higher intensity than at RGB stage.

1. Introduction
\( \alpha \) Tau is K5III star which located in Taurus constellation with distance \( (19.96 \pm 0.38) \) pc from our Sun, as measured by Hipparcos satellite. Its late spectral type and distance make it one of the brightest near-infrared and the largest angular diameter among all stars. Many observations of \( \alpha \) Tau were done to get its precise physical parameters at RGB stage, see [1,2,3,4,5]. Its well determined physical parameters at RGB stage bring it into one of FGK-type benchmark stars for calibration of one billion Gaia stars, see [6].

Helium core contraction and hydrogen burning in the shell which cause oscillations are occurring on this RGB star. When the helium core collapses due to the greater gravitational pressure than its thermal pressure, this star will be entering AGB stage as carbon-oxygen core is formed. At this stage, \( \alpha \) Tau will suffer stronger oscillations than at RGB. It is interesting to learn how this star evolves from RGB into AGB stage and its conditions at AGB, by
computing its physical parameters and atmospheric models. In this work, we use the most recent observational data to compute physical parameters and atmospheric models of α Tau at AGB stage using Modules for Experiments in Stellar Astrophysics (MESA) and SPECTRUM. We present the physical parameters of α Tau at RGB stage adopted from several references in Section 2. We use MESA to simulate the evolutionary track of α Tau from RGB to AGB stage, while the atmospheric conditions is modeled by SPECTRUM (see Section 3). In Section 4, we present our results of physical parameters and atmospheric models of α Tau at AGB stage.

### Table 1. Physical parameters of α Tau at RGB stage.

| Parameters         | Value                      |
|--------------------|----------------------------|
| $M$ (M$_\odot$)    | $1.64 \pm 0.09$            |
| $T_{\text{eff}}$ (K) | $3922 \pm 15$              |
| $\log g$          | $1.36 \pm 0.09$            |
| $d$ (pc)           | $1.65 \pm 0.01$            |
| $F_{\text{bol}}$ (W/cm$^2$) | $(33.57 \pm 1.35) \times 10^{-13}$ |
| $\log R$ (R$_\odot$) | $1.65 \pm 0.01$            |
| $\log L$ (L$_\odot$) | $2.85 \pm 0.12$            |
| $\delta$ (mas)    | $20.63 \pm 0.16$           |

#### 2. Physical Parameters of α Tau at RGB stage

We present physical parameters of α Tau at RGB stage in Table 1. Some of them are obtained from previous observations and others are derived from those observable parameters. We use equation (1) to derive mass of α Tau ($M$) which is the functions of gravitational acceleration at the surface ($\log g$), distance ($d$), and angular diameter ($\delta$), while $G$ is the gravitational constant. Here $\log g$ is adopted from [7,8,9]. Besides that, $\delta$ is adopted from interferometry technique, infrared flux method (IRFM), and lunar occultations, see [1,2,4,5,10,11]. While $d$ is measured from Hipparcos satellite.

$$M = 10^{\log g + 2 \log \delta d - \log 4G} \quad (1)$$

We also derive the value of effective temperature ($T_{\text{eff}}$) of α Tau using equation (2) which is the functions of bolometric flux ($F_{\text{bol}}$) and $\delta$, where $\sigma$ is the Stefan-Boltzmann constant. Here $F_{\text{bol}}$ is adopted from [11] who obtained from observations done by [2,4]. While the radius ($\log R$) of α Tau is derived from $\delta$ and $d$. From these parameters, we also calculate luminosity of α Tau using equation (3).

$$T_{\text{eff}} = \left( \frac{4F_{\text{bol}}}{\sigma \delta^2} \right)^\frac{1}{4} \quad (2)$$

$$L = 4\pi d^2 F_{\text{bol}} \quad (3)$$

#### 3. Simulations

##### 3.1. Evolutionary Track with MESA

We simulate the evolutionary track of α Tau at AGB stage using MESA, see [12]. This platform uses Fortran programming language and it is open source for everyone in the world. In MESA,
Figure 1. HR diagram (a), physical parameters as function of ages (b and c) during evolutionary track from RGB to AGB. Different masses are given in different colors. The orange cross symbols in Figure 1a show starting points of AGB stage. While the orange dot symbols show α Tau’s present position at RGB stage that corresponding to physical parameters in Table 1.

