



Apsidal Motion in Binaries: Probing the Interiors of Stars Using Tides [†]

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Abstract

The apsidal motion in close eccentric binaries is a means to unveil the internal structure of stars. We make use of it to test the internal mixing processes in stars with the stellar evolution code GENEC. Apsidal motion is the slow precession of an eccentric orbit with time. Its rate depends on the tidal interactions that occur between the stars through k_2 , a measure of the star's inner density profile. The apsidal motion rate is commonly derived from the eclipses' times of minima, made possible thanks to high-precision TESS/Kepler observations. We propose an innovative approach: derive the apsidal motion rate from radial velocities obtained over a long timescale combined with light curves to obtain high-accuracy consistent physical and orbital parameters for the binaries. We highlight recent results concerning the most massive binary studied this way. Confronted to observations of massive stars, standard non-rotating single-star models usually predict stars with too low a density contrast; the so-called k_2 -discrepancy. We built bespoke GENEC stellar evolution models including tidally induced/suppressed rotational mixing for the twin massive binary HD152248. The models reveal the instabilities that allow us to reproduce the stellar density profiles. A large overshooting is necessary to converge towards the observed k_2 in both purely hydrodynamic and magneto-diffusive models. While a change in metallicity or mass-loss rate has no significant impact on k_2 , a large initial helium abundance allows us to better reproduce k_2 . However, is not observationally supported. These analyses highlight the need for a process in the stars that extends the size of the convective core. It paves the way for the next generation of stellar models.

Keywords: stars; early-type; evolution; massive; rotation; binaries: close; eclipsing; spectroscopic



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1. Introduction

Massive stars are the building blocks of the universe: their radiation-driven winds and supernova explosions enrich their host galaxies in newly formed chemicals and contribute to their reionisation [1]. Massive stars are predominantly found in binaries or higher-multiplicity systems [2,3]. Stars in binaries follow much more complex pathways than their single-star counterparts: their evolution can be affected by tidal interactions and mass transfer between the stars, leading to a diversity of evolutionary sequences [4–6]. Current uncertainties in the predictions of post-main sequence evolution [7], pre-supernova structure, and core-collapse outcome [8,9] are mainly caused by the treatment, in stellar

models, of convective boundary mixing (through, e.g., overshooting, semi-convection) [10] and internal mixing processes responsible for the transport of angular momentum and chemicals in stars. Over the last few decades, an upward revision of the convective boundary mixing in massive stars has been called for by several independent studies in order to reproduce a variety of stars' properties [11–21]. In this paper, we present the apsidal motion in a binary system as a powerful tool to probe the interiors of stars and constrain the overshooting parameter.

2. Apsidal Motion

In the purely Keplerian problem of two point-like stars orbiting each other on an eccentric orbit, only the position of the stars on their orbit—measured through the true anomaly ϕ —changes over time (see Figure 1a). In reality, stars have a three-dimensional shape and exert tides on each other. These tidal interactions are responsible for the exchange of angular momentum in the binary system. Due to stellar deformations, the gravitational potential of the stars is not spherically symmetric anymore [22,23]. The most prominent consequence of these tides is the slow precession of the line of apsides with time, measured through the longitude of periastron ω (see Figure 1b) [24]. This motion is purely non-Keplerian and the ensuing rate of apsidal motion is referred to as Newtonian. General relativistic effects also contribute to the total apsidal motion rate [24–26]; yet these are, in most systems, of much lower contribution than the Newtonian contribution [27–34].

