Massive Stars Near and Far
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Apsidal motion in NGC 6231: Sounding the internal structure of massive stars

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Abstract. The young open cluster NGC 6231 hosts a rich population of O-type binary stars. We study several of these eccentric short-period massive eclipsing binaries and assess their fundamental parameters. The properties of these systems make them interesting targets to study tidally induced apsidal motion. The analysis of apsidal motion offers a powerful means to obtain information about the internal structure of the stars. Indeed, since the rate of apsidal motion in a binary system is proportional to the internal structure constants of the stars composing it, its value gives direct insight into the internal structure and evolutionary state of these stars. Stellar evolution models are constructed based on the observationally-determined fundamental parameters and a theoretical rate of apsidal motion is inferred. The results are striking: Adopting standard stellar evolution models yields a theoretical rate of apsidal motion much larger than the observational value. This discrepancy results from the standard models predicting too low an efficiency of internal mixing and thus too homogenous stars in terms of density. By enforcing the theoretical rates of apsidal motion to match the observational values, enhanced mixing is required, through a large overshooting parameter and/or additional turbulent/rotational mixing. Our analysis leads to the conclusion that the chemically mixed cores in those massive stars must be more extended than anticipated from standard models.

Keywords. Stars: early-type, evolution, massive, Binaries: spectroscopic, eclipsing

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1. Introduction and motivations

In close binaries, tidal interactions – which are responsible for the non-spherical gravitational fields of the stars – take place between the two components. If the orbit is eccentric, the main effect of these tidal interactions is the precession of the line of apsides with time, which is called apsidal motion. Whilst massive binaries, especially double-line spectroscopic eclipsing ones, are interesting systems as they offer possibilities to constrain the fundamental properties – such as the masses and radii – in a model independent way, massive binaries showing evidence of apsidal motion are even more interesting systems as the apsidal motion allows us to sound the internal structure of the stars (see e.g. Rosu *et al.* 2020a, and references therein). Indeed, the apsidal motion rate depends upon the internal structure constants of the stars, a measure of the density stratification between the core and the external layers of the stars. In this respect, the most promising systems are close short-period eccentric systems for which photometric, spectroscopic, and radial velocity data can be analysed to constrain the fundamental stellar parameters and the apsidal motion rate of the system. Confronting stellar evolution models computed with different prescriptions for the internal mixing and/or the mass-loss rate to the parameters derived from the observations then allows us to constrain the internal mixing processes occurring inside the stars. We focus here on the young and rich open cluster NGC 6231 that hosts

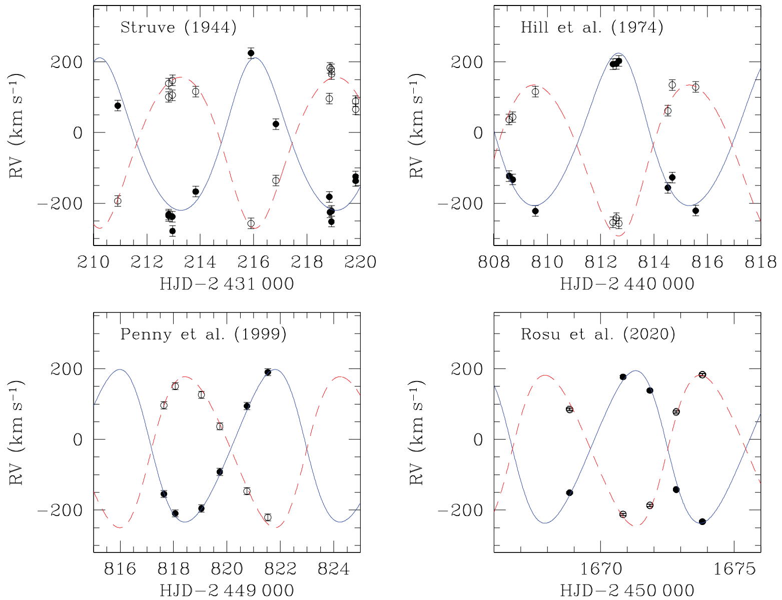

Figure 1. Measured RVs of the primary (filled dots) and secondary (open dots) stars of HD 152248, and best-fit RV curves (blue and red). Figure from Rosu (2021).

a substantial population of O-type binaries which are interesting candidates for such studies, notably HD 152248 (Rosu *et al.* 2020a,b) and HD 152219 Rosu *et al.* (2022).

