Asteroseismic probing of internal rotation in hot B subdwarf stars: Testing spin-orbit synchronism in two close binary systems

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Asteroseismic probing of internal rotation in hot B subdwarf stars: Testing spin-orbit synchronism in two close binary systems

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Abstract. We present internal rotation profiles derived from asteroseismology for the hot pulsating B subdwarf stars PG 1336-018 and Feige 48. These two pulsators are primaries of close binary systems of known orbital period and, therefore, provide laboratories to test, for the first time, spin-orbit synchronization as a function of depth. We show that PG 1336-018 and Feige 48 clearly rotate as solid bodies with periods equal to their orbital periods from the surface down to at least ~ 0.5 and ~ 0.3 their radius, respectively. Deep tidal locking has therefore developed within the relatively short lifetime of these stars ($\sim 10^8$ yr).

1. Introduction

Subdwarf B (sdB) stars are hot ($T_{\rm eff}$ = 20,000−40,000 K) and compact (log g = 5.2 − 6.2) evolved Extreme Horizontal Branch stars (EHB). They are composed of convective helium-burning cores, surrounded by radiative helium mantles and very thin radiative hydrogen-rich envelopes ($M_{\rm env} < 0.02\ M_\odot$, while the total mass is around 0.5 $M_\odot$). They live about 1.5×10^8 yr on the EHB and then evolve, after core-helium exhaustion, directly toward the white dwarf cooling sequence (Dorman et al. 1993). Subdwarf B stars host two groups of non-radial, multiperiodic pulsators. Rapid oscillations (80 − 600 s) in the so-called EC 14026 stars are usually identified to low-degree, low-order p-modes. The longer periods (0.75 − 2 h) in the PG 1716+426 stars are due to low-degree, mid-order g-modes. The presence of excited pulsation modes in both type of pulsators is caused by a classic κ-effect associated with an opacity bump due to partial ionization of heavy metals, especially iron, locally enhanced by radiative levitation at work in the envelope of these stars (Charpinet et al. 2001).

A significant fraction of sdB stars reside in close binaries, with orbital periods from hours to days and white dwarfs or M dwarf companions (e.g. Maxted et al. 2001, Green et al. 2001). The Feige 48 system is made of a short-period pulsating sdB star and an unseen companion (most likely a white dwarf), with an orbital period of 9.024 ± 0.072 h (O'Toole et al. 2004).

PG 1336−018 ($P_{\rm orb} = 2.42438$ h; Kilkenny et al. 2000) is one of the very few *HW Vir*-type sdB + dwarf M close eclipsing binaries, and the only known – to date – that exhibits short-period pulsations for its sdB component.

Tidal forces in binary systems, among other long-term effects such as circularization and alignment of the rotation axis to the normal of the orbit, tend to synchronize the rotation of the two stars with the orbital motion. Theoretical frameworks on tidal interaction have been developed in the last decades essentially by Zahn (1975, 1977, and references therein), where turbulent dissipative processes and radiative damping are invoked. Another model based on large-scale hydrodynamical currents was proposed by Tassoul & Tassoul (1992, and references therein), but the question of its validity is still under debate given its free parameter dependence. The theoretical synchronization times can differ by orders of magnitude depending on the physical mechanism invoked, especially in the case of hot stars with radiative envelopes (such as sdB stars), where tidal forces are less efficient for synchronization. Anyway, the confrontation of theory with observations, through the traditional photometric or spectroscopic techniques, only deals with the surface layers. The synchronization level reached in the inner parts, by transport of the angular momentum from the surface (Goldreich & Nicholson 1989), is only accessible through asteroseismology. It therefore constitutes a unique opportunity to test the theory of stellar synchronization and angular momentum transport as a function of depth.

