

Interacting binaries on the Main Sequence as in-situ tracers of mass transfer efficiency and stability

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ABSTRACT

Understanding the transfer of mass and angular momentum in binary interactions is crucial for modelling the evolution of any interacting binary after the first mass transfer phase. Our assumptions on mass transfer physics shape the predictions for later stages of binary evolution, such as the immediate progenitors of stripped-envelope supernovae and gravitational wave mergers. We constrain the efficiency and stability of thermal timescale mass transfer in massive binary evolution using the observed population of massive interacting binaries on the Main Sequence (‘Algols’) in the Milky Way, Large and Small Magellanic Clouds. Assuming the present-day mass of the donor star represents its initial convective core mass at Zero-Age Main Sequence, we estimate its initial mass using detailed stellar evolution models. From the initial donor mass, we calculate the range of initial accretor masses (for different mass transfer efficiencies). By imposing physical constraints on the above initial parameter ranges, we derive the mass transfer efficiency, stability and angular momentum loss that can reproduce the current properties of each Algol binary. We find that purely conservative or non-conservative mass transfer cannot explain the current mass ratio and orbital period of all massive Algols. Angular momentum conservation rules out conservative mass transfer in $\sim 28\%$ of massive Algols in the SMC. About three-quarters of all massive Algols are consistent with having undergone inefficient mass transfer ($\leq 50\%$), while the remaining systems, mostly residing in the LMC and Milky Way, require mass transfer to have been more efficient than 25% . For our fiducial assumption on the extent of envelope stripping, the current sample of massive Algols does not require mass transfer to be efficient at the shortest orbital periods (2 d) at any metallicity. We find evidence that mass transfer on the Main Sequence needs to be stable for initial accretor-to-donor mass ratios as unequal as ~ 0.6 . Unless biased by observational selection effects, the massive Algols in the SMC seem to have undergone less efficient mass transfer than those in the LMC and Milky Way.

Keywords: stars: massive — binaries: close — stars: evolution — binaries: eclipsing — stars: interiors

1. INTRODUCTION

Massive stars are rarely found alone (D. Vanbeveren et al. 1998b; H. A. Kobulnicky & C. L. Fryer 2007; B. D. Mason et al. 2009; H. Sana et al. 2012; M. Moe & R. Di Stefano 2017; S. S. R. Offner et al. 2023). Surveys of O- and B-type stars have established that a majority reside in multiples (H. A. Abt et al. 1990; D. C. Kiminki et al. 2008; L. Mahy et al. 2009, 2013; R. Chini et al. 2012; H. A. Kobulnicky

et al. 2012; H. A. Kobulnicky et al. 2014; A. Sota et al. 2014; P. R. Dunstall et al. 2015; H. Sana et al. 2008, 2009, 2011; H. Sana et al. 2013, 2014; R. H. Barbá et al. 2017; L. A. Almeida et al. 2017; E. Trigueros Páez et al. 2021; J. I. Villaseñor et al. 2021, 2025; T. Shenar et al. 2022, 2024; G. Banyard et al. 2022; B. W. Ritchie et al. 2022; M. Ramírez-Tannus et al. 2024). Most of them are so close that interactions through tides (J. P. Zahn 1977; P. Goldreich & P. D. Nicholson 1989; P. Marchant et al. 2016; I. Mandel & S. E. de Mink 2016; S. E. de Mink & I. Mandel 2016; M. Sun et al. 2023; S. Rosu 2024; K. A. Rocha et al. 2025; K. Sen et al. 2025), colliding

winds (G. Rauw & Y. Nazé 2016; A. Kashi 2020; A. Kashi et al. 2022; Y. Nazé et al. 2022), Roche-lobe overflow (B. Paczyński 1971; P. Podsiadlowski et al. 1992; D. Vanbeveren et al. 1998a; N. Langer et al. 2003), and/or mergers (P. Podsiadlowski et al. 2006; F. R. N. Schneider et al. 2019; S. Wu et al. 2020; A. Menon et al. 2024; R. A. Patton et al. 2025) are inevitable. These interactions profoundly shape the evolutionary pathways of massive stars (S. E. de Mink et al. 2014; K. Sen et al. 2023), their feedback on the surrounding medium (J. J. Eldridge et al. 2008; E. R. Stanway et al. 2016; Y. Göteborg et al. 2017), and their ultimate fates as progenitors of stripped-envelope supernovae (SESNe, S. C. Yoon et al. 2010; E. Zapartas et al. 2017; N. Sravan et al. 2020; E. Laplace et al. 2020, 2021; D. R. Aguilera-Dena et al. 2022, 2023; A. Ercolino et al. 2024; A. Ercolino et al. 2025) and compact object binaries that may later merge as gravitational-wave (GW) sources (K. Belczynski et al. 2008; J. J. Eldridge & E. R. Stanway 2016; M. U. Kruckow et al. 2018; M. Spera et al. 2019; F. S. Broekgaarden et al. 2022; L. A. C. van Son et al. 2022; J. Riley et al. 2022; M. M. Briel et al. 2023). Understanding the physical processes at play in these systems is therefore essential not only for stellar astrophysics (P. Marchant & J. Bodensteiner 2024) but also for cosmology (P. F. Hopkins et al. 2014) and predicting the rates and properties of transient populations across the Universe (N. Smith et al. 2011; I. Mandel & F. S. Broekgaarden 2022).

However, the treatment of mass transfer and angular momentum loss in massive binaries remains one of the most significant sources of uncertainty in stellar evolution theory (M. S. Hjellming & R. F. Webbink 1987; G. E. Soberman et al. 1997; T. E. Woods & N. Ivanova 2011; K. Pavlovskii et al. 2017; H. Ge et al. 2010, 2015, 2020; K. Temmink et al. 2023; C. Schürmann & N. Langer 2024). Whether the mass transfer is highly efficient or largely inefficient (C. A. Nelson & P. P. Eggleton 2001; J. Petrovic et al. 2005; S. E. de Mink et al. 2007; Y. Shao & X.-D. Li 2016; S. Vinciguerra et al. 2020; Y. Bouffanais et al. 2021; K. Sen et al. 2022; I. Romero-Shaw et al. 2023; M. Nuijten & G. Nelemans 2025; T. Lechien et al. 2025; C. Schürmann et al. 2025), and how the lost mass carries away angular momentum (M. MacLeod et al. 2018a,b; W. Lu et al. 2023), dramatically alters the orbital period and mass-ratio evolution of binaries (J. J. Eldridge et al. 2011; M. Renzo et al. 2019; R. Willcox et al. 2023; T. Wagg et al. 2025). Population synthesis studies demonstrate that these choices can alter the diversity and rates of SESNe and GW mergers respectively (J. J. Eldridge et al. 2013; P. Agrawal et al. 2022, 2023; K. Belczynski et al. 2022; A. P. Boesky et al. 2024; L. Rauf et al. 2024; E. Zapartas et al. 2025; D. Souropanis et al. 2025), while also reshaping the predicted orbital period distribution of compact object binaries, and masses and spin magnitudes of compact objects (K. Belczynski et al. 2020; A. Olejak et al.

2021, 2024; T. M. Tauris 2022; M. Y. M. Lau et al. 2024; A. Dorozsmai & S. Toonen 2024; H. C. G. Larsen et al. 2025). Quantitatively constraining these processes is thus critical for linking present-day massive binaries with their end states (e.g. I. Mandel 2025). Without empirical constraints on early stages of binary evolution, parameter uncertainties and degeneracies in the predicted population of SESNe or GW mergers may not be resolved simply by an increase in their observed number in the coming decades.

An empirical approach is to study Algol-type binaries (L. P. Surkova & M. A. Svechnikov 2004; S. E. de Mink et al. 2007; N. Mennekens & D. Vanbeveren 2017; O. Y. Malkov 2020; K. Sen et al. 2022), which are interacting systems where mass transfer occurs while both stars are still on the Main Sequence (‘Case A’, R. Kippenhahn & A. Weigert 1967; O. R. Pols 1994; C. A. Nelson & P. P. Eggleton 2001). These systems are especially valuable because they represent the earliest phase of mass transfer, prior to the additional complexities introduced by envelope expansion (A. Romagnolo et al. 2023), strong winds (N. Smith 2014; M. Renzo et al. 2017; J. Josiek et al. 2024), or advanced nuclear burning (A. Heger et al. 2002; R. Farmer et al. 2016; A. Grichener et al. 2025). As such, they require the fewest assumptions regarding prior binary evolution, offering a relatively clean probe of the efficiency and stability of thermal-timescale mass transfer.

In Case A binaries, mass transfer begins on the donor’s thermal timescale (fast Case A) and transitions into a slower, nuclear-timescale phase as the donor expands during core hydrogen burning. This long-lived ‘slow Case A’ stage, which spans millions of years, yields observable semi-detached systems. Since all such binaries must have previously undergone an intense, fast Case A episode, comparing models with observed Algols constrains both phases. Moreover, Case A is especially relevant at high masses, where it is more common (S. E. de Mink et al. 2007; K. Sen et al. 2023; C. A. Burt et al. 2025), making massive Algols bright, numerous, and ideal testbeds for mass transfer physics. The demographics of observed Algols across different metallicities—Milky Way, Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC)—therefore provide a powerful benchmark against which theoretical models can be tested (S. E. de Mink et al. 2007; K. Sen et al. 2022).

In this work, we study the mass transfer efficiency, angular momentum loss, and stability of mass transfer in the observed populations of massive Algols in the Milky Way, LMC and SMC, and investigate any metallicity difference. We develop an analytical framework that links current observable binary properties—orbital period, donor mass, and accretor mass—to their initial parameters. By imposing physically motivated boundaries on the initial parameters, we derive constraints on the range of mass transfer efficiency

and angular momentum loss during the mass transfer episode that can reproduce the observed population. We also determine limits on the stability of mass transfer required to obtain meaningful solutions for mass transfer efficiency.

This paper is organised as follows. Section 2 describes the observational sample and our methodology for deriving initial binary parameters. Section 3 presents the range of mass transfer efficiency and angular momentum loss possible, for individual systems to overall trends across the Algol population. In Sect. 4, we compare our results with the literature and evaluate the robustness of our assumptions. We summarise our main conclusions in Sect. 5.

2. METHODS

2.1. Observed systems

In this study, we include all the massive Algol binaries observed in the Magellanic Clouds and the Milky Way. In the SMC, we use the catalogue in S. E. de Mink et al. (2007, Table 1, 29 systems) curated from the observational studies of the T. J. Harries et al. (2003) and R. W. Hilditch et al. (2005). We take the massive Algols listed in Table 1 and Table 2 of K. Sen et al. (2022, 33 systems) in the LMC and the Milky Way, respectively (heterogeneous sample, see references within for details on individual systems). We list the current masses of the donors M_d , accretors M_a and binary orbital periods P_{orb} used in this study for all the systems in Table 1 and Table 2.