2. How to measure the apsidal motion rate

The apsidal motion rate in a binary system can be determined using two different methods, depending on whether the binary system is a spectroscopic binary for which radial velocity measurements are available or it is an eclipsing binary for which photometric observations are available.

In the former case, the spectroscopic observations of the binary are analysed to disentangle the contributions of the two stars and to derive the radial velocities at each time of observation. All radial velocity data (either primary, secondary, or equivalent primary) are fit according to the following equation

$$RV(t) = K\,(\cos(\phi(t) + \omega(t)) + e\cos(\omega(t))) + \gamma, \tag{2.1}$$

where K is the semi-amplitude of the radial velocity curve, γ is the apparent systemic velocity, e is the eccentricity of the orbit, ω is the argument of periastron, and ϕ is the true anomaly. This expression explicitly accounts for apsidal motion through the linear variation of ω with time:

$$\omega(t) = \omega_0 + \dot{\omega}(t - T_0), \tag{2.2}$$

where $\dot{\omega}$ is the apsidal motion rate and ω_0 is the argument of periastron at the time of reference T_0. An example of such a radial velocity adjustment is shown in Fig. 1 for the binary system HD 152248 (see also Rauw *et al.* 2016; Rosu *et al.* 2020b, 2022a).

In the latter case, the inclination i of the system has to be such that the eclipses of the two stars are observed during one orbital cycle. In an eccentric binary, both the depths and the phases of the eclipses change with ω. This is illustrated in Fig. 2 where nine different light curves are plotted for nine different values of ω ranging from 0° to 160°, all other parameters identical ($e = 0.134$, $i = 68.6°$, and stars having the same mass m,

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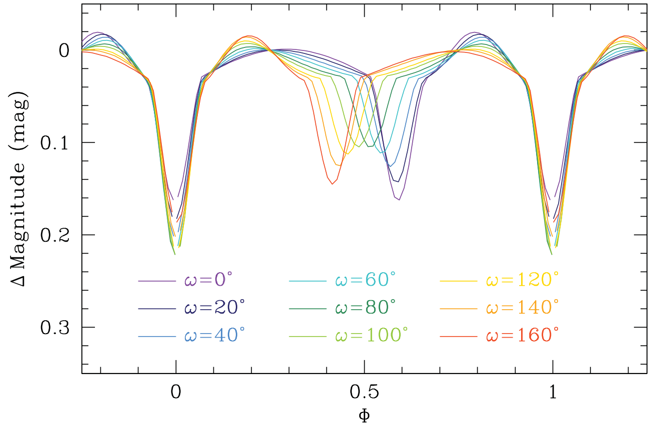

Figure 2. Set of theoretical light curves for different values of ω, all other parameters being identical ($e = 0.134$, $i = 68.6°$, and stars having the same m, R, and $T_{\rm eff}$). Figure from Rosu (2021).

radius R, and effective temperature $T_{\rm eff}$). The method then consists either in directly fitting the light curves taken at different epochs with ω as a free parameter, or in fitting the times of minimum of the eclipses of the corresponding light curves to get values for the phase differences at different epochs that can in turn be fitted to get a value for the apsidal motion rate through the equations of Giménez & Bastero (1995), see also Zasche & Wolf (2019), Baroch *et al.* (2021), and Rosu *et al.* (2022a,b).

3. Apsidal motion equations and internal structure constant

The apsidal motion rate of a system is made, in the two-body problem, of a Newtonian contribution $\dot{\omega}_{\rm N}$, which originates from the non-Keplerian terms of the stellar gravitational potentials, and a general relativistic correction $\dot{\omega}_{\rm GR}$. Their expressions are given by, according to Sterne (1939), where only the contributions arising from the second-order harmonic distorsions of the gravitational potential are considered,

$$\dot{\omega}_{\rm N} = \frac{2\pi}{P_{\rm orb}}\left[15 f(e)\left\{k_{2,1} q \left(\frac{R_1}{a}\right)^5 + \frac{k_{2,2}}{q}\left(\frac{R_2}{a}\right)^5\right\}\right.$$
$$\left. + g(e)\left\{k_{2,1}(1+q)\left(\frac{R_1}{a}\right)^5\left(\frac{P_{\rm orb}}{P_{\rm rot,1}}\right)^2 + k_{2,2}\frac{1+q}{q}\left(\frac{R_2}{a}\right)^5\left(\frac{P_{\rm orb}}{P_{\rm rot,2}}\right)^2\right\}\right], \quad (3.3)$$

