Part 1.2. Pulsations in Close Binaries

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Tidally Induced Oscillations in Close Binaries

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Abstract. In this paper, we present the results of a theoretical investigation on tidally excited oscillation modes in close binaries. We apply our results to the slowly pulsating B star HD 177863 and present evidence for the resonant excitation of the second-degree g_{14}^{+}-mode in this star.

1. Introduction

In close binaries with asynchronously rotating components, each star is subject to the dynamic tides raised by its companion. For binaries with short orbital periods, the forcing frequencies of the dynamic tides may be close to the eigenfrequencies of the free oscillation modes g^{+} of the component stars (Cowling, 1941). These resonances can arise when the orbital period changes due to the orbital evolution of the binary or when the frequencies of the oscillation modes change due to stellar evolution.

2. Basic assumptions

Consider a close binary system of stars in an unvarying Keplerian orbit with semi-major axis a, orbital period $T_{\rm orb}$, and orbital eccentricity e. Let M_1 and R_1 be the mass and the radius of the first star, and M_2 the mass of its companion. We assume the first star to rotate uniformly around an axis perpendicular to the orbital plane with a low angular velocity $\vec{\Omega}$ so that the effects of the Coriolis force and the centrifugal force can be neglected. The second star is treated as a point mass. Furthermore, we denote by $\vec{r} = (r, \theta, \phi)$ a system of spherical coordinates with respect to an orthogonal frame of reference that is corotating with the star.

The tidal force exerted by the companion is derived from the tide-generating potential $\varepsilon_T\, W\,(\vec{r}, t)$, where $\varepsilon_T = (R_1/a)^3\,(M_2/M_1)$. Following Polfliet & Smeyers (1990), we expand the tidal potential in terms of unnormalised spherical harmonics $Y_\ell^m(\theta, \phi)$ and in Fourier series in terms of multiples of the compan-

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ion's mean motion $n = 2\pi/T_{\rm orb}$:

$$\varepsilon_T W(\vec{r}, t) = -\varepsilon_T \frac{G\,M_1}{R_1} \sum_{\ell=2}^{4} \sum_{m=-\ell}^{\ell} \sum_{k=-\infty}^{\infty} c_{\ell,m,k} \left(\frac{r}{R_1}\right)^{\ell} Y_\ell^m(\theta, \phi) \exp\left[{\rm i}\,(\sigma_T t - kn\tau)\right]. \quad (1)$$

Here G is the Newtonian constant of gravitation, $\sigma_T = k\,n + m\,\Omega$ the forcing frequency with respect to the corotating frame of reference, and τ a time of periastron passage. The factors $c_{\ell,m,k}$ are Fourier coefficients depending on the orbital eccentricity. They decrease rapidly with increasing values of the Fourier index k, but the decrease is slower for higher orbital eccentricities. For a definition and a more elaborate discussion of the coefficients $c_{\ell,m,k}$, we refer to Smeyers et al. (1998).

In the remainder of this paper, we restrict Expansion (1) to the terms associated with the second-degree spherical harmonics, which are dominant.

3. Tidally induced radial-velocity variations

The tidal motions of the mass elements located at the star's surface contribute to the radial-velocity variations seen by the observer. The amplitude of the tidally induced radial-velocity variations is generally low, except in cases of resonances of dynamic tides with free oscillation modes. These resonances enhance the tidal action exerted by the companion and excite the oscillation mode involved with the forcing frequency of the tide (Smeyers et al., 1998).

In order to illustrate this, we determined the tidally induced radial-velocity variations for a binary consisting of a $5\,M_\odot$ ZAMS star and a $1.4\,M_\odot$ compact companion. We considered the orbital eccentricities $e = 0.3$ and $e = 0.5$, and various orbital inclinations ranging from $i = 0°$ to $i = 90°$. Both the free and the forced oscillations of the star are considered in the linear, isentropic approximation.

For close resonances, we find the amplitudes to be high enough to be detectable in observations. They are largest when the orbital plane is seen edge-on and they increase with increasing values of the orbital eccentricity. Some of the amplitudes found are larger than the sound speed in the atmosphere of the star. The study of these highly nonlinear tidal motions is currently beyond the scope of our investigation and we limit the applications to binaries that can be well described by the linear theory.

A detailed representation of the amplitudes of the tidally induced radial-velocity variations in the case of the orbital eccentricity $e = 0.5$ is displayed in the left-hand panel of Fig. 1 for orbital periods ranging from 3.3 to 3.7 days. Several orbital periods are seen to give rise to resonances with two oscillation modes simultaneously. For the points labeled (a) – (e), the middle panel of the figure shows the tidally induced radial-velocity variations as a function of the orbital phase. The shape of the radial-velocity curves changes markedly with the proximity of a dynamic tide to a resonance with a free oscillation mode. The reason is that for close resonances the tidally induced radial-velocity variations are almost exclusively caused by the tide involved in the resonance, while outside resonance the radial-velocity variations result from a superposition of a large number of dynamic tides with different forcing frequencies.

