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Effects of triple alpha and CNO reaction rates on the evolution of low- mass stars

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Abstract

In this study, the effects of the energy generation rates of Triple Alpha and CNO nuclear reactions on the evolution of Main sequence star models with masses in the range of 0.65-1.2 M$_\odot$ are investigated. Paczynski's GOB, SCH and HB7 star model programs are used for each model. The ages of stars are calculated using the original NACRE (Nuclear Astrophysics Compilation of Reactions) energy generation rates and NACRE rates reduced by ten percent. The ages of the current IT Cas and V636 Cen stars are calculated and compared with the results in the literature. Since Triple Alpha reactions are very difficult to perform in terrestrial laboratories, this theoretical model study will shed light on observational studies of low-mass and even massive stars.

***Keywords**: Nuclear energy generation rates, low- mass stars, stellar evolution.*

Üçlü alfa ve CNO reaksiyon oranlarının küçük kütleli yıldızların evrimi üzerindeki etkileri

Öz

Bu çalışmada, Üçlü Alfa ve CNO nükleer reaksiyonlarının enerji oluşum oranlarının 0.65- 1.2 M$_\odot$ aralığında kütleye sahip olan Ana kol yıldız modellerinin evrimleri üzerindeki etkileri araştırılmaktadır. Her bir model için Paczynski'nin GOB, SCH ve HB7 yıldız model programları kullanılmaktadır. Yıldızların yaşları orjinal NACRE enerji oluşum oranları ve yüzde on oranında azaltılmış NACRE (Nuclear Astrophysics Compilation of Reactions) oranları kullanılarak hesaplanır. Buna göre IT Cas ve V636 Cen yıldızlarının yaşları hesaplanmıştır ve literatürdeki sonuçlar ile karşılaştırılmıştır. Üçlü Alfa reaksiyonlarının laboratuvar ortamında gerçekleştirilmesi çok zor olduğu için

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bu teorik model çalışmasının, küçük kütleli ve hatta büyük kütleli yıldızların gözlemsel çalışmalarına ışık tutacaktır.

***Anahtar kelimeler**: Nükleer enerji oluşum oranları, küçük- kütleli yıldızlar, yıldızların evrimi.*

1. Introduction

Low-mass stars are the most abundant stellar population in the cosmos. Despite their dim appearance, these stars exhibit unique energy generation mechanisms that profoundly influence their lifecycles and the evolution of planetary systems. Low-mass stars, with masses ranging from 0.6 to 1.2 $M_{\odot}$, play a central role in the stellar landscape [1]. The primary mechanism driving energy production in low-mass stars is the proton-proton chain. The core temperatures and pressures in low-mass stars are conducive to this fusion process, where hydrogen nuclei fuse to form helium, releasing energy. In-depth studies based on nuclear reaction rates [2] and helioseismology [3] have provided essential insights into the efficiency of the proton-proton chain in low-mass stars. The extended lifespans of low-mass stars, estimated to be trillions of years [4], have significant implications for galactic dynamics and the prevalence of habitable environments. Theoretical models incorporating stellar evolution and nucleosynthesis processes have advanced our understanding of the lifecycles of these stars. Observing low-mass stars presents challenges due to their faintness and unique spectral characteristics. Ongoing and upcoming missions, including the James Webb Space Telescope (JWST), promise to provide unprecedented insights into the atmospheres and energy generation processes of M-dwarfs with low mass [5].

Many stellar models have not been sufficient to theoretically reach the measured temperatures and radii of stars with less massive than the Sun [6-8]. The interaction between energy production rates and stellar evolution provides a basis for determining the age of low-mass stars. Isochronous placement techniques, as demonstrated by [9] contribute to our broader knowledge of galactic chronology by leveraging our understanding of energy production to estimate the ages of star clusters and individual stars. For this purpose, different energy generation rates were used in different stellar evolution models and their effects on stellar evolution were investigated [10-13]. The aim of this article is to investigate the effects of triple alpha and CNO NACRE energy generation rates [14], which are reduced by ninety percent, on the luminosity, temperature, density and radius evolution of low-mass stars. The paper is organized as follows: In section 2, we explain stellar evolution models and input physical parameters used in programs. In section 3, the results obtained are presented with graphs and tables. Section 4 contains conclusions obtained from this study .