and by, according to Shakura (1985),

$$\dot{\omega}_{\rm GR} = \left(\frac{2\pi}{P_{\rm orb}}\right)^{5/3} \frac{3(G(m_1+m_2))^{2/3}}{c^2(1-e^2)}, \quad (3.4)$$

where a is the semi-major axis, $q = m_2/m_1$ is the mass ratio, $k_{2,j}$ the internal structure constant and $P_{\rm rot,j}$ the rotational period of star $j (j = 1, 2$ for the primary and secondary stars, respectively), $f(e)$ and $g(e)$ are functions of the eccentricity of the orbit which expressions are given in e.g. Rosu (2021), G is the gravitational constant and c is the speed of light. The internal structure constant k_2 is a measure of the density stratification between the core and the external layers of the star. It is an algebraic expression of the η_2-parameter which is the solution, evaluated at the stellar surface, of the Clairaut-Radau differential equation (Hejlesen 1987) that depends upon the density profile inside the

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Table 1. Set of observationally-determined properties of the massive binaries HD 152248 (Rosu *et al.* 2020b) and HD 152219 (Rosu *et al.* 2022a).

Parameter	Value		
	HD 152248	HD 152219	
		Primary	Secondary
Spectral type	O7.5 III-II(f)	O9.5 III	B1-2 V-III
M ($M_\odot$)	$29.5^{+0.5}_{-0.4}$	18.64 ± 0.47	7.70 ± 0.12
R ($R_\odot$)	$15.07^{+0.08}_{-0.12}$	9.40 ± 0.15	3.69 ± 0.06
$T_{\rm eff}$ (K)	$34\,000 \pm 1000$	$30\,900 \pm 1000$	$21\,700 \pm 1000$
$L_{\rm bol}$ ($L_\odot$)	$(2.73 \pm 0.32) \times 10^5$	$(7.26 \pm 0.97) \times 10^4$	$(2.73 \pm 0.51) \times 10^3$
$\bar{k}_2$	0.0010 ± 0.0001	0.00173 ± 0.00052	
$\dot{\omega}$ ($^\circ$ yr^{-1})	$1.843^{+0.064}_{-0.083}$	1.198 ± 0.300	
$P_{\rm orb}$ (d)	$5.816475^{+000085}_{-0.000075}$	$4.24046^{+0.00005}_{-0.00004}$	
e	$0.134^{+0.0007}_{-0.0004}$	$0.072^{+0.004}_{-0.005}$	

star. k_2 takes its maximum value of 0.75 for an homogenous sphere of constant density, and can take values as low as 10^{-4} for massive stars having a dense core and a diluted atmosphere (Rosu *et al.* 2020a). As the star evolves, its core contracts while its enveloppe expands, hence its k_2 decreases with time, rendering this quantity a good indicator of stellar evolution.

All terms appearing in the right-hand side of Eq. (3.4) are known from observations, hence $\dot{\omega}_{\rm GR}$ is also. As $\dot{\omega}$ is known from observations, all terms – except for $k_{2,1}$ and $k_{2,2}$ – appearing in Eq. (3.3) are also. In the special case of a twin system, that is to say, if the two stars share exactly the same properties in terms of m, R, and $T_{\rm eff}$, we can assume their k_2 are identical. An observational value can then be inferred for k_2 through Eq. (3.3). In the general case of two different stars, we define a weighted-average mean of the internal structure constants

$$\bar{k}_{2,\rm obs} = \frac{c_1 k_{2,1} + c_2 k_{2,2}}{c_1 + c_2} = \frac{\dot{\omega}_{\rm N}}{c_1 + c_2}, \tag{3.5}$$

where c_1 and c_2 are known functions of stellar and orbital parameters, whose expressions can be obtained from Eq. (3.3) and which can be inferred from observations.

