Rotational evolution of intermediate mass stars with OPAL opacities: mass of the convective core *

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Abstract

The theoretical evolutionary models for intermediate mass rotating stars were obtained by the use of OPAL opacities to see the effect on the internal structure and primarily on the mass of the convective core. The new ZAMS positions of rotating intermediate mass stars in the HR diagram were found to be above those of rotating stars obtained by using Cox & Stewart opacities. Rotation led to a reduction in the central value of the radiative temperature gradient and hence the masses of convective cores on the ZAMS for rotating intermediate mass stars were found to decrease relative to those of non rotating stars.

Key words: 08.05.3 Stars: evolution - 08.16.5 Stars:Pre-main sequence 08.18.1 Stars: rotation - Stars: convection

1 Introduction

Models of stellar evolution based on the most recent opacities (OPAL) (Iglesias et al. 1992; Rogers & Iglesias 1992a) were obtained by many authors (Stothers & Chin 1991; Claret & Gimenez 1992; Schaller et al. 1992; Stothers & Chin 1993) to investigate the effect of new opacities in different mass intervals between 0.8 - 120 $M_{\odot}$. These studies covered the evolution from the zero age main sequence toward the red giant phase of the stars. All these authors found the value of the mixing length parameter α between 1.5 and 1.6 and the helium content between 0.28 and 0.30, by mass, in order to obtain present observed properties of the Sun. Stothers & Chin (1991, 1993) and Claret & Gimenez (1992) reported that the revised stellar models of intermediate to high mass showed an improved aggrement with observed zero age main sequence (ZAMS) stars. Schaller et al. (1992) concluded that when OPAL opacities were used the ZAMS positions of the nonrotating intermediate mass stars were slightly different from those based on old opacities.

The effect of rotation on the internal structure of stars has been investigated by numerous authors on the ZAMS and beyond it (Kippenhahn et al. 1970; Sackman & Anand 1970; Endal & Sofia 1978; Pinsonneault et al. 1989). There were also some studies about the pre main sequence phase of rotational evolution (Bodenheimer & Ostriker 1970; Eryurt-Ezer et al. 1986; Celikel & Eryurt-Ezer 1989). The effects of rotation for an intermediate mass star on the ZAMS can be summarized as follows: 1) The equatorial radius increases as the luminosity and effective temperature decrease. 2) The central density and pressure increase while the central temperature decreases. 3) The main sequence lifetime increases. A few authors studied the effect of rotation on the convective core masses of the stars on the ZAMS (Sreenivasan & Wilson 1985; MacGregor & Gilliand 1986; Sreenivasan &Wilson 1989; Clement 1993). Sreenivasan & Wilson (1985, hereafter SW) reported that the mass of the convective core for an upper main sequence star increases by rotation due to the greater magnitude of radiative temperature gradient ∇_{rad}. However, MacGregor & Gilliand (1986, hereafter MG) showed that the value of ∇_{rad} in the central regions of a 30 $M_{\odot}$ rotating star is reduced in comparison to that for a nonrotating star of the same mass and hence they obtained a smaller convective core mass. Clement (1993) computed models of main sequence stars and found that stars with uniform distribution of specific angular momentum have more massive convective cores for M $<$ 12 $M_{\odot}$.

In the present study we first examine the effect of OPAL opacities on the evolution and internal structure of the rotating intermediate mass stars. Secondly, we explore the change in the size of convective cores as a result of rotation when OPAL opacities are used. In Sec. 2 we describe the input physics. In Sec. 3 we discuss the results of our rotating and nonrotating models on the ZAMS obtained by using OPAL opacities. Then we compare our results with the rotating models of Eryurt-Ezer et al. (1986). These authors obtained their rotating models with the same evolutionary code that we used in the present study but by using Cox & Stewart (1970; CS) opacities. The other physical input parameters were the same.

