

## Article

# Unveiling the Evolution of MWC 728: Non-Conservative Mass Transfer in an FS CMa Binary

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## Abstract

We combine corrected *Gaia* DR3 astrometry with non-conservative MESA modelling to retrace the evolution of the FS-CMa binary MWC 728. The revised parallax sets the distance at  $d = 1.2 \pm 0.1$  kpc, leading—after Monte-Carlo error propagation—to luminosities of  $\log(L/L_{\odot})_{\text{acc}} = 2.6 \pm 0.1$  and  $\log(L/L_{\odot})_{\text{don}} = 1.5 \pm 0.1$ , corresponding to the accretor and donor, respectively. A fiducial binary track that starts with  $M_{\text{don}} = 3.6 \pm 0.1 M_{\odot}$ ,  $M_{\text{acc}} = 1.8 \pm 0.1 M_{\odot}$ , and  $P_0 = 21.0 \pm 0.2$  d reproduces the observations provided the Roche-lobe overflow, which is moderately non-conservative: only 39% of the transferred mass is retained by the accretor, while the remainder leaves the system via (i) a fast isotropic wind from the donor ( $\alpha = 0.01$ ), (ii) isotropic re-emission near the accretor ( $\beta = 0.45$ ), and (iii) outflow into a circumbinary torus ( $\delta = 0.15$ , lever arm  $\gamma = 1.3$ ). These channels remove sufficient angular momentum to expand the orbit to the observed  $P_{\text{obs}} = 27.5 \pm 0.1$  d while sustaining the dusty circumbinary outflow. At  $t \simeq 223$  Myr, the model matches every current observable:  $M_{\text{don}} = 1.30 \pm 0.05 M_{\odot}$ ,  $M_{\text{acc}} = 2.67 \pm 0.05 M_{\odot}$ , mass ratio  $q = 2.0 \pm 0.1$ , and an ongoing transfer rate of  $\dot{M} \simeq (1 \pm 0.3) \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ . MWC 728 thus serves as a benchmark intermediate-mass binary for testing how non-conservative outflows regulate angular-momentum loss and orbital growth.

**Keywords:** binary stars; B[e] stars; FS CMa; stellar evolution



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## 1. Introduction

B[e] stars are B-type objects that show both forbidden emission lines and a strong infrared excess, the latter arising from a compact gaseous-and-dusty envelope. Such envelopes are often linked to ongoing or recent mass transfer in binary systems, as demonstrated for FS CMa-type objects by Miroshnichenko et al. [1]. Using these two observables as a definition, Lamers et al. [2] subsequently identified four evolutionary subgroups: supergiants (sgB[e]), pre-main-sequence Herbig Ae/Be stars (HAeB[e]), compact planetary nebulae (cPNB[e]), and symbiotic systems (SymB[e]).

A particularly coherent subset of B[e] stars was singled out by [3] and is now referred to as the FS CMa group. Its members are mid-B to early-A objects situated well away from star-forming regions. Spectroscopically they combine extreme Balmer and [OI] emission with a warm-dust continuum that peaks at 10–30  $\mu\text{m}$ . About one-third of the current list of stars also show faint metallic absorptions from a cooler companion. The class is anchored by FS CMa itself and includes the X-ray transient CI Cam [4], the shell star HD 50138 [5], and the long-period binary system AS 386 [6]. Radio and mid-IR diagnostics imply mass

loss rates of  $10^{-6}$ – $10^{-5} M_{\odot} \text{ yr}^{-1}$ , two orders of magnitude above what the radiative winds of single B-stars can supply. Current explanations therefore invoke binary interaction: highly non-conservative case-B transfer [7], post-common-envelope or merger products [8], or magnetically channelled outflows launched after a merger [9].

Originally identified as an emission-line star by Merrill and Burwell [10], MWC 728 was subsequently classified as an FS CMa object by Miroshnichenko [3]. Long-term high-resolution spectroscopy revealed a 27.5-day binary comprising a B7V primary and a G-type secondary [11], while multi-epoch photometry and interferometry document a dusty, variable circumbinary environment. These properties make MWC 728 an ideal subject for testing evolutionary pathways proposed for the FS CMa phenomenon.

## 2. Fundamental Parameters of the System

We re-evaluated the fundamental properties of MWC 728 using the most recent astrometric, photometric, and dust-mapping data. A Gaia DR3 parallax of  $3.31 \pm 0.28$  mas [12] corresponds, according to the catalogue of the Gaia Collaboration et al. [13], to  $d = 309^{+27}_{-22}$  pc, but the same solution has a renormalised unit-weight error of RUWE = 9.74. Such large values are typical for objects with an extended or non-axisymmetric light distribution (e.g., a disc or envelope) and/or unresolved multiplicity [14], making the single-star fit unreliable. An independent spectrophotometric study by Miroshnichenko et al. [11] gave a considerably larger distance,  $d \simeq 1.0 \pm 0.2$  kpc, while evolutionary models of the system likewise favour  $d \gtrsim 1.0$  kpc. Inflating the formal parallax uncertainty using the empirical factor proposed by El-Badry [15], specifically  $f \simeq 3.50$  for the Gaia DR3, with an RUWE = 9.74 and an adopted apparent magnitude of MWC 728 ( $V \simeq 9.8$  mag), and re-computing the posterior under the exponentially decreasing space density prior of the Gaia Collaboration et al. [13] moves the peak of the posterior distribution to  $d = 1.2 \pm 0.1$  kpc.

