Massive Stars Across Redshifts in the Era of JWST and Large Surveys
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One century data of τ CMa: a (2+1)+1 system with a short-period overcontact binary and an eccentric intermediate orbit with probably no apsidal motion

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Abstract. τ Canis Majoris (CMa) is an intriguing system that has captured astronomers' attention for more than a century. The two main components Aa and Ab are two evolved O stars on a 350 years orbit. Aa is itself a SB1 with a 155-days period and a 0.3 eccentricity. Since Hipparcos, we know that a 1.28-days period eclipsing binary (EB) is hidden somewhere in Aa or Ab, but nowhere else. Our recent analysis finally disentangles the system. We calculated the visual Aa–Ab orbit from AstraLux imaging. We detected the SB2 nature of Aa based on STIS spectra, the companion of the O star (Aa1) being a B+B binary (Aa2 = Aa2a + Aa2b). Multiple lines of evidence point towards Aa2 being the EB: time delays in the eclipsing orbit detected by TESS, high mass for Aa2 from SB1 from constraints from the orbit of Aa1, and a lack of radial-velocity motion of Ab synchronised with the eclipsing orbit. This remains as a tentative conclusion pending further analysis. We detect secular changes in the SB1 orbit of Aa1 on a baseline longer than a century. At this stage, the effect is most likely caused by the change in velocity of the Aa center of mass due to the Aa–Ab visual orbit. Apsidal motion is most probably not the culprit.

Keywords. Binaries (including multiple): close, Binaries: spectroscopic, Binaries: eclipsing, Binaries: astrometric, Stars: early-type, Stars: individual: τ CMa, Stars: massive

† Deceased.

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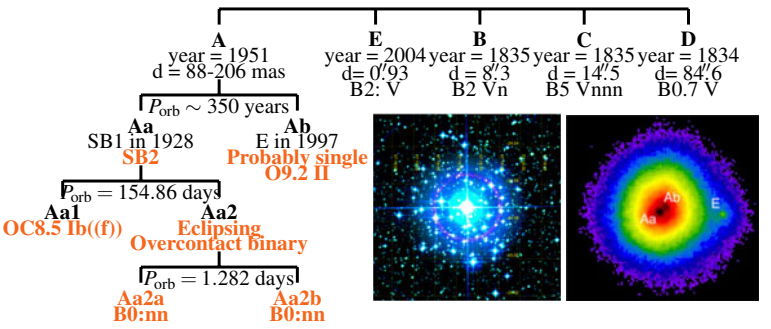


Figure 1. Hierarchy of τ CMa. Results of our analysis are in orange. First image: 3 channel DDS2 RGB image. Second image: AstraLux 3″ × 3″ cut-out of the region around τ CMa A.

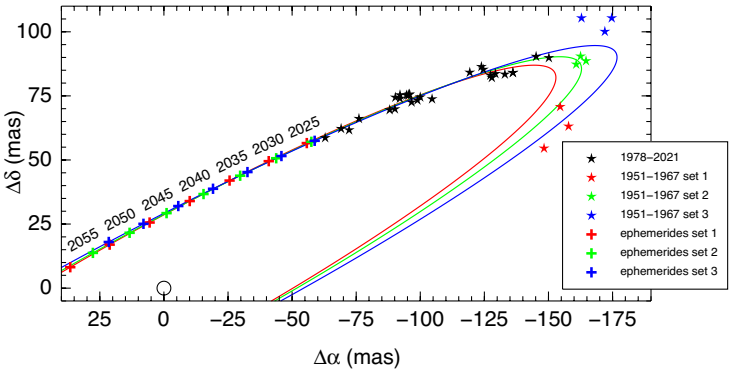


Figure 2. Visual orbit of Aa–Ab. Colours indicate three possible orbits based on different sets of data.