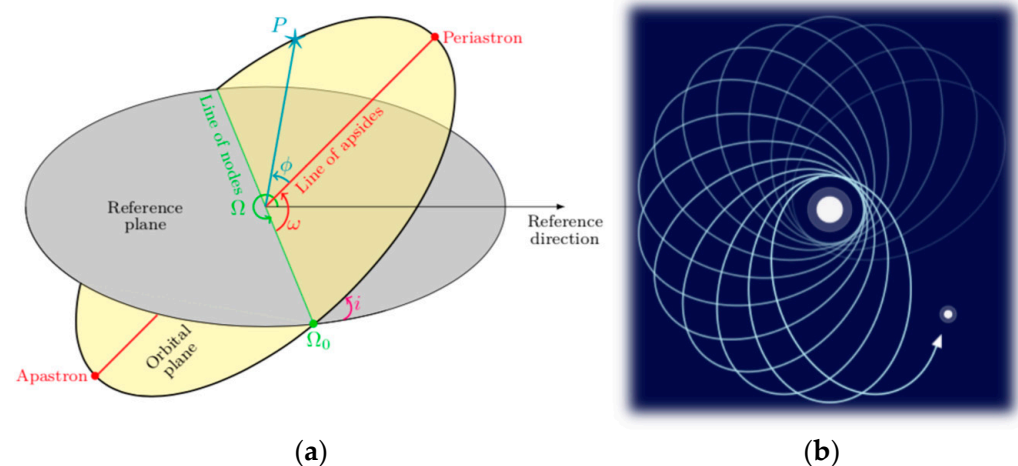


Figure 1. (a) Definition of the orbital elements of a binary. Both the argument of periastron ω and the true anomaly ϕ are measures in the orbital plane. (b) Schematic illustration of the apsidal motion.

The apsidal motion rate is traditionally determined from the light curves of an eclipsing binary, or equivalently, from the times of minima of the eclipses [34]. Indeed, both the depth and phase of eclipses depend upon the orbital separation at the conjunction phase, which is itself dependent on the orientation of the ellipse with respect to the line of sight; that is to say, ω . Figure 2a illustrates this and shows nine theoretical light curves computed with different values of ω , with all other parameters remaining identical. These light curves were computed assuming a twin system in which both stars share the same exact properties in terms of, e.g., mass, radius, and effective temperature. The difference in depths of the eclipses is thus not attributable to a difference in temperature between the stars. Phase 0 of the eclipses is set at primary eclipse. For the range of ω values shown, the primary eclipse happens close to the periastron passage; hence, the stars are closer and the eclipse is deeper than the secondary eclipse happening closer to the apastron passage.

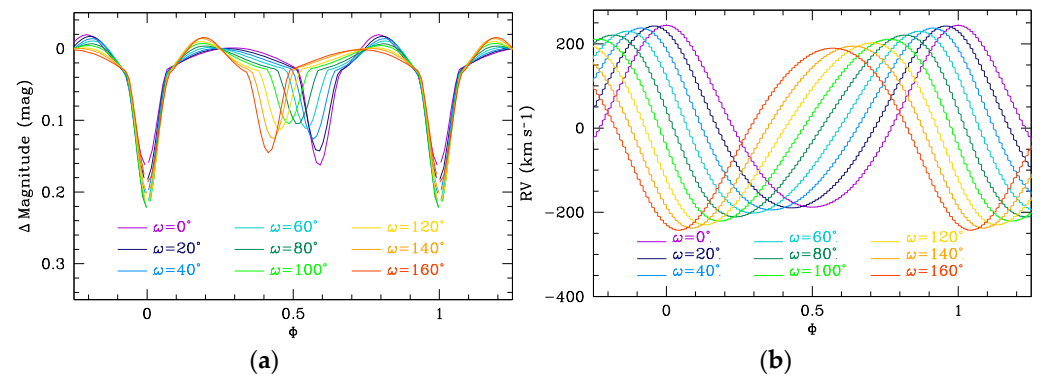


Figure 2. (a) Theoretical light curves for different values of ω , with all other parameters identical. Figure from [35]. (b) Theoretical radial velocity curves for the same models as in (a).

Alternatively, the apsidal motion rate can be derived from the stars' radial velocities provided that the binary is a single- or double-lined spectroscopic system for which spectral lines of the primary or both stars are observed. Figure 2b illustrates the impact of a change in ω on the radial velocity curve for the same parameters as in Figure 2a.

