Possibility of the BF Ori rotation slowdown due to the orbital synchronization

S G Shulman
St.-Petersburg State University, 7-9 Universitetskaya Nab., St.-Petersburg, 199034, Russia
Pulkovo Astronomical Observatory of RAS, 65/1 Pulkovskoye chaussee, St.-Petersburg, 196140, Russia
E-mail: sgshulman@gmail.com

Abstract. BF Ori is an UX Ori type star with a very slow projected rotational velocity. We analyzed a possibility of the slowdown due to the synchronization in close binary systems. We hypothesized that BF Ori has a companion and estimated its properties as it might be massive and close enough to make this slowdown possible. The conclusion that the rotational velocity of BF Ori is apparently not a result of the tidal interaction with a low mass companion is made.

1. Introduction
UX Ori type stars are mainly Herbig Ae/Be stars observed with a small angle between a line of view and a circumstellar disk plane [1, 2]. From the estimates of a disk opening angle [3] we can conclude that the angle between the line of view and the star’s rotation axis is not less then 55°. Hence an equatorial rotation velocity might be close to the observed projected one.

Usually UX Ori type stars have projected rotational velocities about 100–200 km/s [4]. The only known exclusion is BF Ori with the projected rotational velocity of 39 ± 9 km/s [5].

We studied a theory that the rotation of BF Ori was slowed as a result of a tidal interaction with a hypothesized low mass companion (a hypothesis about low mass companion near BF Ori was already represented in the paper Grinin et. al. 2010 [6]).

2. Pre-main sequence model grids
For the detailed analysis of the tidal interaction effects we used pre-main sequence model grids of Siess et. al. 2000 [7]. These models include values of stellar radii, luminosities, moments of inertia, and convective envelopes masses for various ages which where used in the computations.

Early stages of the tracks from these pre-MS model grids were omitted to conform this canonical models with models computed in terms of an accretion paradigm. So, we started computations not from the begging of Siess tracks but from the birthline like it was recommended by Palla and Stahler [8].

3. The tides
An orbital motion of the component produces a periodical perturbation potential. This potential influences on the orbit and the rotation of the star. As a result secular changes of the orbit exist. Usually this perturbation potential does not lead to sensible changes itself. But there are various inner processes in the star which make the influence of the component much stronger [9].
We studied main processes which make the tidal interaction stronger. These processes were suggested by Zahn [9, 10], Press [11] and Tassoul [12, 13]. They are based on a viscosity friction in turbulent convective envelops, an exciting of low frequency modes of the star’s oscillation, a fully developed turbulence driven by a tidal shear in stars with radiative envelopes and tidally driven meridional currents. Magnetic torques are not discussed because BF Ori has a very low magnetic field [5].

BF Ori is a young intermediate mass object (\(M = 2.5M_\odot\), age \(\approx 3\) Myr [5]). As we can see in Siess models, BF Ori had a convective envelope for the first 2.5 Myr and was radiative after it. The analysis of tidal interactions lead us to conclusion that Zahn’s mechanism with a viscosity friction in the convective envelope should be used in the beginning of the evolution. The less effective mechanism connected with a tidal shear is suitable for the last half a million years.

In our case an exiting of low frequency modes of the star’s oscillation is ineffective. Tassouls’ hydrodynamical mechanism has some restrictions on the use [13] which do not allow to apply it for BF Ori.

In Zahn’s theory [9, 10] the angular rotation velocity of the star and the semi-major axis of its orbit vary with time according to

\[
\frac{d}{dt}(I\Omega) = \frac{6}{t_F} q^2 MR^2 \left(\frac{R}{a}\right)^6 \lambda_2 (\Omega - \omega),
\]

\[
\frac{da}{dt} = -a \frac{12}{t_F} q (1 + q) \left(\frac{R}{a}\right)^8 \lambda_2 \left(1 - \frac{\Omega}{\omega}\right),
\]

where

\[
t_F = \left[\frac{MR^2}{L}\right]^{\frac{1}{3}},
\]

\[
\lambda_2 \approx 0.019 \alpha^4 \sqrt{\frac{3160}{3160 + \eta^2}}, \quad \eta = 2(\Omega - \omega)t_F.
\]

Here \(I\) is a moment of inertia, \(R\) is a radius of the star, \(L\) is a luminosity of the star, \(\omega\) is an angular velocity of the orbital motion, \(q\) is a mass ration, \(t_F\) is a friction time (the smaller this time, the more efficient the dissipation), \(\alpha \approx 2\) is a mixing length.

When the star does not have any convective envelope another physical mechanism is taken into attention. Press et. al. 1975 [11] stated that local tidal driven shares are turbulent unstable. Hence the viscosity in these turbulent shares is important for the tidal effects. We obtain the following expression for the secular variation of the angular rotation velocity

\[
\frac{d}{dt}(I\Omega) = \frac{224}{75} K_{\mu} R_T (1 - e^2)^{9/2} q^2 MR^2 \left(\frac{R}{a}\right)^9 (\Omega - \omega)^2.
\]

Here \(R_T \approx 20\) is the effective Reynolds number , \(K_{\mu} \approx 0.025\) is a dimensionless parameter, and \(e\) is an orbital eccentricity.

4. Results

We computed rotational velocities corresponding to the age of BF Ori (3.2 Myr) using various initial velocities, semi-major axes and mass ratios. Figures 1–3 show the time variations of the rotational speed and its dependencies on the model parameters.

