Understanding the Evolutionary Track of Tau Sco

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Abstract. The τ Scorpii (τ Sco) star, was known as Al-Niyat in medieval Islamic period, is a B0V single star with mass of 15 solar mass (M☉). It means that τ Sco is a massive star that has properties like B-type star such as has 31,440 K temperature effective and so on. The evolution simulation using MESA simulation software was conducted from pre-main sequence phase to red supergiant phase for τ Sco. We obtain that the age of τ Sco currently is 5.22 million years and it’s in main sequence phase. The τ Sco will reach the red supergiant phase at the age of 11.6 million years after formation.

1. Introduction
The star of τ Sco in the Scorpius constellation has coordinates (J2000) of 28°12′57.6615″, 16h35m2.95285s [1] and an apparent magnitude of 2.82 [2]. The constellation is called as al–’Aqrab in Arabic and it’s named by Arab astronomer Abd Ar-Rahman ash-shufy [17]. Due to the position of τ Sco at asterism with Antares (α Sco) and σ Sco, τ Sco had been known to the human civilisation such as the medieval Islamic era that Arabs named τ Sco as Al-Niyat, which means the arteries, together with σ Sco [18]. The star of τ Sco is a B0V spectrum class star [3], which means that τ Sco is a main sequence star that has a high surface (effective) temperature like a typical B spectrum class star. The τ Sco has a very massive mass of about 15 solar masses [7] [11] and has an effective temperature of about 31,440 K [10]. We can find easily τ Sco using Stellarium using method from Setiawan and Putraga [15] and also according to Stellarium, τ Sco has apparent magnitude of 2.8.

According to Schneider et al. [12], τ Sco is one of around 10% of massive stars that have strong large-scale surface magnetic field. Its dipole moment \( \mu_B \) is 2x 10^{37} G cm^3 and the magnetic strength around its polar region is about \( \approx 500 \ G \) [13]. Schneider et al. [12] predicted the reason why other stars that have strong magnetic field like τ Sco has is because they were merging from two main-sequence stars. However, since τ Sco is a single star, the cause of its majestic magnetic field isn’t well known and so we therefore won’t analyse the magnetic field properties of τ Sco.

The evolution of τ Sco isn’t well known. Pecaut et al. [6] estimated the age of B-, A-, and G-type stars around upper Scorpius region using isochrones methods. They found that the age of τ Sco is about 5 million years. This age is estimated to be the age from formation to the main sequence phase. However, Pecaut et al. [6] didn’t simulate the evolution of τ Sco for the next evolutionary phases.

In this paper, we will report our initial study of evolution simulation of τ Sco. The second section is our methodology which contains the procedure and process of our research. The next section is our
result which we will explain every phase of τ Sco evolution. We will give our conclusion on the last section.

2. Methodology
The evolution of τ Sco is modelled by using the Modules for Experiments in Stellar Astrophysics (MESA) software to determine the evolutionary life of τ Sco. We used a massive star code from MESA for running the simulation with the assumption that the rotation value is uniform and there is no mass loss. The input parameters that were entered into the code are as shown in table 1.

The simulation starts from Pre-Main Sequence phase to red supergiant phase. The simulation process will stop when Hydrogen mass fraction ($h1$) reaches 0 and Helium mass fraction ($he4$) is 0 in the core, it means that τ Sco is in red supergiant phase. The results of the simulation will be presented and explained according to their phase in the results and discussions section.

| No | Parameter                          | Value | References |
|----|-----------------------------------|-------|------------|
| 1  | Initial Mass (M/M$_\odot$)        | 15    | [11] [7]   |
| 2  | Rotation velocity at equator (km s$^{-1}$) | 200   | [4]        |
| 3  | Initial Metallicity               | 0.02  | -          |

3. Results and Discussions
We separate the result based on μ Sco life from pre-main sequence to red supergiant.

3.1. Pre-Main Sequence
The evolution of μ Sco begins in the pre-main sequence (PMS) phase. The PMS phase of the μ Sco begins when the proto-star between the interstellar matter merges with several other interstellar particles due to the gravitational force so that the interstellar material cloud shrinks. Due to shrinkage, the proto-star will experience a decrease in luminosity but the proto-star temperature remains constant. This stage is known as the 'Hayashi track' [5], however for the massive star like τ Sco, the Hayashi track tends to make a curve to left into Henyey track in the HR diagram. The Henyey track is a track before Zero Age Main Sequence (ZAMS). Henyey track is characterised by a slow collapse in near ZAMS and its curvature is almost horizontal in HR diagram. It is estimated that the star μ Sco experienced the PMS phase which is for 0.02 million years. The μ Sco PMS phase track is shown in figure 1.
Figure 1. The μ Sco PMS track. Hayashi track is shown from (B) to (C); The Henyey track is shown from (C) to (D); The final stage of the PMS is shown at (D); Beginning of MS is from (D) to (E)

Figure 2. Chemical composition of μ Sco nucleus on PMS phase are colour-coded. (1) initial chemical composition; (2) Chemical composition after passing through the Hayashi track; (3) Chemical composition after passing the Henyey track; (4) chemical composition in the final stage of PMS. The μ Sco PMS track. Hayashi track is shown from (1) to (2); The Henyey track is shown from (2) to (3); The final stage of the PMS is shown from (3) to (4)
The chemical composition of the dominant proto-star nucleus is light elements such as Hydrogen and Helium. The elements other than Hydrogen (h1) and Helium (he4 and he3) are Oxygen (o16), Carbon (c12) Neon (ne20), Silicon (si28), Phosphorus (p30), Nitrogen (n14), Iron (fe55 and 54), Magnesium (mg24), and others. All heavy elements have a mass fraction that is not as much as the elements hydrogen and helium with no more than 1%. These elements can be seen in Figure 2 and they are colour-coded so it’ll be easy to see, example h1 is in yellow, he3 is in dark blue, he4 is in light blue and so on.

