

Critically rotating stars in binaries - an unsolved problem -

S. E. de Mink, O. R. Pols and E. Glebbeek

*Astronomical Institute Utrecht, Princetonplein 5, NL-3584 CC Utrecht, The Netherlands,
S.E.deMink@astro.uu.nl*

Abstract. In close binaries mass and angular momentum can be transferred from one star to the other during Roche-lobe overflow. The efficiency of this process is not well understood and constitutes one of the largest uncertainties in binary evolution.

One of the problems lies in the transfer of angular momentum, which will spin up the accreting star. In very tight systems tidal friction can prevent reaching critical rotation, by locking the spin period to the orbital period. Accreting stars in systems with orbital periods larger than a few days reach critical rotation after accreting only a fraction of their mass, unless there is an effective mechanism to get rid of angular momentum. In low mass stars magnetic field might help. In more massive stars angular momentum loss will be accompanied by strong mass loss. This would imply that most interacting binaries with initial orbital periods larger than a few days evolve very non-conservatively.

In this contribution we wish to draw attention to the unsolved problems related to mass and angular momentum transfer in binary systems. We do this by presenting the first results of an implementation of spin up by accretion into the TWIN version of the Eggleton stellar evolution code.

Keywords: Binaries, rotation, mass loss, angular momentum loss

PACS: 97.10.Pg, 97.20.Tr, 97.80.-d

INTRODUCTION

The majority of stars are found in binary systems and a large fraction of them are so close that the two stars interact during their lifetime by exchanging mass. This completely alters the evolution of both stars compared to that of isolated stars.

Model calculations of mass transfer in binaries have been around since almost 40 years and have successfully explained the main characteristics of for example Algol systems, binaries in which the less massive star is more evolved than the more massive star. In these first models it was commonly assumed that mass transfer is a conservative process, i.e. neither mass nor angular momentum is lost from the system. It has become clear that this picture is not valid, at least for some systems.

The first approaches to model non-conservative mass transfer assumed that a fraction β of the transferred mass is lost from the system, where $\beta = 0.5$ has been commonly adopted regardless of the physical mechanism behind the mass loss or the properties of the binary system.

In [1] we compared a large grid of detailed binary models, making different assumptions for β , to observations of double lined eclipsing binaries. We found poor agreement when adopting one constant value for β . The slightly wider systems in the observed sample seem to have evolved less conservatively than the closer systems. We speculated that

this might be explained by the fact that in close systems tidal forces can keep the accreting star in synchronous rotation with the orbit, while in the wider systems the accreting star is spun up by the accretion stream [10]. As it rotates faster it experiences enhanced mass loss [7], which may explain why the wider systems evolved less conservatively.

The need for a more physical description of non-conservative mass transfer was already suggested by [15, 8, 11]. They assume that mass loss in the form of stellar winds is enhanced by the rotation. Mass is accreted until the star reaches critical rotation.

We recently implemented a model of spin up by mass transfer in the TWIN code, a detailed binary evolution code suitable for calculating large grids of binary models if used on a computer cluster. In this contribution we present the first results.

IMPLEMENTATION OF SPIN UP IN THE EVOLUTION CODE

The TWIN code [4, 5] is a binary evolution code based on the STARS code [2, 3, 13]. It solves the structure and composition equations for the two stars in a binary simultaneously with equations for the orbit assuming rigid rotation. Non-conservative mass transfer is implemented by assuming that a constant fraction β , a free parameter, of the transferred mass is lost from the system. After showing that observations do not support a constant fraction [1] we implemented a more realistic model of angular momentum transfer in the TWIN code.

We distinguish between accretion from a disk and accretion by a direct impact stream. We use an analytic fit by [14] to calculations of [9], which give the minimum distance R_{\min} between the mass transfer stream and the center of mass of the accreting star as function of the separation and the mass ratio. By comparing the radius of the accreting star R_A to the minimum distance of the stream we determine whether disk accretion, when $R_A < R_{\min}$, or direct impact accretion, when $R_A > R_{\min}$, occurs. In the case of disk accretion we assume that material is accreted with the specific angular momentum equivalent to that of a Keplerian orbit with the radius of the accreting star,

$$h = \sqrt{GM_A R_A}.$$

In the case of impact we assume the specific angular momentum is that of the Keplerian disk that would have formed if the accreting star had been a point mass, which has a radius of $1.7R_{\min}$ [according to 9], so that

$$h = \sqrt{GM_A 1.7R_{\min}}.$$

For the mass losing star we assume that the material is lost from the inner Lagrangian point with specific angular momentum