2. Method

In this study, Paczynski's stellar structure and evolution programs are used. The first of these programs, GOB (Generates the Outer Boundary) , establishes the outer boundary conditions of a star in hydrostatic equilibrium and ideal gas conditions. As physical input, the star's mass, luminosity, effective temperature and mixing length parameters are entered by the user [15, 16]. Kurucz opacity tables are used in this program, which is taken from [17]. The mixing length parameter was entered as 1. The second program, SCH (Generates a zero Age Main Sequence Model), uses the outputs of the GOB program. This program creates zero-age main sequence star models. The program works with nuclear energy generation rates. As physical input; The Luminosity of the star in terms of the Sun, its effective temperature, its core temperature and its core density are given. While the GOB program models the star from the outside to the inside, the SCH program models the star from its center to the outside. The NACRE rates [14] were used in this project. The last program in the code, HB7 (Takes the output of SCH) , uses the outputs of the SCH program. This program determines the chemical composition according to nuclear energy formation rates. It forms a stellar evolution pattern in which it changes step by step.

3. Evolutionary tracks and the data obtained

In this study, Kurucz opacity tables were used in the GOB program that created the external boundary conditions [17]. The mixing length parameter was taken as α = 1. NACRE energy generation rates are used in the SCH program, which reads the nuclear energy rates and creates a star model moving from the center to the inside of the star. The CNO and triple alpha ratios are changed while keeping the formation rates of the P-P chain constant. Calculations are made for star models in the 0.65-1.2 M⊙ mass range. The results obtained using NACRE energy formation rates are compared with the results obtained with 0.10 x NACRE energy formation rates. Decreasing energy ratios give older ages for the relevant stellar models. The results are presented in Table 1.

Table 1. Ages obtained for star models for Z=0.02.

M/M⊙	**log L/L⊙**	**log Teff**	**log Tc**	**log ρc**	**Age(My) with NACRE**	**Age(My) with 0.1xNACRE**
0.65	-0.97	3.62	6.98	1.88	16986	17132
0.8	0.40	3.69	7.09	2.07	15488	15633
1	0.12	3.76	7.14	2.14	14723	14867
1.2	0.15	3.78	7.15	2.17	13098	13243

The ages of the observed low-mass stars IT Cas and V636 Cen were calculated . The results are presented with the result of Torres et al. [18] in Table 2.

Table 2. Ages calculated with metal ratio Z=0.02 for IT Cas and V636.

Star	**Metallicity**	**Age (This study)**	**Age from Torres et al. (2010)**
IT Cas	Z=0.02	1,4 G y	1,9 G y
V636	Z=0.02	0.93 Gy	1.2 Gy

As shown in Figure 1, the age of the binary star V636 Cen is calculated from the radius-age graph. The star appears to reach its observational radius at 0.93 G years. Clausen et al. have found the age of this star to be 1.33 ±0.13 G years [19]. Many current models have failed to achieve measured temperatures and radii for many binary star components with masses less than the Sun [8, 20-23]. By using models created by reducing the mixture length parameter, results compatible with observational results were obtained [24]. It is known that the spectrum lines of the companion star are fainter than those of the main star [25].