Interstellar reddening along the sight line ( $l = 162.3^{\circ}$ ,  $b = -19.6^{\circ}$ ) was obtained from the Bayestar 3D dust map [16]. At  $d \simeq 1.20$  kpc, this map gives  $E(B - V) = 0.23 \pm 0.01$  mag, corresponding to  $A_V = 0.71 \pm 0.04$  mag for  $R_V = 3.1$ .

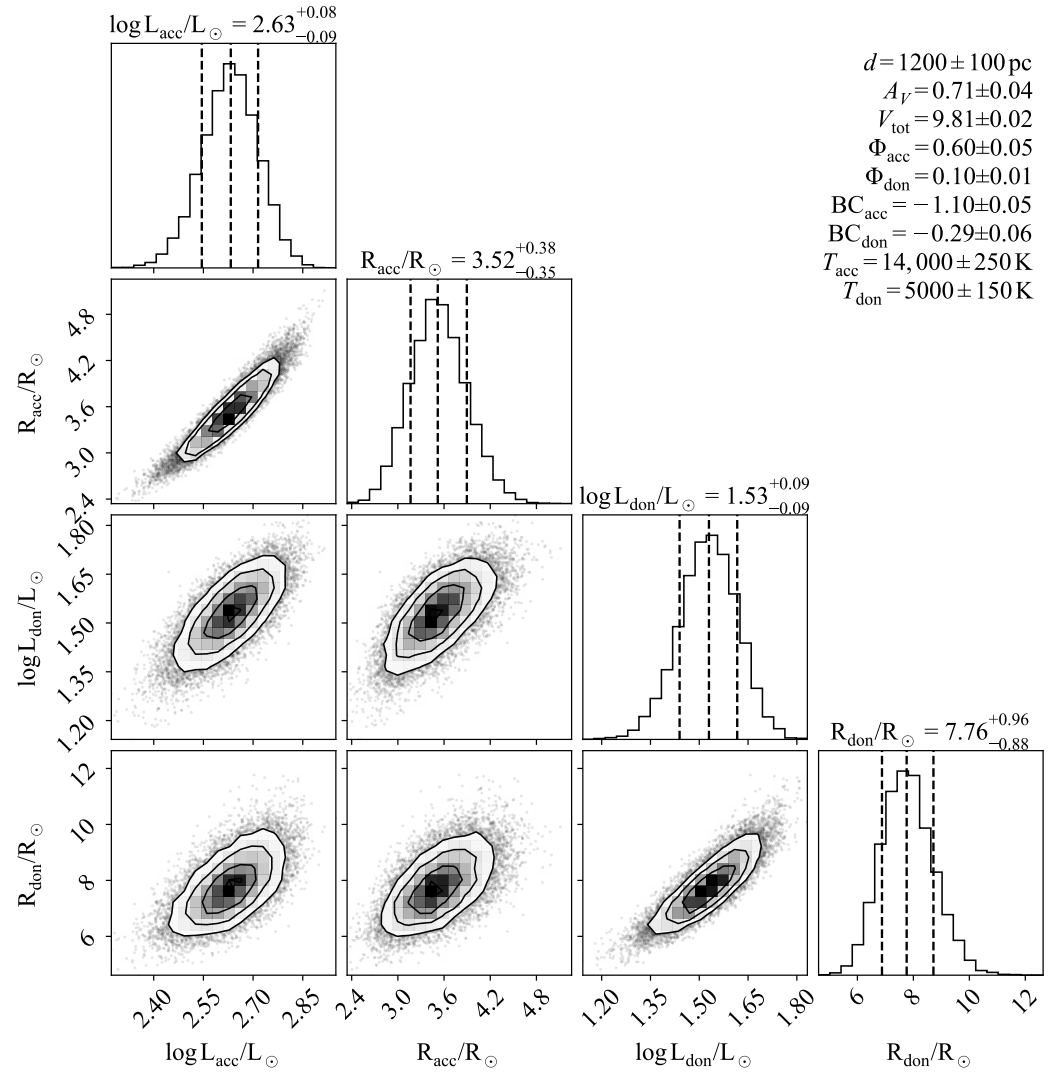
Following the spectral decomposition carried out by Miroshnichenko et al. [11], we adopt the fractional  $V$ -band flux contributions  $\Phi_{\text{acc}} = 0.60 \pm 0.05$ ,  $\Phi_{\text{don}} = 0.10 \pm 0.01$ , and  $\Phi_{\text{disk}} = 0.30 \pm 0.05$  for the donor (we consider mass transfer from the initially more massive, or “donor,” component onto the initially less massive, or “accretor,” component; hence the terms *primary* ( $\equiv$  donor) and *secondary* ( $\equiv$  accretor) are used interchangeably), accretor, and circumbinary disc, respectively. Each coefficient is defined as  $\Phi_i \equiv F_i / F_{\text{tot}}$ , where  $F_i$  is the continuum flux of component  $i$  and  $F_{\text{tot}}$  is the total continuum flux of the system at  $\lambda \simeq 5500 \text{ \AA}$  (central wavelength of the  $V$  band) used in the decomposition. Bolometric corrections are taken from the updated scale of Pecaut and Mamajek [17]:  $\text{BC}_V(\text{accretor}) = -1.10 \pm 0.05$  mag and  $\text{BC}_V(\text{donor}) = -0.29 \pm 0.06$  mag.

