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PECULIAR INTRINSIC PARAMETERS OF MASSIVE STARS AS A RESULT OF AN EARLY PHASE OF HOMOGENEOUS EVOLUTION

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ABSTRACT Rotationallly induced mixing can explain several observational peculiarities of massive stars. Homogeneous evolution of differentially rotating stars including spindown due to stellar winds is studied by means of homology transformations of ZAMS models.

INTRODUCTION

Stellar parameters from careful analysis of photospheric or wind spectra are often in disagreement with masses and compositions predicted by stellar evolution theory. The immediate influence of rotation leads to age estimates of open star clusters, which are too small by almost a factor two. This was shown in a study of α Persei and other galactic clusters by Maeder (1971) and is caused by atmospheric effects rather than changes of the internal structure. However, Groenewegen et al. (1989) pointed out that O-star masses derived from spectroscopic gravity are on the average smaller than those derived from evolutionary tracks. An extended study of 25 galactic OB-stars by Herrero et al. (1992) confirmed this result and found many OB-stars to be overabundant in helium at a position in the HRD where this is not expected from theoretical evolutionary tracks. An overabundance of helium in OBN-stars was first detected by Schönberner et. al (1988) and the abundance pattern of helium and CNO was found to be consistent with the assumption that CNO cycled matter is to be seen in the photospheres of these stars. Standard evolutionary theory fails in explaining these peculiarities.

A scenario, which can explain such peculiarities, is that of homogeneous evolution due to rotationally induced mixing. This mechanism was studied by Maeder (1987) in order to explain the evolutionary status of ON blue stragglers. However, Maeder paid no attention to the fact that massive stars lose angular momentum by stellar winds and that the rotational levitation effect changes the stellar structure.

HOMOLOGY, HOMOGENEOUS EVOLUTION AND SPINDOWN

An homology transformation for massive, rotating stars can be found if we assume that a potential function Φ exists, and that all local variables depend only on this potential (barotrope stars). This assumption is consistent only

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with rotational laws which do not vary with distance from the equatorial plane (Poincare-Wavre theorem). The distribution of angular velocity is assumed to be known and to remain constant.

It must be noted that these assumptions are not fully self-consistent. Ignoring the existence of meridional flows and introducing a potential function makes the assumption of radiative equilibrium inconsistent with the assumption of energy transfer by radiative diffusion only. This is the well known "von Zeipel Paradox"(von Zeipel, 1924). Because the effects to be studied are much larger than the errors introduced by this inconsistency, we will ignore this problem.

We choose the only independent structural variable to be the potential normalized to the the stellar surface, φ. The independent global parameters, total mass M and mean molecular weight μ, are complemented by the rotational parameter η, which represents the equatorial angular velocity in units of the critical angular velocity.

The structural equations must be be modified in order to take the effects of rotation into account. If, for the sake of simplicity, the equipotential surfaces are assumed to be of ellipsoidal shape with the ablation of the corresponding Roche potential, we simply must replace the mass parameter M_φ by $M_\varphi/a(\eta)$ in the hydrostatic equilibrium equation. In the equation of radiative transfer the luminosity L_φ must be replaced by L_φ/I_1. I_1 is an integral over the stellar interior, which is easily evaluated for simple potentials:

$$I_1(\varphi) = -\frac{1}{4\pi G M(\varphi)} \int_{V(\varphi)} \Delta\Phi \, dV'$$

The well known "Eddington Quartic" equation

$$\frac{1-\beta_c}{\beta_c^4} = \Psi_a(T_c) M^2 \mu^4 a(\eta)^{-2} \tag{1}$$

is complemented with an equation derived from radiative transfer and thermal equilibrium

$$\frac{(1-\beta_c)^2}{\beta_c} = \Psi_b(T_c)(1+X_H) X_H X_{CN} \mu I_1(\eta)^{-1} \tag{2}$$

If we consider stars of the same central temperature to form a homology family, the functions $\Psi_a(T_c)$ and $\Psi_b(T_c)$ are homology transformation invariants, which can be found from an appropriate set of numerical ZAMS models of nonrotating stars. $I_1(\eta)$ is the integral I_1 at the surface and depends on η and the chosen rotational law. Given M, μ, and η, as well as X_H and X_{CN}, these two nonlinear equations define β_c and T_c. Knowing β_c and T_c, the total luminosity and the density follow from homology transformations.

In order to compute the loss of angular momentum we can use results from modern theory of spherically symmetric stellar winds, though rapidly rotating stars exhibit a significant ablation in conjunction with a severe variation of T_{eff} and gravity from pole to equator. It can be shown that the mass flux is almost constant on the surface and that $\dot{M}$ scales with luminosity. The angular momentum loss rate is given by:

$$\dot{J} = \int_O \frac{d\dot{M}}{do} s^2 \Omega(s) do = \frac{d}{dt}\left\{\int_V \varrho(s,z) s^2 \Omega(s) dV\right\}$$

From this we find the spin down equation ($\overset{\circ}{x}$ denotes the change rate $\frac{d}{dt}\ln(x)$):

$$\overset{\circ}{\eta}\left\{6-\frac{d\ln a}{d\ln\eta}\right\}+\overset{\circ}{\beta}_c\left\{\frac{1}{\beta_c}\right\}+\overset{\circ}{T}_c\left\{3+\frac{d\ln(\rho_c/\bar{\varrho})}{d\ln T_c}+6\frac{d\ln\bar{\omega}}{d\ln T_c}+12\frac{d\ln r_g}{d\ln T_c}\right\}=$$
$$10\,\overset{\circ}{M}\left\{\frac{2}{5r_g^2}\frac{I_2}{I_1\bar{\omega}}-1\right\}+\overset{\circ}{\mu} \qquad (3)$$

with the gyrational radius r_g, a weighted mean $\bar{\omega}$ of $\omega(s)$, and the surface integral I_2, which is unity for nonrotating stars:

$$I_2=\frac{3}{8\pi\,G\,M}\int_O s^2\omega\;\mathrm{grad}\Phi\;do$$

$\bar{\omega}$ is dependent on the density stratification and is an homology invariant like the gyration radius. For $\omega(s)\sim s^{-\alpha}$ with $\alpha\ll 1$ the parameter $\bar{\omega}$ is only slightly larger than unity. If $\overset{\circ}{M}$ and $\overset{\circ}{\mu}$ are given, the equations (1), (2) and (3) form a closed set, which determines the time development of β_c, T_c, and the rotational parameter η.

RESULTS

HRD positions of homogeneously mixed, rotating massive stars can be found by means of an homology transformation. We used scaled models of Maeder (1990), and the mass loss rates are calculated according to Kudritzki et al. (1989). If a velocity of at least 350 km/s is taken to be a precondition of the mixing process, as Maeder (1987) suggested, the mixing ends before hydrogen is exhausted. After the mixing has stopped, the stars enter an evolutionary path for helium enriched stars with an equilibrium C/N ratio, and with O essentially unchanged. Due to their increased helium content these stars are slightly overluminous. Timescales of the homogeneous phase and initial masses can be estimated and, if available from spectral analysis, the C/N ratio gives hints to the central temperature at the end of the mixed phase.

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