4. Two concrete cases: `Clés` models

We built stellar structure and evolution models for the massive binaries HD 152248 and HD 152219 with the `Clés` code (Scuflaire *et al.* 2008). The observationally determined properties of the two binaries are summarised in Table 1. Whilst HD 152248 is a twin system, hence the individual k_2 are identical and equal to $\bar{k}_2$, HD 152219 is made of a primary star bigger and more massive than the secondary companion, hence we have $k_{2,1} \leq \bar{k}_2 \leq k_{2,2}$. In the `Clés` models, we included overshooting, implemented as a step-function through the overshooting parameter $\alpha_{\rm ov}$, as well as turbulent diffusion, implemented as a partial mixing process with velocities of chemicals $V_i = -D_T \frac{d \ln X_i}{dr}$, where D_T is the turbulent diffusion coefficient (measured in cm^2 s^{-1}). Turbulent diffusion acts as reducing the abundance gradient of the chemicals. Both mechanisms bring additional hydrogen from the external layers to the chemically mixed core, that is to say, fuel for nuclear reactions, and, therefore, increase the lifetime of the star on its main-sequence phase. The additional mixing leads to a reduced mass concentration at a given age. Mass-loss is implemented as in Vink *et al.* (2001). We used the `min-Clés` routine, in which a Levenberg-Marquardt minimisation technique is implemented, to search for best-fit models of the stars in terms of their observational properties (Rosu *et al.* 2020a).

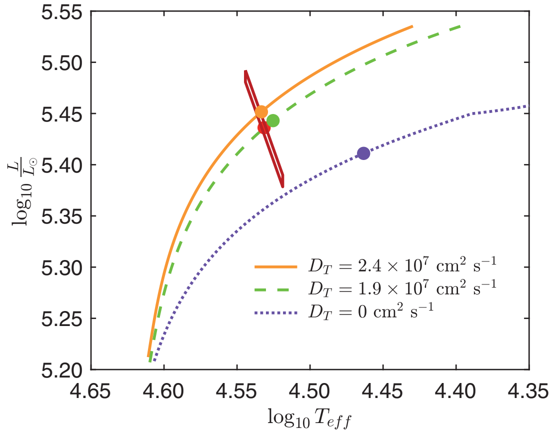

Figure 3. HR diagram for HD 152248: evolutionary tracks of Clés models. The dots over-plotted on the tracks correspond to the models that fit the observational k_2. The observational value and its error bars are represented in red.

HD 152248 (see Rosu et al. 2020a). We first requested the Clés models to reproduce the stellar mass, radius, and position in the Hertzsprung-Russell (HR) diagram only. To this aim, we built a first best-fit model with $\alpha_{\rm ov} = 0.20$ and $D_T = 0\,{\rm cm}^2\,{\rm s}^{-1}$. The corresponding evolutionary track is shown in Fig. 3 (purple dotted line) together with the observational value and its error bars (in red). This model does not reproduce the physical properties of the stars, even within the error bars. We then built a second model leaving the turbulent diffusion coefficient as a free parameter of the adjustment and obtained $D_T = 1.9 \times 10^7\,{\rm cm}^2\,{\rm s}^{-1}$. The mass, radius, and position in the HR diagram are well-reproduced, as the corresponding track indicates (green dashed line in Fig. 3). However, we observe that the model that reproduces the observational k_2-value, symbolised by the dot over-plotted on the track, is located further away on the evolutionary track compared to the location of the best-fit model. It means that our best-fit model has too high a k_2-value, that is to say, too low a density contrast between its core and external layers. We solved this issue by enforcing enhanced turbulent diffusion inside the models. We obtained a best-fit model in terms of the mass, radius, position in the HR diagram, k_2, and the apsidal motion rate that has $D_T = 2.4 \times 10^7\,{\rm cm}^2\,{\rm s}^{-1}$. The corresponding track is shown in Fig. 3 (orange line). This is a valuable result in the sense that without taking into account the apsidal motion occurring in this binary system, we would not highlight that the standard models predict too low a density contrast between the core and the external layers compared to what is expected from observations.

HD 152219 (see Rosu et al. 2022a). Given that the secondary star has a much smaller radius than the primary star, we can assume that $c_2 \ll c_1$ in Eq. 3.5, and hence, $k_{2,1} \sim \bar{k}_2$. We hence focus here on the primary star only. As for HD 152248, the best-fit model in terms of the mass, radius, and position in the HR diagram has too high a $k_{2,1}$-value, as indicated in Fig. 4 (pink dotted and green dashed lines for $D_T = 0$ and $2.12 \times 10^6\,{\rm cm}^2\,{\rm s}^{-1}$, respectively). We proceeded as for HD 152248 and obtained a best-fit model in terms of the afore-mentioned parameters and of the internal structure constant, adopting the least stringent constraint on $k_{2,1}$, that is to say, enforcing $k_{2,1} = \bar{k}_2$, that has $D_T = 9.92 \times 10^6\,{\rm cm}^2\,{\rm s}^{-1}$. The corresponding evolutionary track is shown in Fig. 4 (orange line). The discrepancy in k_2 is lowered at the cost that now the best-fit model does not reproduce the position in the HR diagram anymore.

