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Apsidal motion in massive binaries: or how to sound stellar interiors

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Abstract. One of the most efficient and reliable observational technique allowing to probe the internal structure of a star is the determination of the apsidal motion in close eccentric binary systems. This secular precession of the binary orbit's major axis depends on the tidal interactions occurring between the two stars. The rate of this motion is directly related to the internal structure of the stars, in particular their inner density profile.

The most common way to derive the apsidal motion of a binary from observations, together with the fundamental parameters of the stars, is the analysis of the times of minima of the eclipses. While this technique has been used for decades, it returned to popularity lately thanks to the incredible precision of observations acquired with space-borne facilities such as TESS and Kepler, among others. Aside, a less common – but not less accurate though – method to determine a binary's apsidal motion rate is through the fit of the stars' radial velocity curves as a function of time. This technique relies on radial velocities collected over a (very) long timescale. While it points out the utility of gathering spectroscopic data of the same object over several decades, requiring dealing with the tricky task of combining and simultaneously analysing data from a variety of Earth-based instruments having their own characteristics each, it also gives old spectroscopic observations a second lease of life.

But what do you think if we decide to simultaneously and consistently analyse both spectroscopic and photometric data, that is to say, all available data of the same binary, rather than ignoring part of them? This challenging objective comes with a real deserved reward: consistent physical and orbital parameters for the binaries, including the apsidal motion rate, are obtained with unprecedented accuracy. The confrontation of the observationally determined parameters to theoretical models of stellar structure and evolution then allows us to finely constrain the internal structure of the stars.

This powerful technique has been known for years but has been seldom applied to massive stars. I will highlight its interest and reveal recent results concerning several massive binaries.

While standard 1D stellar evolution models predict stars having a smaller internal stellar structure constant, that is to say, stars having a smaller density contrast, than expected from observations, I demonstrate that the addition of mixing inside the models helps to solve, at least partially, this discrepancy. Whether this additional mixing might be fully explained by rotational mixing is under investigation. Ongoing studies with the non-perturbative code `MoBiDICT` show that the perturbative model assumption is not justified in highly distorted stars, in which cases the apsidal motion is underestimated, exacerbating even more the need for enhanced mixing inside the models.

Key words: stars: early-type – stars: evolution – stars: massive – binaries: eclipsing – binaries: spectroscopic

1. The origin of the apsidal motion

In the Keplerian problem, the two stars of a binary, assumed to be point-like particles, orbit one another on elliptic orbits which maintain a constant orientation in space over time; Only the true anomaly (the positions of the stars on their orbit) changes with time (see Fig. 1). While this two-body problem is arguably valid for wide eccentric binaries, it is inappropriate for close eccentric binaries as the three-dimensional extension of the stars cannot be ignored. The stars exert on one another tidal forces which are responsible for the exchange of angular momentum in the system as well as the stellar deformations and the ensuing non-spherical gravitational fields of the stars. The major observable consequence of these tidal interactions on the orbital motion is the apsidal motion, that is to say, the precession of the line of apsides with time (see Fig. 1). I here insist upon the fact that this motion is a purely Newtonian (i.e. non-Keplerian) motion. It should not be mistaken with the relativistic apsidal motion which contributes to the total rate of apsidal motion in a binary system though, but is of minor importance for most binaries.

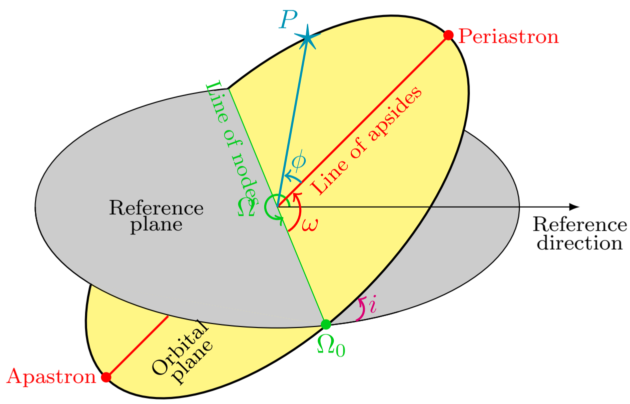

Figure 1. Definition of the orbital elements of a binary system.

Although relatively small, on the order of a few degrees per year, this apsidal motion has been measured in hundreds of binaries. I here refer to Rosu et al. (2024, figure 2), Hong et al. (2016, figure 6), and Zasche et al. (2020, figure 15) for the most up-to-date sample of binaries in our Galaxy, the Large and Small Magellanic Clouds, for which an apsidal motion determination exists in the literature.