The binaries span an accretor mass range of $\sim 8\text{--}40 M_\odot$, accretor-to-donor mass ratios $q = M_a/M_d$ from near unity up to ~ 3 , and orbital periods between ~ 1 and 10 d (the observed systems in the SMC are limited by a maximum orbital period of 5 d, T. J. Harries et al. 2003; R. W. Hilditch et al. 2005). Circular orbits were assumed for most systems. This sample of short-period, massive binaries thus enables a systematic comparison with grids of binary evolution tracks to probe the efficiency of Case A mass transfer across a large range of metallicities (near Solar to $\sim$ one-fifth of Solar).

2.2. Initial stellar and binary parameters

Detailed binary evolution models predict that the fast thermal timescale mass transfer on the Main Sequence strips the outer envelope of the mass-donating star approximately up to its initial convective core at Zero-Age Main Sequence (Fig. 2 of C. Schürmann et al. 2024, see also Fig. 1 of K. Sen et al. 2023). We assume that the present masses of the donors in the massive Algols correspond to their initial convective core masses that include the overshooting region (we discuss the caveats in this assumption in Sect. 4.2). Therefore, the initial mass of the donor star can be estimated from its initial convective core mass $M_{\text{ccd},i}$. At the range of donor masses relevant for our study ($2\text{--}20 M_\odot$), the slow nuclear timescale mass transfer (the ‘Algol’ phase) removes $\leq 1 M_\odot$ mass from

the donor (O. R. Pols 1994; S. E. de Mink et al. 2007; K. Sen et al. 2022). Using grids of detailed binary evolution models (Sect. 2.4), we estimate the initial donor mass $M_{d,i}$ of each massive Algol binary (listed in Table 1) and Table 2.

For each value of initial donor mass, there exists a maximum initial orbital period $P_{\text{orb},i,\text{max}}$ up to which mass transfer can initiate on the Main Sequence (C. A. Nelson & P. P. Eggleton 2001; S. E. de Mink et al. 2007; K. Sen et al. 2022; D. Pauli et al. 2022). This maximum initial orbital period is weakly dependent on the initial mass ratio of the binary, but sensitive to stellar radii and the physics that determines them (opacity primarily, and at second order mass loss and inflation, e.g., D. Sanyal et al. 2015; C. Xin et al. 2022). For each massive Algol, we estimate the maximum initial orbital period $P_{\text{orb},i,\text{max}}$ that the binary could have started with, using the binary models described in Sect. 2.4 (listed in Table 1) and Table 2.

The difference between the initial donor mass and the current donor mass in each Algol donor gives the mass lost by the donor ΔM_d and is equal to the maximum amount of mass that the mass accreting star could have accreted during the fast thermal timescale mass transfer phase. Subtracting the above difference from the present mass of the accretor gives the lowest initial mass of the accretor $M_{a,i,\text{min}}$ at its Zero-Age Main Sequence, if the accretor could accrete all the transferred mass (conservative mass-transfer limit). Here, we limit the lowest possible initial accretor mass to be $0.08 M_\odot$, required to initiate core hydrogen burning in its core.

If the accretor does not accrete any of the mass lost by the donor, the initial mass of the accretor is equal to its observed current mass (assuming negligible mass lost via stellar winds on the Main Sequence). Here, the maximum initial accretor mass $M_{a,i,\text{max}}$ is limited to the initial donor mass estimated above, so as not to invert the direction of mass transfer at its initiation. The above procedure gives a range of possible initial accretor masses for each system analysed in this study (Table 1 and Table 2).

2.3. Mass transfer efficiency and specific angular momentum loss

We define the mass transfer efficiency ε as the ratio of the mass accreted by the accretor to the mass lost by the donor. In terms of initial and current masses,

$$\varepsilon = -\frac{\Delta M_a}{\Delta M_d} = \frac{M_a - M_{a,i}}{M_{d,i} - M_d}, \quad (1)$$

where $M_{a,i} \in [M_{a,i,\text{max}}, M_{a,i,\text{min}}]$ is the initial mass of the accretor. For the corresponding range of initial accretor masses $[M_{a,i,\text{max}}, M_{a,i,\text{min}}]$, we calculate the range of possible mass transfer efficiencies for each system $[\varepsilon_{\text{min}}, \varepsilon_{\text{max}}]$.

Equation (1) can be written in terms of the total mass $M_T = M_a + M_d$ and mass ratio $q = M_a/M_d$ of the binary system

as (G. E. Soberman et al. 1997; M. Nuijten & G. Nelemans 2025)

$$\varepsilon = \left(\frac{1+q}{1+q_i} - \frac{M_T}{M_{T,i}} \right) \left(q \frac{M_T}{M_{T,i}} - q_i \frac{1+q}{1+q_i} \right)^{-1}, \quad (2)$$

where $M_{T,i} = M_{a,i} + M_{d,i}$ and $q_i = M_{a,i}/M_{d,i}$ are the initial total mass and initial mass ratio of the binary, respectively.

For conservative mass transfer $\varepsilon = 1$, there is no angular momentum lost from the binary (neglecting stellar winds; moreover, winds tap into the spin angular momentum of the stars, which is much smaller than the orbital angular momentum), and the initial orbital period $P_{\text{ini,cons}}$ is given by (e.g. T. M. Tauris & E. P. J. van den Heuvel 2023)

$$\ln \left(\frac{P_{\text{orb,i,cons}}}{P_{\text{orb}}} \right) = 3 \ln \left(\frac{M_d M_a}{M_{d,i} M_{a,i}} \right). \quad (3)$$

For each possible value of mass transfer efficiency $\varepsilon \in [\varepsilon_{\text{min}}, \varepsilon_{\text{max}}] \neq 1$, a range of initial orbital periods can lead to the present orbital period, depending on the assumed angular momentum lost ΔJ per unit mass lost ΔM from the binary

$$j_{\text{loss}} = \frac{\Delta J}{\Delta M} = \gamma \frac{J_{\text{orb}}}{M_T} = \gamma j_{\text{orb}}, \quad (4)$$

where $\gamma (> 0)$ is a multiplicative factor to capture different modes of mass loss (O. R. Pols & M. Marinus 1994), J_{orb} is the total orbital angular momentum of the binary, j_{orb} is the specific orbital angular momentum of the binary and j_{loss} is the specific angular momentum lost from the binary.

In reality, γ depend on how the mass flows away from the binary (e.g. G. E. Soberman et al. 1997; W. Lu et al. 2023), and thus could vary as the stars evolve through mass transfer. As a first approximation, we consider γ as constant to relate analytically the initial and present-day period. The initial orbital period $P_{\text{orb,i}}$ can be related to the orbital period and masses of the binary components (see Eq. (A2) of O. R. Pols & M. Marinus 1994)

$$\ln \left(\frac{P_{\text{orb,i}}}{P_{\text{orb}}} \right) = 3 \ln \left(\frac{M_d M_a}{M_{d,i} M_{a,i}} \right) + \left(3\gamma + \frac{3}{2} \right) \ln \left(\frac{M_{T,i}}{M_T} \right). \quad (5)$$

We calculate the initial orbital period values for $\gamma = 0, 1, 2, 3$. Values of $\gamma > 3$ are expected to be unlikely (see discussion in Sect. 2.4 of M. Nuijten & G. Nelemans 2025). Magnetic braking (D. A. Bour et al. 2025) or L2 mass loss (W. Lu et al. 2023) can lead to high values of γ , but most massive stars are not found to host detectable dipolar magnetic fields (G. A. Wade et al. 2016). The strong differential rotation during the accretion phase, however, may generate magnetic fields (J. Braithwaite & H. C. Spruit 2017). For isotropic re-emission from the surface of the accretor, $\gamma = M_d/M_a$. We discuss the possibility of $\gamma > 3$ in Sect. 4. The initial orbital period $P_{\text{orb,i}}$ is limited by the maximum initial orbital period $P_{\text{orb,i,max}}$ up

to which mass transfer can initiate on the Main Sequence. The initial orbital period (for ε constant over time, Eq. (A4-A5) of O. R. Pols & M. Marinus 1994) is given by

$$\ln \left(\frac{P_{\text{orb,i}}}{P_{\text{orb}}} \right) = 3 \ln \left(\frac{M_d}{M_{d,i}} \right) + \frac{3}{\varepsilon} \ln \left(\frac{M_a}{M_{a,i}} \right) + \frac{3}{2} \ln \left(\frac{M_T}{M_{T,i}} \right), \text{ for } 0 < \varepsilon \leq 1 \quad (6)$$

and

$$\ln \left(\frac{P_{\text{orb,i}}}{P_{\text{orb}}} \right) = 3 \ln \left(\frac{M_d}{M_{d,i}} \right) + \frac{3}{2} \ln \left(\frac{M_T}{M_{T,i}} \right) + 3 \frac{M_{d,i} - M_d}{M_a}, \text{ for } \varepsilon = 0. \quad (7)$$

2.4. Detailed binary evolution models

We calculate the cumulative mass transfer efficiency in detailed binary evolution models introduced in C. Wang et al. (2020, for the SMC) and K. Sen et al. (2022, for the LMC). At any timestep during the evolution of the binary, the cumulative mass transfer efficiency of the model is defined as in Eq. (1), where M_d and M_a denote the mass of the donor and accretor at that timestep, and $M_{d,i}$ and $M_{a,i}$ denote their initial masses at the Zero-Age Main Sequence. The contribution from each model is weighted by the initial mass function (E. E. Salpeter 1955), the orbital period and mass ratio distribution (H. Sana et al. 2012, 2013), and the timestep during the Algol configuration (see Eq. (4) of K. Sen et al. 2022).

While the detailed binary models include wind mass loss, we do not remove the contribution from the wind mass loss in calculating the mass transfer efficiency in the models. We discuss the effects of ignoring wind mass loss on our conclusions in Sect. 4.4. From our synthetic Algol population, we removed timesteps where mass transfer occurs from the initially less massive accretor to the donor, that is, when inverse mass transfer occurs. We also remove the timesteps where both binary components fill its Roche lobe (contact configuration, A. Menon et al. 2021; M. Fabry et al. 2022, 2023; J. Henneco et al. 2024; J. Vrancken et al. 2024)

The stellar and binary physics assumptions in the models are described in detail in C. Wang et al. (2020); K. Sen et al. (2022). During a mass transfer phase, mass accretion onto the accretor is limited by the spin of the accretor star. Critically rotating accretors are assumed not to be able to accrete any more mass (N. Langer 1998). The excess mass transferred is lost as winds from the accretor, carrying the specific orbital angular momentum of the accretor (N. Langer et al. 2003; J. Petrovic et al. 2005). Mass transfer is assumed to be stable as long as the excess mass lost can be driven by the combined luminosity of both the binary components (see Eq. (2) of K. Sen et al. 2022). Strong tides (J. P. Zahn 1977, implemented as in R. G. Detmers et al. 2008) in short-period (≤ 5 d) systems can halt the accretor spin-up and lead to efficient mass accretion; longer period systems undergo inefficient mass transfer (K. Sen et al. 2022). This leads to an orbital period-dependent mass transfer efficiency in the models.

When the combined luminosity of both stars is insufficient to drive the required excess mass loss, the binary is assumed to merge.