The combination of the two methods allows us to derive consistent apsidal motion rates as well as stellar and orbital properties [36–39]. This is illustrated for the twin massive binary HD152248 in Figure 3, with all properties summarised in Table 1.

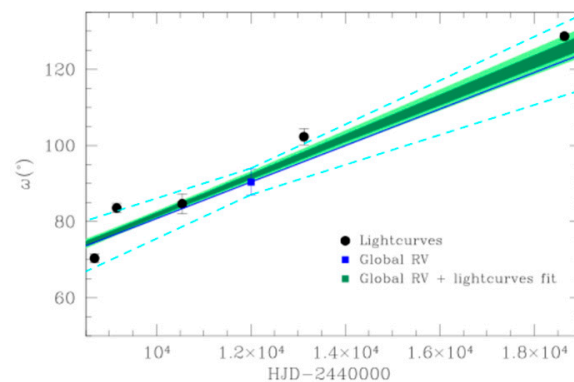


Figure 3. Longitude of periastron ω as a function of time from radial velocities and light curves of HD152248. © Adapted from [36].

Table 1. Observational stellar and orbital parameters of the massive binary HD152248 [36].

Parameter	Symbol (Unit)	Value
<i>Stellar</i>		
Mass	M_* ($M_\odot$)	29.5 ± 0.5
Radius	R_* ($R_\odot$)	15.07 ± 0.12
Effective temperature	$T_{\text{eff},*}$ (K)	$34,000 \pm 1000$
Bolometric luminosity	$L_{\text{bol},*}$ ($L_\odot$)	$2.73 \pm 0.32 \times 10^5$
Internal stellar structure constant	$k_{2,*}$	0.0010 ± 0.0001
Surface velocity	$V_{\text{surf},*}$ (kms $^{-1}$)	149 ± 12
Mass-loss rate	$\dot{M}_*$ ($M_\odot \text{yr}^{-1}$)	$\leq 8 \times 10^{-7}$
Nitrogen abundance	N/H_* (nb)	1.24 ± 0.98
<i>Orbital</i>		
Period	P_{orb} (d)	5.816498 ± 0.000018
Semi-major axis	a ($R_\odot$)	53.0 ± 0.3
Eccentricity	e	0.130 ± 0.002
Apsidal motion rate	$\dot{\omega}$ ($^\circ \text{yr}^{-1}$)	1.843 ± 0.083

3. Internal Stellar Structure Constant

The apsidal motion rate equation reduces, for twin systems, to the following expression:

$$\dot{\omega} = \frac{4\pi k_{2,*}}{P_{orb}} \left(\frac{R_*}{a} \right)^5 \left[15f(e) + 2g(e) \frac{P_{orb}^2}{P_{rot,*}^2} \right] + \left(\frac{2\pi}{P_{orb}} \right)^{5/3} \frac{3(2GM_*)^{2/3}}{c^2(1-e^2)}, \quad (1)$$

where $f(e)$ and $g(e)$ are function of the eccentricity defined in [40], G is the gravitational constant, c is the speed of light, and other parameters are defined in Table 1. The first and second terms in Equation (1) are the Newtonian and general relativistic contribution, respectively [24]. The internal stellar structure constant

$$k_{2,*} = \frac{3 - \eta_2(R_*)}{4 + 2\eta_2(R_*)}, \quad (2)$$

is a function of η_2 , the logarithmic derivative of the surface harmonic of the distorted star, function of the ellipticity, and solution of the Clairaut–Radau differential equation

$$r \frac{d\eta_2(r)}{dr} + \eta_2^2(r) - \eta_2(r) + 6 \frac{\rho(r)}{\bar{\rho}(r)} (\eta_2(r) + 1) - 6 = 0 \quad (3)$$

evaluated at the stellar surface R_* with the boundary condition $\eta_2(0) = 0$ [41]. In Equation (3), r is the radial distance from the core to R_* , $\rho(r)$ is the density in a shell at radius r , and $\bar{\rho}(r)$ is the density in a sphere of radius r .