2 Procedure

The evolutionary computations were started when models become stable against gravitational collapse. This is the point of threshold of stability. Through the gravitational contraction, pre main sequence phases up to the ZAMS the evolutions of 2, 3, 4, 5, and 7 $M_\odot$ rotating and nonrotating intermediate mass stars were followed. The physical inputs are the same for both rotating and nonrotating models to make a safe comparison. The code used here is that of Ezer (Eryurt-Ezer et al. 1986). To compute the rotating and nonrotating models with the new (OPAL) opacities first the evolution of the Sun was studied. The present luminosity of the Sun was obtained for the composition of X= 0.675 and Z= 0.019. The present solar radius was found for the value of the mixing length parameter α= 1.62 (Kızıloğlu & Yıldız 1995). The evolutionary study was carried out using the Henyey method which was applied from the center to the surface.

At the threshold of stability point, where the evolutionary time t= 0, the initial rotating models for each mass were obtained from the nonrotating ones. In the models we assume that, as given in the study of Roxburgh (1966), convective regions of the stars rotate uniformly and radiative regions rotate differentially. The convective mass motions force the convective regions to rotate uniformly but in the radiative regions viscosity forces are too low to keep rotation uniform and we assume that each shell in the radiative regions of the stars conserves its angular momentum. Hence, in our models, angular momentum was constant locally in the radiative regions and only globally in the convective regions. The angular velocity distribution at the threshold of stability was chosen such that on the ZAMS stars did not exceed their critical velocities. The distribution of angular velocity was known at the beginning of computations. To make a comparison with the rotating models of Eryurt-Ezer et al. (1986) obtained with the CS opacities, the initial angular velocity distribution of stars were taken to be the same as theirs.

The opacities used in the present study are the OPAL opacities (Iglesias et al. 1992; Rogers & Iglesias 1992b) which are tabulated for temperatures greater than 6000 K. At low temperatures, Alexander et al. (1983) and Sharp (1992) opacities as described by Stothers & Chin (1993) were used. Stellar convection was treated by the mixing length theory and the Schwarzschild criterion for the onset of convective instability was applied. The method of computation for rotating models and other details were given in the study of Eryurt-Ezer et al. (1986).

3 Results and discussion

In Table I, some physical parameters of nonrotating and rotating intermediate mass stars on the ZAMS position were given. For each star mass, the first and second rows show the properties of nonrotating and rotating models obtained by using OPAL opacities. The third row shows the rotating models of Eryurt-Ezer et al. (1986) obtained by using CS opacities. The columns have their usual meanings. The central value of the radiative gradient, the convective core masses, central and surface angular velocities of stars were shown in the eighth, ninth, tenth and eleventh columns, respectively.

The comparison of rotating models obtained with OPAL and CS opacities shows that the effective temperature of stars decreases while the luminosity increases by the use of OPAL opacities. The maximum increase in luminosity is 35 % while the maximum decrease in T_e is about 1 %. The ZAMS positions of rotating stars in the HR diagram shift upward without a noticeable change in T_e relative to the effective temperatures of rotating models of Eryurt-Ezer et al.

(1986).

As seen in the table, rotating stars have lower luminosity and lower effective temperature relative to their nonrotating counterparts. That is, positions of rotating stars in the HR diagram shift to the lower right relative to those of nonrotating stars. In the present study, for example for a 3 $M_{\odot}$ star on the ZAMS we find that rotation reduces T_e and L by 2 % and 38 %, respectively, while the central temperature T_c is reduced by 1.3 %. We find that the ZAMS lifetimes are increased, for example by 42 % for a rotating star of 3 $M_{\odot}$. This longer ZAMS lifetime is probably associated with the decrease in T_c.

On the ZAMS as the mass of star increases from 2 to 7 $M_{\odot}$ the magnitude of ∇_{rad} at the center increases for both rotating and nonrotating models. At the convective core boundaries ∇_{rad} decreases as the mass increases. On the other hand, the value of adiabatic temperature gradient ∇_{ad} decreases at the center and at the core boundary as the mass increases for rotating and nonrotating stars. The central value of ∇_{rad} for the 7 $M_{\odot}$ star is about 34 times that of 2 $M_{\odot}$ star for the rotating and 65 times for the nonrotating case.