1. τ CMa: Stellar multiplicity does not have to be simple

τ CMa, located at the center of NGC 2362, is among the 15 brightest O-type systems in our sky. Its multiplicity is complex, as illustrated in Fig. 1. We combined astrometry (Sect. 2), spectroscopy (Sect. 3), photometry (Sect. 4), and three-body simulations (Sect. 5) to disentangle τ CMa A's, though more is to come (Sect. 6).

2. Astrometry: Long visual outer orbit Aa–Ab

We combined data from Maíz Apellániz & Barbá (2020) with new AstraLux and STIS data.

AstraLux lucky imaging. Data taken between 1951-1967 are incompatible with each others. We thus computed three possible orbits assuming $e = 0$ (see Table 1 and Fig. 2), and showed that the parameters $i, \Omega, M_{\rm Aa,Ab}, K_{\rm Aa,Ab}$ are well-constrained.

HST/STIS spectroscopy. Aa shows a broad component that moves in anti-phase with Aa1 (see Fig. 3). Thus, Aa is a SB2, with Aa2 a fast rotator. We determine the mass of Ab ~ $25 \pm 5\,M_\odot$ from the cluster age and its O9.2 II spectral type.

3. Spectroscopy: Intermediate orbit Aa1–Aa2

Radial velocity analysis. We combined 125 RVs spanning 117 years that we analysed as in Rosu et al. (2020, 2022a,b) to derive the orbital solution (Table 2). Newly

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Table 1. Three possible orbital solutions for Aa–Ab.

$P_{\rm orb}$ (yr)	T_0 (yr)	a (mas)	i (°)	Ω (°)	$M_{\rm Aa,Ab}$ ($M_\odot$)	$K_{\rm Aa,Ab}$ (km s^{-1})
306.8	1970.4	174.1	81.7	298.9	103.5	20.5
354.5	1960.9	184.5	82.1	298.3	92.3	18.8
408.7	1949.3	198.8	82.5	297.5	86.9	17.6