The k_2 is thus a measure of the density stratification inside the star. It takes its maximum value of 0.75 for a homogenous sphere. As a massive star evolves, its core contracts while its envelope expands; its k_2 consequently decreases. The k_2 is thus a good indicator of stellar evolution [40,42].

4. The k_2 Discrepancy: GENEC Stellar Evolution Models

Over the last decade, several studies have highlighted what we call the k_2 -discrepancy between models and observations for massive stars. Models systematically predict larger k_2 values than those determined from observations [30,37,40]. This means that models predict stars with a lower density contrast between their core and external layers than what observations suggest. This k_2 -discrepancy is observed in massive stars only; their less massive counterparts do not suffer from this problem [30]. We investigated this discrepancy in HD152248 with the GENeVa stellar Evolution Code (GENEC) [43].

4.1. GENEC: Input Physics

We computed GENEC stellar evolution models adopting two different prescriptions for the transport of angular momentum in stars: purely hydrodynamic (hydro) [44] and magneto-diffusive (magnetic) models [45]. We computed both single- and binary-star models. The latter include dynamical tides and equilibrium tides of small subsurface convective zones [46–48]. We adopted the mass-loss rate $\dot{M}$ of [49] as it is best at reproducing observed stars in this temperature regime [50,51]. We adopted the NACRE II reaction rates [52] and a metallicity $Z = 0.0183 \pm 0.0032$ as estimated for the NGC 6231 cluster to which HD152248 belongs [53]. The initial helium abundance is not observationally constrained. We adopted the solar value. We varied the overshooting parameter α_{ov} from 0.5 to 1.4. We set the initial mass M_{ini} of the star such that the mass of the model when it reaches the observed radius equals the observed mass. For single-star models, we set the initial velocity of the models such that the surface velocity of the model that reproduces the radius is equal to the observed surface velocity. For binary-star models, we initialised the star synchronised with the orbital motion.

4.2. Single- or Binary-Star Models? The Impact of Tidal Locking

We show in Figure 4 the evolution of the k_2 , mass, effective temperature, age, surface velocity, and angular surface velocity Ω_{surf} as a function of radius for single- and binary-star models with $\alpha_{ov} = 0.5$. For a thorough discussion of the interplay between rotation velocity and overshooting, we refer to [54]. If single-star models are apparently better at reproducing the current properties of the stars, it is because we chose their initial velocity such that it is the case; that is to say that $V_{surf}(R_*) = V_{surf,*}$. The velocity evolution of a single-star model is driven by stellar evolution: Ω_{surf} decreases with time while the stellar radius increases with time. V_{surf} is thus roughly constant over time. In reality, in a binary system, the star has a companion and its Ω_{surf} is fixed by the orbital motion. The binary is pseudo-synchronised, so Ω_{surf} is roughly constant over time. The angular velocity evolution is driven by tides and V_{surf} increases with time following the increase in the stellar radius. When $R = R_*$, both models have $\Omega_{surf} = \Omega_{surf,*}$ and $V_{surf} = V_{surf,*}$, but the binary-star model saw its Ω_{surf} and V_{surf} lower during the whole evolution. The binary-star model thus has had less mixing throughout its evolution; hence, its k_2 is larger when $R = R_*$. In conclusion, single-star models are not better at reproducing the properties of the stars, as they do not properly capture the evolution of the stars. Binary interactions need to be accounted for to correctly predict the evolution of a close binary such as HD152248.

