EVLON OF ROTATIONAL VELOCITIES OF A-TYPE STARS

Wuming Yang1,2, Shaolan Bi1, Xiangcun Meng2, and Zhijia Tian1

1 Department of Astronomy, Beijing Normal University, Beijing 100875, China;
yangwuming@ynao.ac.cn, yangwuming@bnu.edu.cn
2 School of Physics and Chemistry, Henan Polytechnic University, Jiaozuo 454000, Henan, China

ABSTRACT

The equatorial velocity of A-type stars undergoes an acceleration in the first third of the main sequence (MS) stage, but the velocity decreases as if the stars were not undergoing any redistribution of angular momentum in the external layers in the last stage of the MS phase. Our calculations show that the acceleration and the decrease of the equatorial velocity can be reproduced by the evolution of the differential rotation zero-age MS model with the angular momentum transport caused by hydrodynamic instabilities during the MS stage. The acceleration results from the fact that the angular momentum stored in the interiors of the stars is transported outward. In the last stage, the core and the radiative envelope are uncoupling, and the rotation of the envelope is a quasi-solid rotation; the uncoupling and the expansion of the envelope indicate that the decrease of the equatorial velocity approximately follows the slope for the change in the equatorial velocity of the model without any redistribution of angular momentum. When the fractional age 0.3 \( \lesssim t / t_{\text{MS}} \lesssim 0.5 \), the equatorial velocity remains almost constant for stars whose central density increases with age in the early stage of the MS phase, while the velocity decreases with age for stars whose central density decreases with age in the early stage of the MS phase.

Key words: stars: early-type – stars: evolution – stars: rotation

Online-only material: color figures

1. INTRODUCTION

Helioseismology and asteroseismology have successfully shown the internal rotation of the Sun and red-giant stars. For example, the Sun has a flat rotational profile (Brown et al. 1989; Kosovichev et al. 1997), but red-giant stars have a fast rotation core (Aerts et al. 2003; Beck et al. 2012), which provided some constraints on the processes of angular momentum transport in the Sun and red-giant stars. In order to reproduce the flat solar rotational profile, the magnetic angular momentum transport (Eggenberger et al. 2005; Yang & Bi 2006) or the gravity-wave angular momentum transport (Zahn et al. 1997; Talon & Charbonnel 2005) should be considered in solar models, besides the angular momentum transport caused by hydrodynamic instabilities.

Most A-type stars are known to be fast rotators, with a typical rotational velocity of about 160 km s\(^{-1}\) (Royer et al. 2007) for stars with masses between about 1.3 and 3.0 \( M_\odot \). Thus, there may be a non-negligible effect of rotation on the structure and evolution of these stars. However, these stars are always hotter than the red edge of the instability strip (Saio & Gautschy 1998). They are generally not expected to exhibit solar-like oscillations. Therefore, the effects of rotation and rotation scenarios of these stars are difficult to understand as that of the Sun and red-giant stars via seismology.

Fortunately, the surface rotational velocities of thousands of stars with spectral types between late-B and early-F have been observed (Abt & Morrell 1995; Wolff & Simon 1997; Royer et al. 2002a, 2002b, 2004a, 2004b, 2007; Wolff et al. 2004; Díaz et al. 2011; Zorec & Royer 2012). These stars include pre-main sequence (PMS) and main sequence (MS) stars. The observed surface rotational velocity of a star depends on the initial angular momentum, the rate of angular momentum loss, the angular momentum transport in stellar interiors, and the changes in the moment of inertia of the star.

For stars with masses greater than 1.6 \( M_\odot \), there is no concrete evidence of activity and any significant angular momentum loss during MS evolution (Wolff & Simon 1997). For these MS stars, the observed surface rotational velocities are thus mainly dependent on the initial rotational profile at the zero-age main sequence (ZAMS), the angular momentum transport in stellar interiors, and the changes in the moment of inertia of stars. The changes of the moment of inertia can be understood from evolutionary models. Therefore, the observed rotational velocities of A-type stars could provide important clues about the initial rotational profile at the ZAMS and the efficiency of angular momentum transport in stellar interiors.