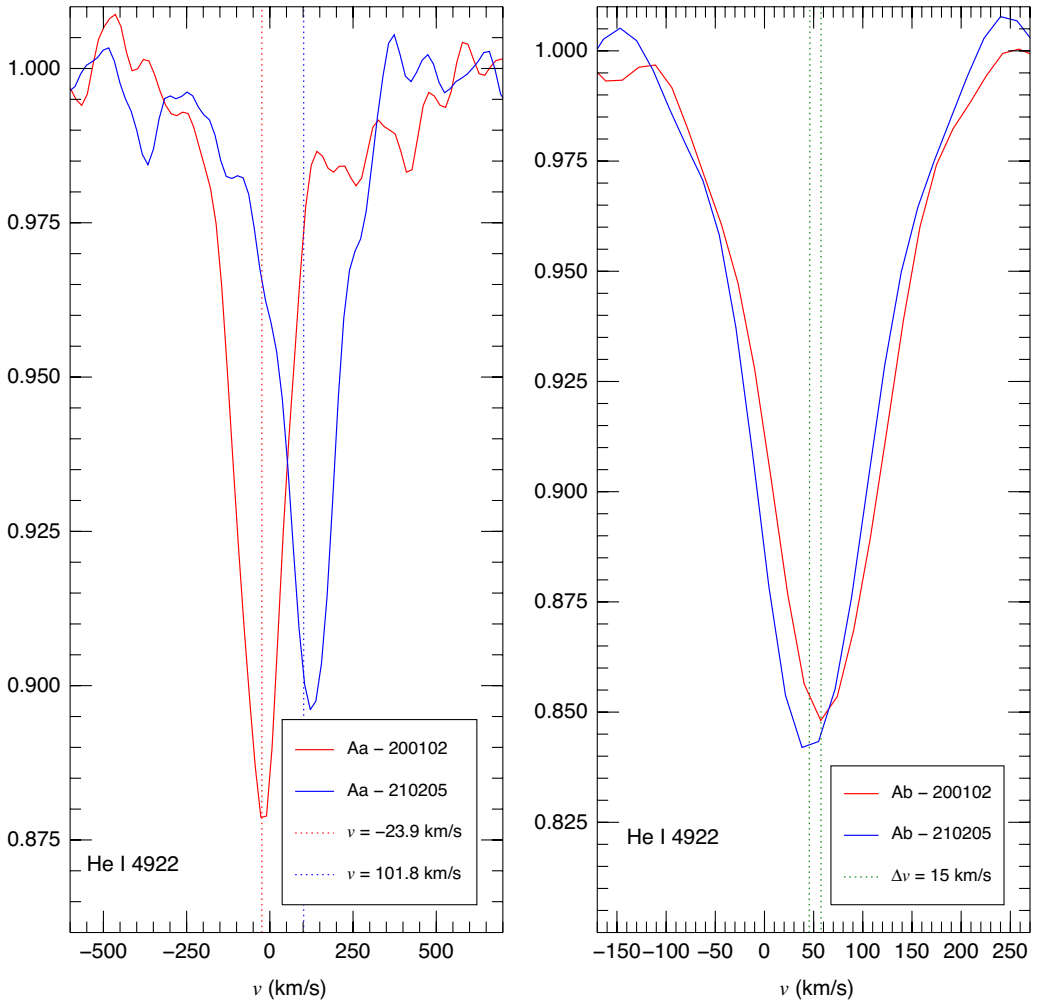


Figure 3. STIS spectroscopy: Aa (left) and Ab (right).

accumulated data were combined with data from Struve & Pogo (1928); Struve & Kraft (1954); Stickland et al. (1998), and LiLiMaRlin (Maíz Apellániz et al. 2019). Combining $M_{\rm Aa,Ab}$ with constraints on $\sin i_{\rm Aa1,Aa2}$ and $M_{\rm Aa2}/M_{\rm Aa1} \sim 1.0 - 1.5$, we deduced that the orbit is nearly edge on, and that $M_{\rm Aa1} \sim 30\,M_\odot$, and $M_{\rm Aa2} \sim 38\,M_\odot$. The only sign of Aa2 in the deconvolved spectra is under broad profiles in some lines, suggesting that Aa2 has early-B spectrum/spectra. Furthermore, the velocity amplitude of Aa2 is much lower than that of Aa1, thus $M_{\rm Aa2} > M_{\rm Aa1}$. It only works if Aa2 is made up of two early-B fast rotators of $\sim 19\,M_\odot$ each!

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Table 2. Orbital solution for Aa1–Aa2.

Parameter	Value
T_0 (HJD)	$2\,455\,098.3 \pm 0.4$
ω_0 (°)	84.3 ± 1.1
e	0.280 ± 0.005
$P_{\rm orb}$ (d)	154.900 ± 0.004
K_P (km s^{-1})	87.0 ± 0.5
$a_P \sin\, i$ ($R_\odot$)	1.189 ± 0.007
$M_P \sin^3 i$ ($M_\odot$)	9.34 ± 0.16
$\chi^2_{\rm red}$	0.89

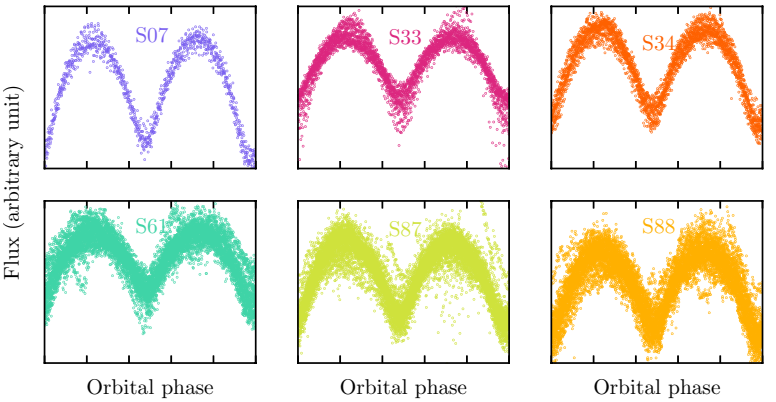


Figure 4. TESS light curves of the eclipsing binary.