Taking into account the distance, extinction, and fixed split of the flux, after bolometric correction, we obtained  $M_{\text{bol}}^{\text{acc}} = -1.85 \pm 0.22$  mag and  $M_{\text{bol}}^{\text{don}} = 0.98 \pm 0.46$  mag, i.e.,  $\log(L/L_{\odot})_{\text{acc}} = 2.63 \pm 0.09$  and  $\log(L/L_{\odot})_{\text{don}} = 1.53 \pm 0.09$ , respectively (Figure 1.).

The corresponding radii of the components are  $R_{\text{acc}} = 3.5 \pm 0.4 R_{\odot}$  and  $R_{\text{don}} = 7.8 \pm 1.0 R_{\odot}$  (Table 1). All input quantities ( $d$ ,  $A_V$ ,  $V_{\text{tot}}$ , flux fractions, and  $\text{BC}_V$ ) were modelled as independent Gaussians; uncertainties came from a 5000-cycle Monte-Carlo propagation.

**Table 1.** Revised parameters of MWC 728 ( $d = 1.20$  kpc).

| Parameter           | Accretor        | Donor           |
|---------------------|-----------------|-----------------|
| $\log(L/L_{\odot})$ | $2.63 \pm 0.09$ | $1.53 \pm 0.09$ |
| $R/R_{\odot}$       | $3.5 \pm 0.4$   | $7.8 \pm 1.0$   |



**Figure 1.** Corner plot of the posterior distributions for the stellar radius and luminosity derived from Monte Carlo simulations. Diagonal panels show marginalized distributions with median and 16th/84th percentiles marked by dashed lines. Joint distributions are shown as shaded density contours.

### 3. Method and Numerical Input

We computed detailed binary evolution models for MWC 728 with the MESA code (version 24.05.1; [18–23]) on a multicore, multiprocessor server at the Laboratory of Astrophysics of the Al-Farabi Kazakh National University Research Center “Data Science in Astrophysics” (accessed on 17 May 2025). The MESA code allows modelling of interacting B[e] binaries (e.g., HD 327083 [24]). Using the fundamental parameters derived in Section 2 as starting constraints, we explored a grid in which the initial orbital period was varied from 5.0 to 30.0 days, while the zero-age donor and accretor masses were increased from 4 to 7  $M_{\odot}$  and from 1 to 3  $M_{\odot}$ , respectively.

We adopted a near-solar metallicity of  $Z = 0.014$  [25]. Mass loss was treated with the standard MESA scheme that combines the line-driven formulation of Vink et al. [26] for hot stars ( $T_{\text{eff}} \gtrsim 10^4 \text{ K}$ ) and the formulation of de Jager et al. [27] once the temperature falls below 8000 K. Following recent evidence that canonical rates tend to be overestimated in the B-type and cool supergiant regimes, e.g., [28,29], we applied a uniform reduction factor,  $\alpha_{\text{wind}} = 0.5$ ,  $\alpha_{\text{wind}}$ , which corresponds to the `Vink_scaling_factor` and `de_Jager_scaling_factor` in MESA, which scale the mass loss rates of the two formula-

tions. See the [MESA documentation](#) (accessed on 17 May 2025). This value halves the theoretical rates, reflecting the moderate winds typically inferred for FS CMa objects while still allowing for episodes of enhanced outflow reported in some systems [30,31]. Because our focus is on the effects of non-conservative Roche-lobe overflow,  $\alpha_{\text{wind}}$  was kept fixed throughout the grid rather than being treated as a free parameter.

For the mass-transfer phase, we adopt the Ko1b implementation of the [32] formalism (`mdot_scheme = 'Ko1b'`). This scheme integrates the hydrostatic density profile above the donor's photosphere, giving the exponential response of the mass loss rate to the degree of overfill of the Roche lobe. Compared with the original Ritter formulation, the Ko1b variant (i) removes the formal discontinuity that appears when the stellar radius approaches the Roche-lobe radius and (ii) remains numerically stable during the  $\tau_{\text{KH}} \sim 10^5$  yr donor's Kelvin–Helmholtz adjustment phase [33]. We compute the Roche radius with the Eggleton formula [34] and keep the default photospheric scale-height factor. No Kelvin–Helmholtz timestep limiter is imposed, which allows MESA to resolve the full thermal-timescale episode without artificial suppression. Exploratory runs performed with the Ritter [35] and implicit options occasionally produced under-resolved  $\dot{M}$  spikes or premature contact for initial donor masses of  $M_{\text{don}} \gtrsim 5 M_{\odot}$ . Although these artefacts vanish when the global timestep is reduced by two orders of magnitude, such fine gridding renders large parameter surveys computationally prohibitive. The Ko1b choice avoids this issue without additional fine-tuning and was therefore retained throughout our model grid.