2.5. Mass transfer stability

Mass transfer on the Main Sequence is not stable down to arbitrarily low values of initial mass ratios, owing to the increasingly divergent thermal timescales of the donor and the accretor (H. Ge et al. 2020). The mass transfer rate is typically set by the evolutionary timescale of the donor star (thermal initially and later nuclear), while the accretor can readjust its structure on its longer thermal timescale as compared to the donor. As such, most binaries with initial mass ratios > 0.65 may merge during the thermal timescale mass transfer on the Main Sequence (S. E. de Mink et al. 2013; H. Ge et al. 2020).

In the models of K. Sen et al. (2022, Fig. 1, green models), there exist two threshold values of initial mass ratios, such that 1) above the higher value $q_{\max}$ (bottom left of green region above the black shaded region), all binary models survive the thermal timescale mass transfer; 2) below the lower value $q_{\min}$ (top left of green region below the Case A boundary) of the initial mass ratio, all binary models are predicted to merge. The value of $q_{\max}$ and $q_{\min}$ are a function of the initial donor mass of the binary (K. Sen et al. 2023, Fig. 1). Between the two thresholds, the fate of the binary depends on its initial orbital period. Below the mass ratio $q_{\max}$, all the accretors spin up to critical rotation soon after the onset of thermal timescale mass transfer (W. Packet 1981), and the mass transfer efficiency in such models is less than 10% (top panels of Fig. F2 of K. Sen et al. 2022).

As a conservative estimate and for the sake of simplicity, we assume that all binaries may undergo arbitrarily efficient stable mass transfer up to an initial mass ratio given by $q_{\max}$ in the rotationally limited mass accretion scheme. Below $q_{\max}$, a higher mass transfer efficiency may be supported by the formation of a disk, where the coupling of the disk to the accretor can aid the accretion of mass while removing angular momentum from the accretor (B. Paczynski 1991; R. Popham & R. Narayan 1991). C. Schürmann & N. Langer (2024) investigate the response of non-rotating accretor stars for constant mass transfer efficiencies. We parametrise their results for the onset of L2 overflow, as a function of the initial donor mass and mass transfer efficiencies, to derive the minimum mass ratio for stable mass transfer in the presence of a disk (Fig. 8 of C. Schürmann & N. Langer 2024).

Table 3 lists the values of $M_{\text{ccd},i}$, $q_{\min}$, $q_{\max}$ and $P_{\text{orb},i,\max}$ for different values of initial donor mass in the LMC and SMC. We linearly interpolate between the values and assume that the stellar and binary parameters for LMC metallicity are applicable for the Milky Way systems. The difference in values of $M_{\text{ccd},i}$ are within $0.1 M_{\odot}$ between the LMC and SMC for

the same initial donor mass. The values of $q_{\min}$, $q_{\max}$ for the two metallicities are separated by at most 0.05. The maximum initial orbital period $P_{\text{orb},i,\max}$ is a significant function of metallicity, and we discuss in Sect. 3.2 that our conclusions on angular momentum loss are not strongly affected by metallicity.

3. RESULTS

In this section, we evaluate the possible range of mass transfer efficiency ε and angular momentum loss factor γ for each massive Algol binary in Table 1 and Table 2. We describe in detail our analysis for one representative binary (Sect. 3.1), discuss the outliers (Sect. 3.2), and then show the population properties in Sect. 3.3 and derive empirical constraints on mass transfer efficiency during the thermal timescale mass transfer phase on the Main Sequence.

3.1. Example analysis

We describe our analysis in detail for the massive Algol in the Milky Way, LZ Cep (Fig. 1, left panel). The binary has a Roche-lobe filling donor star of mass $6.5 M_{\odot}$ in a 3.07 d orbit with a $16 M_{\odot}$ companion (L. Mahy et al. 2011). For the current donor mass $M_d = 6.5 M_{\odot}$, we find the initial donor mass $M_{d,i} = 13.46 M_{\odot}$ and maximum possible initial orbital period $P_{\text{orb},i,\max}$ of 5.62 d (see Table 3). This implies that the donor has lost $6.96 M_{\odot}$ during the fast Case A mass transfer phase. For the case of conservative mass transfer, the accretor could have accreted all the mass lost by the donor (neglecting wind mass loss), and the minimum initial mass of the accretor could be $9.04 M_{\odot}$. Since the initial mass of the accretor cannot be higher than that of the donor, the maximum initial accretor mass can be $13.46 M_{\odot}$. Hence, the initial mass of the accretor can range between 9.04 – $13.46 M_{\odot}$.

The accretor $M_a = 16 M_{\odot}$ must have accreted at least $2.54 M_{\odot}$ of matter from the donor, up to the maximum of $6.96 M_{\odot}$. So, the mass transfer efficiency for this binary ranges from ~ 0.36 to 1 (Fig. 1, left bottom panel). However, since binaries with low initial mass ratios are not expected to survive an arbitrarily efficient thermal timescale mass transfer on the Main Sequence (grey regions), the higher values of mass transfer efficiency are less likely. The white area in Fig. 1 shows the permitted range of mass transfer efficiency and specific angular momentum loss for LZ Cep. Hence, we expect that the mass transfer efficiency in this system may lie in the range ~ 0.36 – 0.85 (bottom panel), where we exclude the values of ε in the grey regions.

For conservative mass transfer ($\varepsilon = 1$), we can calculate the initial orbital period the binary must have had to reach its current orbital period of 3.07 d (Eq. (3), top left panel of Fig. 1). The upper limit to the initial orbital period is given by the maximum initial orbital period for which mass transfer can occur on the Main Sequence. For LZ Cep, we see that angular momentum conservation allows for conservative mass

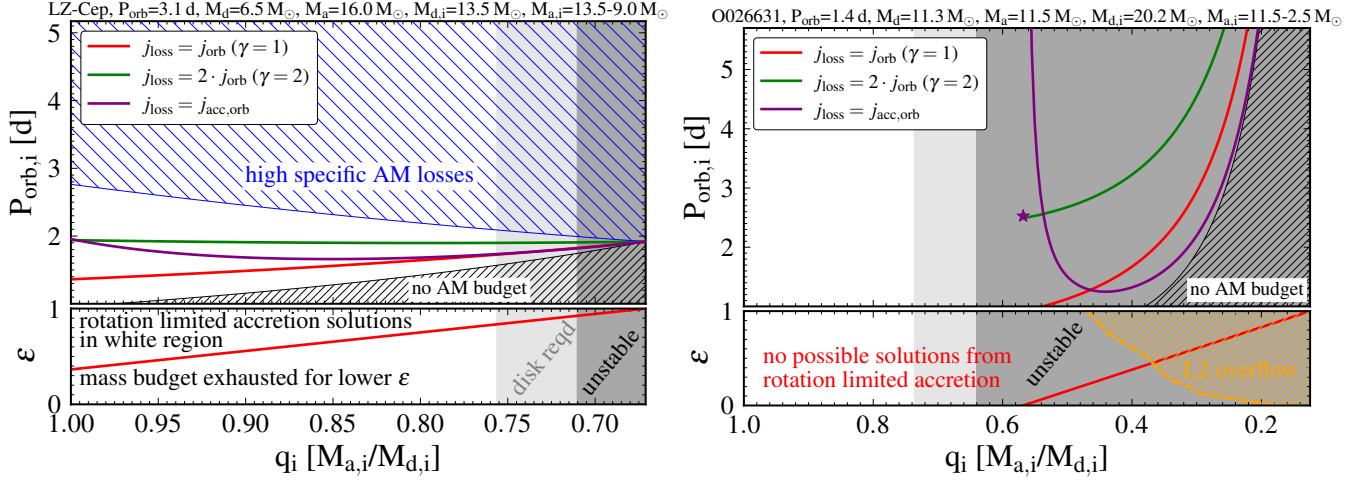


Figure 1. The parameter space of mass transfer efficiency ε (bottom panels) and initial orbital period $P_{orb,i}$ (top panels) as a function of the decreasing initial mass ratio q_i for LZ Cep (left panel, representing a typical case) and O026631 (right panel, representing an outlier system). The white region indicates the most likely values of mass transfer efficiency and specific angular momentum loss from the rotation-limited accretion model. Different colours correspond to curves of $P_{orb,i}$ for alternative assumptions of $\gamma=1$ (red), 2 (green) and M_d/M_a (purple, isotropic remission from the surface of the accretor). In the right panel, the purple star shows the initial orbital period for $\varepsilon = 0$ (Eq. (7)). The black and blue hatched regions correspond to $\gamma \leq 0$ and $\gamma \geq 3$, respectively. The dark grey colour shows the region where all detailed binary evolution models survive the thermal timescale mass transfer to the left of the light grey region (the highest value of q_i in the light grey region is the q_{max} limit). Models in the light grey region merge or survive depending on the binary orbital period; the shortest-period models merge, and vice versa (the lowest value of q_i in this region is the q_{min} limit). The orange dashed line shows the limiting mass transfer efficiency as a function of the initial mass ratio for which non-rotating models of C. Schürmann & N. Langer (2024) undergo L2 overflow. The orange shaded region, therefore, denotes the parameter space where an accretion disk-mediated mass transfer onto the accretor may not be stable. The upper limit to the top panels is given by $P_{orb,i,max}$ calculated for each system.

transfer, although mass transfer stability arguments make it unlikely. For each value of inefficient mass transfer possible for LZ Cep ($0.36 \leq \varepsilon < 1$), we can calculate a range of values of initial orbital period, depending on the assumption of specific angular momentum loss from the binary (Eq. (6), different colored lines in the upper panels of Fig. 1).

We can derive the plausible range of specific angular momentum loss factor γ that can lead to the current orbital period $P_{orb} = 3.07$ d of the binary, for each value of $\varepsilon \neq 1$. The black hatched region is excluded because $\gamma < 0$ implies the binary gains angular momentum on mass loss. We deem the blue shaded region unlikely because the system has to lose a high amount of angular momentum ($\gamma > 3$, M. Nuijten & G. Nelemans 2025). To the left of the grey regions, we find the plausible range of the initial orbital period $P_{orb,i}$, and in turn γ . We set the lower limit to the initial orbital period to 1 d as most binaries having shorter orbital periods are expected to enter into a nuclear timescale contact phase shortly after the onset of mass transfer on the Main Sequence (A. Menon et al. 2021; M. Abdul-Masih et al. 2021, 2022; M. Fabry et al. 2022, 2023; M. J. Rickard & D. Pauli 2023; J. Henneco et al. 2024; J. Vandersnickt & M. Fabry 2025; M. Gull et al. 2025). The allowed range of γ for this system is $\sim 0.5 - 3.0$. We also note that the binary is less likely to have originated from the most extended initial orbital periods due to considerations of angular momentum loss (blue hatched regions have $\gamma > 3$).