2. Inclusion of rotation in the forward modeling approach

The group of rapidly pulsating sdB stars has proved its potential for performing objective asteroseismic analyses (see Fontaine et al. 2008 for a recent review). The method implements to so-called forward modeling approach, built on the requirement of global optimization: theoretical pulsation spectra computed from sdB models must match *all* the observed periods simultaneaously. The goodness of the fit is evaluated through a merit function defined as

$$S^2 = \sum_{i=1}^{N_{\rm obs}} \Big(\frac{P^i_{\rm obs} - P^i_{\rm th}}{\sigma_i}\Big)^2 \tag{1}$$

where $N_{\rm obs}$ is the number of observed periodicities. The method performs a double-optimization procedure in order to find the minima of the merit function, which constitutes the potential asteroseismic solutions (see details in Charpinet et al. 2005b). The codes have been recently improved to incorporate the effect of the rotation of the star, which lifts the $(2l + 1)$- fold degeneracy of eigenfrequencies of a perfectly spherically symetric star (Van Grootel al. 2008). Assuming an internal rotation law $\Omega(r)$, the rotational multiplets are calculated, with the perturbative method to first order, by

$$\sigma_{klm} = \sigma_{kl} - m \int_0^R \Omega(r) K_{kl}(r) dr \quad ; \quad K_{kl} = \frac{\xi_r^2 - [l(l+1) - 1]\xi_h^2 - 2\xi_r\xi_h}{\int_0^R [\xi_r^2 + l(l+1)\xi_h^2]\rho r^2 dr} \rho r^2 \tag{2}$$

where K_{kl} is the rotational kernel. The optimal solution gives the structural parameters of the star ($T_{\rm eff}$, log g, M_*, etc.) and, of utmost interest here, the internal dynamics $\Omega(r)$ as a function of the radius of the star.

The effects of higher orders on rotation have recently been evaluated for polytropic ($N = 3$) models of sdB stars, with a full (nonperturbative) treatment of stellar rotation developed by one of us (Reese et al. 2006). The main results show that these higher-order perturbation effects due to rotation and tidal deformation of the star cannot affect in a significant way the proposed asteroseismic solution, for Feige 48 as well as for PG 1336−018, at the present level of accuracy (further details are given in Charpinet et al. 2008).

