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N. St-Louis & A.F.J. Moffat

Mass and Angular Momentum Loss in Massive Binary Evolution

Onno R. Pols

Astronomical Institute Utrecht, P.O. Box 80000, 3508 TA Utrecht, The Netherlands

Abstract. I discuss uncertainties in the amount of mass loss and angular momentum loss during mass transfer in massive close binaries, concentrating on the first phase of mass transfer. On the basis of the reaction of the accreting star, one expects the fraction of mass lost from the binary to be a function of the orbital parameters, i.e. mass ratio and orbital period. Although spin-up of the accretor is expected to play a crucial role in limiting the amount of accretion, some binaries (e.g. ϕ Per) manage to have evolved in an almost conservative manner. On the other hand, common-envelope evolution is usually expected to lead to substantial mass loss, and very substantial angular momentum loss from a binary. Nevertheless there are systems that have apparently evolved through such a phase without losing much angular momentum, resulting in fairly wide current orbits.

1. Introduction

One of the unsolved problems in close-binary evolution is the question of the efficiency of mass transfer, i.e.: how much mass and angular momentum are lost from the binary system during phases of Roche-lobe overflow (RLOF), and how does this depend on the masses and orbital parameters of the binary. In this contribution I will take a look at these questions and the uncertainties involved in answering them, concentrating on the first phase of mass transfer in fairly massive binaries. In that case, the evolutionary history of observed binaries can be traced back with some confidence, while the uncertainties compound with every subsequent phase of interaction. The main part (Sect. 2) is devoted to the situation where stable RLOF is expected, and I will briefly consider the case of common-envelope evolution in Sect. 3.

2. Stable Mass Transfer

I first consider binaries with relatively short orbital periods (less than a few hundred days), so that when mass transfer starts, the donor star has a radiative envelope, i.e. the donor is on the main sequence (case A) or crossing the Hertzsprung gap (early case B). Provided that the initial mass ratio $q_0 = M_2/M_1$ (accretor mass over donor mass) is not too extreme (say $q_0 \gtrsim 0.25$), this will lead to stable RLOF on the thermal timescale of the donor. The mass transfer stream either hits the accreting star directly, or (for longer periods) forms an accretion disk around it. The question is whether this situation necessarily leads to conservative mass transfer. The fraction of the transferred mass that is accreted by the companion is often denoted by the symbol β, i.e. $\beta = -\Delta M_2/\Delta M_1$; completely conservative evolution then corresponds to $\beta = 1$. The value of β crucially depends on the response of the secondary star to accretion, which can result in both expansion and spin-up of the secondary.

2.1. Expansion of the Secondary and Formation of Contact Binaries

During the first mass-transfer phase, the thermal timescale of the secondary is longer than that of the donor, so that the accretor will be brought out of thermal equilibrium. This makes it brighter than the main-sequence luminosity appropriate for its mass, and for sufficiently high accretion rates, also causes substantial expansion of the star over its main-sequence radius. Hence, the secondary may fill its own Roche lobe and a contact binary can be formed.

A number of studies have investigated for which binary parameters the secondary can evolve into contact (Pols 1994; Nelson & Eggleton 2001, Wellstein et al. 2001). In these binary evolution calculations the rotation of the secondary was neglected (however, see Sect. 2.2). The results indicate that contact arises in three different circumstances:

1. During rapid (thermal timescale) RLOF, either in case A or early case B. This occurs for $q_0 < q_{\rm cr}$, where $q_{\rm cr}$ is in the range $0.5 - 1$ depending on primary mass. In this case the thermal timescale of the accretor is much longer than the accretion timescale, so that it swells up quickly and fills its Roche lobe after accreting only a small amount of mass.

2. During the late phase of RLOF in case B for fairly long periods, when $\dot{M}$ accelerates as the envelope of the donor becomes partly convective. In this case, a contact binary is formed after substantial mass accretion has already taken place.

3. During the slow (nuclear timescale) phase RLOF in case A after the mass ratio is reversed. For very short $P_{\rm orb}$ the nuclear evolution of the secondary can then overtake that of the primary. The ensuing contact stage may be quite long-lived given that massive contact binaries are not uncommon, but the evolution of such systems is not well understood.

Based on the above, regions in parameter space (q_0 and P_0) where contact is avoided can be identified, and examples can be found in the papers cited above.

Neglecting other effects, one might expect conservative mass transfer in those systems that avoid contact altogether, and up to the point where contact is reached in the other cases. However, the further evolution of contact binaries is highly uncertain, and how much mass and angular momentum these systems lose are still open questions. It seems likely that a case-A contact binary must eventually merge to a single star, while in a case-B situation the contact binary may quickly evolve into a common-envelope configuration (Sect. 3).