3.2. Outliers

The right panel of Fig. 1 shows that the mass transfer stability consideration (exclusion of grey regions) can lead to cases (e.g. O026631 in the SMC) where we find no solutions for mass transfer efficiency or angular momentum loss factor. We see that our assumption on the mass transfer stability has to be relaxed at least to $q_{max} \approx 0.56$ for this system to have a non-conservative solution ($\varepsilon = 0$), and below 0.5 to have increasingly more efficient mass transfer ($\varepsilon > 0$). A similar case in the Milky Way is TT Aur (Fig. 6), where the mass transfer stability criterion needs to be relaxed to at least $q_{min} = 0.68$ at the lowest initial donor mass to have a $\varepsilon = 0$ solution.

Detailed binary evolution models predict that the mass transfer leads to mergers at increasing initial mass ratios for decreasing initial donor masses (Table 3). We find that our analytical approach leads to no or highly inefficient solutions in most of the least massive Algols, both in the Milky Way and the SMC (see the top few rows of Fig. 5 and Fig. 6). The least massive Algols have the strongest constraints from the mass transfer stability criterion ($q_{min} \sim 0.75$). Hence, we conclude that the least massive Algols give evidence that mass transfer must be stable up to $q_{min} \sim 0.6$ at initial donor masses $M_{d,i} \approx 10 - 15 M_{\odot}$. This implies that the difference in stability of mass transfer when using detailed models compared to when using semi-analytic fits from J. R. Hurley et al.

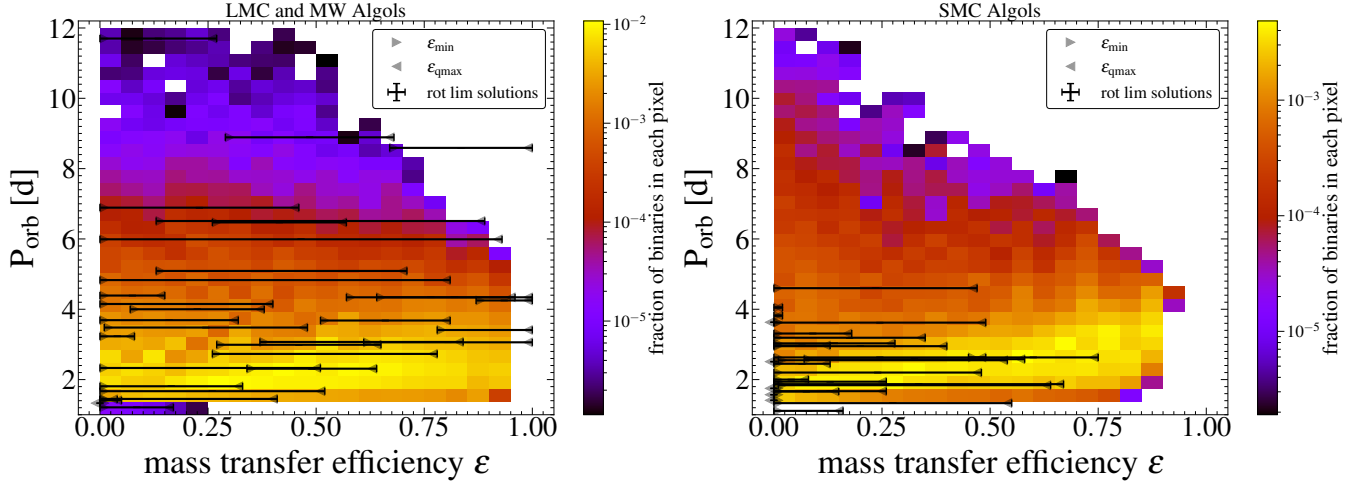


Figure 2. Inferred range of mass transfer efficiency (black lines) as a function of the orbital period of massive Algols in the LMC and Milky Way (left panel) and the SMC (right panel). Triangles indicate the minimum and maximum mass transfer efficiency possible for each system, in the rotationally limited mass accretion scheme. The 2D histogram displays the calculated mass transfer efficiency in detailed binary evolution models that also incorporate the rotationally limited mass accretion prescription (note the log scale on the colour bar). The total probability is normalised such that the integrated sum over the entire area is 1.

(2002) may impact rates of astrophysical events of interest, including neutron star X-ray binaries and binary neutron star mergers (X. T. Xu et al. 2025, see also J. J. Eldridge et al. 2017; P. Agrawal et al. 2023; T. Fragos et al. 2023; A. Chat-taraj et al. 2025).

The allowed range of mass transfer efficiency ε is more strongly constrained from the mass transfer stability criterion than from angular momentum conservation (c.f. grey region vs black hatched area in the right panel of Fig. 1). We also find that high values of γ are forbidden by the maximum limit on initial orbital period for Case A mass transfer (absence of blue hatched regions in the top right panel of Fig. 1). Therefore, the upper limit to the maximum initial orbital period for mass transfer to initiate on the Main Sequence $P_{\text{orb},i,\text{max}}$ plays a less restrictive role in deriving our conclusions on mass transfer efficiency and stability in this system. The above case is similar for the least massive Algols in the Milky Way as well (c.f. first few rows of Fig. 5 and Fig. 6). Hence, even though we assume the same upper limit to initial orbital periods for the LMC and Milky Way binaries, we do not expect that the range of mass transfer efficiency inferred from our analysis will change by increasing $P_{\text{orb},i,\text{max}}$. The allowed range of γ will increase if $P_{\text{orb},i,\text{max}}$ is increased for the Milky Way systems, although the highest values of initial orbital period will remain less likely.

To obtain a non-zero solution to the mass transfer efficiency, our detailed binary models will require a mechanism to remove angular momentum from the accretor while continually accreting mass, in the form of a decretion disk or magnetic braking. The orange dashed line shows the minimum mass ratio as a function of mass transfer efficiency such that non-rotating accretors do not undergo L2 overflow (C.

Schürmann & N. Langer 2024). The intersection of the orange dashed line with the black line represents the maximum mass transfer efficiency that the system could achieve in the presence of a disk to siphon angular momentum out of the accretor. For O026631, the maximum mass transfer efficiency $\varepsilon_{\text{max}}^{\text{disk}} \sim 0.45$. We also note that rotation, however, can reach critical values in the accretor’s outer layers and have a large effect on the radius; therefore, we consider the models of C. Schürmann & N. Langer (2024) conservative in the sense that nature may reach L2 overflow at much higher initial mass ratios than inferred from non-rotating models. Moreover, it has been recently shown that L2 mass loss can occur when the decretion disk itself extends beyond the L2 point, significantly shrinking the orbit and leading to possible merger scenarios well before the non-rotating limit above (W. Lu et al. 2023).

3.3. Population properties

In this section, we derive the possible range of mass transfer efficiencies if each of the observed systems had undergone rotationally limited mass transfer only (Sect. 3.3.1), or for the case of a disk-mediated mass transfer that can siphon angular momentum from the accretor to the orbit while the accretor continually accretes mass (Sect. 3.3.2). We calculate the maximum value of mass transfer efficiency possible in the rotationally limited mass accretion case for each system at q_{max} , and tabulate our results as $\varepsilon_{q_{\text{max}}}$ in Table 1 and Table 2. We also show the minimum and maximum values of the angular momentum loss factor, tabulated as $\gamma_{\text{min},q_{\text{max}}}$ and $\gamma_{\text{max},q_{\text{max}}}$ in Table 1 and Table 2. We also show the maximum value of mass transfer efficiency possible for a disk-supported mass transfer $\varepsilon_{\text{max}}^{\text{disk}}$ in Table 1 and Table 2.

For about $\sim 50\%$ massive Algols in the LMC (e.g. HV 2241, VFTS 652, SC1 105) and Milky Way (e.g. XX Cas, AB Cru), we find that non-conservative mass transfer ($\varepsilon = 0$) is ruled out because the allowed range of initial accretor masses has to be lower than the initial donor mass (mass budget). In these systems, the current accretor masses are higher than the calculated initial donor masses, such that the accretors must have accreted mass from the donor to reach the current configuration. However, only two out of 29 systems in the SMC necessarily require such non-zero solutions to mass transfer efficiency.

In some systems (e.g. V356 Sgr, AQ Cas, see Fig. 6), conservative mass transfer ($\varepsilon = 1$) is also excluded from angular momentum loss constraints. In such cases, the initial orbital period required for conservative mass transfer by the binary is much higher than the maximum initial orbital period where mass transfer can occur on the Main Sequence. Angular momentum conservation rules out conservative mass transfer in $\sim 28\%$ of massive Algols in the SMC and $\sim 11\%$ of massive Algols in the Milky Way. However, we find that the constraint on mass transfer efficiency from angular momentum loss consideration ($\gamma < 0$) is less restrictive than the mass transfer stability consideration ($q_{\max}$ and L2 overflow limits) in all the analysed massive Algols (see Fig. 5 and Fig. 6).

3.3.1. Rotationally limited mass accretion scheme

Figure 2 shows the allowed range of mass transfer efficiencies as a function of the current orbital period of each massive Algol. We observe that the current population of massive Algols does not require mass transfer to be very efficient at the shortest periods, unlike what is theoretically expected for rotationally limited accretion in the presence of strong tides. We observe evidence for an increase in the upper limit to the mass transfer efficiency as a function of the binary orbital period for systems in the Milky Way and the LMC. However, the mass transfer efficiency of the SMC systems shows no correlation with the orbital period (c.f. S. E. de Mink et al. 2007). Detailed binary evolution models predict that the majority of massive Algols at the shortest orbital period undergo fairly conservative mass transfer. However, the observed population of massive Algols do not populate the highest probability regions marked by the yellow background area in the $P_{\text{orb}} - \varepsilon$ plane.

Comparing the top and middle panels of Fig. 3 in K. Sen et al. (2022), we see that most models that undergo highly efficient thermal timescale mass transfer ($\varepsilon > 0.8$) merge during the Main Sequence after entering into a contact configuration. Most of the predicted population of massive Algols that do not merge on the Main Sequence undergoes inefficient mass transfer ($\varepsilon < 0.5$). Therefore, the observed population of massive Algols may only represent the predicted population of Algols that do not merge on the Main Sequence. We

speculate that highly efficient mass transfer at the shortest periods may lead to a contact phase on the Main Sequence (due to radial expansion of the accretor) at a much faster timescale than predicted by current binary evolution models (see also A. Menon et al. 2021; J. Henneco et al. 2024).

In the orbital period range 3-5 d, the observed systems in the Milky Way and LMC form two separate sub-populations, one requiring $\varepsilon < 0.5$ and vice versa. In detailed binary evolution models, systems with initial mass ratios above 0.8 undergo fairly efficient mass transfer and vice versa (Fig. F2 of K. Sen et al. 2022). Therefore, the observed sub-populations of Algols in the Milky Way and the LMC may suggest a mass ratio dependence in mass transfer efficiency, which could also be an outcome of thermal timescale-limited mass transfer efficiency (e.g. K. Belczynski et al. 2008; F. R. N. Schneider et al. 2015).