Recently, Zorec & Royer (2012) studied the evolution of surface rotational velocities of more than one-thousand A-type MS stars. They found that the surface velocities of the stars with masses between about 1.7 and 3.2 \( M_\odot \) undergo a strong acceleration in the first third of the MS evolutionary phase, which strongly differs from that theoretically predicted by two limiting cases of internal angular momentum redistributions: (1) rigid rotation; (2) conservation of angular momentum in stellar shells. In the last third of the MS, however, the velocities decrease as if the stars were not undergoing any redistribution of the angular momentum in the external layers (Zorec & Royer 2012).

In the calculations of the evolution of rotating stars, the ZAMS models are assumed to rotate uniformly. If this assumption was correct, a special mechanism might be required to extract angular momentum from the stellar interiors to achieve the acceleration of the equatorial velocity. In fact, Wolff & Simon (1997) and Wolff et al. (2004) studied the angular momentum evolution of A- and F-type stars from the birth line to the MS. They concluded that A- and early-F-type stars do not lose angular momentum and that the angular momentum could be conserved in the shells of the stars as the stars evolve from the end of fully convective phase to the ZAMS. Thus, for these stars,
the rotation at the ZAMS should be differential (hereafter this differential rotation ZAMS model obtained from the evolution with the conservation of angular momentum in shells is referred to as the Wolff ZAMS model), and the core could serve as a reservoir of angular momentum that can be transported from the fast rotation core to the slow rotation envelope to produce the acceleration of the equatorial velocity. Moreover, too high or too low efficiency of angular momentum transport in stellar interiors could not reproduce the acceleration of the surface velocity. Furthermore, too high efficiency of angular momentum transport in stellar interiors could not reproduce the acceleration of the equatorial velocity in the first third of the MS evolutionary phase (Zorec & Royer 2012). Thus, the results of Zorec & Royer (2012) provide an opportunity to test the conclusions of Wolff et al. (2004) and the angular momentum transport in the interiors of A-type stars.

In this work, we focus mainly on the evolution of the equatorial velocity of A-type stars. The paper is organized as follows. We present our stellar models and calculation results in Section 2. In Section 3, we discuss and summarize the results.

2. STELLAR MODELS AND CALCULATION RESULTS

2.1. Stellar Models

We used the Yale Rotation Evolution Code (Pinsonneault et al. 1989; Yang & Bi 2007) to compute the evolution of rotating models with different masses and metallicities. Hydrodynamical instabilities considered in this code are meridional circulation, the Goldreich–Schubert–Fricke instability, and the secular shear instability (Endal & Sofia 1978; Pinsonneault et al. 1989). The OPAL EOS tables (Rogers & Nayfonov 2002), OPAL opacity tables (Iglesias & Rogers 1996), and the opacity tables for low temperature provided by Alexander & Ferguson (1994) were used. Energy transfer by convection is treated according to the standard mixing length theory. The value of 1.72 for the mixing-length parameter (α) was calibrated against the standard model with a solar metallicity. The initial metallicity Z was fixed at 0.02 and 0.008, and the hydrogen abundance was determined by X = 0.767 − 3Z. For a given mass, the initial angular momentum is estimated by using the formula of Kawaler (1987). Angular momentum loss due to magnetic braking and mass loss could be negligible in A-type stars (MacGregor & Charbonneau 1994; Wolff & Simon 1997; Zorec & Royer 2012). Thus, we assumed that the total angular momentum is conserved in our models.

We calculated the following four evolutionary cases: (1) C1: models were evolved from the PMS to the terminal-age main sequence (TAMS) without any exchange of angular momentum in shells; (2) C2: models were computed as a rigid rotator; (3) C3; and (4) C4. In the last two cases, models were evolved from the ZAMS to the TAMS with angular momentum transport caused by the rotationally induced instabilities, and the ZAMS model is a uniform rotator for the C3 but is a Wolff ZAMS model for the C4. Moreover, we assumed that the rotation of the surface layers (the fractional mass δM/M ≃ 10−4) is uniform.