the parameters $M$ and metallicity ($Z$) are necessary as input parameters (see Table 2). We run three simulations with different $M$ in the range of its uncertainty. Two stellar wind schemes are implemented to describe mass loss in α Tau, i.e. Reimers scheme [13] for RGB stage and Blocker scheme [14] for AGB stage. Typical scaling factors ($\eta$) for stellar wind schemes, mixing length ($l$) and input parameters are given in Table 2. We also set the stopping condition, where the simulations will stop at AGB stage when the fraction of carbon at the core is less than or equal to $10^{-3}$.

Table 2. Input parameters for evolutionary track of α Tau using MESA.

| Parameters          | Value       |
|---------------------|-------------|
| $M_1, M_2, M_3$ (M$_\odot$) | 1.56, 1.65, 1.72 |
| $Z$                 | 0.02        |
| $\eta_{Reimers}$    | 0.5         |
| $l_{Reimers}$       | 2.0         |
| $\eta_{Blocker}$    | 0.2         |

Generally, MESA consists of three project files, i.e. inlist file, inlist project file, and inlist pgstar file. We set all input parameters, stellar wind schemes, and stopping condition in inlist project file. Settings for various kind of plots done in inlist pgstar file. Then the inlist file will combine both project files to run in one simulation. MESA needs 10 GB minimum storage of computer and 4 GB minimum RAM to run a simulation. Our simulations were done using workstation#1 computer (8 cores) in the Department of Astronomy, Institut Teknologi Bandung. It took 8 hours for running one simulation.
Figure 2. Chemical compositions at the core of $\alpha$ Tau as function of age during evolutionary track from RGB to AGB. Different colors show different chemical compositions at the core.

3.2. Atmospheric Models with SPECTRUM

We compute the atmospheric physical parameters as the function of optical depth ($\tau$) to make the atmospheric model of $\alpha$ Tau at AGB stage. Those parameters are obtained from bi-cubic interpolation of Kurucz atmospheric model. We use Kurucz grid with micro turbulent velocity ($\xi$) and metallicity ($[M/H]$) are equal to 0, respectively (as initial condition) for $T_{\text{eff}} = 3500, 3750, 4000$ K and $\log g = 1.0, 2.0, 3.0$. Besides that, the values of $\tau$ are obtained from Eddington approximation in equation (4), where $T$ is the temperature at every layer of atmosphere. Then we compute synthetic spectrum of $\alpha$ Tau at AGB stage using SPECTRUM package, where its input parameters are adopted from physical parameters those already interpolated from Kurucz model.

Our synthetic spectrum is made in low resolution ($300 \mu m - 4000 \mu m$) using three lists of atomic and molecular lines, i.e. luke.lst ($300 \mu m - 680 \mu m$), luke.nir.lst ($680 \mu m - 1000 \mu m$), and luke.ir ($1000 \mu m - 4000 \mu m$). We then correct the synthetic spectrum of $\alpha$ Tau by its rotational velocity ($v \sin i$) and $\xi$. Here $v \sin i = 3.48$ km/s is obtained from radius and rotational period of $\alpha$ Tau ($P = 643$ days) and $\xi = 2$ km/s from [15].

$$T^4 = \frac{3}{4} T_{\text{eff}}^4 \left(\tau + \frac{2}{3}\right)$$  \hspace{1cm} (4)

4. Results

We present the evolutionary track of $\alpha$ Tau from RGB to AGB stage in Figure 1a. During $\alpha$ Tau is at RGB stage, the increasing core’s density and its temperature fluctuation (see Figure 1b) indicate its core is contracting. This process yields heat that carried up and trigger hydrogen burning at shell (burning shell). Then $\alpha$ Tau will expand and collapse after the heat is carried out away. This process is looped in order to keep the star in hydrostatic equilibrium (oscillations). The oscillations can be detected from the variation of physical parameters in Figure 1c.