We treat mass and angular-momentum losses with the  $\alpha$ – $\beta$ – $\delta$  formulation of Soberman et al. [33], as implemented in MESA [20]. In this formalism,

- $\alpha$  is the fraction of the transferred mass removed as isotropic wind from the donor;
- $\beta$  is the fraction isotropically re-emitted near the accretor (hot boundary layer and  $L_2/L_3$  outflow);
- $\delta$  is the fraction fed into a circumbinary torus located at  $R_{\text{tor}} = \gamma a$ , where  $a$  is the instantaneous orbital separation of the binary, carrying a specific angular momentum of  $j_{\text{tor}} = \gamma j_{\text{orb}}$ ;
- $\eta_{\text{acc}}$  is the mass-accretion efficiency: the fraction of the transferred mass that is effectively accreted by the secondary (accretor), computed as  $\eta_{\text{acc}} = 1 - \alpha - \beta - \delta$  [33].

The four channels are set in the inlist via `mass_transfer_alpha`, `mass_transfer_beta`, `mass_transfer_delta`, and `mass_transfer_gamma`. For MWC 728, we adopt

$$\alpha = 0.01, \quad \beta = 0.45, \quad \delta = 0.15, \quad \gamma = 1.3,$$

so that  $\eta_{\text{acc}} = 0.39$ . This choice is motivated by three empirical and theoretical considerations:

1. *Donor wind* ( $\alpha$ ). Two regimes imposed boundaries on the expected isotropic wind from the Roche-filling star.
  - (i) When the donor was a B7-type star, the Vink formulation predicted that  $\dot{M}_{\text{wind}}^{\text{Vink}} \lesssim 2 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$  [26], i.e.,  $\alpha \lesssim 3 \times 10^{-4}$  relative to the peak mass-transfer rate adopted in the grid.
  - (ii) After the Algol reversal, the donor was an F-type subgiant; a Reimers-style scaling gave an even weaker  $\dot{M}_{\text{wind}}^{\text{Reimers}} \sim 10^{-11} M_{\odot} \text{ yr}^{-1}$  [36], implying  $\alpha \lesssim 10^{-5}$ .
 Both limits lie well below the non-spherical channels ( $\beta$ ,  $\delta$ ), so we adopt a single constant value,  $\alpha = 0.01$ . Tests with  $\alpha = 0$ – $0.03$  change the orbital period by  $< 1\%$ , confirming its negligible effect.
2. *Re-emission from the gainer* ( $\beta$ ). Three-dimensional simulations show that gainers rotating at  $v_{\text{rot}} \gtrsim 0.8 v_{\text{crit}}$  re-emit 40–60 % of the incident stream [37]. For the accretor with  $M_{\text{acc}} = 1.8 M_{\odot}$  and  $R_{\text{acc}} = 3.5 R_{\odot}$ , the Roche-corrected expression gives  $v_{\text{crit}} \simeq 3.3 \times 10^2 \text{ km s}^{-1}$ . The observed projected rotation velocity is  $v \sin i \simeq 110 \text{ km s}^{-1}$ , and

with the binary inclination  $i = 14^\circ \pm 1^\circ$  [11], the equatorial (true) rotation speed, obtained via  $v_{\text{rot}} = (v \sin i) / \sin i$ , is  $v_{\text{rot}} \simeq (1.0 \pm 0.1) v_{\text{crit}}$ . This places the accretor well within the simulated high-rotation regime, so we adopt the representative value  $\beta = 0.45$ .

3. *Circumbinary torus* ( $\delta, \gamma$ ). The SED of MWC 728 shows a smooth, featureless infrared excess and exceeds the combined stellar photospheres by more than an order of magnitude [11]. Free–free emission from a Be-type envelope cannot reproduce such a broad hump, whereas radiative-transfer models with a warm, optically thick circumbinary dust reservoir match both the slope and the absolute flux level [38]. SPH calculations that include dust formation further show that 10–20% of the transferred mass can settle into a long-lived torus at  $R_{\text{tor}} \simeq 1\text{--}2\text{ au}$  [39]. For MWC 728, the observed IR luminosity is reproduced for  $\delta = 0.12\text{--}0.18$  and a lever-arm factor of  $\gamma = R_{\text{tor}}/a \simeq 1.3$ .

The minimum dynamically stable torus radius is  $R_{\text{tor}} \gtrsim 1.3 a$  [40]. With the current mass ratio  $q_{\text{now}} = M_{\text{acc,now}}/M_{\text{don,now}} = 2.00$ , we take the specific angular momentum of the escaping material to be

$$\dot{J}_{\text{tor}} = \gamma \dot{J}_{\text{orb}} \quad (1)$$

so that the fractional angular-momentum loss carried away by the torus is

$$\frac{\dot{J}_{\text{tor}}}{J_{\text{orb}}} = (1 + q) \delta \gamma \frac{\dot{M}_{\text{tr}}}{M_{\text{don}}} \quad (2)$$

This mechanism lengthens the orbital period from the contact value  $P_c = 21.0\text{ d}$  to the observed value  $P_{\text{obs}} = 27.5 \pm 0.1\text{ d}$  within  $1\sigma$ . Exploratory runs show that  $\gamma > 1.5$  or  $\delta < 0.10$  under-estimate the period and the infrared excess, whereas  $\delta > 0.25$  over-extends the period and suppresses the peak accretion rate. Values in the range  $\delta \simeq 0.10\text{--}0.20$  reproduce both the orbital period and the IR luminosity, while the stellar HR tracks remain virtually unchanged (deviations  $\lesssim 0.02\text{ dex}$ ) across this  $\delta$  interval. We therefore adopt  $\delta = 0.15$  and  $\gamma = 1.3$ .