2.2. Spin-up of the Secondary and the Angular Momentum Problem

The above considerations are for the implicit assumption that the Roche model applies, i.e. that the secondary star remains in synchronous rotation with the orbit. However, the matter that is transferred also carries a significant amount

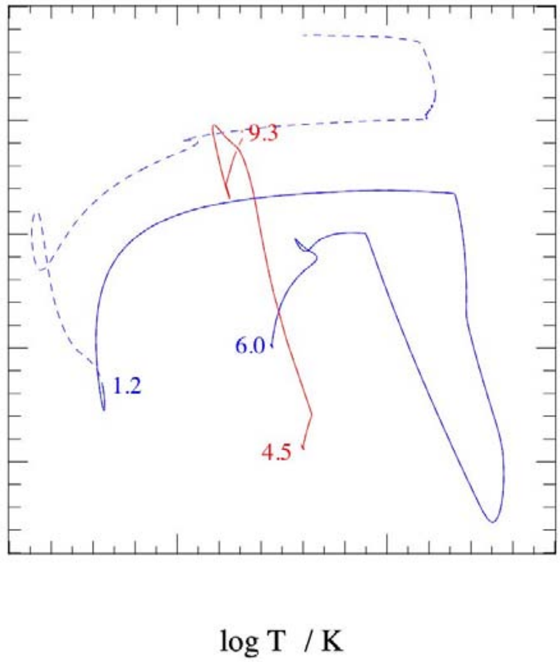

Figure 1. Binary evolution model for ϕ Per, starting with $6.0\,M_\odot$ and $4.5\,M_\odot$ in a 8.0-day circular orbit. The currently observed parameters of ϕ Per are reached at the end of the solid portions of the tracks, after case B mass transfer. The dashed lines indicate the expected future evolution.

of angular momentum, particularly if the orbit is not very tight and the transfer stream forms an accretion disc around the secondary. This can bring the secondary to break-up rotation after accreting only about 10 % of its original mass (Packet 1981; see also Dewi in these proceedings). The secondary then has to get rid of some, or most, of its angular momentum before further accretion can take place. Hence this 'angular momentum catastrophe' potentially limits the amount of accretion much more than the effect of expansion discussed above. Tidal interaction with the companion can transfer spin angular momentum back into the orbit, thus preventing critical rotation, but only in very close binaries with periods less than a few days. Langer et al. (2003; see also Petrovic in these proceedings) have explored another way by which the accreting star might deal with this situation. They consider that the (normally weak) stellar wind may be enhanced enormously when the star is rotating very close to critical; this enhanced wind takes away the excess angular momentum but also leads to very low β values unless the orbital period is very short.

In spite of these theoretical considerations, it appears that close-to-conservative mass transfer *does* occur in practice even in systems that are too wide for tidal interaction to be important, and of too low mass for stellar winds to be significant. A case in point is the Be-star binary ϕ Per.

2.3. The Case of ϕ Persei

ϕ Persei is a binary with $P_{\mathrm{orb}} = 127\,\mathrm{d}$ consisting of a B1e main-sequence star and a He emission-line object, presumably a naked He-burning star. The masses have been determined to be 9.3 and 1.15 $M_\odot$, respectively (Gies et al. 1998). It is one of very few examples of a binary system observed at an intermediate stage of evolution, between the first phase of mass transfer and the formation of a compact object. The He star is the core of the original primary, and transfer of (part of) the envelope mass to the secondary was probably responsible for producing the rapidly rotating Be star. If the component masses had been a factor ~ 2 higher, ϕ Per would have been the perfect progenitor system of a Be/X-ray binary.

The current binary parameters allow us to put constraints on the value of β during the mass-transfer phase that formed the system. Assuming case B evolution (which is reasonable given the current $P_{\rm orb}$) the initial primary mass is a simple function of the current He-star mass; models with a moderate amount of overshooting yield $M_{1,i} \approx 6\,M_\odot$. This implies that the secondary (the current Be star) started out with $< 6\,M_\odot$, hence it accreted at least $4.3\,M_\odot$ which implies a value of $\beta > 0.7$. A completely conservative ($\beta = 1$) case B model is quite feasible (see Fig. 1); it starts with ZAMS masses $6.0 + 4.5\,M_\odot$ and $P_{\rm orb} = 8\,$d. This yields the currently observed binary parameters ($1.2 + 9.3\,M_\odot$, $P_{\rm orb} = 120\,$d) after $\sim 70\,$Myr of evolution. A contact phase is easily avoided. Apparently, accretion was effective in producing a rapidly spinning star, but the rapid rotation did not prevent the star from accreting most of the transferred envelope.

3. Common-Envelope Evolution

The term common envelope (CE) is usually reserved for the situation where a binary is deeply embedded in a relatively tenuous, and probably differentially rotating, envelope — which distinguishes this case from contact binaries as discussed above. Two kinds of instability can give rise to the formation of a CE: (1) dynamically unstable RLOF, triggered either by the donor having a convective envelope (in binaries with sufficiently long periods, undergoing late case B or case C mass transfer), or after initially stable RLOF turns dynamically unstable due to the flattening of the entropy gradient in the mass-losing star (delayed dynamical instability, occurring for mass ratios $q_0 \lesssim 0.25$; Hjellming 1989); (2) a tidal instability, which can occur for extreme mass ratios if the angular momentum of the donor is larger than $\frac{1}{3}$ of the orbital angular momentum (the Darwin instability).