$$h = \omega_D R_{L_1}^2,$$

where ω_D is the angular speed of rotation of the donor star and R_{L_1} is the distance of the center of mass of the donor star to the inner Lagrangian point. We implement enhanced mass loss $\dot{M}(\omega)$ for stars rotating at a fraction $\omega/\omega_{\text{cr}}$ of critical rotation as in Langer [7]:

$$\dot{M}(\omega) = \dot{M}_0 * (1 - \omega/\omega_{\text{cr}})^{-0.43},$$

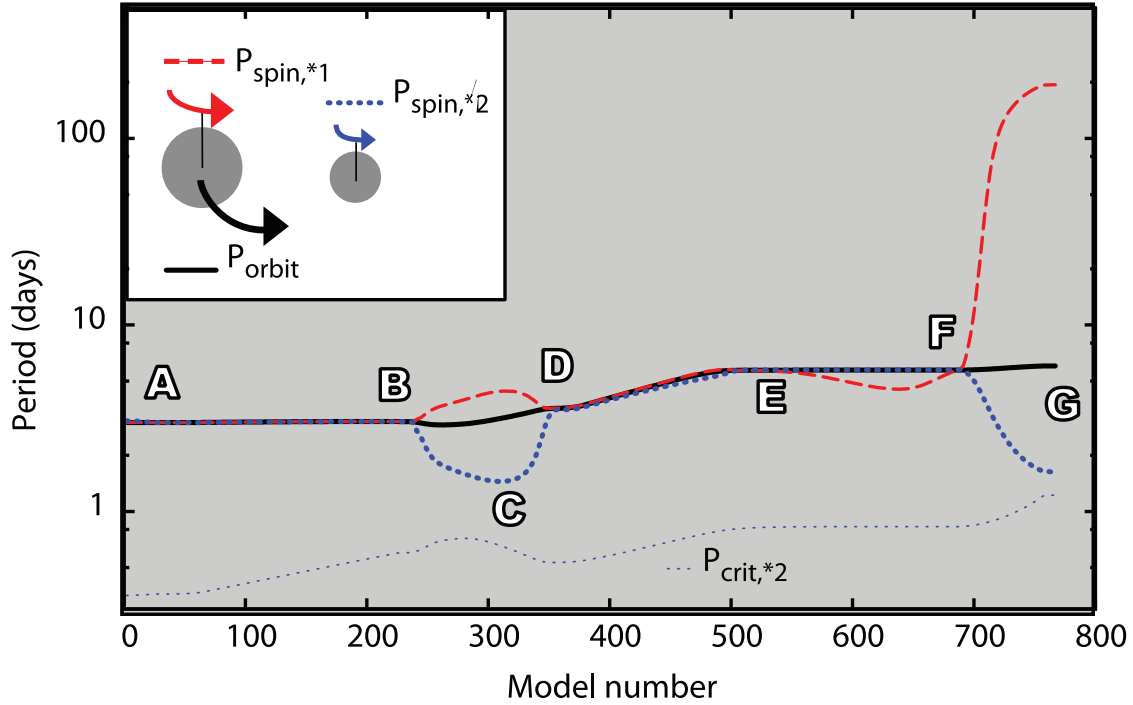


FIGURE 1. Example of the evolution of the orbital period P_{orbit} and the spin periods $P_{\text{spin},*1,2}$ of a binary consisting of a $20 M_{\odot}$ and a $16 M_{\odot}$ star. The labels are explained in the main text.

where \dot{M}_0 is the mass loss of a non-rotating star. When the the rotation rate of the accreting star reaches 99% of critical rotation we prevent any more accretion. At this moment our code experiences convergence problems when the accreting star rotates too fast so we stop our calculations. We hope to solve this in the near future.

FIRST RESULTS

As an example we show the evolution of a massive binary, consisting of a $20 M_{\odot}$ and a $16 M_{\odot}$ star, with an initial orbital period of 3 days, in such a close orbit that the tidal forces can prevent the accreting star from reaching critical rotation in the first phases of mass transfer. Figure 1 shows the orbital period and the spin periods of both stars against the number of the computed model, which is essentially a non-linear time axis stretching rapid phases of the evolution.

We start the evolution with the spin periods of both stars synchronized and aligned with the orbit (A). The primary star expands as it evolves on the main sequence and fills its Roche lobe (B). It starts to transfer mass and angular momentum on a thermal time scale to its companion. During this rapid phase of mass transfer the accreting star spins up (blue), while the donor spins down (red) (C). When the mass ratio is reversed the orbit widens and the mass transfer rate slows down. Tidal interaction again synchronizes the rotation of the stars with the orbit (D). Mass transfer continues on a nuclear time scale. At (E) the primary has burned all its central Hydrogen and starts to contract at

the end of the main sequence until hydrogen ignites in a shell and the star expands on a thermal timescale as it crosses the Hertzsprung gap (F). Mass is now being transferred on a thermal timescale. The accreting star is spun up close to critical rotation and our simulation ends (G).