We include tidal interactions via MESA’s binary-tide module. Equilibrium tides in convective envelopes follow the constant-viscosity formalism of Hut [41], whereas radiative damping in radiative envelopes is treated in accordance with Zahn [42,43]. The resulting tidal torque is two orders of magnitude weaker than the wind-driven angular-momentum loss before contact and therefore has a negligible impact on the pre-Roche-lobe period evolution.

We model convective energy transport with the standard mixing-length formalism of Böhm-Vitense [44]. We keep the solar-calibrated value `mixing_length_alpha` = 1.84 [45]. Convective core growth is treated with the exponential–diffusive formalism of Herwig [46] (`overshoot_scheme` = ‘exponential’). We adopt `overshoot_f` = 0.014 and `overshoot_f0` = 0.002, which correspond to an e-folding length of  $\simeq 0.20 H_P$  at the convective boundary. This choice is guided by eclipsing binary calibrations in the  $2\text{--}5 M_\odot$  range [47] and lies well within the empirically supported interval  $f_{\text{ov}} = 0.010\text{--}0.016$  for intermediate-mass stars.

## 4. Results

The evolutionary models were computed in two stages. First, a coarse grid ( $\Delta M = 0.5 M_\odot$ ,  $\Delta P_0 = 1\text{ d}$ ) was constructed, imposing only the condition  $M_{\text{don}} > M_{\text{acc}}$ . Models matching the observed constraints—orbital period, mass function, mass ratio, luminosities, effective temperatures, and stellar radii (Section 2)—clustered near  $M_{\text{don}} \approx 3.2\text{--}3.8 M_\odot$ ,  $M_{\text{acc}} \approx 1.6\text{--}2.0 M_\odot$ , and  $P_0 \approx 15\text{--}30\text{ d}$ .

Subsequently, a fine grid ( $\Delta M = 0.1 M_{\odot}$ ,  $\Delta P_0 = 0.1$  d) was developed over this parameter space. Filtering by the same observables significantly narrowed down the solutions. The optimal initial configuration was  $M_{\text{don}} = 3.6 M_{\odot}$ ,  $M_{\text{acc}} = 1.8 M_{\odot}$ , and  $P_0 = 21.0$  d. This model is thus adopted as the fiducial evolutionary track for MWC 728.

Having fixed the initial conditions, we now follow the subsequent evolution of the binary in chronological order (Figure 2).

(0) Initial stage ( $t = 0$ ). At the zero-age main sequence, the donor and accretor have  $M_{\text{don}} = 3.6 M_{\odot}$  and  $M_{\text{acc}} = 1.8 M_{\odot}$ , yielding an initial mass ratio of  $q_0 = 0.5$ . The orbital period is set to  $P_0 = 21$  d because, for these masses, Kepler’s law combined with the Eggleton Roche-lobe relation gives  $R_{\text{L, don}} \simeq 0.38 a \simeq 19 R_{\odot}$ , matching the terminal-age main-sequence radius of a  $3.6 M_{\odot}$  star; thus, the donor naturally reaches contact at the end of core-hydrogen burning. Detached, circular binaries with periods of a few tens of days are a typical starting point for the evolution of intermediate-mass systems [48].