I explain how we can measure the apsidal motion rate in a binary and illustrate it by one well-chosen specific case in Sect. 2. In Sect. 3, I introduce the apsidal motion equations and their link to the internal stellar structure constants. In Sect. 4, I show how to use these latter to sound the interior of stars through the confrontation of observationally-determined stellar and orbital parameters with dedicated 1D stellar structure and evolution models as well as 3D non-perturbative models. I review the study of the apsidal motion in (massive) binaries in Sect. 5.

2. From observations to the apsidal motion determination

The determination of the apsidal motion rate $\dot{\omega}$ is made following two different approaches (see Rosu, 2024, for a more careful explanation):

1. In an eclipsing binary, both the depths of the eclipses and their phase depend upon the orbital separation at conjunction phase that itself depends on the orientation of the ellipse with respect to our line of sight, that is to say, to ω. The adjustment of a set of lightcurves and/or times of minimum of the eclipses taken at different epochs therefore allows the determination of $\dot{\omega}$;

2. In a spectroscopic binary, the stars' radial velocities (RVs) depend upon $\cos\omega(t)$. The adjustment of the RV curves explicitly accounting for the linear rate of change of ω allows us to derive a value for $\dot{\omega}$.

While the former technique, thanks to the high-quality photometric data such as TESS, allows the determination of accurate apsidal motion rates using much shorter timespans than the decades of observations necessary for the RV adjustments, this latter technique turns out to be more powerful and accurate provided sufficient data are available (Rauw et al., 2016; Rosu, 2022; Rosu et al., 2020b, 2022a,b, 2023). Among all binaries, the short-period eccentric eclipsing double-line spectroscopic binaries for which photometric, spectroscopic, and RV data are available, are the most promising and intrinsically invaluable systems. Not only they are the only ones for which we can constrain the stars' fundamental properties (masses, radii) in a model independent way, but also their apsidal motion rate is used to probe the internal structure of the stars (see Sect. 3). Examples of such binaries are HD 152248 and HD 152219: Rosu et al. (2020b) and Rosu et al. (2022a) derived $\dot{\omega} = 1.84 \pm 0.08^\circ\,\mathrm{yr}^{-1}$ and $\dot{\omega} = 1.198 \pm 0.300^\circ\,\mathrm{yr}^{-1}$, respectively, based on the global adjustment of the RVs and lightcurves of the system (see Figs 2 and 3).

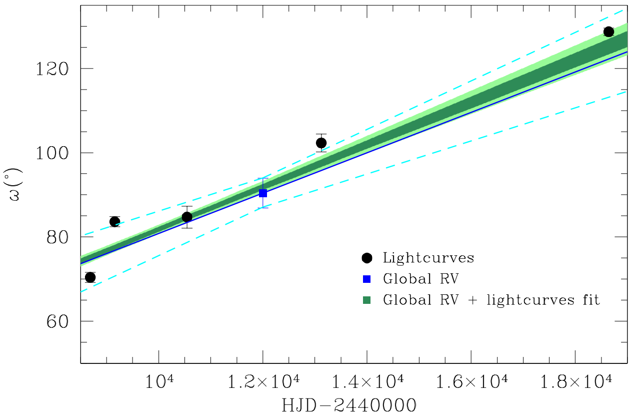

Figure 2. Values of ω as a function of time inferred from the RVs (blue and cyan), lightcurves (black), and both simultaneously (green) of HD 152248. Credit: Rosu et al. (2020b), reproduced with permission ©ESO.

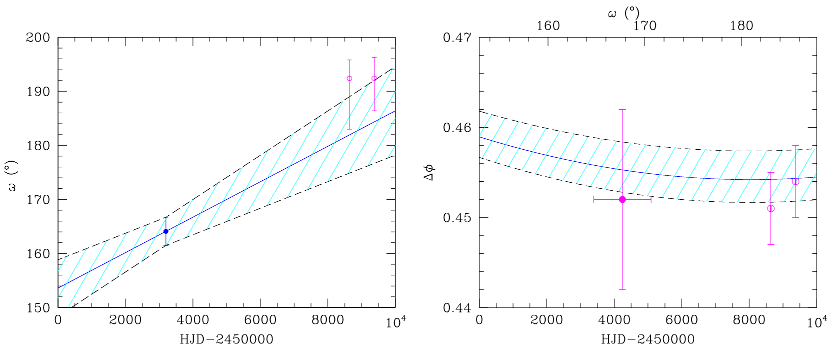

Figure 3. *Left panel:* Values of ω (left panel) and the phase difference $\Delta\phi$ between the primary and secondary eclipses (right panel) as a function of time inferred from the RVs (blue and cyan) and lightcurves (pink) of HD 152219. Figures from Rosu et al. (2022a).