2.2. Calculation Results

Figure 1 shows the evolution of the equatorial velocity of models with M = 1.7 M⊙ and Z = 0.02 in the MS lifetime span (tMS). The notation VZAMS is the equatorial velocity at the ZAMS. For cases C1, C2, and C3, from ZAMS to t/tZAMS ≈ 0.95 the equatorial velocities decrease. In case C1, the equatorial velocity descends about 45%, which is consistent with the expectation of the law of conservation of angular momentum in shells (Ve = V0R0/Rc, where Rc is the stars’ radius and V0 and R0 refer to initial values). In case C2, the equatorial velocity decreases by around 20%. These two limiting cases did not reproduce the acceleration of the surface velocity in the early stage of MS. The evolution of the equatorial velocity in case C3 is similar to that in case C2 except for in the last stage of the MS. This is because the rotation of the radiative region of the MS models of C3 is a quasi-solid body rotation and the core and the envelope are decoupling in the last stage. In case C4, the equatorial velocity accelerates in the early stage of the MS phase. From t/tMS ≃ 0.017 to t/tMS ≃ 0.3, the equatorial velocity increases by about 20%. However, when t/tMS increases from about 0.3 to 0.5, the velocity remains almost constant. After t/tMS > 0.5, the velocity decreases as evolution proceeds until the evolution approaches the end of the MS stage. When the fractional age t/tMS > 0.7, the decrease of the equatorial velocity in case C4 is similar to that in case C1, which is consistent with the finding of Zorec & Royer (2012).

Figure 2 shows the radial distributions of the internal angular velocity at different evolutionary stages. The solid (red) line shows the distribution at Xc = 0.703. The long-dashed (green) line indicates the distribution at Xc = 0.535. The dash-triple-dotted (blue) line shows the distribution at Xc = 0.451, and the dotted (cyan) line refers to the distribution at Xc = 0.254.
slow rotation envelope, which almost fully impedes the decrease in the angular velocity of the envelope, and even leads to an increase in the angular velocity. In addition, due to the increase in radius, the equatorial velocity obviously increases. When the model evolves from \( t / t_{\text{MS}} \approx 0.3 \) to \( t / t_{\text{MS}} \approx 0.5 \) the core and the envelope are strongly coupled by hydrodynamic instabilities. Although the core still contracts, its angular velocity decreases with the decrease in the angular velocity of the envelope. The angular momentum stored in the stellar interiors is continually transported outward, which is insufficient to allow the velocity to remain almost constant. When \( t / t_{\text{MS}} > 0.6 \), due to the fact that the core contracts and the envelope expands rapidly, the hydrodynamical instabilities are insufficient to couple the core to the envelope. Thus, the core and the envelope are uncoupling. However, the instabilities are sufficient to keep the envelope rotating as a quasi-solid body. In our models, the differential rotation results from the contraction/expansion of stars. Due to the uncoupling of the core and the envelope, the decrease of the angular velocity of the envelope depends almost exclusively on the expansion of the envelope. Moreover, Figure 3 shows that most of the radiative region spins down at an approximately equal rate from \( t / t_{\text{MS}} \approx 0.7 \) to \( t / t_{\text{MS}} \approx 0.9 \) in the evolution in case C1, which is similar to quasi-solid rotation. Thus, when the fractional age \( t / t_{\text{MS}} > 0.7 \), the decrease in the equatorial velocities of cases C1 and C4 follows an approximate slope.