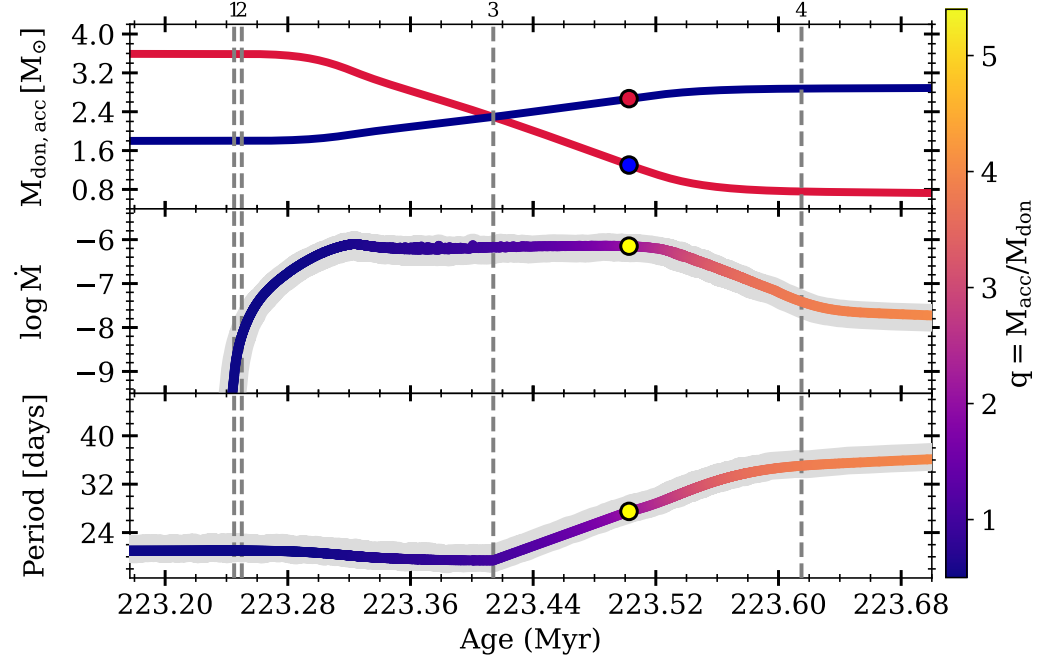
(1) Start of Roche-lobe overflow ( $t = 223.250 \pm 0.005$  Myr). When the initially more massive donor fills its Roche lobe [34], the orbital period decreases from the initial  $P_0 = 21.0 \pm 0.2$  d to  $P = 19.6 \pm 0.1$  d. This shrinkage is dominated by conservative mass transfer from the more massive donor to the less massive accretor, which contracts the orbit while  $q < 1$  [33]. Line-driven winds remove some angular momentum, but their integrated effect prior to contact is an order of magnitude smaller. At this stage, the donor has  $T_{\text{eff, don}} = 8000 \pm 150$  K,  $\log(L/L_{\odot})_{\text{don}} = 2.50 \pm 0.05$ , and  $R_{\text{don}} = 9.5 \pm 0.2 R_{\odot}$ , whereas the accretor has  $T_{\text{eff, acc}} = 8800 \pm 150$  K,  $\log(L/L_{\odot})_{\text{acc}} = 1.30 \pm 0.05$ , and  $R_{\text{acc}} = 2.5 \pm 0.1 R_{\odot}$ . The mass-transfer rate is still modest ( $\dot{M} \lesssim 10^{-8} M_{\odot} \text{ yr}^{-1}$ ), and the mass ratio has risen only to  $q = 0.50 \pm 0.02$ . Such a gentle approach to contact is typical for case-B evolution in intermediate-mass binaries.

(2) Thermal-timescale RLOF ( $t = 223.255 \pm 0.005$  Myr;  $\Delta t = 5 \pm 1$  kyr after the onset of RLOF). Once the donor’s radiative envelope becomes weakly bound, mass loss proceeds on the Kelvin–Helmholtz timescale and the transfer rate climbs to a peak value of  $\dot{M}_{\text{max}} = (1.0 \pm 0.3) \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ . During this brief phase, the stellar parameters change little: the donor stays at  $T_{\text{eff, don}} = 8000 \pm 150$  K,  $\log(L/L_{\odot})_{\text{don}} = 2.50 \pm 0.05$ , and  $R_{\text{don}} = 9.5 \pm 0.2 R_{\odot}$ , while the accretor remains at  $T_{\text{eff, acc}} = 8800 \pm 150$  K,  $\log(L/L_{\odot})_{\text{acc}} = 1.30 \pm 0.05$ , and  $R_{\text{acc}} = 2.5 \pm 0.1 R_{\odot}$ . Because  $q < 1$ , the orbit contracts further to the dynamical minimum  $P_{\text{min}} = 19.4 \pm 0.1$  d.

(3) Algol reversal ( $t = 223.414 \pm 0.005$  Myr;  $\Delta t = 169 \pm 2$  kyr after the onset of RLOF,  $164 \pm 2$  kyr after the previous stage). When the component masses equalise ( $q = 1.00 \pm 0.02$ ), the orbit reaches its dynamical minimum,  $P_{\text{min}} = 19.4 \pm 0.1$  d. At this stage, the donor has shrunk to  $T_{\text{eff, don}} = 5400 \pm 100$  K,  $\log(L/L_{\odot})_{\text{don}} = 1.40 \pm 0.05$ , and  $R_{\text{don}} = 5.7 \pm 0.2 R_{\odot}$ , whereas the accretor has expanded significantly and grown hotter, reaching  $T_{\text{eff, acc}} = 13,000 \pm 300$  K,  $\log(L/L_{\odot})_{\text{acc}} = 2.70 \pm 0.05$ , and  $R_{\text{acc}} = 4.1 \pm 0.2 R_{\odot}$ . Conservative terms now act to widen the binary, and within  $\sim 3 \times 10^4$  yr, the period starts to increase, while the mass-transfer rate rapidly drops from  $\log \dot{M} = -6.0 \pm 0.2$  to  $-8.0 \pm 0.2$ . Such rapid post-Algol expansion is a robust prediction of (i) semi-analytic stability analyses [33,49], (ii) 3D hydrodynamic simulations for radiative donors [37], and (iii) the long-term timing of classical Algols that show a switch from  $\dot{P} < 0$  to  $\dot{P} > 0$  after mass-ratio reversal [50]. Our evolutionary track duplicates this behaviour precisely: the angular momentum removed through the  $\beta$ -re-emission and  $\delta$ -torus channels is sufficient to lift the orbit back to the observed value  $P_{\text{now}} = 27.5 \pm 0.1$  d without triggering dynamical instability or a common envelope.