3. Apsidal motion equations and internal stellar structure constants

In the perturbative case, the apsidal motion rate of a binary is the sum of the Newtonian contribution $\dot{\omega}_{\rm N}$ and a general relativistic correction $\dot{\omega}_{\rm GR}$. The Newtonian term has the following expression according to Sterne (1939) under the assumption that only the contributions arising from the second-order harmonic distorsions of the gravitational potential are considered:

$$\begin{aligned}\dot{\omega}_{\rm N} =&\frac{2\pi}{P_{\rm orb}}\left[15f(e)\left\{k_{2,1}q\left(\frac{R_1}{a}\right)^5+\frac{k_{2,2}}{q}\left(\frac{R_2}{a}\right)^5\right\}\right.\\ &\left.+g(e)\left\{k_{2,1}(1+q)\left(\frac{R_1}{a}\right)^5\left(\frac{P_{\rm orb}}{P_{\rm rot,1}}\right)^2+k_{2,2}\,\frac{1+q}{q}\left(\frac{R_2}{a}\right)^5\left(\frac{P_{\rm orb}}{P_{\rm rot,2}}\right)^2\right\}\right].\end{aligned} \tag{1}$$

In this expression, $q = m_2/m_1$ is the mass ratio, $P_{\rm orb}$ is the orbital period of the system, a is the semi-major axis of the orbit, R_* the radius, $k_{2,*}$ the internal structure constant, and $P_{{\rm rot},*}$ the rotational period of the considered star, and $f(e)$ and $g(e)$ are functions of the eccentricity of the orbit which expressions are given in e.g., Rosu (2021). The expression of $\dot{\omega}_{\rm GR}$ is attributed to Shakura (1985) and depends on $P_{\rm orb}, e, m_1$, and m_2.

The internal stellar structure constant k_2 is an algebraic expression of the η_2 function evaluated at the stellar surface, itself solution of the Clairaut-Radau differential equation (Hejlesen, 1987) that depends on the density profile inside the star (see Rosu, 2024, for more details). In a nutshell, k_2 is a measure of the density stratification between the core and the external layers of the star: The higher the k_2, the more homogeneous the star in terms of density ($k_2 = 0.75$ for an homogeneous sphere of constant density); On the contrary, the smaller the k_2, the higher the radial density gradient inside the star. As the star evolves, its k_2 decreases as the stellar core contracts while the stellar envelope expands. This renders k_2 a good indicator of stellar evolution just like the hydrogen mass fraction in the stellar core (see figures 12 and 15 in Rosu et al., 2020a).

In the apsidal motion equation, all terms appearing in the expressions of $\dot{\omega}_{\rm N}$ and $\dot{\omega}_{\rm GR}$ can be derived from observations, except for $k_{2,1}$ and $k_{2,2}$. In the case of a twin system, meaning both stars share the same properties in terms of mass, radius, and effective temperature, we can assume the stars also share the same density profile, so the same k_2. In this lucky case, we can solve the apsidal motion equation for k_2 and get an observational determination for this latter quantity. In the general case of a non-twin system, the situation is slightly more complex; I refer to Rosu et al. (2022a,b); Rosu (2024) for a thorough discussion and analysis of these cases. For the sake of this paper, I will focus on twin binaries only, with a particular attention to HD 152248 (Rosu et al., 2020a,b; Fellay et al., 2024).