We also calculated the evolution of the equatorial velocity of models with \( M = 2.0, 2.5, \) and \( 3.0 M_\odot \). The comparisons of the evolutions of the equatorial velocities of our models with the results of Zorec & Royer (2012) are shown in Figure 4. The evolution of cases C1, C2, and C3 of these models are similar to those of a model with \( M = 1.7 M_\odot \), i.e., the equatorial velocity decreases with age. But in the early stage (\( t / t_{\text{MS}} \lesssim 0.3 \)) of the MS in case C4, the equatorial velocity accelerates. However, the magnitude of the increase of the ratio \( V_e / V_{\text{ZAMS}} \) of our models is obviously lower than that obtained by Zorec & Royer (2012). For example, at \( t / t_{\text{MS}} = 0.35 \), the value of the observed \( V_e / V_{\text{ZAMS}} \) is 1.265 ± 0.079 for the star with \( M = 2.5 M_\odot \), but the value for our models is about 1.11. The discrepancy is about 2\( \sigma \). When the fractional age \( t / t_{\text{MS}} \) increases from around 0.3 to 0.5, the theoretical velocities decrease slightly, but the observed velocities decrease rapidly for stars with \( M = 2.5 \) and \( 3.0 M_\odot \). When the age \( t / t_{\text{MS}} > 0.5 \), the value of the theoretical \( V_e / V_{\text{ZAMS}} \) is lower for a star with \( M = 2.0 M_\odot \) but is higher for a star with \( M = 3.0 M_\odot \) than the observed one. However, for a star with \( M = 2.5 M_\odot \), the evolution of the theoretical
decreases for stars with $M \gtrsim 2.1\,M_\odot$, but the central density decreases (see Figure 5) for stars with $M \lesssim 2.0\,M_\odot$. As a consequence, the velocities of cases C1 and C4 follow an approximate slope when $t/t_{\text{MS}} \gtrsim 0.7$. As a consequence, although the velocities of A-type stars decrease as if the stars were not undergoing any redistribution of the angular momentum in their envelope during the final stages of the MS phase, the rotation of the envelope of A-type stars might be quasi-solid with the decoupling of the core and the envelope. Thus, the rotation of A-type stars might be closer to quasi-solid body rotation during $t/t_{\text{MS}} \approx 0.3$–0.5 than in the early or last stage of the MS.

Compared with the Ekström et al. (2008) models used by Zorec & Royer (2012), our ZAMS models for C4 are the Wolff ZAMS model but the rotation of the ZAMS models of Ekström et al. (2008) and our C3 is a solid body rotation. The equatorial velocity of our C3 decreases with age, which is similar to that obtained by Zorec & Royer (2012) from Ekström et al. (2008) models. Cases C3 and C4 have the same instabilities, which may imply that the Wolff ZAMS model is required to achieve the acceleration. Moreover, we neglected the angular momentum loss caused by mass loss. Finally, there are some differences in the treatments of instabilities between our models and the Ekström et al. (2008) models (Pinsonneault et al. 1989; Maeder & Zahn 1998), which can lead to the differences in the efficiency of angular momentum transport and the mixing of elements. Besides the hydrostatic and Von Zeipel effects, mixing caused by rotationally induced instabilities is one of the key factors that affects the distribution of density and the instability of convection by changing the distribution of elements. In our models, the effects of rotation lead to a decrease in the convective core for stars with $M \lesssim 2.0\,M_\odot$ but an increase in the convective core for stars with $M \gtrsim 2.1\,M_\odot$ (Yang et al. 2012). As a consequence, near the end of the MS, the radii of rotating models are smaller than those of non-rotating ones for stars with $M \lesssim 2.0\,M_\odot$ but larger than those of non-rotating models for stars with $M \gtrsim 2.1\,M_\odot$. Because the decrease of the ratio $V_e/V_{\text{ZAMS}}$ is relevant to the increase in radius, allow the instabilities stars with $M \lesssim 2.0\,M_\odot$ to more easily retain this ratio at a high value than stars with $M \gtrsim 2.1\,M_\odot$.

In this work, we calculated the evolution of the equatorial velocity of A-type stars with different conditions. The evolution

The instabilities caused the angular momentum to be transported outward in the early stage of the MS, which resulted in an increase of $V_e/V_{\text{ZAMS}}$. Although the magnitude of the increase in the fractional velocity of our models is less than that obtained by Zorec & Royer (2012), who gave a magnitude as high as 30%, the velocity increases as the evolution proceeds during the first third of the MS phase, which is consistent with the finding of Zorec & Royer (2012). This might offer support for the Wolff ZAMS model and imply that the core and the envelope are decoupling as A-type stars evolve from the end of the fully convective phase to the ZAMS but are decoupling in the early stage of the MS. The theoretical magnitude is lower than the observed one. This might be caused because the efficiency of angular momentum transport was not calibrated.