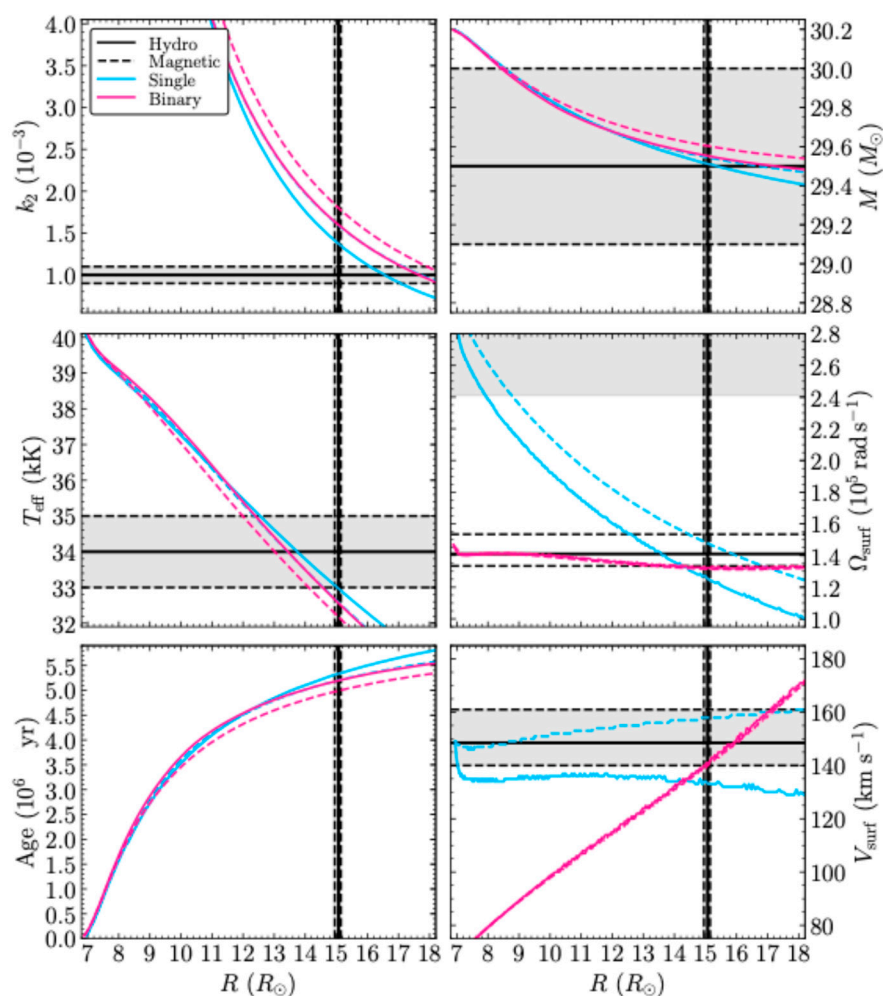


Figure 4. Evolution of stellar parameters with stellar radius for hydro and magnetic single- and binary-star models. Models have $M_{ini} = 30.2 M_{\odot}$, $\alpha_{ov} = 0.5$, $Z = 0.0183$, and $\dot{M}$ from [49]. Observational values and their error bars are shown (plain black lines and shaded grey area).

4.3. Binary-Star Models!

We show in Figure 5 the evolution of stellar parameters for binary-star models with α_{ov} ranging from 0.5 to 1.4. We observe that a larger α_{ov} of at least 1.2–1.3 is necessary to reproduce the properties of the stars, including their k_2 . It is justified as follows: a larger α_{ov} implies a larger convective core, and hence more fuel for burning and an extension of the main-sequence lifetime. The model is older when it reaches R_* and thus has had more time to contract its interior and extend its envelope. Consequently, its k_2 is smaller. Figure 6 shows the density profile and density function, defined as Equation (5) in [54] inside models with $R = R_*$ and $\alpha_{ov} = 0.5$ and 1.4. Models with $\alpha_{ov} = 1.4$ have a more extended and overall denser core and a more diluted envelope than their $\alpha_{ov} = 0.5$ counterpart.