UNSOLVED PROBLEMS

As first shown by Packet [10], angular momentum transfer is so efficient that a star can reach critical rotation after accreting only a small fraction of its own mass. In systems slightly wider than the example discussed above, this effect will severely limit the amount of mass that can be accreted by the secondary, and will lead to very non-conservative binary evolution. While this is consistent with some observed binaries, there are several counterexamples indicating that even in rather wide post-mass transfer binaries, with periods of 100 days or more, mass transfer has been fairly conservative, e.g. ϕ Per [12].

In order for fairly conservative mass transfer to be possible in all but the closest binaries, an effective angular momentum loss mechanism must operate. We briefly discuss several such mechanisms below, noting that how effective most of these mechanisms are is very uncertain.

Tidal interaction tends to keep the spin period of the accreting star synchronized with the orbit. However, tides are not efficient enough during rapid mass transfer or in systems wider than a few days, as shown in the example above.

Rotation-enhanced wind mass loss and the associated angular momentum loss in massive binaries with strong intrinsic winds can slow down the star when mass is lost preferentially in the equatorial plane or spin up the star when it is lost preferentially at the poles. In both cases it leads to highly non-conservative evolution.

Mass shedding of accreted material from the equator when the rotation is close to critical might work for intermediate-mass and/or low-metallicity binaries. Similar to rotation-enhanced wind mass loss, it should lead to very non-conservative mass transfer. Since conservative evolution seems possible even in fairly wide systems, a mechanism to lose angular momentum without much mass loss must exist.

Delayed accretion . Perhaps the transferred mass and angular momentum can be stored temporarily in a circumstellar or circumbinary disk. In an accretion disk mass can be transported inwards, while angular momentum is transported outwards and eventually transferred back to the orbit by tidal interaction with the disk. This allows the possibility to accrete the stored mass on a slower timescale than the rapid mass transfer timescale. If this process is effective, it can conserve both the mass and the angular momentum of the binary.

Magnetic fields have the potential to carry angular momentum away from the star with relatively little mass loss. This process of magnetic braking works efficiently for low-mass stars with convective envelope, so that low-mass binaries can lose angular momentum without losing much mass. However, massive main sequence stars with radiative envelopes do not generally have strong magnetic fields, with a

few exceptions [6]. This process might be effective if strong magnetic fields can be generated during the accretion process itself.

Many open questions remain. Future research should address simple but proper ways to model angular momentum loss mechanisms, which are not well understood, and a comparison of such models to observed post-mass transfer binaries with well-determined parameters.

ACKNOWLEDGMENTS

We would like to thank Peter Eggleton for his stellar evolution code. SdM thanks LKBF for financial support to attend this conference.

REFERENCES

1. De Mink S. E., Pols O. R., Hilditch R. W., 2007, *A&A*, 467, 1181
2. Eggleton P. P., 1971, *MNRAS*, 151, 351
3. Eggleton P. P., 1972, *MNRAS*, 156, 361
4. Eggleton P. P., Kiseleva L. G., Hut P., 1998, *ApJ*, 499, 853
5. Eggleton P. P., Kiseleva-Eggleton L., 2002, *ApJ*, 575, 461
6. Henrichs H. F., Schnerr R. S., Ten Kulve E., 2005, in Ignace R., Gayley K. G., eds, *The Nature and Evolution of Disks Around Hot Stars Vol. 337 of Astronomical Society of the Pacific Conference Series*, Observed magnetism in massive stars. p. 114
7. Langer N., 1998, *A&A*, 329, 551
8. Langer N., Wellstein S., Petrovic J., 2003, in van der Hucht K., Herrero A., Esteban C., eds, *A Massive Star Odyssey: From Main Sequence to Supernova Vol. 212 of IAU Symposium*, On the evolution of massive close binaries. p. 275
9. Lubow S. H., Shu F. H., 1975, *ApJ*, 198, 383
10. Packet W., 1981, *A&A*, 102, 17
11. Petrovic J., Langer N., van der Hucht K. A., 2005, *A&A*, 435, 1013
12. Pols O. R., 2007, in St-Louis N., Moffat A. F. J., eds, *Massive Stars in Interacting Binaries Vol. 367 of ASP Conf. Series*, . p. 397
13. Pols O. R., Tout C. A., Eggleton P. P., Han Z., 1995, *MNRAS*, 274, 964
14. Ulrich R. K., Burger H. L., 1976, *ApJ*, 206, 509
15. Wellstein S., 2001, PhD thesis