(4) The end of the RLOF, wind-driven phase ( $t = 223.615 \pm 0.005$  Myr;  $\Delta t = 370 \pm 3$  kyr after the onset of RLOF,  $201 \pm 3$  kyr after the previous stage). By this epoch, the donor has been reduced to  $M_{\text{don}} = 0.80 \pm 0.03 M_{\odot}$ , showing  $T_{\text{eff, don}} = 5600 \pm 100$  K,

$\log(L/L_{\odot})_{\text{don}} = 1.90 \pm 0.05$ , and  $R_{\text{don}} = 9.5 \pm 0.3 R_{\odot}$ , while the accretor has reached  $M_{\text{acc}} = 2.90 \pm 0.03 M_{\odot}$  and contracted to  $T_{\text{eff,acc}} = 13700 \pm 300 \text{ K}$ ,  $\log(L/L_{\odot})_{\text{acc}} = 2.30 \pm 0.05$ , and  $R_{\text{acc}} = 2.7 \pm 0.2 R_{\odot}$ . The mass-transfer rate has fallen below  $\dot{M} \lesssim (1 \pm 0.3) \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ . Most of the residual flow is expelled from the system ( $\sim 15\% \pm 3\%$  via a low-specific-momentum circumbinary outflow), causing the orbit to expand secularly to  $P = 32.5 \pm 0.2 \text{ d}$ . Post-mass-transfer widening of this magnitude is a standard outcome for moderately non-conservative case-B binaries [51].



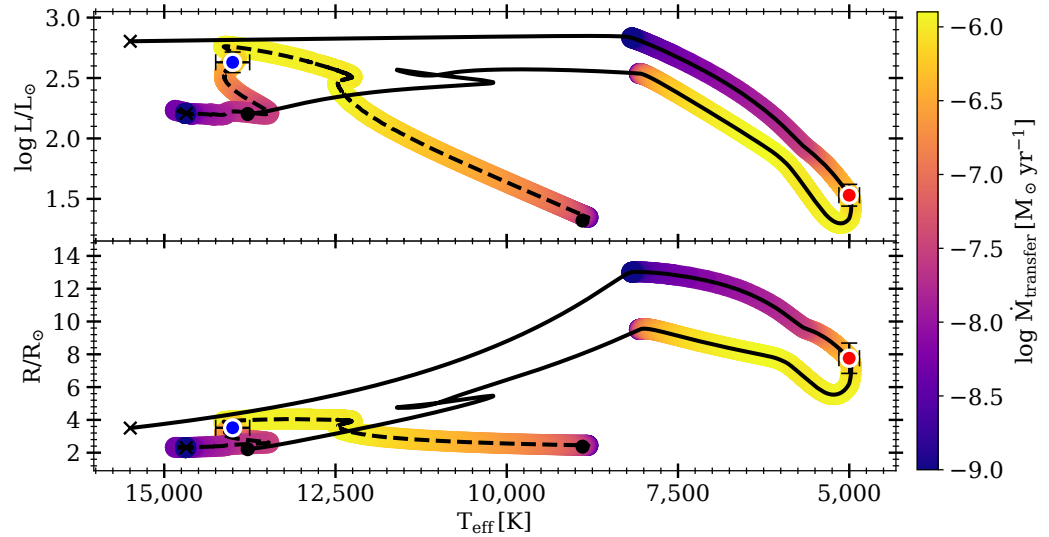
**Figure 2.** Time evolution of our fiducial MWC 728 model over the interval  $223.20 \lesssim t \lesssim 223.68 \text{ Myr}$ . **Top panel:** donor (red curve) and accretor (blue curve) masses; the red and blue filled circles mark the present epoch ( $t = 223.503 \text{ Myr}$ ). **Middle panel:** logarithm of the mass-transfer rate,  $\log \dot{M} (M_{\odot} \text{ yr}^{-1})$ ; the yellow circle highlights the present epoch. **Bottom panel:** orbital period  $P$ ; the yellow circle shows the current system's parameters. For the middle and bottom panels, the coloured curve shows the fiducial model, while the grey areas enclose the range obtained when the circumbinary–torus fraction is varied over  $0.10 \leq \delta \leq 0.25$ . All coloured curves are additionally colour-coded by the instantaneous mass ratio  $q = M_{\text{acc}}/M_{\text{don}}$  (colour bar on the right). Vertical dashed lines labelled 1, 2, 3, and 4 indicate the evolutionary milestones discussed in Section 4.

The present epoch ( $t \simeq 223.503 \text{ Myr}$ ). Along the fiducial track, MWC 728 is an active post-Algol system with an observed orbital period of  $P_{\text{obs}} = 27.5 \pm 0.1 \text{ d}$ . The Roche-filling donor (spectral type G/F) has  $M_{\text{don}} = 1.30 \pm 0.05 M_{\odot}$ ,  $\log L/L_{\odot} = 1.53 \pm 0.05$  ( $L_{\text{don}} = 34 \pm 4 L_{\odot}$ ),  $\log R/R_{\odot} = 0.89 \pm 0.03$  ( $R_{\text{don}} = 7.7 \pm 0.6 R_{\odot}$ ), and an effective temperature of  $T_{\text{eff,don}} = 6000 \pm 200 \text{ K}$ , matching the cool component seen in high-resolution spectra.