At low metallicity, accretors spin down more slowly on the Main Sequence due to weaker stellar winds. For rotationally limited mass accretion, as in the detailed binary evolution models, the accretors spin up faster due to mass transfer at lower metallicity, because stars are more compact and hence have a smaller moment of inertia. Tides are also less effective in halting the spin-up of the accretor because the radius of the accretor is smaller. Starting from the same initial rotation velocity, orbital period of the binary and mass of the accretor, the above three effects combine to predict a less efficient mass transfer episode at lower metallicity. The maximum mass transfer efficiency of the models in the right panel is lower compared to the left panel of Fig. 2. Likewise, we find that the observed Algols in the SMC seem to have undergone less efficient mass transfer on average than those in the LMC and Milky Way.

3.3.2. Possible disk solutions

Here, we assume that the presence of a disk during the thermal timescale mass transfer phase can support arbitrarily efficient mass transfer, unless the accretor's radial response to the mass accretion leads to L2 overflow in the binary. Therefore, mass transfer efficiency solutions up to $\varepsilon_{\max}^{\text{disk}}$ may be possible for each system in the presence of a disk.

Fig. 3 shows the range of mass transfer efficiency solutions possible for the different models of mass transfer- rotationally limited (light blue) and disk-mediated (dark blue, but also includes the light blue region by construction). We observe a strong mass ratio dependence in the allowed range of mass transfer efficiencies. Systems with a mass ratio less than ~ 2 are consistent with them having undergone largely inefficient mass transfer and vice versa. We see that L2 Overflow rules out conservative mass transfer in the smallest mass ratio systems, while the mass budget constraints rule out non-conservative mass transfer in the highest mass ratio systems.

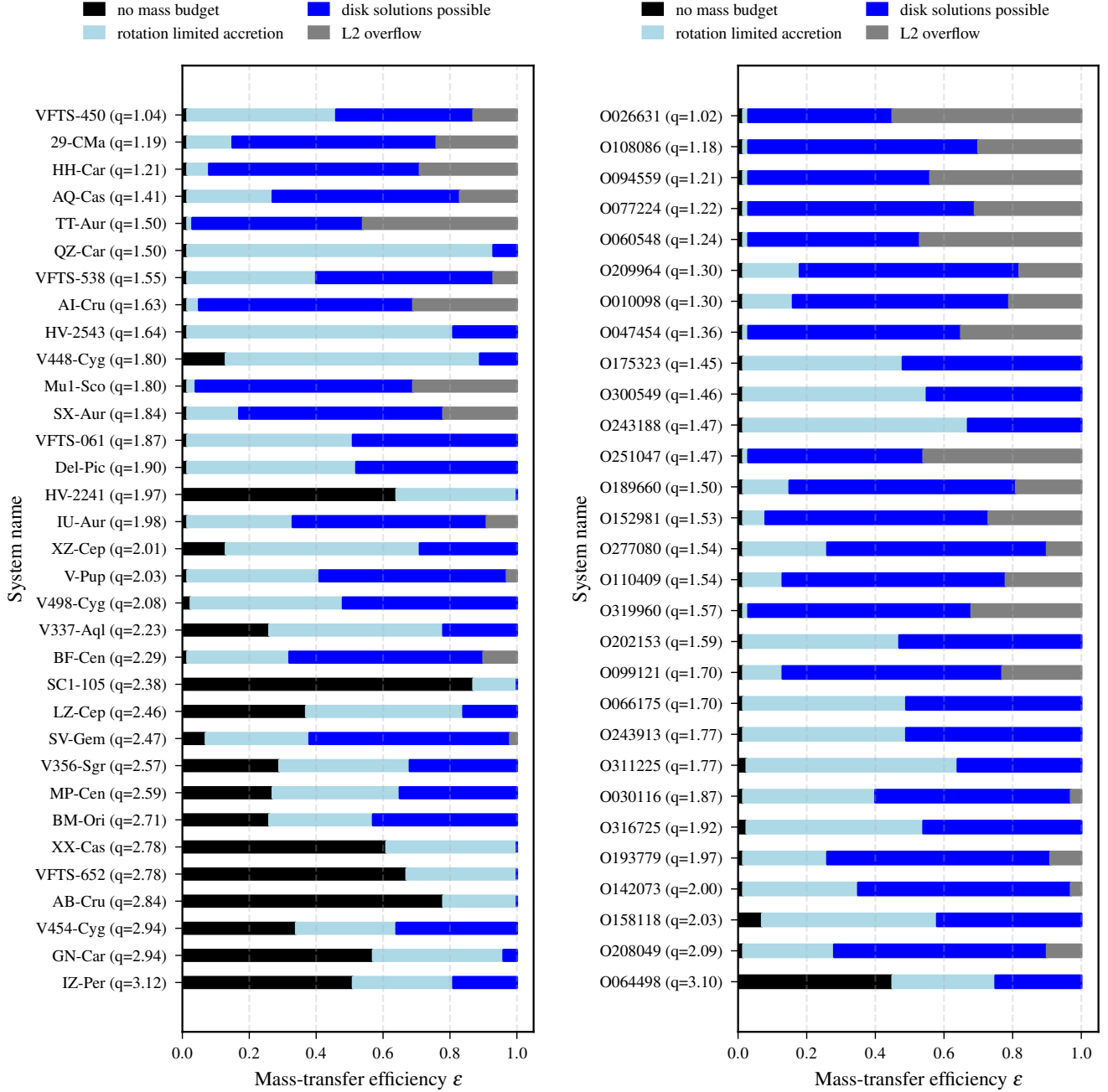


Figure 3. Disallowed range (black bar - initial accretor mass becomes larger than initial donor mass; grey bar - L2 overflow of the accretor) and allowed range (light blue - rotationally limited mass accretion scheme; dark blue - disk supported mass transfer scheme) of mass transfer efficiencies for each system in the LMC & Milky Way (*left panel*) and SMC (*right panel*), arranged in increasing order of observed mass ratio.

Most of the current population of observed massive Algols in the SMC has mass ratios less than 2, whereas half of the Algol population in the LMC and Milky Way has mass ratios above 2. This may be an observational selection effect where it is harder to detect unequal mass ratio binaries in the SMC than the Milky Way (note that there are only seven observed massive Algols in the LMC in the current sample, and four of them are from the recent multi-epoch high-resolution VFTS-

TMBM survey). However, there is a system with mass ratio above 3, and it is one of the least massive systems in our sample (Table 1, second row). If not biased by observational selection effects, our results strongly suggest that there may be a metallicity dependence in the mass transfer efficiency. A future multi-epoch spectroscopic survey of the remaining eclipsing binary sample from T. J. Harries et al. (2003) and R. W. Hilditch et al. (2005), can extend the observed sample

and shed light on the lack of observed unequal mass ratio binaries in the SMC.

4. DISCUSSION

4.1. Mass transfer efficiency and stability

In K. Sen et al. (2022), we found that the orbital period and mass ratio distribution of massive Algols in the LMC and Milky Way give evidence for efficient mass transfer in some systems, while others have undergone inefficient mass transfer. We also found that the least massive systems are not well reproduced by their accretor spin-dependent mass transfer prescription. In this work, we show that the mass transfer stability criterion that requires the combined luminosity of two stars to be able to drive the excess mass loss via winds during an inefficient mass transfer episode is too strict to provide acceptable solutions for mass transfer efficiency in the least massive Algols (Fig. 6). S. E. de Mink et al. (2007) reported a similar lack of acceptable solutions for the least massive Algols in the SMC (see their Table 3, $\chi^2 > 10$), which may again be due to the lack of models that underwent stable mass transfer at low initial mass ratios. Mass loss from the L2 Lagrangian point (W. Lu et al. 2023) may provide an additional mechanism to remove the excess mass. However, L2 mass loss inherently implies a high value for γ , which may be ruled out by the upper limit on the maximum orbital period for Case A mass transfer (see blue regions, or the lack thereof, in the top four rows of the Fig. 5 and Fig. 6).

In the SMC, S. E. de Mink et al. (2007) found a weak correlation between the mass transfer efficiency and initial orbital period of their best-fit binary models to the observed population of massive Algols. In our work, we also see a weak dependence of the allowed range of mass transfer efficiency on the current orbital period of the same sample, where the upper limit to the mass transfer efficiency from the rotationally limited accretion model decreases for increasing orbital period (Fig. 2). The detailed binary model grids of S. E. de Mink et al. (2007); C. Wang et al. (2020); K. Sen et al. (2022) assume that the mass lost due to inefficient mass transfer carries away the specific orbital angular momentum of the accretor. If ε is assumed to be constant during the entire mass transfer episode, purple curves in Fig. 1 represent the initial orbital periods for various mass transfer efficiencies. However, the mass transfer efficiency in the detailed binary evolution models is not constant during the mass transfer phase (e.g. M. Renzo & Y. Götberg 2021).

From our analytical study, we observe that the assumption of higher mass transfer efficiencies necessitates that the binary models begin with longer orbital periods (see black shaded region in the lower right of the left panel of Fig. 1). In some of the least massive Algols in the SMC (first four rows in Fig. 5), strongly efficient mass transfer ($\varepsilon > 0.8$) is also ruled out from angular momentum conservation argu-

ments alone: the initial orbital period required for $\varepsilon > 0.8$ is higher than the maximum initial orbital period for mass transfer to commence on the Main Sequence in the SMC.

The observed population of short-period stripped star+OB star binaries is expected to be the evolved counterparts of massive Algol binaries (S. Wellstein et al. 2001; K. Sen et al. 2022). At the high masses, these constitute the Wolf-Rayet+O star (WR+O) binaries. Most of the WR+O binaries have been found to require highly inefficient mass transfer, both in the Milky Way (J. Petrovic et al. 2005; Y. Shao & X.-D. Li 2016; M. Nuijten & G. Nelemans 2025) and the SMC (C. Schürmann & N. Langer 2024). This is in agreement with our finding that a large majority of the massive Algols may have undergone inefficient mass transfer. On the other hand, low- and intermediate-mass Algols require a wide range of efficiencies to explain the observed populations (C. A. Nelson & P. P. Eggleton 2001; R. Deschamps et al. 2013, 2015; N. Mennekens & D. Vanbeveren 2017; A. Dervişoğlu et al. 2018; S. H. Negu & S. B. Tessema 2018).

Recent studies on Be+sdOB binaries found that they require mass transfer to be significantly more efficient than in the case of massive Algols and WR+O binaries (T. Lechien et al. 2025; Y. Bao et al. 2025, see also A. Schootemeijer et al. 2018; L. Wang et al. 2021; A. Picco et al. 2025). Most of these systems are predicted to have undergone mass transfer after the main-sequence evolution of the donor star (Fig. 4 of T. Lechien et al. 2025), that is, they are not the direct evolutionary counterparts to Algol binaries. These systems strongly disfavour the accretion spin-up dependent mass transfer efficiency model (see also, A. Dervişoğlu et al. 2010), as tides in long-period systems are less effective in tidally locking the accretor to the orbital angular velocity of the binary. The presence of a viscous decretion disk around the Be star in these binaries may allow for the loss of angular momentum via the boundary layer coupling between the star and the disk while continually accreting mass (B. Paczynski 1991; R. Popham & R. Narayan 1991; M. Colpi et al. 1991; G. S. Bisnovatyi-Kogan 1993; S. E. de Mink et al. 2013; R. G. Martin et al. 2025).