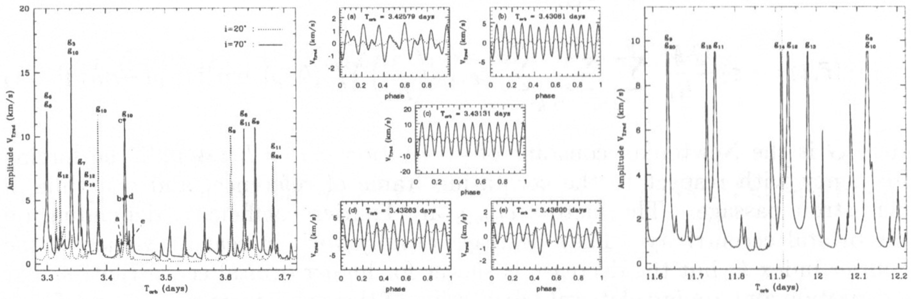

Figure 1. Left: Observed amplitude of the tidally induced radial-velocity variations in the $5\,M_\odot$ ZAMS stellar model. Middle: Tidally induced radial-velocity variations in the $5\,M_\odot$ ZAMS stellar model as a function of the orbital phase. Right: Observed amplitude of the tidally induced radial-velocity variations in HD 177863.

4. Application to HD 177863

The single-lined spectroscopic binary HD 177863 was classified as a slowly pulsating B star (SPB) by Waelkens (1991). The binary nature of the system was discovered by De Cat et al. (2000) who derived an orbital eccentricity of 0.60 and an orbital period of 11.9154±0.0009 days. From the orbital separation and the mass function given by the authors one furthermore infers that the orbital inclination is between 30° and 40°, and the companion has a mass between $1.7\,M_\odot$ and $2.4\,M_\odot$. We also note that De Cat (2001) found the primary to rotate super-synchronously with an equatorial rotational velocity of about $80\,\mathrm{km\,s^{-1}}$, if the orbital and rotational inclination axes are assumed to be aligned.

De Cat (2001) also performed a detailed frequency study on both extensive spectroscopic and photometric time series. He found two intrinsic frequencies for the star, $0.84059\,\mathrm{c\,d^{-1}}$ and $0.10108\,\mathrm{c\,d^{-1}}$, of which the first one differs less than $0.001\,\mathrm{c\,d^{-1}}$ from 10 times the orbital frequency. This observation, together with the binary configuration, led De Cat (2001) to conclude that one may be dealing with a resonantly excited mode.

In order to investigate the suggestion made by De Cat (2001), we repeated the analysis presented in the previous section for a $3.5\,M_\odot$ ZAMS star representing the primary in HD 177863. The various parameters adopted in our calculation are taken from De Cat (2001). The resulting amplitudes of the tidally induced radial-velocity variations are shown in the right-hand panel of Fig. 1 as a function of the orbital period. Since the expressions established in our theory are derived in the linear approximation, we restrict ourselves to the presentation of radial-velocity variations with amplitudes smaller than the sound speed in the atmosphere of the star ($\sim 9.5\,\mathrm{km/s}$).

A strong resonance with the g^+_{14}-mode is seen to occur near the observed orbital period of HD 177863. The resonance is caused by the partial dynamic tide associated with the azimuthal number $m = -2$ and the Fourier index $k = 10$

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in Expansion (1) of the tide-generating potential. This result implies the first achievement of a mode identification, namely $\ell = 2$, $m = -2$, $N = 14$, in a slowly pulsating B star.

5. Conclusions

For binaries with short orbital periods and eccentric orbits resonances between dynamic tides and free oscillation modes can have a significant impact on the observed tidally induced radial-velocity variations. In the case of HD 177863, we find evidence for the resonant excitation of the g_{14}^{+}-mode with a frequency equal to ten times the orbital frequency.

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Discussion

J.-P. Zahn : What limits the amplitude in the resonances, which should grow to infinity in the isentropic approximation ? Have you tried to estimate the effect of radiative damping on the tidal amplitude ?

B. Willems : The amplitude indeed grows to infinity for exact resonances. In the results shown, we limited the calculations to forcing frequencies for which the relative difference $(\sigma_{\ell,N} - \sigma_T)/\sigma_{\ell,N}$ does not become more than an order of magnitude smaller than the tidal parameter ε_T. This restriction stems from the perturbation theory underlying our analysis (see Smeyers et al., 1998). The nonadiabatic effects are only important for very close resonances. We plan to incorporate these effects in a future investigation.

G. Handler : Did you ever try to do model calculations for tidal excitation in γ Dor stars ?

B. Willems : No, so far we only considered binaries containing a slowly pulsating B star or a β Cep star.

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