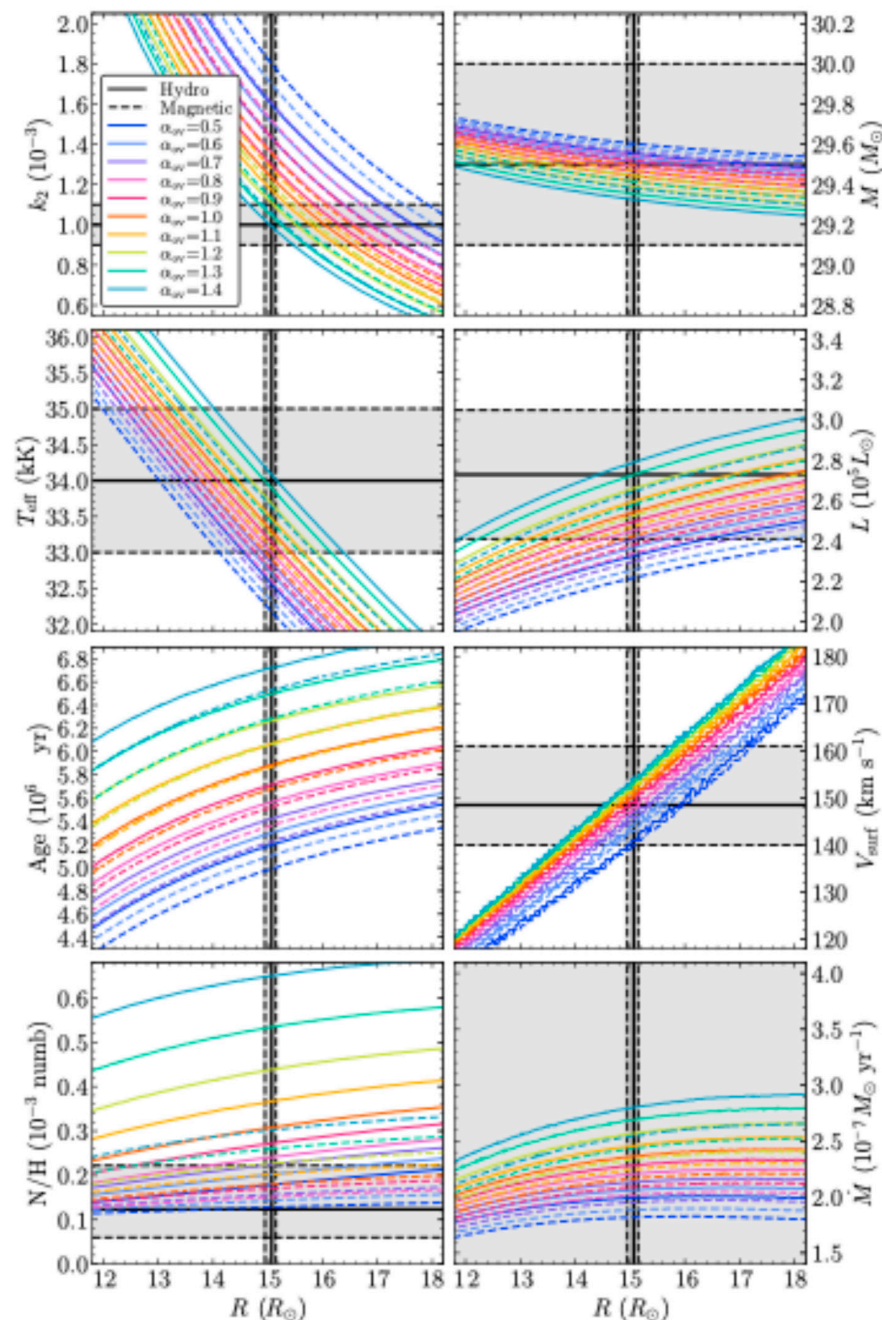


Figure 5. Evolution of stellar parameters with stellar radius for hydro and magnetic binary-star models for different α_{ov} values. Observational values and their error bars are shown (plain black lines and shaded grey area). Adapted from [54].