To reduce the predicted binary black hole merger rate in gravitational wave population synthesis models, I. Romero-Shaw et al. (2023) proposed conservative Case B mass transfer to increase the orbital periods of the resulting compact object binaries such that they do not merge within Hubble time. Similarly, previous studies propose that the mass transfer efficiency should be as high as 50% to explain the observed population of long-period Be X-ray binaries (Y. Shao & X.-D. Li 2014; S. Vinciguerra et al. 2020; C. Schürmann et al. 2025), where such binaries are expected to have undergone Case B mass transfer. On the other hand, the observed population of short-period WR+O binaries in the local Universe seems to have undergone relatively inefficient mass transfer

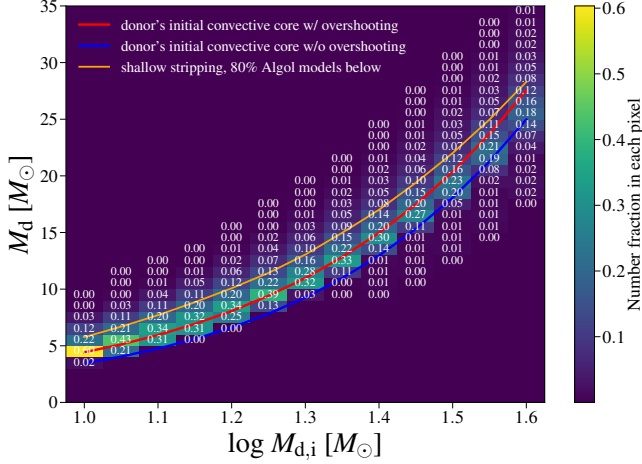


Figure 4. 2D-histogram showing the distribution of the donor masses as a function of the logarithm of initial donor mass during the Algol phase, for the detailed binary evolution models with LMC metallicity (K. Sen et al. 2022). The total probability is normalised such that the sum over all pixels for each logarithmic initial mass bin is unity (overplotted numbers show contribution from each pixel up to two significant digits). The red and blue curves show the convective core mass of the donor at Zero-Age Main Sequence with and without overshooting, respectively. The orange curve indicates that 80% of donor models during the Algol phase are stripped below the curve.

(J. Petrovic et al. 2005; Y. Shao & X.-D. Li 2016; M. Nuijten & G. Nelemans 2025). Likewise, M. Y. M. Lau et al. (2024) discuss that the observed population of gravitational wave sources may have undergone very inefficient mass transfer (see also, Y. Bouffanais et al. 2021; L. A. C. van Son et al. 2022; A. Picco et al. 2024). Recently, E. Zapartas et al. (2025) interpreted that the current sample of binary companions to stripped-envelope supernovae also favours inefficient mass accretion.

C. Schürmann & N. Langer (2024, Fig. 8) showed that the lowest mass ratio for which L2 Overflow is avoided is a function of the mass transfer efficiency, and it is always greater than 0.5 for conservative mass transfer. While their models are at SMC metallicity, the accretors swell up even more at higher metallicities, and the parameter space for contact formation and L2 overflow increases to even higher initial mass ratios. This is consistent with our finding that the least massive Algols require inefficient mass transfer.

4.2. Extent of envelope stripping

Figure 4 shows the distribution of donor masses during the Algol phase. During the thermal timescale mass transfer on the Main Sequence, the donor may get stripped up to its initial convective core mass, which includes the overshooting region (e.g. Fig. 2 of C. Schürmann et al. 2024). The above is represented by the red curve in the 10–40 $M_{\odot}$ range of initial donor masses, where the majority of the donor masses

at each initial donor mass bin reside during the Algol phase. During the nuclear timescale mass transfer phase, the donors lose further mass. We observe that the blue curve, representing the donor’s initial convective core mass excluding the overshooting region, provides an adequate approximation to the deepest extent of envelope stripping due to mass transfer on the Main Sequence (including both fast- and slow-Case A, e.g., J. Klencki et al. 2025).

Physically, the response of the (inner layers of the) donor to the mass lost is primarily determined by its thermal state, that is the temperature gradient. Therefore, whether to include or not the convective boundary mixing region should be decided based on its gradient: for convective penetration (e.g., E. H. Anders et al. 2022), the gradient is adiabatic and no distinction with the convective core should be expected. However, other processes are known to contribute to convective boundary mixing, and the thermal gradient they establish on timescales that are long compared to the convective turnover is not always clear. In our study, we used the red curve (including convective boundary mixing) to determine the initial donor masses of the observed Algols (Sect. 2) as our fiducial extent of envelope stripping during the fast Case A mass transfer. Assuming a deeper extent of envelope stripping to estimate the initial donor mass in our analysis would lead to the inference of more inefficient mass transfer occurring in the observed systems.

We see that a non-negligible fraction of Algol donor models lie above the red curve. If our models accurately capture the extent of envelope stripping during the Algol phase, some of the observed Algols may have donors that have not yet stripped down to their initial convective core mass. If we assume a shallower stripping, such that all the observed donors get stripped up to the orange curve, the maximum mass transfer efficiency that the observed systems may have undergone shifts to higher values (Fig. 7), and many observed Algols may have undergone fairly efficient mass transfer. Inefficient mass transfer solutions also become possible for the least massive Algols without having to relax the mass transfer stability criterion for the least massive Algols. However, there are six systems where the minimum initial accretor mass for conservative mass transfer exceeds the initial donor mass derived from the shallow stripping curve (see black triangles at $\varepsilon = 1$); hence, these are unphysical solutions and indeed give evidence that not all observed Algols justify the shallow stripping assumption. We also see that a handful of Algols in the SMC still require inefficient mass transfer ($\varepsilon < 0.5$). Even for the shallower stripping assumption, the observed Algols in the SMC appear to have undergone less efficient mass transfer, on average, than those in the LMC and Milky Way systems. Surface nitrogen abundance measurements of the observed population of massive Algols can be another

independent diagnostic to constrain the efficiency of mass transfer in these systems.

Finally, the extent of envelope stripping may non-trivially depend on the mass transfer efficiency itself, where the mass and angular momentum exchange between the donor and the accretor determines the closest orbit during the thermal timescale of mass transfer. The mass transfer efficiency in our models is dependent on both the initial orbital period and the initial mass ratio for a given initial donor mass. The detailed models cover the full range of mass transfer efficiencies (Fig. F2 of K. Sen et al. 2022). While quantifying the effect of mass transfer efficiency on the extent of envelope stripping is beyond the scope of this work, we note that the occurrence of both extremes in mass transfer efficiencies in our models also implies that the predicted spread of donor masses during the Algol phase in Fig. 4 includes the effect of mass transfer efficiency.

Our detailed binary evolution models suggest that slow Case A mass transfer, occurring at the nuclear timescale, is highly efficient except at the longest initial orbital periods ($\varepsilon > 0.6$, see Fig. F2 of K. Sen et al. 2022). The estimates for mass transfer efficiency derived in this work give the time-averaged mass transfer efficiency for each system (O. R. Pols & M. Marinus 1994). Starting from the same initial donor mass, if the current donor mass is an outcome of mass lost during both fast and slow Case A, we expect that the prior thermal timescale mass transfer phase may have been slightly less efficient than our derived range of values for each observed massive Algol.

4.3. Convective core mass

We calculate the initial mass of the donor from the initial mass of the convective core. The Ledoux criterion sets the initial convective core mass in our models for convection. Assuming the Schwarzschild criterion (e.g. in S. E. de Mink et al. 2007) for convection will lead to higher estimates of initial convective core masses for the same initial mass. Recent studies of gravity-mode asteroseismology of B stars (M. G. Pedersen et al. 2021) and analyses of eclipsing binaries (A. Claret & G. Torres 2019; A. Tkachenko et al. 2020) suggest that the convective cores of stars are larger than assumed in many stellar evolution models. Building on this observational evidence, theoretical work has demonstrated that convective penetration in O- and B-type stars can enlarge the convective core by about 10–30% of the pressure scale height at the core boundary (E. H. Anders et al. 2022; A. S. Jermyn et al. 2022; C. Johnston et al. 2024). Larger convective cores in donors imply smaller envelopes for the same total initial mass. For systems where the current accretor mass is larger than the initial donor mass, the lower limit on mass transfer efficiency shifts to higher values. The initial mass ratio re-

quired for conservative mass transfer also relaxes to higher values.

The detailed binary evolution models treat convective boundary mixing with parametric algorithms, which assume a radiative gradient in this region. The models of C. Wang et al. (2020); K. Sen et al. (2022) have a step overshooting parameter equal to 0.335 times the local pressure scale height and a radiative gradient in the overshooting region, calibrated to rotational velocity measurements from the FLAMES Survey of Massive Stars at $\sim 15 M_{\odot}$ (I. Hunter et al. 2008; I. Brott et al. 2011, see also the recent theoretical study by R. Andrassy et al. 2024). N. Castro et al. (2014, 2018) later confirmed this calibration for stars of similar mass in the Milky Way and the SMC, but noted that stars of lower or higher mass appear to require correspondingly smaller or larger overshooting values (see also I. Baraffe et al. 2023; E. H. Anders & M. G. Pedersen 2023; C. Johnston et al. 2024). Moreover, C. Johnston (2021) also find evidence of scatter in the convective core masses for the same total mass of an observed star, up to stellar masses $\leq 24 M_{\odot}$. This scatter in convective core masses for the same total stellar mass may also be responsible for the separate sub-populations of massive Algols in the LMC and the Milky Way, which require either efficient or inefficient mass transfer at the same orbital period.

4.4. Wind mass loss

The wind mass loss rate in the detailed binary evolution models are set as in I. Brott et al. (2011). The mass loss rate on the Main Sequence is low compared to that of evolved systems and also decreases with decreasing metallicity (J. S. Vink et al. 2001; M. R. Makiem et al. 2007; M. Renzo et al. 2017; R. Björklund et al. 2021; C. Hawcroft et al. 2021; S. A. Brands et al. 2022; A. C. Gormaz-Matamala et al. 2023; J. Krticka et al. 2025). The donors in the binary models typically lose $\leq 1 M_{\odot}$ via stellar winds before the thermal timescale mass transfer phase initiates on the Main Sequence (I. Brott et al. 2011; K. Sen et al. 2022). Uncertainties in the wind mass-loss rates can also impact these predicted core masses, but this effect is small for initial masses below $\approx 30 M_{\odot}$: at solar metallicity, the corresponding systematic error on Helium core masses is $\lesssim 0.4 M_{\odot}$ (M. Renzo et al. 2017). The amount of mass lost via winds is lower for SMC metallicity. The mass transfer rate is orders of magnitude higher than the wind mass loss rate, such that our conclusions on mass transfer efficiency are not significantly affected by ignoring the mass lost by the donor and accretor via winds during the mass transfer phases.