We assume that the angular momentum of the star changes only as a result of a tidal interaction. This assumption is reasonable because other ways of angular momentum loss from young stars are possible only when stars have strong magnetic fields.
The moment of inertia decreases during the pre-MS evolution. This leads to an acceleration of the rotation. Under some conditions Zahn’s dissipation mechanism can counteract the acceleration. After the reaching the age of 2.5 Myr the star becomes almost fully radiative. Zahn’s mechanism does not slowdown the star any more. The rotation becomes much faster.

Figures 2 and 3 show that the minimal achievable velocity weakly depends on the initial velocity and heavily depends on the mass ratio. The observed projected rotation velocity $\approx 40 \text{km/s}$ may be reached when the mass ratio is $0.2 - 0.5$ (when the mass ratio is $0.2 - 0.3$ there must be a minimum possible angle between the line of sight and the star’s rotation axis). With these mass ratios the companion will be of $0.5 - 1.3 M_\odot$. The star of such a mass and the age of 2–3 Myr is usually a T Tau star with strong emission lines of metals. In the spectrum of BF Ori we do not see these lines. So it is hardly believable that BF Ori has a companion with mass ratio $q = 0.2 - 0.5$ which slowed it.

---

**Figure 1.** Temporal variations of the rotational speed. On the left panel the results for the mass ratio $q = 0.25$ and different semi-major axes are shown. On the right panel the data for various mass ratios and the semi-major axis equal to 30 Solar radii are demonstrated. On the both panels black curves correspond to the star rotation speed and gray lines show the speed of a fully synchronized star.

**Figure 2.** The semi-major axis dependence of rotational velocities in the cases of different initial velocity values. The mass ratio $q = 0.3$. 

**Figure 3.** The semi-major axis dependence of rotational velocities in the cases of different initial velocity values. The mass ratio $q = 0.3$. 


Figure 3. The semi-major axis dependence of rotational velocities for systems with different mass ratios.

5. An orbital momentum
We studied one more hypothesis explaining the slow rotation of BF Ori. When a star is forming from a protostars cloud the angular momentum shares between the star, a disk, a companions etc. It is easy to see that a small body on an orbit around the star may have an orbital momentum compared to the angular momentum of the star.

The semi-major axis of a companion with such properties near a typical UX Ori applies

\[ \frac{a}{R} = 0.2 \left( \frac{I}{MR^2} \right)^2 \frac{R}{R_\odot} \frac{M_\odot}{M} \frac{1}{q^2}. \]  

(5)

for BF Ori with \( R = 3R_\odot \) and \( M = 2.5M_\odot \) it is equal to

\[ \frac{a}{R} = 2.5 \cdot 10^{-3} \frac{1}{q^2}. \]  

(6)

Hence, a low-mass companion with \( q = 0.01 \) and \( a = 25R \) has the angular moment equal to the star’s one.

6. Conclusion
We calculated the tidal cause slowdown of the rotational velocity for various mass ratios and semi-major axes. We found that the stars rotation on the pre-MS stage of evolution may be significantly slowed. It is shown that the observed rotational velocity of BF Ori \( \approx 40 \text{ km/s} \) may be reached when the mass ratio is larger then 0.2. We think it is hardly possible because a star of the mass greater then 0.5\( M_\odot \) at the age of 3 Myr is a T Tau star. The T Tauri star near BF Ori could be detected by its spectral features. A low-mass T Tauri star may be undetected yet, but it must be extremely particular condition for a significant slowdown.

We also estimated a mass and semi-major axis of a low-mass hypothetical companion with an orbital momentum equal to the typical UX Ori angular momentum. We find that a companion with the mass ratio about 0.01 and the semi-major axis of 25 star radii has the orbital momentum compared to the angular momentum of the star. This may explain the rotational velocity of BF Ori in the assumption that protostars momentum was shared between the star and the companion.
A detailed analysis is presented in the paper [14]. We expect an interferometric observation of BF Ori to clear up the disks inclination and solve the question about a duality of the star.

Acknowledgments
This work was partially supported by the Russian Foundation for Basic Research (RFFI), grant 15-02-09191.

References
[1] Grinin V P et al 1991 Astrophys. Space Sci. 186 283–298
[2] Natta A, Grinin V P, Mannings V and Ungerechts H 1997 Astrophys. J. 491 885–890
[3] Natta A, Grinin V and Mannings V 2000 Protostars & Planets IV (Tuscon, AZ: University of Arizona Press) p 559
[4] Grinin V P and Kozlova O V 2000 Astrophysics 43 239-244
[5] Alecian E et al 2013 Mon. Not. Roy. Astron. Soc. 56 1001–1026
[6] Grinin V P, Rostopchina A N, Barsunova O Yu and Demidova T V 2010 Astrophysics 53 367-372
[7] Siess L, Dufour E and Forestini M 2000 Astron. Astrophys. 358 593–599
[8] Palla F and Stahler S W 1993 Astrophys. J. 418 414–425
[9] Zahn J-P 1977 Astron. Astrophys. 57 383–394
[10] Zahn J-P 2008 EAS Publ. Ser. 29 67–90
[11] Press W H, Wiita P J and Smarr L L 1975 Astrophys. J. 202 L135–L137
[12] Tassoul J-L 1987 Astrophys. J. 322 856–861
[13] Tassoul M and Tassoul J-L 1997 Astrophys. J. 481 363–368
[14] Shulman S G 2016 Astrophysics 59 20–30