THE EVOLUTION OF RAPIDLY ROTATING B/BE STARS

A. S. Endal
Dept. of Physics and Astronomy, Louisiana State University, U.S.A.

ABSTRACT

Rotation can significantly change the moment-of-inertia of a main sequence star. As a result, the ZAMS rotation rate need only be within ~30% of the critical value in order to reach critical rotation during the hydrogen burning stage. Calculations of the evolution of rotating stars show that the Be stars result from a normal (Maxwellian) distribution of B-star rotation velocities.

1. INTRODUCTION

The classical model for a Be star involves a single star rotating so rapidly that material is ejected from its surface, forming a disk in the equatorial plane. The high incidence of Be stars (~10% of all B stars) requires that the critical velocity be reached during the long-lived main sequence stage. The locations of the Be stars relative to the ZAMS (Bond, 1973; Schild and Romanishin 1976) suggest that many of these stars arrive on the ZAMS with subcritical velocities and reach critical rotation as they evolve away from the ZAMS.

2. EFFECTS OF ROTATION ON MAIN SEQUENCE STARS

Sackmann and Anand (1970) computed the evolution of a rigidly-rotating $10M_\odot$ star and found that a moderate initial rotation (~½ of critical) is sufficient to reach critical rotation during the main sequence stage. This differs from the results of Hardorp and Strittmatter (1970), based on the moments of inertia of nonrotating models. They concluded that the initial rotation rate must be very close to critical in order to produce critical rotation from core contraction during the main sequence stage. The difference between these results can be understood in terms of the effect of rigid-body rotation on stellar structure.

M. Jaschek and H.-G. Groth (eds.), Be Stars, 299–302.

If a star rotates rigidly, the centripetal acceleration is greatest at the surface. As a result, the fraction of the gravitational force which must be supported by the pressure gradient increases inward, i.e., the pressure gradient is more centrally concentrated in the rotating star than in the nonrotating case. This can be achieved by changing either the density stratification or the temperature stratification (or both), but the temperature structure is largely fixed by the requirement of thermal equilibrium. (Rigid-body rotation does not significantly affect the core luminosity.) Thus, rotation tends to increase the density gradient and, thereby, decrease the moment of inertia. If, during the main sequence stage, the rotation increases due to core contraction, the above effect tends to amplify the contraction. This amplification effect would not be present in nonrotating models.

Figure 1 shows the main sequence evolution of four sequences of rotating models ($M = 5M_\odot$) computed by Endal and Sofia (1979). The ZAMS surface rotation velocities of sequences A to D are: 178, 239, 324, and 418 km/s, respectively. By comparison, the ZAMS critical velocity at this mass is 580 km/s. The quantity λ is the ratio of centripetal acceleration to gravity, at the surface and in the equatorial plane.

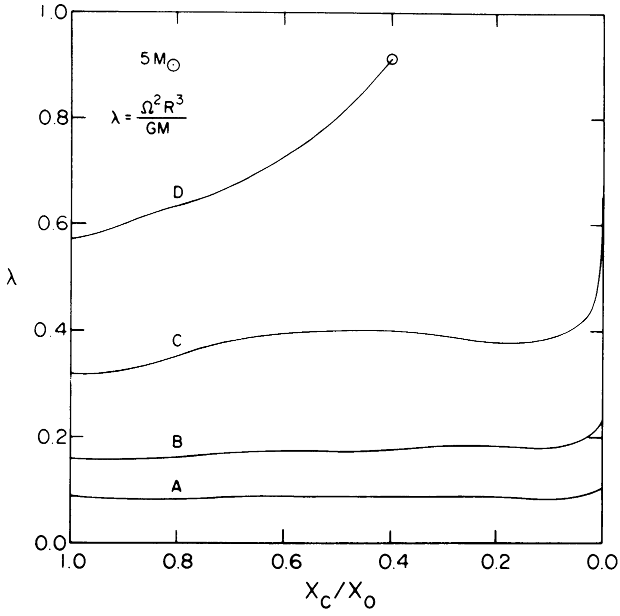

Fig. 1 - The evolution of the rotation parameter λ as a function of core hydrogen abundance.