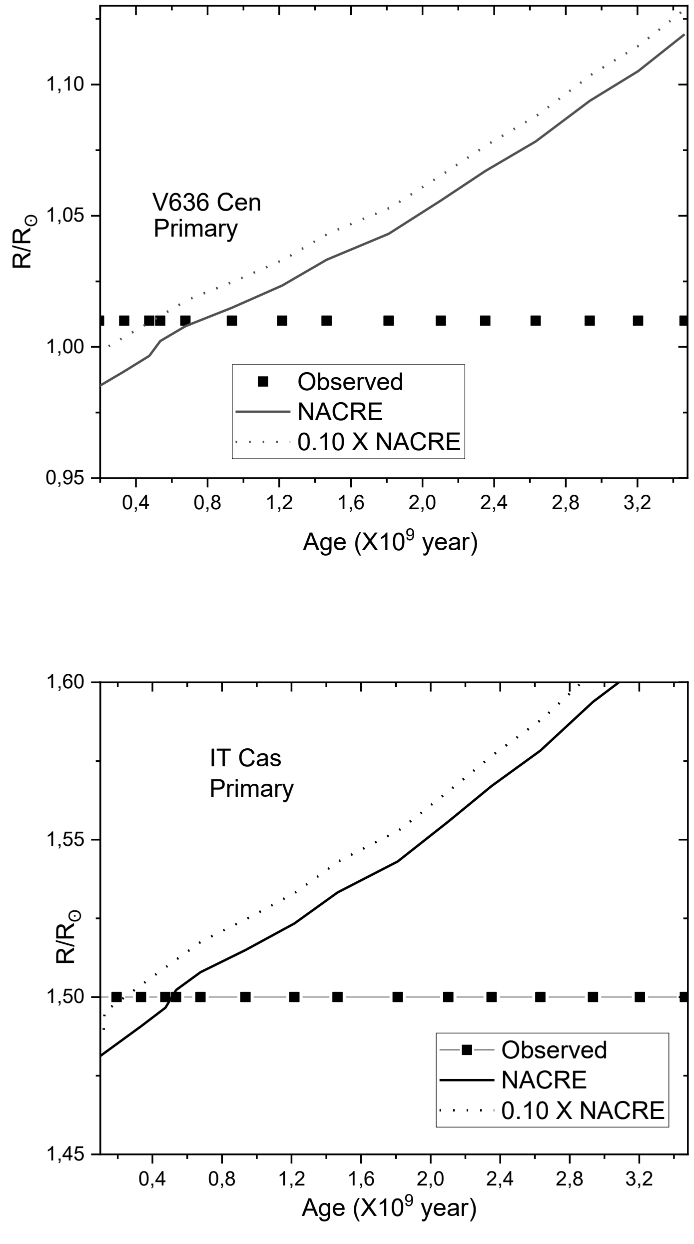

Figure 1. Radius- age curves of the binary stars V636 Centauri and IT Cas.

Imbriani et al. concluded that an increase in the CNO ratio gives dimmer turning points for the change of luminosity with effective temperature for a given age, or may give younger ages for a given luminosity return [26].

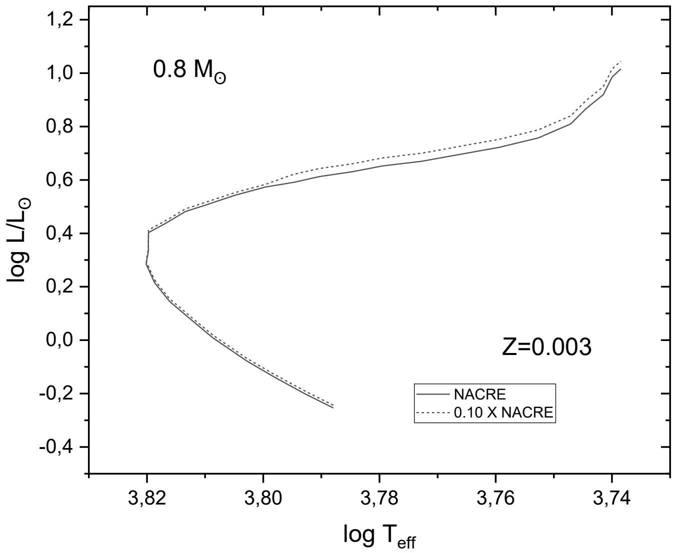

Figure 2. Variation of luminosity with effective temperature for the 0.8 M$_\odot$ mass stellar model.

Figure 2 shows the luminosity change of the 0.8 Solar mass star model for the Z = 0.003 metallicity value. It is seen that the turning points of the reduced energy rates do not deviate very far from the turning points given by the old rates. It is seen that the curve gives larger values after the turning points. To see the effect of decreasing energy generation rates for the same star model, the evolution graph showing the change of the central density with temperature is drawn in Figure 3.

Reduced NACRE ratios start the evolution of density with temperature at lower temperatures and end at approximately the same value. The data of this graph is presented in Table 3. Reduced NACRE energy generation rates yielded greater density and temperature values.