4. Without enhanced mixing in the models, impossible to reproduce the observations... even in 3D

Dedicated stellar structure and evolution models were built for HD 152248 using the `Clés` code (Scuflaire et al., 2008) and its `min-Clés` routine to search for best-fit models of the stars in terms of observational properties using the Levenberg-Marquardt minimisation technique (Rosu et al., 2020a). Overshooting was implemented in the models as a step-function through the overshooting parameter α_{ov} while additional mixing was introduced through the turbulent diffusion implemented as a partial mixing process with velocities of the elements being the product of the turbulent diffusion coefficient D_T to the radial abundance gradient of the element. As such, the turbulent diffusion acts as reducing the abundance gradient of the elements. Both the overshooting and the turbulent diffusion increase the main-sequence lifetime of the stars as they bring additional hydrogen from the external layers to its core, hence fuel for nuclear reactions. Rosu et al. (2020a) showed that including overshooting in their models but no turbulent diffusion did not allow the simultaneous reproduction of the stellar mass, radius, and position in the Hertzsprung-Russell (HR) diagram of HD 152248 (see dotted purple track in Fig. 4). Indeed, to reproduce these observational parameters, the authors had to introduce a certain amount of turbulent diffusion and this, especially as the overshooting was small (see dashed green track in Fig. 4). However, the best-fit models obtained this way had systematically too high a k_2 value. Rosu et al. (2020a) further showed that to reproduce the apsidal motion rate and the k_2 of the stars in addition to the previously mentioned parameters, they had to introduce even more mixing in the models (see orange track in Fig. 4). That the standard models predict stars that are too homogeneous in terms of density stratification compared to what is expected from the observations is a key result that could not be achieved for this system without the study of the apsidal motion. At this juncture, it is of primordial importance to understand the physical origin of this required enhanced mixing required in the models. Rosu et al. (2020a) built stellar evolution models with the `GENEC` code (Eggenberger et al., 2008) including stellar rotation and suspected from their preliminary study that rotationally induced mixing is certainly the key, though further investigations are needed and ongoing.

We here note that these results were corroborated using the same method for the massive binaries HD 152219 (Rosu et al., 2022a), and CPD-41° 7741 and HD 152218 (Rosu et al., 2022b), and independently using 2D hydrodynamical simulations for these three binaries (Baraffe et al., 2023).

Whether this need of enhanced mixing in the models is due to the inherent 1D stellar modelling is a question worth asking, and answering. We used the `MoBiDICT` (Modelling Binaries Deformations Induced by Centrifugal and Tidal forces) code (Fellay & Dupret, 2023), a non-perturbative method that computes the entire precise 3D deformed structure of each component including the effets of stellar deformations on the mass redistribution, as opposed to the perturbative model assumption adopted in the 1D stellar modelling that considers the centrifugal and tidal forces as small perturbations of the spherical symmetry and only accounts for leading terms. `MoBiDICT` calculates the instantaneous non-perturbative tidal acceleration perturbation and its consequence on the apsidal motion (Fellay & Dupret, 2023; Fellay et al., 2024).

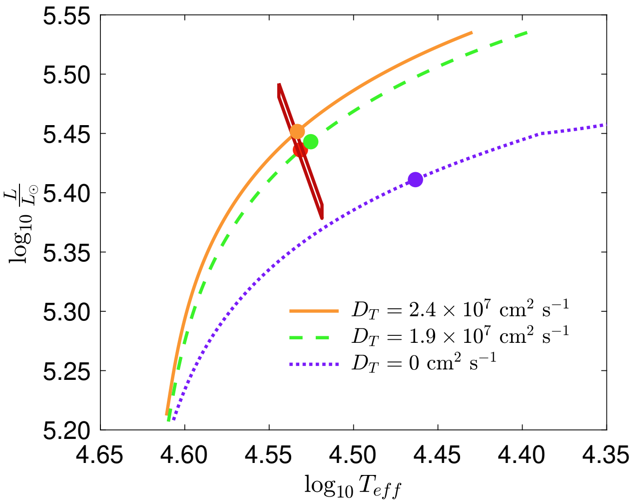

Figure 4. HR diagram for HD 152248: evolutionary tracks of `Clés` models. The observational values and their error bars are represented in red. The dots over-plotted on the tracks correspond to the models that fit the observational k_2. Credit: Rosu et al. (2020a), reproduced with permission ©ESO.

Fellay & Dupret (2023) demonstrated that the perturbative models significantly underestimate the deformations of binaries measured through η_2, a fortiori when stars have significant envelope mass compared to their total mass and when binaries have small orbital separation (i.e. a is comparable to the stellar radii) (see the adapted figure 11 in Rosu, 2024). The apsidal motion rate is affected the same way: The higher the envelope mass compared to the total stellar mass, the higher the relative difference between the non-perturbative and perturbative $\dot{\omega}$. This is illustrated in Fig. 5 for four kind of twin binaries and different values of the eccentricity. Low-mass main-sequence (MS) stars and reg giants (RGB) reach the most significant discrepancies with up to 70% and 40% errors on the $\dot{\omega}$ determination at small orbital separation and low eccentricity. For a given orbital separation but higher eccentricity, the discrepancy is even higher as the stars get closer during periastron passage, therefore exacerbating the stellar deformations and the ensuing impact on the apsidal motion rate.