A reasonable analytic fit to the increase (with age) of the rotational parameter λ is given by

$$\lambda(\lambda_o, X_c/X_o) = \lambda_o[1+(2.57\lambda_o-0.31)(1-X_c/X_o)], \qquad (1)$$

where subscript o refers to ZAMS values. The minimum λ_o required to reach critical rotation (λ=1) prior to hydrogen exhaustion is $\lambda_o = 0.50$, which corresponds to 70% of the critical rotation rate. This is higher than the value of Sackmann and Anand (1970) because a $5M_\odot$ star contracts less in response to hydrogen depletion than a $10M_\odot$ star.

3. COMPARISON TO OBSERVATIONS

Equation (1) was combined with an analytic fit to the time dependence of X_c/X_o and the result convolved with a Maxwellian distribution of ZAMS velocities (characterized by the mean velocity $\langle v\rangle$). This gives the fraction of B stars which will be Be stars for a random distribution of ages. The results are given in Table 1. The percentages have been multiplied by 0.75 to account for close binaries (~25%), where synchronization will prevent critical velocities; $\langle v\rangle$ has been corrected for close binaries and evolutionary effects.

Table 1. Predicted frequency of Be stars

$\langle v\rangle$	% Be	$\langle v\rangle$	% Be	$\langle v\rangle$	% Be
169	2	204	7	231	13
185	4	218	10	243	16

According to Bernacca and Perinotto (1974), the mean rotation rate at $5M_\odot$ is 215 km/s, so our models predict that 10% of these stars should be Be stars. Massa (1975) finds that ~20% of the B stars brighter than $m_V = 5.5$ have shown emission at some time. However, the Be stars are, on the average, ~0.5 magnitude brighter than normal B stars (Slettebak, 1979) and this implies a Malmquist correction factor of 2, due to the larger volume sampled for the brighter objects. Thus, the correct number of Be stars is closer to 10%, in agreement with the prediction.

This research was supported by the National Science Foundation grant AST 79-19688.

REFERENCES

Bernacca, P. L., and Perinotto, M.: 1974, Astron. Astrophys., 33, pp. 443-450.
Bond, H. E.: 1973, Pub. Astron. Soc. Pac., 85, pp. 405-407.
Endal, A. S., and Sofia, S.: 1979, Astrophys. J., 232, pp. 279-290.
Hardorp, J., and Strittmatter, P. A.: 1970, in "Stellar Rotation" ed. A. Slettebak (Dordrecht: Reidel) pp. 48-59.

Massa, D.: 1975, Pub. Astron. Soc. Pac., 87, pp. 777-784.
Sackmann, I.-J., and Anand, S.P.S.: 1970, Astrophys. J., 162, pp. 105-124.
Schild, R., and Romanishin, W.: 1976, Astrophys. J., 204, pp. 493-501.
Slettebak, A.: 1979, Space Sci. Rev., 23, pp. 541-580.

DISCUSSION

Thomas: Suppose you use your imagination and lift the quasistatic corrections: leaving free the possibility of $F_M \neq o$ at the outer boundary of your interior: Do you think that this nonstatic interior could possibly give F_M up to 10^{-4}, independent of any atmospheric modeling?

Endal: The stellar structure equations are highly nonlinear, especially for rotating stars where you have shear instabilities, etc. contributing additional nonlinear effects. For this reason, it is difficult to predict (without detailed calculations) how the interior will react to a change in boundary conditions. My guess is that the effect would be quite small, but this is purely a guess and should be checked by real calculations. My experience is that the response of a stellar interior model to a given change is very difficult to predict a priori.

Marlborough: Is the neglect of the effect of circulation currents on the structure of the outer regions of your models a reasonable assumption?

Endal: In terms of the global structure of the star, this is certainly a good assumption. Circulation currents have velocities many orders-of-magnitude smaller than the rotational velocities. Departures from hydrostatic equilibrium may, however, have a substantial feedback effect on the circulation itself.

Andrillat: What catalogue do you use for the values of v sin i?

Endal: I used the results of Bernaca and Perinotto (1974), based on their catalogue.

Peters: The published rotational velocities for eclipsing (Algol) binaries are systematically low because they are based upon the widths of lines formed in the circumstellar disk. R. Polidan and I are analyzing the Mg II line (λ 4481) in Algol systems, which usually is not formed in the disk, and find considerably larger values of v sin i.