The rejuvenated accretor is the B7 IV primary, and it has grown to  $M_{\text{acc}} = 2.67 \pm 0.05 M_{\odot}$ ,  $\log L/L_{\odot} = 2.34 \pm 0.05$  ( $L_{\text{acc}} = 220 \pm 25 L_{\odot}$ ), and  $\log R/R_{\odot} = 0.44 \pm 0.03$  ( $R_{\text{acc}} = 2.8 \pm 0.2 R_{\odot}$ ), with  $T_{\text{eff,acc}} = 14,000 \pm 500 \text{ K}$ , fully consistent with the spectroscopic estimate of Miroshnichenko et al. [11].

Mass transfer is still ongoing at a rate of  $\dot{M}_{\text{transfer}} \simeq 10^{-6} M_{\odot} \text{ yr}^{-1}$ , as indicated by the colour scale in Figure 3; this places the system in a steady, optically thick overflow regime.

These values give a present mass ratio of  $q = M_{\text{acc}}/M_{\text{don}} = 2.67/1.30 \simeq 2.0$ , identical, within the range of uncertainties, to the dynamical value derived from the same dataset.



**Figure 3.** Evolutionary tracks of both binary components displayed in two panels. **Top panel:** effective temperature,  $T_{\text{eff}}$ , versus luminosity,  $\log(L/L_{\odot})$ . **Bottom panel:**  $T_{\text{eff}}$  versus radius  $R/R_{\odot}$ . The dashed curve follows the star that began with an initial mass of  $M_{\text{init}} = 1.8 M_{\odot}$ ; the solid curve shows the track of the star that started with  $M_{\text{init}} = 3.6 M_{\odot}$ . The red symbol marks the current observed position of the cooler component, while the blue symbol indicates the current position of the hotter component. The accompanying colour bar encodes the instantaneous mass-transfer rate,  $\dot{M}_{\text{transfer}}$ , within the system.

Figure 3 marks the current locations of the cool donor (red) and hot accretor (blue) on both the HR and  $T_{\text{eff}}$ -radius diagrams; their close match to the predicted tracks demonstrates that our moderately non-conservative evolutionary model reproduces all observed properties of MWC 728.

## 5. Conclusions

In this paper, we combined corrected *Gaia* DR3 astrometry, Monte-Carlo photometric modelling, and non-conservative binary-evolution calculations to refine the properties and evolutionary history of the FS-CMa system MWC 728. Our main conclusions are as follows:

- **Distance and extinction:** correcting the *Gaia* DR3 parallax for its large RUWE ( $\simeq 9.7$ ) with the method of El-Badry [15] gives  $d = 1.20 \pm 0.10$  kpc, which is fully consistent with a spectrophotometric distance of  $1.0 \pm 0.2$  kpc [11].
- **Fundamental parameters:** a 5000-cycle Monte-Carlo propagation yields  $\log(L/L_{\odot})_{\text{acc}} = 2.6 \pm 0.1$ ,  $\log(L/L_{\odot})_{\text{don}} = 1.5 \pm 0.1$ ,  $R_{\text{acc}} = 3.5 \pm 0.4 R_{\odot}$ , and  $R_{\text{don}} = 7.7 \pm 0.9 R_{\odot}$ , confirming a hot B7IV accretor ( $T_{\text{eff}} = 14,000 \pm 250$  K) and a cool G-type donor ( $T_{\text{eff}} = 6000 \pm 150$  K).
- **Binary evolution:** The best-fit MESA track starts with  $M_{\text{don}} = 3.6 \pm 0.1 M_{\odot}$ ,  $M_{\text{acc}} = 1.8 \pm 0.1 M_{\odot}$ , and  $P_0 = 21.0 \pm 0.2$  d and evolves through thermally driven, moderately non-conservative Roche-lobe overflow. Mass loss fractions of  $\alpha = 0.01$ ,  $\beta = 0.45$ ,  $\delta = 0.15$ , and  $\gamma = 1.3$  reproduce the dusty torus and expand the orbit to the observed  $P_{\text{obs}} = 27.5 \pm 0.1$  d. At  $t \simeq 223.5$  Myr, the model matches the present-day masses ( $M_{\text{don}} = 1.30 \pm 0.05 M_{\odot}$ ,  $M_{\text{acc}} = 2.67 \pm 0.05 M_{\odot}$ ), the ratio  $q = 2.0 \pm 0.1$ , and an ongoing transfer rate of  $\dot{M}_{\text{tr}} \simeq (1 \pm 0.3) \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ .

Taken together, our results establish MWC 728 as a rare subject for testing angular-momentum loss calculations and dust-torus formation in intermediate-mass binaries, and they underscore the value of sustained, high-resolution spectroscopic and interferometric monitoring to capture their continuing, non-conservative evolution.

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## Abbreviations

The following abbreviations are used in this manuscript: RV—radial velocity; MCMC—Bayesian Markov Chain Monte Carlo; MESA—Modules for Experiments in Stellar Astrophysics; MLT—mixing length theory; RLOF—Roche-lobe overflow; PMS—pre-main sequence; ZAMS—zero-age main sequence.

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