In the last stage of the MS (0.7 $\lesssim t/t_{\text{MS}} \lesssim$ 0.95), the core and the radiative envelope are decoupling in the evolution of cases C1, C3, and C4. The contraction of the core has almost no affect the rotation of the envelope. For case C1, although the rotation of the whole radiative envelope is differential, the envelope spins down at an approximately equal rate in our models, which is similar to the manner of the quasi-solid body rotation. For case C4, the rotation of the radiative envelope is a quasi-solid rotation. Thus the decrease of the fractional velocity of cases C1 and C4 follows an approximate slope when $t/t_{\text{MS}} \gtrsim 0.7$. As a consequence, although the velocities of A-type stars decrease as if the stars were not undergoing any redistribution of the angular momentum in their envelope during the final stages of the MS phase, the rotation of the envelope of A-type stars might be quasi-solid with the decoupling of the core and the envelope. Thus, the rotation of A-type stars might be closer to quasi-solid body rotation during $t/t_{\text{MS}} \approx 0.3$–0.5 than in the early or last stage of the MS.

Compared with the Ekström et al. (2008) models used by Zorec & Royer (2012), our ZAMS models for C4 are the Wolff ZAMS model but the rotation of the ZAMS models of Ekström et al. (2008) and our C3 is a solid body rotation. The equatorial velocity of our C3 decreases with age, which is similar to that obtained by Zorec & Royer (2012) from Ekström et al. (2008) models. Cases C3 and C4 have the same instabilities, which may imply that the Wolff ZAMS model is required to achieve the acceleration. Moreover, we neglected the angular momentum loss caused by mass loss. Finally, there are some differences in the treatments of instabilities between our models and the Ekström et al. (2008) models (Pinsonneault et al. 1989; Maeder & Zahn 1998), which can lead to the differences in the efficiency of angular momentum transport and the mixing of elements. Besides the hydrostatic and Von Zeipel effects, mixing caused by rotationally induced instabilities is one of the key factors that affects the distribution of density and the instability of convection by changing the distribution of elements. In our models, the effects of rotation lead to a decrease in the convective core for stars with $M \lesssim 2.0\,M_\odot$ but an increase in the convective core for stars with $M \gtrsim 2.1\,M_\odot$ (Yang et al. 2012). As a consequence, near the end of the MS, the radii of rotating models are smaller than those of non-rotating ones for stars with $M \lesssim 2.0\,M_\odot$ but larger than those of non-rotating models for stars with $M \gtrsim 2.1\,M_\odot$. Because the decrease of the ratio $V_e/V_{\text{ZAMS}}$ is relevant to the increase in radius, allow the instabilities stars with $M \lesssim 2.0\,M_\odot$ to more easily retain this ratio at a high value than stars with $M \gtrsim 2.1\,M_\odot$.

In this work, we calculated the evolution of the equatorial velocity of A-type stars with different conditions. The evolution

![Figure 5. Central density ($\rho_c$) as a function of the mass fraction of central hydrogen. The dashed (red) lines show the results of models without rotation. The dotted (cyan) lines indicate the results of models with rotation.](image-url)
of case C4 reproduces the most number of characteristics of the equatorial velocity of A-type stars that were found by Zorec & Royer (2012). From the ZAMS to $t/t_{\text{MS}} \approx 0.3$, the equatorial velocity accelerates. But in the last stage of the MS stage ($t/t_{\text{MS}} \gtrsim 0.7$), the core and the envelope of A-type stars are uncoupling; the envelope rotates as a quasi-solid body, but the decrease of the equatorial velocity approximately follows the slope of the velocity of the model without any redistribution of the angular momentum in this stage. However, the magnitude of the increase of the fractional velocity $V_e/V_{\text{ZAMS}}$ of our models is less than that obtained by Zorec & Royer (2012). Moreover, our models with $M = 2.5$ and $3.0 \, M_\odot$ did not reproduce the rapid decrease in the equatorial velocity during the middle stage of the MS phase. This might imply that some mechanisms for the transport or loss of angular momentum are missing in our models.