Secular changes in the SB2 orbit of Aa1. Over the period 2004-2025, we detected a relative average acceleration of the center of mass of Aa with respect to Ab of 0.22 ± 0.06 km s^{-1} yr^{-1} that is consistent with the expectations of the visual Aa–Ab orbit if it is circular (Sect. 2), as well as a mass ratio between Ab and Aa of 1.00 ± 0.53 consistent with the expected one (within the large error bar). Most likely, and to the first author dismay, there is no apsidal motion.

4. Photometry: Short-period orbit Aa2a–Aa2b

TESS light curves of τ CMa reveal that the close eclipsing binary is an overcontact binary with a 1.282 days period (Fig. 4). Detailed analysis is ongoing to derive stars and orbital parameters.

5. Three-body simulations with TRES

We performed three-body simulations with TRES (Toonen et al. 2016; Sciarini et al. 2025) to assess whether Aa2a–Aa2b (Case 1, Fig. 5, left panel) and/or Ab (Case 2, Fig. 5, right panel) could be (partly) responsible for an apsidal motion in Aa1–Aa2.

Case 1. We considered the triple system Aa1–(Aa2a–Aa2b). If the mutual inclination $i_{\rm mut}$ between the two orbits is 0°, the apsidal motion rate $\dot{\omega}$ amounts to $\sim 3.1°$ yr^{-1}, while if $i_{\rm mut} = 180°$, $\dot{\omega} \sim -2.2°$ yr^{-1}. These are the two extreme cases; any other $i_{\rm mut}$ leads to a value for $\dot{\omega}$ intermediate between 3.1 and $-2.2°$ yr^{-1}.

Case 2. We considered the triple system (Aa1–Aa2)–Ab. Whatever $i_{\rm mut}$, $\dot{\omega} \leq 0.002°$ yr^{-1}. Should an apsidal motion be measured in Aa1–Aa2, would Aa2a–Aa2b be the culprit, not Ab.

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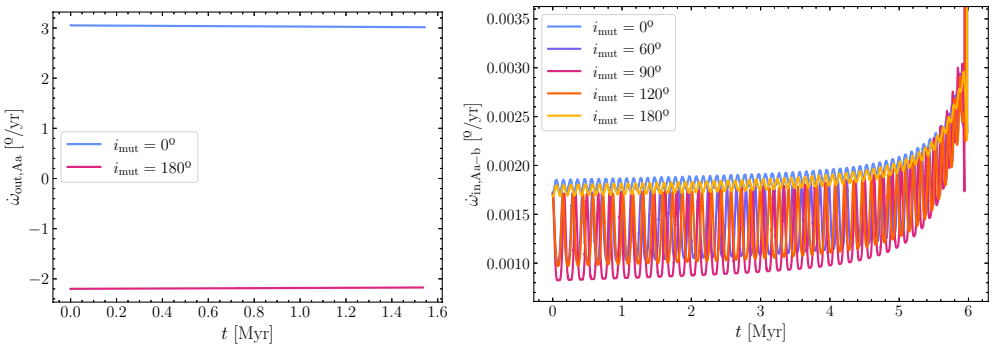


Figure 5. TRES simulations: $\dot{\omega}$ in Aa1–Aa2 if induced by Aa2a–Aa2b (left) or Ab (right) for different $i_{\rm mut}$.

6. What we still do not know but will soon

Our analysis of τ CMa A allowed us to unravel its mystery. Yet, it remains to perform a quantitative spectroscopic analysis of its components Aa1, Aa2a, Aa2b, and Ab to derive the effective temperatures and luminosities of the stars as well as their surface chemical abundances and wind properties. Furthermore, the origin of the secular changes of the SB1 Aa1–Aa2 orbit as well as the properties of the overcontact binary Aa2 are still to be determined.

Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S1743921325103815

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