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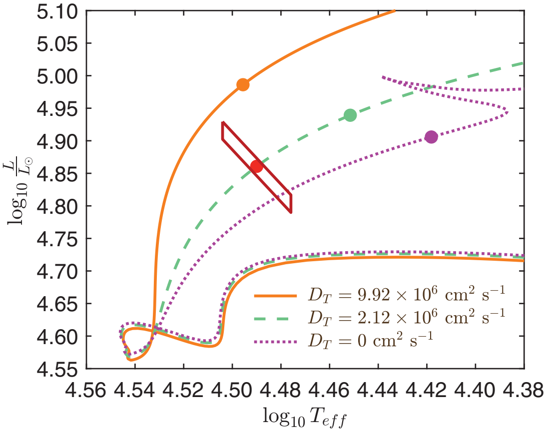

Figure 4. HR diagram for HD 152219: evolutionary tracks of `Clés` models. The dots overplotted on the tracks correspond to the models that fit the observational $\bar{k}_2$. The observational value and its error bars are represented in red.

5. Conclusion

We studied the apsidal motion in massive binary systems from a theoretical point of view. We highlighted that the best candidates for this purpose are the twin systems, for which the apsidal motion equations can be solved for the internal structure constants. We built stellar structure and evolution models for two massive binaries, HD 1522448 and HD 152219, based on the observationally-determined stellar parameters (masses, radii, and effective temperatures). The standard models obtained in this way predicted too high a value of the apsidal motion rate compared to the observational value. We then enforced the models to reproduce the apsidal motion rate of the system through the internal structure constants of the stars. The best-fit models obtained in this way require enhanced mixing through the turbulent diffusion compared to standard ones. We conclude that standard models predict too low an efficiency of internal mixing and thus stars that have too low a density contrast between their core and external layers, and that the chemically mixed cores in these massive stars must be more extended than usually considered in stellar evolution.

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Discussion

HIGGINS: I was just wondering how do you translate these values of $k_{2,1}$ and $k_{2,2}$ into your mixing. So is it like a model grid and then how fine would the spacing be because I saw that for one component it was like an $\alpha_{\rm ov}$ of 0.3 and other was an $\alpha_{\rm ov}$ of 0.2 so how do you translate your extra mixing into like values so that we can use them for stellar evolution?

ROSU: Basically, I tried several values of $\alpha_{\rm ov}$. I made a grid from 0.1 to 0.4 and got different values of the turbulent mixing so, as we don't really know the value of $\alpha_{\rm ov}$, it translates into the change in turbulent diffusion. But whatever the value of $\alpha_{\rm ov}$ in this range, we get models that are able to reproduce the different parameters in the same way. For instance for the first system, I only presented one value but we can get models that have different values of $\alpha_{\rm ov}$ and so different values of the turbulent diffusion, and the corresponding tracks mostly overlap.

HIGGINS: Yes, that was I was kind of wondering and how you would get like a unique solution because if you have other parameters like the rotation or other efficiencies you know you could have multiple solutions for your k_2-values.

ROSU: Yes, we get several solutions and we also tested the rotational influence. We cannot put rotation inside the `Clés` models but we used `GENEC` models with rotation included and we arrived to the conclusion, for this system at least, that the rotation can be simulated through this turbulent diffusion for instance.

BOWMAN: Maybe I missed the values but can you comment perhaps on this turbulent mixing being mass dependant because I think I saw that your primary needed larger values than the secondary? Is that correct?

ROSU: Exactly. Here, we expect that the turbulent diffusion depends upon the masses of the stars but it might also depend on the rotation of the stars as it might also simulate a bit the rotation of the stars. We expect that if the star is rotating faster than it should have a turbulent diffusion much higher than a star rotating slower.

BOWMAN: I am just thinking about synchronicity though in such short-period systems as well so if they are approximately synchronous and then you still find larger values in the primary that is very interesting.