We thank the anonymous referee for helpful comments and J. Zorec and F. Royer for providing data. We acknowledge the support from the NSFC 11273012, 11273007, 10933002, and 11003003, and the Project of Science and Technology from the Ministry of Education (211102).

REFERENCES
Abt, H. A., & Morrell, N. I. 1995, ApJS, 99, 135
Aerts, C., Thouss, A., Daszyńska, J., et al. 2003, Sci, 300, 1926
Alexander, D. R., & Ferguson, J. W. 1994, ApJ, 437, 846
Beck, P. G., Montalban, J., Kallinger, T., et al. 2012, Natur, 481, 55
Brown, T. M., Christensen-Dalsgaard, J., Dziembowski, W. A., et al. 1989, ApJ, 343, 526
Díaz, C. G., González, J. F., Levato, H., & Grosso, M. 2011, A&A, 531, A143
Eggenberger, P., Maeder, A., & Meynet, G. 2005, A&A, 440, L9
Ekström, S., Meynet, G., Maeder, A., & Barblan, F. 2008, A&A, 478, 467
Endal, A. S., & Sofia, S. 1978, ApJ, 220, 279
Iglesias, C., & Rogers, F. J. 1996, ApJ, 464, 943
Kawaler, S. D. 1987, PASP, 99, 1322
Kosovichev, A. G., Schou, J., Scherrer, P. H., et al. 1997, SoPh, 170, 43
MacGregor, K. B., & Charbonneau, P. 1994, in ASP Conf. Ser. 64, Cool Stars, Stellar Systems, and the Sun, ed. J.-P. Caillault (San Francisco, CA: ASP), 174
Maeder, A., & Zahn, J. P. 1998, A&A, 334, 1000
Pinsonneault, M. H., Kawaler, S. D., Sofia, S., & Demarqure, P. 1989, ApJ, 338, 424
Rogers, F. I., & Nayfonov, A. 2002, ApJ, 576, 1064
Royer, F., Gerbaldi, M., Faraggiana, R., & Gómez, A. E. 2002a, A&A, 381, 105
Royer, F., Grenier, S., Baylac, M. O., Gómez, A. E., & Zorec, J. 2002b, A&A, 393, 897
Royer, F., Zorec, J., & Frémat, Y. 2004a, in IAU Symp. 215, Stellar Rotation, ed. A. Maeder & P. Eenens (San Francisco, CA: ASP), 55
Royer, F., Zorec, J., & Gómez, A. E. 2004b, in IAU Symp. 224, The A-Star Puzzle, ed. J. Zverko et al. (Cambridge: Cambridge Univ. Press), 109
Royer, F., Zorec, J., & Gómez, A. E. 2007, A&A, 463, 671
Saiio, H., & Gautschy, A. 1998, ApJ, 498, 360
Talon, S., & Charbonnel, C. 2005, A&A, 440, 981
Wölfle, S. C., & Simon, T. 1997, PASP, 109, 759
Wölfle, S. C., Strom, S. E., & Hillenbrand, L. A. 2004, ApJ, 601, 979
Yang, W. M., & Bi, S. L. 2006, A&A, 449, 1161
Yang, W. M., & Bi, S. L. 2007, ApJL, 658, L67
Yang, W. M., & Bi, S. L. 2012, ApJ, in press (arXiv:1212.1511)
Zahn, J. P., Talon, S., & Matias, J. 1997, A&A, 322, 320
Zorec, J., & Royer, F. 2012, A&A, 537, A120

We acknowledge the support from the NSFC 11273012, 11273007, 10933002, and 11003003, and the Project of Science and Technology from the Ministry of Education (211102).