Table 3. Variation of temperature with central density for the 0.8 M$_\odot$ model.

log ρ_C NACRE	log T_C NACRE	log ρ_C 0.10XNACRE	log T_C 0.10XNACRE
2,027	7,076	2,077	7,096
2,244	7,128	2,294	7,148
2,511	7,192	2,561	7,212
2,800	7,273	2,85	7,293
3,144	7,327	3,194	7,347
3,574	7,348	3,624	7,368
4,604	7,463	4,654	7,483
5,157	7,536	5,207	7,556
5,416	7,626	5,466	7,646
5,594	7,711	5,644	7,731
5,734	7,790	5,784	7,810
5,852	7,863	5,902	7,883

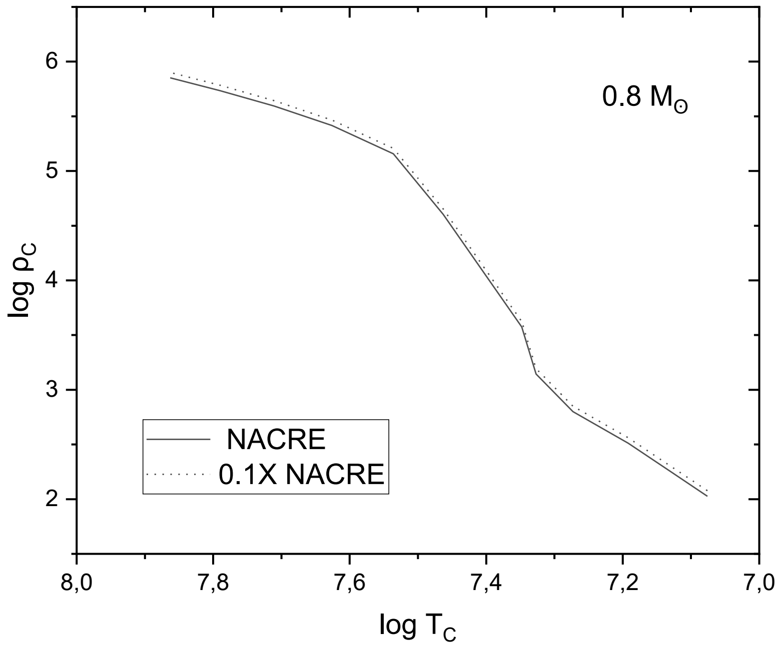

Figure 3. Central temperature-density variation for the 0.8 M$_\odot$ model at a metal value of Z= 0.003.

4. Results and discussion

Paczynski's stellar evolution models were used in this study. Stellar evolution models have been created with NACRE energy generation rates reduced by ninety percent. Reduced energy generation rates yielded older ages for star models in the 0.65-1.2 M$_\odot$ mass range. When we look at the results in Table 1, it can be seen that the age calculated with generally reduced energy formation rates is 145 million years older for a star model. The age of the observed IT Cas star is calculated with different metal ratios. According to the results in Table 2, the age of the star decreases with increasing metal content. Compared to the result of Torres et al., in this study, the age found by NACRE energy generation rates is calculated to be $0.5x10^9$ years younger. This may be due to Kurucz opacity tables used. Brocato et al. [27] investigated the effects of nuclear reaction rates on the evolution of population II star models and found that the effect on the ages of these stars was $1x10^9$ years. The age found for the observed star V636 Cen is 0.4 Gy younger than the age found by Clausen et al [19]. In the evolution calculations made for the 0.8 Solar mass star model, it is seen that with NACRE energy generation rates reduced by ninety percent, the central density increases by approximately 3% and the central temperature increases by approximately 0.3% in the star model stages. As a result, NACRE energy formation rates, which include all of the energy formation rates released from p-p, CNO and triple alpha processes, are reduced. These ratios give younger ages for low-mass star models and for observed real stars. Very recently, Monpribat and his colleagues examined the effects of new carbon-carbon nuclear reactions on stellar evolution [28]. Our Future work is planned for massive star models. We also planned to investigate the effects of metallicity on the evolution of the low-mass stars in the next study.

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