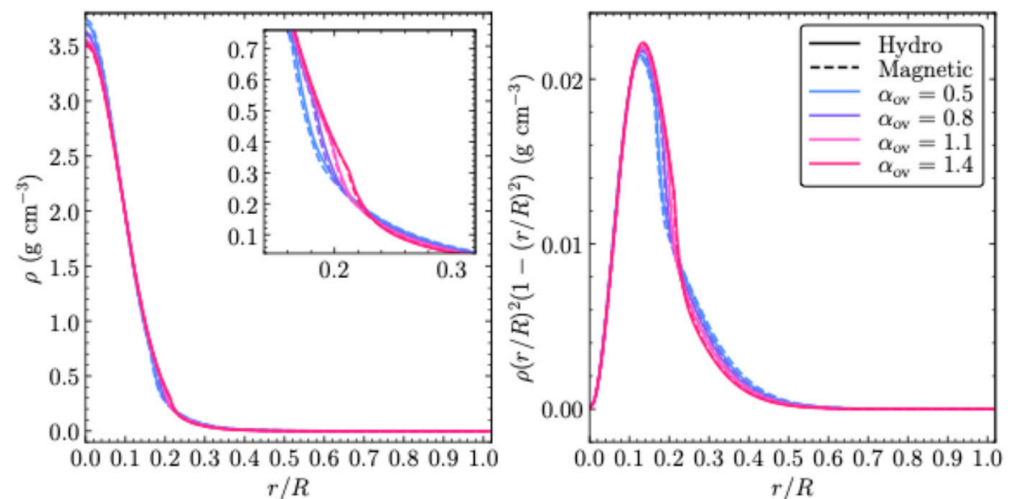


Figure 6. Density profiles and density function in binary-star models as a function of the normalised radial distance in the star for different α_{OV} values.

We investigated the impact of the mass-loss rate prescription on the results. The winds of massive stars are clumped. If the clumping starts close to the photosphere, theoretical mass-loss rates are underestimated by a factor $f^{0.25}$ with $f = 8$ – 10 . We computed binary-star models adopting the Krucka mass-loss rate multiplied by a factor of 1.8 (clumped models). This mass-loss rate should be an upper limit on possible mass-loss rates [55]. The initial mass of the models was set to a slightly larger value of $32.0 M_{\odot}$. The comparison between clumped and standard models is shown in Figure 7. Clumped models, due to their slightly larger initial mass, evolve at a larger effective temperature and luminosity. Yet the evolution of their k_2 is identical to that of standard models. Indeed, while the star sees its k_2 decreasing faster because it is initially more massive, it reaches R_* earlier, meaning that it does not have time to evolve as much as the standard model, which compensates the faster decrease in k_2 . In conclusion, even if the mass-loss rate is underestimated, it has no significant impact on the parameters evolution, and a α_{OV} of at least 1.2–1.3 is still necessary to reproduce the stellar properties, including k_2 . It demonstrates that k_2 is probing the interiors of stars and is not significantly sensitive to the stars' atmosphere, making the apsidal motion a powerful technique for probing stellar interiors.

We tested the impact of various input parameters on the evolution of the stars: the initial mass, metallicity, and initial helium abundance. None of the parameters had a significant influence on the evolution of stellar parameters except for the initial helium abundance. However, a very large initial abundance was required to reproduce the observed properties of the stars, which is not observationally supported.