During the oscillations at RGB stage, radius of $\alpha$ Tau is increasing until it reaches the maximum size. We compute that $\alpha$ Tau will reach this condition at age $(2.05 \pm 0.27)$ Gyr and this is the end of RGB stage for this star. Once this condition is reached, the star then collapses and the core’s density and temperature are increasing. The core is degenerated and yields helium flash reaction. When the core’s temperature reaches $\sim10^8$ K, the core will be collapsed and $\alpha$
Figure 3. Graphics of mass (top), log $g$ (middle), and mass loss (bottom) as function of ages during evolutionary track from RGB to AGB.

$\alpha$ Tau is now entering into Horizontal Branch stage (HB). Our simulations show that $\alpha$ Tau is just $\sim 63$ Myr at this stage. The collapsed helium core triggers the fusion reaction of helium burning into carbon and oxygen. The core is now the combination of oxygen and carbon, instead of helium. When carbon-oxygen core is formed, $\alpha$ Tau has been entering into AGB stage. From Figure 2, we can see that carbon-oxygen core is covered by helium and hydrogen shells at higher radius from the core.

We present the physical parameters of $\alpha$ Tau at AGB stage in Table 3. We compute the carbon to oxygen ratio ($C/O$) is 0.26 which means that this star is M-AGB type. This conclusion is considered to [16] who argued that a star which has $C/O > 1$ will be C-AGB type and star with $C/O < 1$ will be M-AGB type. Besides that, a star with $C/O \sim 1$ will be S-AGB type. But only for star with $\sim 1$ M$_\odot < M < \sim 4$ M$_\odot$ can transform from M-AGB to S-AGB and ending into C-AGB type [17]. During the evolution from RGB to AGB stage, the mass and surface gravitational acceleration of $\alpha$ Tau are decreasing (see Figure 3). These show that mass loss is occurring in this star. We find that the highest mass loss occurs at the end of RGB stage, i.e. $(4.48 \pm 0.32) \times 10^{-8}$ M$_\odot$/yr. At the beginning of AGB stage, mass loss of this star is still smaller than RGB, but it is highly believed to be more higher during this stage.

Table 3. Computed physical parameters of $\alpha$ Tau at AGB.

| Parameters                  | Value                        |
|-----------------------------|------------------------------|
| $M$ (M$_\odot$)             | 1.52 $\pm$ 0.07              |
| $T_{eff}$ (K)               | 4545 $\pm$ 18                |
| log $L$                     | 1.98 $\pm$ 0.07              |
| log $R$                     | 1.20 $\pm$ 0.92              |
| log $g$                     | 2.22 $\pm$ 0.02              |
| $dM/dt$ (M$_\odot$/yr)      | $(2.07 \pm 0.09) \times 10^{-10}$ |
| $C/O$                       | 0.26                         |
| Age at AGB stage (Gyr)      | 2.11 $\pm$ 0.27              |
Figure 4. Physical parameters as function of $\tau$. Red, green, and blue lines are atmospheric conditions with different mass, effective temperature, and $\log g$ (in range of their uncertainties) at AGB stage. Orange line is atmospheric condition at RGB stage.

Figure 5. The synthetic spectrums of $\alpha$ Tau at RGB stage (orange) and AGB stage (other colors). Different colors for AGB stage represent different masses, effective temperatures, and $\log g$ (as explained in Figure 4).