### 3.2. Main Sequence

The main sequence (MS) phase of μ Sco are divided into three basic processes. The first process begins when the core of the star is in a state of hydrostatic equilibrium. In the simulation, we called it as zero age main sequence (ZAMS). ZAMS begins when luminosity of μ Sco in sun's luminosity (L/L⊙) has reached up to 19000 with an effective temperature of 30754 K. The abundance of elements in the surface layer of μ Sco is still dominated by light elements (h1 and he4). The second stage is the stage where the μ Sco experiences an increase in luminosity and a decrease in effective temperature. The increase in L/L⊙ can reach up to 18066, while the decrease in effective temperature can reach up to -5652 K (points A to B in figure 3).

The star μ Sco is estimated to be having age of 10.6 million years old after formation when it ended the main sequence phase. The L/L⊙ of the μ Sco is 41000 with an effective temperature of 25010 K. At this phase, the core of the τ M Sco is estimated to be dominated by helium, with a fraction of 97% with the hydrogen fraction only 0 of the total element abundance. This is due to the helium formation process in the carbon-nitrogen-oxygen (CNO) reaction as a result of the star's very high core temperature (~47 million K). The CNO reaction also produces other heavy elements such as carbon, nitrogen, oxygen, and magnesium, which have a total fraction of ~3%. The evolutionary track of the μ Sco is shown in figure 3 and the abundance of elements can be seen in figure 4.

**Figure 3.** The evolutionary track of the τ Sco at the MS phase. from (A) ZAMS to (C) final stage
Figure 4. The chemical abundance in the interior of τ Sco. (A) early stage; (C) final stage; (B) The current composition of μ Sco is (5 million years [6]), where hydrogen is almost completely ignited into helium

3.3. Red Giant and Red Supergiant
The μ Sco has several phases after going through the main sequence phase that has been obtained during the simulation. The first phase is the red giant (RG) phase. The μ Sco experienced a decrease in temperature by -21228 K and L/ L⊙ by -26551. The μ Sco will look like a red giant for 10801 years after passing through the main sequence phase. The percentage abundance of elemental hydrogen in the core of μ Sco, when the final stage of the RG phase, has reached 0%. This is because when this phase starts the hydrogen element has been exhausted 'burnt' into element helium (~ 98%).

After RG phase and before red supergiant (RSG) phase, there is a thermal pulsation. Thermal pulsation is thought to be due to the presence of layers under the surface of the star. Massive stars, such as μ Sco, will have an inner layer like the skin of an onion [8]. According to El Eid [9], stars that experience thermal pulsation of the hydrogen and helium envelope will experience a reduction in luminosity because of the hydrogen burning in the envelope was stopped due to the expanding envelope. As a result, the star contracts to make the helium in the envelope 'ignite'. The change in the luminosity of the μ Sco star is ±18569 and the change in the effective temperature value is 152.5 K.
In the RSG phase, the luminosity of the μ Sco is equal to 58884 or 1.48 times the luminosity of the final main series phase. The effective temperature of the μ Sco is 747.7 K or about 0.03 times the effective temperature of the final MS phase. The evolutionary track of μ Sco is shown at figure 5 and output parameter of μ Sco life can be seen in table 2.

![Figure 5. Evolutionary track of τ Sco. A; ZAMS; A – C: MS phase; C – D: RG phase; E: Thermal Pulsation; F: RSG phase](image)

| Phase      | Age (Years) | L (L☉)  | T eff (K) | R (R☉) | Xc | Yc  | Zc |
|------------|-------------|---------|----------|--------|----|-----|----|
| Final PMS  | 2 x 10⁴     | 19 x 10³| 30,754   | 4.92   | 0.69 | 0.28 | 0.03 |
| ZAMS       | 2.12 x 10⁷   | 19 x 10³| 30,754   | 4.92   | 0.69 | 0.28 | 0.03 |
| Current    | 5.22 x 10⁹   | 25 x 10³| 28,862   | 6.42   | 0.47 | 0.5  | 0.03 |
| Final MS   | 1.06 x 10⁷   | 41 x 10³| 25,010   | 10.93  | 0   | 0.97 | 0.03 |
| Final RG   | 1.07 x 10⁷   | 15 x 10³| 3,907    | 267.8  | 0   | 0.98 | 0.02 |
| RSG        | 1.16 x 10⁷   | 58 x 10³| 747.7    | 747.7  | 0   | 0    | 1   |

4. Conclusion

From this study, we conclude several points:

- The τ Sco will have at least 2 conditions between current condition and RSG phase. They are RG phase and the process of thermal pulsation.
- Currently, the τ Sco is in the main sequence phase with an age of 5.22 million years, while according to Pecaut, et al. [6] τ Sco age is 5 million years, so the simulation result gets error difference of Sco's age is 4%.
- The current chemical abundance of τ Sco’s core mostly contains Helium (mass fraction 0.5) with Hydrogen (0.47) and metallic elements (0.03). It’s because the Hydrogen is still burning into Helium.
- The current effective temperature of τ Sco is 28862 K, while according to Snow [7] the effective temperature of the star τ Sco is 30000 K so that the effective temperature error difference is 3.79%. The τ Sco effective temperature is in the range of B-type star according to Freedman and Kaufmann III [16] which is 11,000 – 30,000 K.
• The τ Sco will reach RSG phase at the age of 11.6 million years and before reaching RSG phase, τ Sco will undergo thermal pulsation for at least 873,800 years
• The age of τ Sco until its RSG phase is estimated at 11.6 million years while according to Prialnik [14] τ Sco has age of 11.8 million years so therefore its error difference is 1.69%.

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