Fellay et al. (2024) applied `MoBiDICT` to four well-known twin binaries (HD 152248, PV Cas, IM Per, and Y Cyg) to compare their obtained parameters to those from 1D stellar modelling. The authors included overshooting in the models as the only mixing process to avoid any degeneracies between different mixing mechanisms as explored by Rosu et al. (2020a, 2022a). Fellay et al. (2024) found that a systematic higher overshooting parameter was necessary in the `MobiDICT` code than in the 1D stellar models (see their table 2). This stands

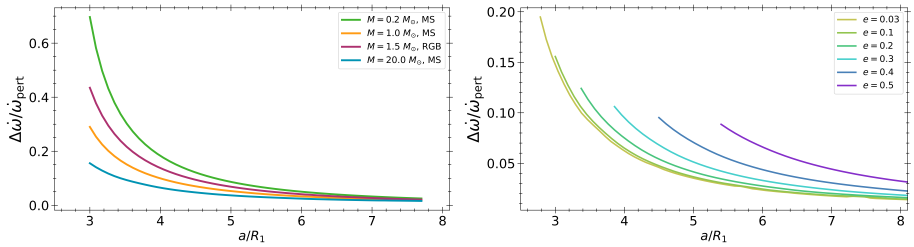

Figure 5. Apsidal motion relative difference as a function of the orbital separation normalised by the stellar radii for four twin binaries and $e = 0.1$ (*left panel*), and for $20\,M_\odot$ main-sequence stars but different values of e (*right panel*). Figure adapted from Fellay et al. (2024).

from the higher deformations in the non-perturbative approach that lead to smaller k_2 and hence, additional mixing is necessary to reproduce the internal density stratification. Far from solving the enhanced mixing issue encountered with 1D standard stellar models, the non-perturbative modelling enhances it. Furthermore, the non-perturbative approach, though being small compared to the perturbative approach, is on the same order of magnitude as the general relativistic correction and cannot be ignored anymore in the study of the apsidal motion in close eccentric binaries (see table 3 in Fellay et al., 2024).

5. Status quo of the apsidal motion

Close eccentric (massive) binaries might undergo apsidal motion, which means their longitude of periastron might precess in time, as a consequence of the tidal interactions that occur between the two stars. This motion has been measured in hundreds of systems during the last decades, historically using the times of minima of the eclipses, a method that returned to popularity lately thanks to the incredible precision of observations acquired with space-borne facilities such as TESS and Kepler, among others. The other less common but potentially more accurate method to derive the apsidal motion rate of the system is through the fit of the stars' radial velocity curves as a function of time provided a sufficient long timespan of the spectroscopic observations is available. In the lucky but challenging case of an eccentric eclipsing double-line spectroscopic binary, the simultaneous analysis of all spectroscopic and photometric data allows us to derive consistent physical and orbital parameters for the binaries, including the apsidal motion rate.

Far from being an observational curiosity, the measure of the apsidal motion rate in a binary is a powerful and robust means to sound the interior of the stars. In the perturbative case assumption, the apsidal motion rate is directly proportional to the internal stellar structure constants k_2 of the stars, a measure of the stars' inner density profile. Thus, the measure of the apsidal motion rate of a binary system allows us to efficiently and reliably probe the interior of stars.

Through the confrontation of 1D stellar evolution models to the observational constraints of massive eccentric binaries, we reached the conclusion that the inner density profiles of the stars, measured through k_2 and $\dot{\omega}$, can only be reproduced provided enhanced mixing is included in the models. Indeed, standard model prescriptions predict stars having a smaller density contrast between the core and the external layers of the stars, than what is expected from the observations. The physical origin behind this enhanced mixing is most probably rotational mixing, though it is still under investigation. The results obtained with the 3D non-perturbative `MoBiDICT` code showed that the perturbative case assumption systematically underestimates the apsidal motion rate. As a matter of consequence, even more mixing needs to be included in `MoBiDICT` to reproduce the internal structure of the stars, exacerbating even more the results obtained with the 1D models. The more affected systems seem to be the massive stars which, despite their lower envelope mass compared to their total mass, are usually found in closer binaries and thus suffer more important deformations. It is therefore about time to adopt a perturbative approach to study those systems.

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