4.5. Observational sample

The current sample of massive Algol binaries is highly heterogeneous. The component masses for the Galactic Al-

gols were taken from individual studies, and the data analysis techniques vary from one study to another. Moreover, most of the observational data were taken several decades ago, without recent spectroscopic follow-ups. The mass estimates are often without error bars. Only four out of the seven massive Algols in the LMC have estimates on surface abundances and rotational velocities of the individual components. Of the eight massive Algols in the LMC and the Milky Way that have surface rotation measurements, only two show donors that are rotating synchronously with the orbit (K. Sen et al. 2022), while our current binary evolution models predict that all Roche-lobe filling donors should be synchronised to the orbit.

None of the SMC systems has surface abundance or rotational velocity measurements either. The effective temperature measurements of the primary components of the massive Algols in the SMC were based on spectral type classification and the effective temperature of the binary companion was derived from the I-band flux ratios (T. J. Harries et al. 2003; R. W. Hilditch et al. 2005), which lie in the Rayleigh-Jeans tail and are not the most sensitive probes of the effective temperatures of the O- and B-type stars. Therefore, modern spectroscopic surveys of massive Algols binaries are essential to obtain accurate information on most of the existing literature, beyond the component masses and the orbital periods. Moreover, a larger number of observational constraints, such as rotational velocities and surface abundances, can be crucial to understand the extent of envelope stripping and the mode of mass transfer (disk or no disk) occurring in these massive Algols. Like the OGLE survey, the ASAS-SN survey (C. S. Kochanek et al. 2017) can be an excellent dataset to mine eclipsing semi-detached binaries for follow-up homogeneous spectroscopic monitoring campaigns in the Milky Way and the Magellanic Clouds.

5. CONCLUSION

We investigated the efficiency, angular momentum loss, and stability of mass transfer in massive interacting binaries on the Main Sequence (Algols) across the Milky Way, Large Magellanic Cloud (LMC), and Small Magellanic Cloud (SMC). Using an analytical framework that connects present-day binary properties (donor mass, accretor mass, and orbital period) to their initial parameters, and combining these with physical constraints, we derived the ranges of mass transfer efficiency and angular momentum loss consistent with the observed populations. Our main conclusions are:

- Conservative ($\varepsilon = 1$) or non-conservative ($\varepsilon = 0$) mass transfer cannot reproduce the observed properties of all massive Algols at any metallicity. A majority of systems favour inefficient transfer ($\varepsilon \leq 0.5$), and we find no necessity for highly efficient mass transfer even

at the shortest orbital periods (~ 2 d) for our fiducial assumption on envelope stripping (Fig. 2).

- The current set of massive Algols requires that mass transfer remain stable down to initial mass ratios of ~ 0.6 , lower than typically assumed in the literature (S. E. de Mink et al. 2013; H. Ge et al. 2020) for mass transfer on the Main Sequence. The least massive Algols ($M_{d,i} < 20 M_{\odot}$) provide the most substantial evidence for these relaxed stability criteria.
- We find a correlation between efficiency and stability: more efficient mass transfer requires its stability at initial mass ratios significantly below standard limits. Constraints from angular momentum loss exclude conservative mass-transfer solutions in a quarter of systems, particularly in the SMC, but are generally less restrictive than the stability criterion.
- The current population of massive Algols in the SMC may have undergone less efficient mass transfer than their counterparts in the LMC and the Milky Way. However, we cannot rule out an observational bias in the current population of Algols in the SMC, as all except one have mass ratios below ~ 2.1 , while there are a lot of observed Algols in the Milky Way and LMC with more unequal mass ratios (Fig 3).
- Our results show that massive Algols serve as powerful in-situ probes of mass transfer physics across a range of metallicities. Follow-up observational studies on Algols in the SMC can provide further constraints on the possibility of a metallicity dependence in mass transfer efficiency.

Multi-epoch spectroscopic surveys of massive stars and binaries (e.g. the OWN survey, R. H. Barbá et al. 2017; the IACOB project, S. Simón-Díaz & A. Herrero 2014; the VFTS survey, C. J. Evans et al. 2011; the BLOeM survey, T. Shenar et al. 2024), especially with constraints from rotational velocities and surface abundances, are crucial for further disentangling the degeneracy between efficiency and stability, and for anchoring population synthesis predictions of stripped-envelope supernovae and gravitational-wave sources. Simultaneous improvements in multi-dimensional modelling of the thermal timescale mass transfer (D. V. Bisikalo et al. 1998; L. Dessart et al. 2003; W. Lu et al. 2023; J. Cehula & O. Pejcha 2023; T. Ryu et al. 2025; P. Scherbak et al. 2025a,b) and improved orbital modelling in 1D codes (K. A. Rocha et al. 2025; A. Parkosidis et al. 2025) will help advance the field, enabling more accurate modelling of the early stages of mass transfer.

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APPENDIX

A. ADDITIONAL PLOTS AND TABLES

Table 1. Possible range of mass transfer efficiencies and angular momentum loss for massive Algols in the SMC.

System	P_{orb}	M_{d}	M_{a}	$P_{\text{orb,i,max}}$	$M_{\text{d,i}}$	$M_{\text{a,i,min}}$	$M_{\text{a,i,max}}$	ϵ_{min}	ϵ_{qmax}	$\epsilon_{\text{max}}^{\text{disk}}$	$\gamma_{\text{min,qmax}}$	$\gamma_{\text{max,qmax}}$
O251047	2.51	5.50	8.10	3.72	11.75	1.85	8.10	0.00	0.00	0.54	0.00	0.00
O064498	2.63	2.71	8.40	2.71	6.63	4.48	8.40	0.45	0.75	1.00	1.35	3.00
O208049	3.03	4.78	10.00	3.44	10.52	4.26	10.00	0.00	0.28	0.90	0.66	2.32
O319960	4.05	6.75	10.60	4.35	13.75	3.60	10.60	0.00	0.02	0.68	0.37	1.83
O060548	3.63	8.72	10.80	5.14	16.69	2.83	10.80	0.00	0.00	0.53	0.00	0.00
O099121	2.45	6.64	11.30	4.30	13.58	4.36	11.30	0.00	0.13	0.77	0.82	2.49
O026631	1.41	11.26	11.50	5.70	20.24	2.52	11.50	0.00	0.00	0.45	0.00	0.00
O193779	1.67	5.90	11.60	3.93	12.42	5.08	11.60	0.00	0.26	0.91	1.38	3.00
O094559	1.75	9.93	12.00	5.40	18.41	3.52	12.00	0.00	0.00	0.56	0.00	0.00
O152981	2.00	8.15	12.50	5.01	15.88	4.77	12.50	0.00	0.08	0.73	0.97	2.78
O142073	3.19	6.30	12.60	4.13	13.05	5.85	12.60	0.00	0.35	0.97	0.31	2.57
O047454	1.57	9.25	12.60	5.26	17.45	4.40	12.60	0.00	0.00	0.65	0.00	0.00
O110409	2.97	8.87	13.70	5.17	16.91	5.66	13.70	0.00	0.13	0.78	0.42	2.45
O030116	2.95	7.65	14.30	4.78	15.12	6.83	14.30	0.00	0.40	0.97	0.14	2.93
O189660	1.66	10.21	15.30	5.46	18.80	6.71	15.30	0.00	0.15	0.81	1.08	3.00
O077224	3.82	13.05	15.90	6.36	22.57	6.38	15.90	0.00	0.02	0.69	0.00	2.19
O158118	2.58	7.88	16.00	4.89	15.47	8.41	16.00	0.07	0.58	1.00	0.00	3.00
O108086	0.88	14.28	16.90	6.80	24.14	7.04	16.90	0.00	0.01	0.70	1.73	3.00
O316725	2.55	8.82	16.90	5.16	16.84	8.88	16.90	0.01	0.54	1.00	0.00	3.00
O010098	1.11	13.65	17.80	6.58	23.33	8.12	17.80	0.00	0.16	0.79	1.46	3.00
O277080	1.94	11.30	17.40	5.72	20.29	8.41	17.40	0.00	0.26	0.90	0.73	3.00
O243913	2.63	10.52	18.60	5.52	19.23	9.89	18.60	0.00	0.49	1.00	0.00	3.00
O066175	3.62	11.51	19.60	5.79	20.56	10.55	19.60	0.00	0.49	1.00	0.00	3.00
O209964	3.31	14.46	18.80	6.87	24.37	8.89	18.80	0.00	0.18	0.82	0.00	2.71
O202153	4.60	12.50	19.90	6.16	21.86	10.54	19.90	0.00	0.47	1.00	0.00	2.52
O311225	1.84	11.96	21.20	5.96	21.15	12.01	21.20	0.01	0.64	1.00	0.12	3.00
O175323	2.20	16.19	23.50	7.47	26.52	13.17	23.50	0.00	0.48	1.00	0.00	3.00
O300549	1.33	17.42	25.40	7.90	28.03	14.79	25.40	0.00	0.55	1.00	0.81	3.00
O243188	1.87	18.62	27.30	8.72	29.47	16.45	27.30	0.00	0.67	1.00	0.00	3.00

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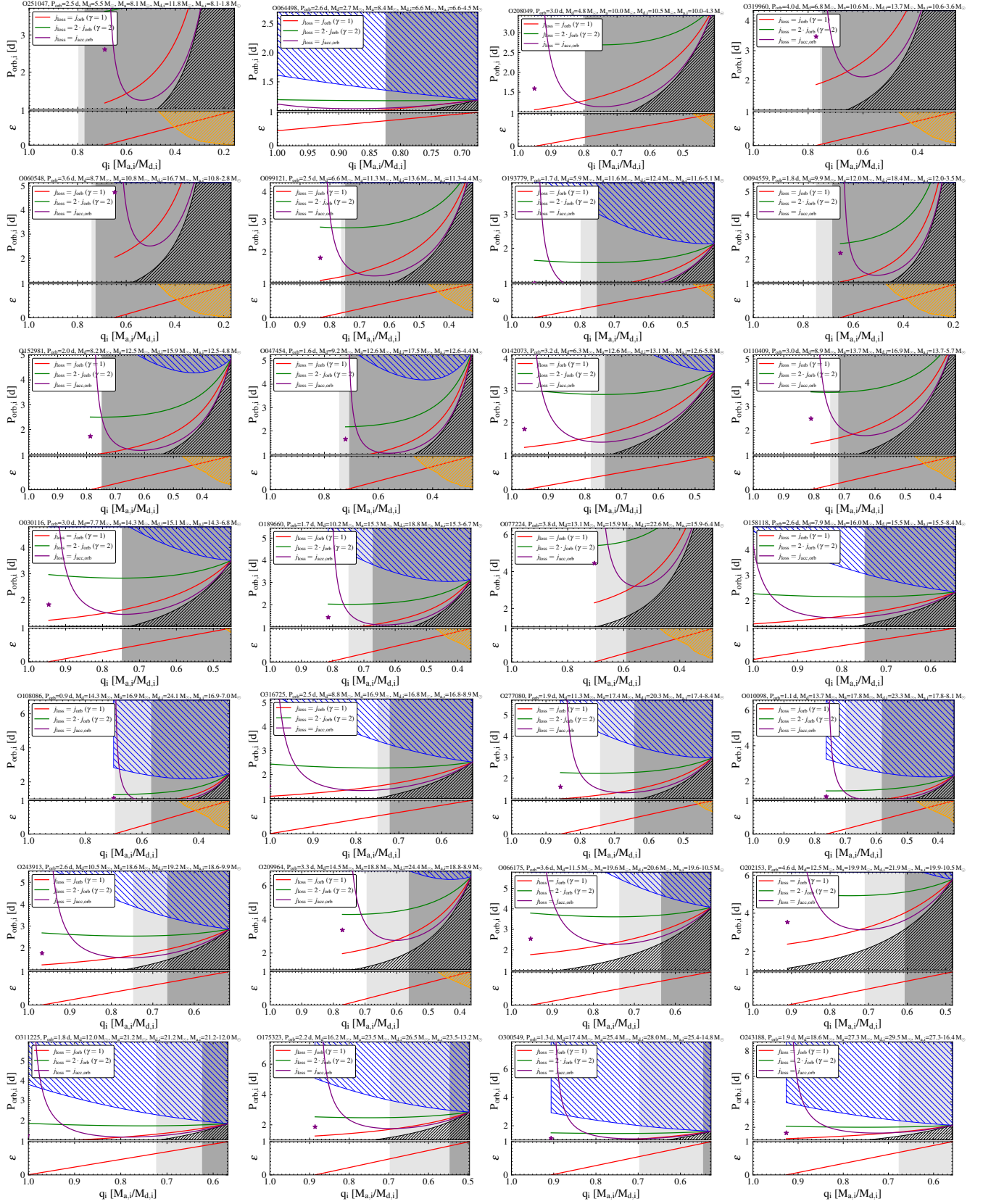