Common-envelope evolution can give rise to extreme forms of mass and angular momentum loss from a binary. The standard picture is that frictional drag leads to a strong spiral-in of the two cores, and a common way of estimating the outcome of CE evolution is to compare the loss of orbital energy in the spiral-in process with the energy necessary to unbind the envelope. Such estimates lead to a reduction of the orbital period by a factor $\gtrsim 100$, which is just what is needed to explain the orbital properties of compact-object binaries such as cataclysmic variables, low-mass X-ray binaries, and double neutron stars.

However, there are several examples of binaries which have apparently ejected most of the transferred mass, like in CE evolution, but where this has not led to a strong spiral-in but only to mild angular-momentum loss. I will discuss the two most striking examples.

- υ Sgr contains a hydrogen-deficient A supergiant and an unclassified companion (probably a MS star) in a 138 d orbit. The mass ratio ($M_{\rm A}/M_{\rm MS}$) is 0.63, and the minimum masses are $2.5 + 4.0\,M_\odot$ (Dudley & Jeffery 1990). Adopting these as the actual masses (i.e. supposing the inclination is not far from 90°), then the initial mass of the primary was $M_{1,i} \approx 10\,M_\odot$ if the system formed by case-B mass transfer. The large current mass ratio is indicative of non-conservative evolution. Considering the current total mass and the minimum initial binary mass, we can infer $\beta < 0.5$. If we suppose the system to have avoided dynamically unstable mass transfer, the initial secondary must have been at least $\sim 2.5\,M_\odot$ and we infer $\beta < 0.2$. However, the current orbital period indicates that only a modest amount of angular momentum was lost: $\Delta J/J \lesssim 2\Delta M/M_{\rm bin}$.

- V379 Cep is an even more remarkable binary consisting of two B2III stars in a 100 d orbit with eccentricity $e = 0.15$. The masses are known accurately due to the binary's double-lined eclipsing nature: $1.9 + 2.9\,M_\odot$ (Gordon et al. 1998), i.e. both stars are strongly *undermassive* for their spectral types (which imply $\sim 10\,M_\odot$ for MS stars). This suggests they are both the stripped cores of more massive stars, probably in the He-burning stage. For both stars to be in this advanced phase requires $q_0 > 0.9$ and two phases of mass transfer. It is quite a conundrum to explain what kind of evolution produces this binary. Eggleton (2002) discusses an evolutionary scenario which starts with a $7 + 6.3\,M_\odot$ binary with $P \approx 3$ d that evolves into a $1.1 + 12.2\,M_\odot$ binary with $P \approx 100$ d after case A mass transfer. Subsequently the $12\,M_\odot$ star transfers mass back in a highly non-conservative way ($\beta \approx 0.1$), without however shedding much angular momentum so that the orbital period stays at 100 d, leaving the $2.9\,M_\odot$ core as a remnant. The non-zero eccentricity implies that the envelope was ejected on a short timescale. Eggleton speculates that the combination of being near the Humphreys-Davidson limit and/or the Cepheid instability strip in the H-R diagram, while at the same time filling the Roche lobe, might induce such envelope ejection. Questions that remain to be answered are whether the components are really ordinary B stars, and whether expected nitrogen and helium enhancements can be observed.

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Discussion

Norbert Langer: Onno, I think it's a very interesting suggestion to use ϕ Per to constrain the mass-transfer accretion efficiency model. I don't see in the current situation a conflict, though, for two reasons. One is that the models we've done so far are concerned with more massive stars. So we haven't gone down to that kind of low mass. And our model involves very strong winds due to the spin-up, so radiation should be high. If we go to lower masses, this would break down at one point - and we still have to find out when. The other point is that you first said it's a wide 127-day binary, but in *your* model you start out with a very close binary, 8 days. I think if we ignore the mass dependence and use our mass-transfer efficiency model for an 8d binary, with this initial mass ratio we would probably also predict something like 70% mass-transfer accretion efficiency.

Onno Pols: Yes, well I would like to see that, because I doubt that it would work. When starting with a period of 8 days, tidal interaction is not that strong.

Norbert Langer: Tides are a minor factor in this. Tides are not exceptional.

Onno Pols: But isn't it the tides that keep the star from rotating near break-up?

Norbert Langer: No, it's the mass-loss.

Onno Pols: But this system does not lose much mass.

Philipp Podsiadlowski: In V379 Cephei you were quoting an eccentricity of 0.15. Is that *real* and if so, how do you explain that?

Onno Pols: That's a good point. The radial-velocity curve shows it quite clearly, so it's probably a real eccentricity. In a common-envelope model, that is indeed hard to explain. It indicates that either the mass-transfer occurred very rapidly, or erratically, so that the loss of the envelope occurred during the second mass-transfer phase. Alternatively, it might be that the mass that was ejected in the common envelope sort of hung around the system for a while, forming a circumbinary ring or disk, which also can extract angular momentum from the system and increase the eccentricity. Of course, you don't want it to extract too much angular momentum, but it is a process that can increase the eccentricity.