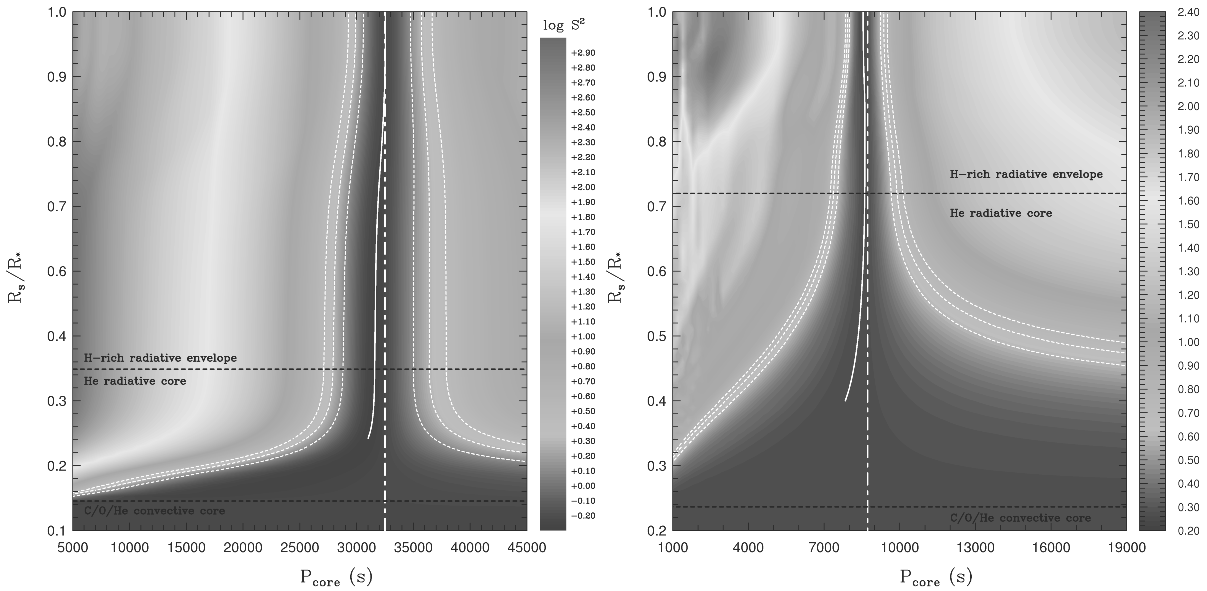

Figure 1. Seismic internal rotation profile of the sdB star in Feige 48 (left; $P_{\rm orb} = 9.024$ h) and PG 1336−018 (right; $P_{\rm orb} = 2.424$ h). This S^2 map (on a logarithmic scale) shows the quality of fit to the observed pulsation periods as a function of the parameters $P_{\rm core}$ and R_S/R_*. The continuous white line indicate the minima of the merit function. The white dot-dashed vertical lines indicates the orbital period. White dotted-line contours indicates the 1-σ, 2-σ et 3-σ confidence level relative to the best-fit solution. The transitions between the H-rich envelope and the radiative He core; and between the radiative He core and the convective C-O-He core are also indicated.

3. Asteroseismic tests of spin-orbit synchronism as a function of depth

The pulsating sdB star in the Feige 48 system exhibits nine pulsation periods in the range 343 − 383 s, as observed in white light photometry at the 3.6-m CFHT during six nights in June 1998 (Charpinet et al. 2005a). Three groups of modes can naturally be constructed from this pulsation spectrum, as components of rotational multiplets approximately evenly distributed in frequency with a mean spacing of about ~ 28 μHz. These nine pulsation periods are used in the optimization procedure in order to find the minima of the merit function, assuming several internal rotation laws. First, the hypothesis of a solid-body rotation ($\Omega(r) = \Omega =$ constant) is tested, and the star rotation period $P_{\rm rot} = 2\pi/\Omega$ therefore constitutes a free parameter in the optimization procedure. This leads to the determination of the structural parameters of the star and to a rotation period $P_{\rm rot} = 9.028 \pm 0.48$ h (details can be found in Van Grootel al. 2008), in excellent agreement with the orbital period of the system $P_{\rm orb} = 9.024 \pm 0.072$ h measured from RV variations. This result strongly suggests that the sdB star is tidally locked in the Feige 48 system.

To investigate further this question, the hypothesis of differential rotation is tested by dividing the star in two regions that rotate each independently as solid structures. The transition between the two layers is allowed to vary from 0.1 to 1.0 R_*, while the structural parameters are fixed to their optimal values. The surface rotation is fixed to the value of 32,500 s, and the core rotation period $P_{\rm core}$ can vary, as shown in Fig. 1 (left panel), from 5,000 to 45,000 s. All the merit functions are shown in Fig. 1, with a gray scale in logarithmic units. The optimal core rotation period $P_{\rm core}$ (continuous white line) is not significantly different from the surface rotation period (equal to the orbital period, vertical dot-dashed line) in most of the star: the sdB component in the Feige 48 system is tidally locked and rotates as a solid-body from the surface down to ~ 0.22

R_* at least. The dark-gray valley enlarges significantly under this limit, which translates the insensitivity of the pulsation modes to these deep regions. Nonetheless, a very fast core rotation can be rejected from Fig. 1, as it would lead to much poorer merit functions.

The same exercise is carried out with the 25 pulsation periods in the frequency spectrum of the sdB star in the PG 1336−018 system (Kilkenny et al. 2003). Details on the asteroseismic analysis is reported in Charpinet et al. (2008), and the internal rotation profile is shown in Fig. 1 (right panel). The sdB star is also tidally locked, down to $\sim 0.55\ R_*$ at least. Again, the dynamics of deeper regions (under the H-rich envelope much thinner in this case compared to the envelope of Feige 48), cannot be probed by the p-modes in action here.

4. Conclusion

We have demonstrated, for the first time by asteroseismic means, that spin-orbit synchronism is reached in most of two short-period pulsating sdB stars residing in close binary systems, namely Feige 48 and PG 1336−018. Both rotate as solid bodies with periods equal to their orbital periods from the surface down to at least $\sim$ 0.22 and 0.55 of their radius, respectively. The rotation of deeper layers cannot be inferred with the type of modes observed in short-period pulsating sdB stars. This observed synchronization as a function of depth, achieved within $\sim 1.5\times10^8$ yr (the lifetime of a sdB star on the EHB), could provide constraints to tidal evolution theories, concerning particularly the angular momentum transport from the surface to the center. In a next step, the more internal dynamics of sdB stars residing in binaries could be probed by the deep g-modes of long-period pulsating sdB stars.

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