Figure 5. Same as Fig. 1, for all massive Algols in the SMC.

Figure 6. Same as Fig. 1, for all massive Algos in the Milky Way and LMC.

Table 2. Possible range of mass transfer efficiencies and angular momentum loss for massive Algols in the Milky Way and LMC.

System	P_{orb}	M_d	M_a	$P_{\text{orb},i,\text{max}}$	$M_{d,i}$	$M_{a,i,\text{min}}$	$M_{a,i,\text{max}}$	ϵ_{min}	ϵ_{qmax}	$\epsilon_{\text{max}}^{\text{disk}}$	$\gamma_{\text{min,qmax}}$	$\gamma_{\text{max,qmax}}$
TT-Aur	1.33	5.40	8.10	4.82	11.69	1.81	8.10	0.00	0.00	0.54	0.00	0.00
Mu1-Sco	1.44	4.60	8.30	4.53	10.30	2.60	8.30	0.00	0.04	0.69	1.52	2.95
SV-Gem	4.00	3.37	8.34	3.97	8.04	3.67	8.34	0.07	0.38	0.98	0.45	2.50
V454-Cyg	2.31	2.86	8.40	3.68	7.00	4.26	8.40	0.34	0.64	1.00	1.58	3.00
BF-Cen	3.69	3.80	8.70	4.17	8.85	3.65	8.70	0.00	0.32	0.90	0.51	2.47
BM-Ori	6.47	3.51	9.50	4.04	8.30	4.71	9.50	0.26	0.57	1.00	0.00	2.15
IZ-Per	3.68	3.20	9.97	3.88	7.69	5.48	9.97	0.51	0.81	1.00	0.00	3.00
AI-Cru	1.41	6.30	10.30	5.11	13.15	3.45	10.30	0.00	0.05	0.69	1.45	3.00
SX-Aur	1.21	5.60	10.30	4.89	12.02	3.88	10.30	0.00	0.17	0.78	1.70	3.00
MP-Cen	2.99	4.40	11.40	4.46	9.95	5.85	11.40	0.27	0.65	1.00	0.30	3.00
IU-Aur	1.81	6.07	11.99	5.04	12.79	5.27	11.99	0.00	0.33	0.91	1.21	3.00
V356-Sgr	8.89	4.70	12.10	4.57	10.48	6.32	12.10	0.29	0.68	1.00	0.00	1.47
V-Pup	1.45	6.33	12.85	5.12	13.20	5.98	12.85	0.00	0.41	0.97	1.56	3.00
V498-Cyg	3.48	6.45	13.44	5.16	13.39	6.50	13.44	0.01	0.48	1.00	0.00	3.00
GN-Car	4.34	4.59	13.49	4.53	10.28	7.80	13.49	0.57	0.96	1.00	0.00	3.00
LZ-Cep	3.07	6.50	16.00	5.17	13.46	9.04	16.00	0.37	0.84	1.00	0.00	3.00
Del-Pic	1.67	8.60	16.30	5.75	16.62	8.28	16.30	0.00	0.52	1.00	1.02	3.00
XX-Cas	3.06	6.07	16.85	5.04	12.79	10.13	16.85	0.61	1.00	1.00	0.00	3.00
HH-Car	3.23	14.00	17.00	9.21	23.88	7.12	17.00	0.00	0.08	0.71	0.05	2.91
V337-Aql	2.73	7.83	17.44	5.56	15.50	9.77	17.44	0.26	0.78	1.00	0.00	3.00
AQ-Cas	11.70	12.50	17.63	8.17	21.96	8.17	17.63	0.00	0.27	0.83	0.00	1.07
XZ-Cep	5.09	9.30	18.70	5.92	17.62	10.38	18.70	0.13	0.71	1.00	0.00	3.00
29-CMa	4.39	16.00	19.00	10.71	26.39	8.61	19.00	0.00	0.15	0.76	0.00	2.83
AB-Cru	3.41	6.95	19.75	5.31	14.17	12.53	19.75	0.78	1.00	1.00	0.00	3.00
V448-Cyg	6.51	13.70	24.70	9.01	23.50	14.90	24.70	0.13	0.89	1.00	0.00	3.00
QZ-Car	5.99	20.00	30.00	15.39	31.22	18.78	30.00	0.00	0.93	1.00	0.00	3.00
VFTS-061	2.33	8.70	16.30	5.78	16.76	8.24	16.30	0.00	0.51	1.00	0.26	3.00
VFTS-652	8.59	6.50	18.10	5.17	13.46	11.14	18.10	0.67	1.00	1.00	0.00	3.00
VFTS-538	4.15	11.80	18.30	7.67	21.04	9.06	18.30	0.00	0.40	0.93	0.00	2.97
HV-2543	4.83	15.60	25.60	10.39	25.89	15.31	25.60	0.00	0.81	1.00	0.00	3.00
VFTS-450	6.89	27.80	29.00	30.43	40.60	16.20	29.00	0.00	0.46	0.87	0.00	3.00
SC1-105	4.25	13.00	30.90	8.53	22.61	21.29	30.90	0.87	1.00	1.00	0.00	3.00
HV-2241	4.34	18.40	36.20	13.18	29.31	25.29	36.20	0.64	1.00	1.00	0.00	3.00

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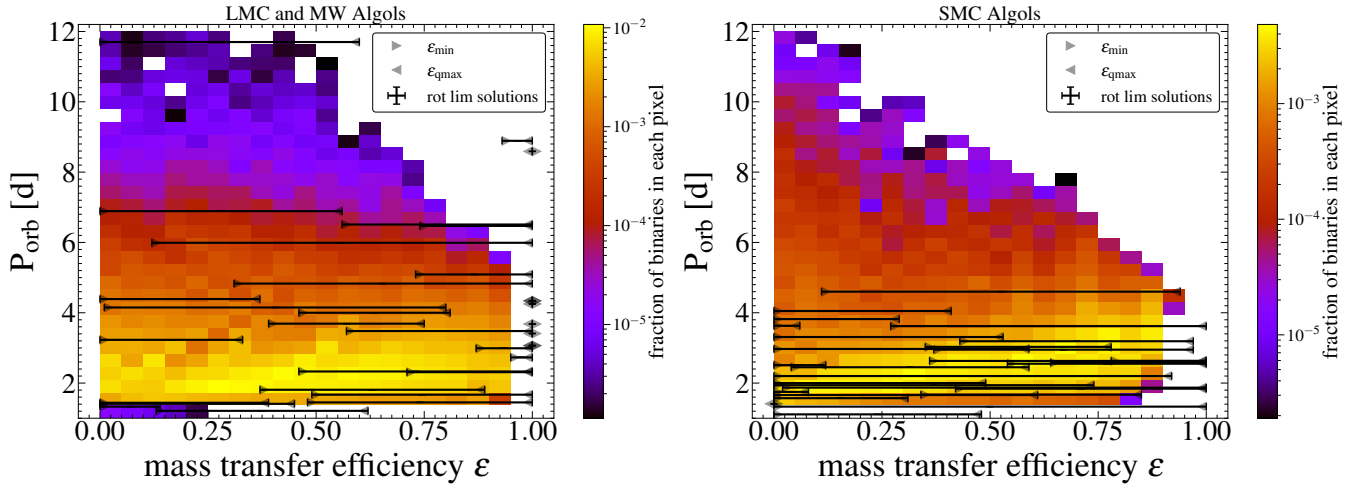
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Table 3. Stellar and binary parameters used in this work (see Sect. 2) taken from detailed binary evolution models for the LMC and SMC.

$M_{d,i}$	$M_{\text{ccd},i}$	q_{min}	q_{max}	$P_{\text{orb},i,\text{max}}$	$M_{\text{ccd},i}$	q_{min}	q_{max}	$P_{\text{orb},i,\text{max}}$
	i—	LMC	models	—i	i—	SMC	models	—i
6.31	2.52	0.800	0.825	3.48	2.55	0.825	0.825	2.64
7.08	2.90	0.800	0.825	3.70	2.93	0.825	0.825	2.80
7.94	3.32	0.800	0.825	3.95	3.36	0.800	0.800	2.98
8.91	3.83	0.775	0.800	4.18	3.88	0.800	0.800	3.16
10.00	4.43	0.775	0.787	4.47	4.48	0.800	0.800	3.35
11.22	5.12	0.750	0.775	4.73	5.18	0.800	0.800	3.55
12.59	5.94	0.725	0.767	5.00	6.00	0.750	0.800	3.98
14.12	6.92	0.700	0.750	5.30	6.99	0.750	0.750	4.47
15.85	8.06	0.675	0.737	5.62	8.13	0.750	0.750	5.01
17.78	9.41	0.650	0.725	5.95	9.48	0.700	0.750	5.31
19.95	10.97	0.600	0.700	7.08	11.04	0.650	0.750	5.62
22.39	12.83	0.560	0.687	8.41	12.91	0.600	0.700	6.31
25.12	14.97	0.500	0.675	9.88	15.05	0.550	0.700	7.08
28.18	17.46	0.450	0.650	11.88	17.54	0.550	0.700	7.94
31.62	20.33	0.390	0.625	15.85	20.41	0.500	0.650	10.00
35.48	23.70	0.325	0.600	19.95	23.80	0.450	0.650	12.59
39.81	27.54	0.275	0.575	26.61	27.64	0.400	0.650	15.85

**Figure 7.** Same as Fig. 2, but for the shallow stripping assumption (orange curve) in Fig. 4.

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