The central value of ∇_{rad} for the rotating 2 $M_{\odot}$ increases by 14 % relative to the nonrotating counterpart. But, in contrast to this, if the rotating star has mass between 3 and 7 $M_{\odot}$, the central value of ∇_{rad} is about 94 % of its value in the nonrotating star of the same mass. The magnitudes of ∇_{ad} at the center and at the core boundary increase by at most 3 % for the rotating models of given masses.

The change in the value of ∇_{rad} arises from the changes in the physical properties of the core region due to rotation. The radiative gradient in a rotating star is modified as

$$\nabla_{rad}= (\nabla_{rad})_0\,(1-(2/3)(W^2 r^3/GM))^{-1}.$$

W is the angular velocity at the considered distance from the center and $(\nabla_{rad})_0$ denotes the radiative gradient for non rotating stars:

$$(\nabla_{rad})_0= (3\chi P/64\pi\sigma T^4)(L/GM)$$

The principal energy source for the intermediate mass stars is the nuclear energy generated by the CNO cycle reactions. On the ZAMS, reaction rates of the pp cycle for rotating stars are close to those of nonrotating stars, but rates of the CNO cycle are smaller for the rotating stars because the CNO cycle reactions are highly temperature sensitive. Since the central temperature is decreased for rotating stars the energy generated is lower which lowers the luminosity and hence the value of ∇_{rad}.

In the case of a 2 $M_{\odot}$ star, nuclear energy generation by CNO cycle reactions is only 3 times that of pp reactions but for a 3 $M_{\odot}$ star this factor is already 100. For a 2 $M_{\odot}$ star, there is no strong temperature dependence of energy generation by CNO cycle reactions as in the case of 3 to 7 $M_{\odot}$ rotating stars. Therefore, the central value of ∇_{rad} for 2 $M_{\odot}$ rotating star can still be larger than that of the nonrotating counterpart. However, the value of $(\nabla_{rad})_{rot}$ at the core boundary is smaller than that of the nonrotating model. We found that the application of the Schwarzschild criterion (i.e., $\nabla_{rad} > \nabla_{ad}$) for the onset of convective instability leads to a smaller convective core mass for the rotating ZAMS stars of intermediate masses under consideration. In the present study, the masses of the convective cores on the ZAMS for rotating models decrease by at most 7 % in comparison to those of the nonrotating models. Our results on the convective core masses of the intermediate mass rotating stars are similar with the result obtained for the upper main sequence stars by MG but inconsistent with that of SW. SW omitted the changes in the structural parameters resulting from rotational effects in their computations. They only consider the additional term considered in ∇_{rad} due to rotation. On the ZAMS, especially the decrease in the value of central temperature plays an important role on the magnitude of ∇_{rad} as discussed in detail by MG. However, in a later paper, Sreenivasan & Wilson (1989) argued that the rigidly rotating convective core of a 24 $M_{\odot}$ model on the ZAMS was smaller than those of the nonrotating models. They showed that the reverse was true if the convective cores rotated differentially for the upper main sequence stars.

4 Conclusions

The use of OPAL opacities in the evolution of intermediate mass rotating stars does not give rise to a noticable change in T_e when we compare our models with the rotating models of Eryurt-Ezer et al. (1986), but the luminosity of stars increases by, on the average, 25 %. That is, in the HR diagram, the new ZAMS positions of rotating stars are shifted upward relative to those of rotating models obtained by using CS opacities.

We find smaller convective core masses for the intermediate mass rotating stars. A reduction in the flux of radiative energy and luminosity due to the smaller interior temperatures of rotating stars causes ∇_{rad} to become smaller to transport the flux to the surface. Therefore, due to the change of magnitude of the radiative gradient a small decrease in the rigidly rotating convective core masses of the stars is found relative to their nonrotating counterparts. Our conclusion about the convective core masses of the intermediate mass stars under consideration is that models obtained in the present study confirm the hypothesis that stars with rigidly rotating convective cores have smaller convective cores as in the case of upper main sequence stars.

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