The parameters $\log g$ and $T_{\text{eff}}$ of $\alpha$ Tau at AGB stage are used to interpolate the Kurucz’s atmospheric grids. The results of interpolation are five physical parameters as the function of $\tau$ (see Figure 4). This $\alpha$ Tau’s atmospheric condition at AGB stage shows higher gas pressure ($\log P_{\text{gas}}$), temperature ($\log T$), and electron density ($\log n_e$) than at RGB stage. The high pressure and temperature at AGB atmosphere can ionize much more atoms and the decreasing mean free path are given as its consequence. This condition yields the increasing mass depth ($\log \int \rho \, dx$) and decreasing Rosseland absorption coefficient ($\log \kappa_{\text{ross}}$) than at RGB atmosphere. Besides that, the synthetic spectrum of $\alpha$ Tau at AGB as seen in Figure 5 shows that the peak of spectrum shifts toward smaller wavelength and the intensity is three times higher than RGB. These are the consequence of higher effective temperature of $\alpha$ Tau at AGB stage.
In this work, we share an understanding of how does $\alpha$ Tau evolve from RGB to AGB stage as one of stars in our Galaxy where its physical parameters are well known from observations. This work has done for simulating $\alpha$ Tau until the starting point of AGB stage. It is interesting to investigate in the future work of how does this star evolve during its AGB stage, as we know in the theory of stellar evolution that thermal pulse is occurring during this stage and the fate of planetary nebulae formation is waiting for this star.

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References

[1] Beavers W I and Eitter J J 1979 Astrophys. J. 228 L111
[2] di Benedetto G P and Rabbia Y 1987 Astron. Astrophys. 188 114
[3] Robinson R D, Carpenter K G and Brown A 1998 Astrophys. J. 503 396
[4] Mozurkewich D, Armstrong J T, Hindsley R B, Hummel C A, Hutter D J, Johnston K J, Hajian A R, Elias II N M, Buscher D F and Simon R S 2003 Astron. J. 126 2502
[5] Richichi A, Dyachenko V, Pandey A K, Sharma S, Tasuya O, Balega Y, Beskalotov A, Rastegaev D and Dhillon V S 2017 Mon. Not. R. Astron. Soc. 464 231
[6] Jofre P, Heiter U, Soubiran C, Blanco-Cuaresma S, Worley C C, Pancino E, Cantat-Gaudin T, Magrini L, Bergemann M, Gonzalez-Hernandez J I, Hill V, Lardo C, de Laverty P, Lind K, Masseron T, Montes D, Mucciarelli A, Nordlander T, Recio Blanco A, Sobeck J, Sordo R, Sousa S G, Tabernero H, Vallenari A and Van Eck S 2014 Astron. Astrophys. 564 A133
[7] Bonnell J T and Bell R A 1993a Mon. Not. R. Astron. Soc. 264 334
[8] Decin L, Vandenbussche B, Vaelkens C, Decin G, Eriksson K, Gustafsson B, Plez B and Sauval A J 2003 Astron. Astrophys. 400 709
[9] Cayrel de Strobel G, Soubiran C and Ralite N 2001 Astron. Astrophys. 373 159
[10] Blackwell D E, Lynam-Gray A E and Petford A D 1991 Astron. Astrophys. 245 567
[11] Richichi A and Roccatagliata V 2005 Astron. Astrophys. 433 305
[12] Paxton B, Bildsten L, Dotter A, Herwig F, Lesaffre P and Timmes F 2011 Astrophys. J. Suppl. 192 3
[13] Reimers D 1975 in Problems in Stellar Atmospheres and Envelopes, ed B Baschek, W H Kegel and G Traving (New York: Springer) p 229
[14] Bloecker T 1995 Astron. Astrophys. 297 727
[15] Ohnaka K 2013 Astron. Astrophys. 553 A3
[16] Herwig F 2005 Annu. Rev. Astron. Astrophys. 43 435
[17] Danilovich T, Teyssier D, Justianont K, Olofsson H, Cerrigone L, Bujarrabal F, Alcolea J, Cernicharo J, Castro-Carrizo A, Garcia-Lario P and Marston A 2015 Astron. Astrophys. 581 A60