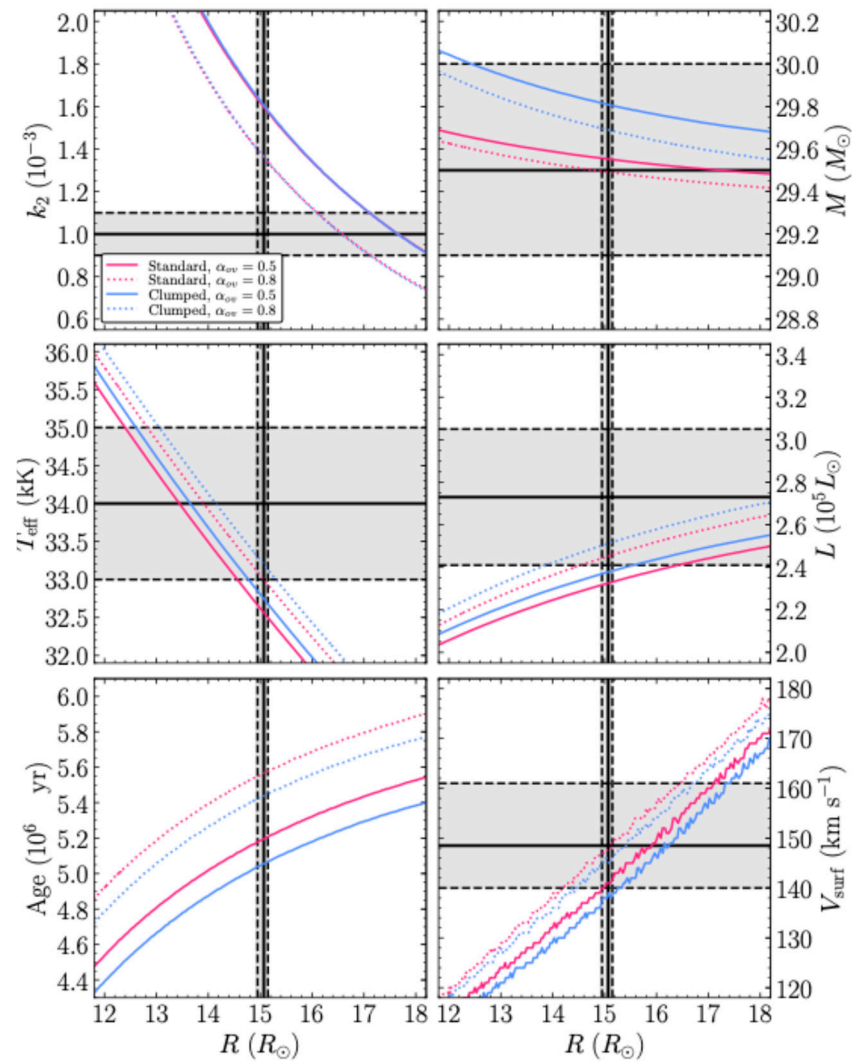


Figure 7. Evolution of stellar parameters with stellar radius for hydro binary-star models for standard and clumped models. Observational values and their error bars are shown (plain black lines and shaded grey area).

5. Conclusions

The observed apsidal motion in the twin massive binary HD152248 was used to probe the interiors of the stars and constrain convective boundary mixing. We built single- and binary-star evolution models with GENEC adopting two different prescriptions for the transport of angular momentum: purely hydrodynamic and magneto-diffusive models. In addition to the overshooting, measured through α_{ov} , we investigated the impact of initial mass, mass-loss rate, metallicity, initial helium abundance, and mixing-length parameter on the evolution of stellar parameters, including the internal stellar structure constant k_2 . We demonstrated that it is crucial to take into account binary interactions through tides in short-period systems as HD152248 as the stellar angular velocity quickly synchronises with the orbital motion. Mixing is thus reduced in binary-star models compared to their single-star counterparts. We showed that standard models computed with a moderate value of α_{ov} systematically overpredict k_2 , a result referred to as the k_2 -discrepancy. Only models with α_{ov} larger than 1.2–1.3 reproduce all stellar parameters, including k_2 . Other parameters have a limited impact on the results. The necessary large overshooting points toward the need for more efficient core boundary mixing in massive stars. Whether it is

strictly an extension of the convective core or/and a strong mixing in the radiative envelope close to the core is under investigation.

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