Research Article

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Rotation in sdB stars as revealed by stellar oscillations

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Abstract: An interesting opportunity offered by the detection of stellar oscillations is the possibility to infer the internal rotation rate of a star through the so-called rotational splittings. Such seismic measurements remained rather scarce for hot B subdwarf (sdB) stars until the advent of space observations with the *Kepler* spacecraft. Nowadays, however, a number of rotation measurements have become available, offering a glimpse on the global rotational properties of sdB stars. Here, we briefly discuss what asteroseismology starts to reveal on the rotation rate of these stars. We also make connections with the internal rotation of red-giant and white-dwarf stars. In particular, we show that the very slow rotation rates derived for single sdB stars, and their similarities with the dynamical properties of the cores of red-clump stars, strongly suggest that they evolved from red-giants rather than merger events. We also point out that no more angular momentum seems to be lost by stellar cores throughout the helium burning phase until the cooling white-dwarf stage, indicating that all the braking occurs before, most likely during red-giant branch evolution.

Keywords: subdwarfs, stars:oscillation, stars:rotation, stars:evolution

1 Introduction

Twenty years ago, was discovered the first pulsating hot B subdwarf (sdB) star (Kilkenny et al. 1997), oscillating rapidly in pressure (p-)modes. Objects of this kind are now known as the *V361 Hya* class of short-period ($P \sim 80-600$ s) sdB pulsators. A few years later, the detection of slower ($P \sim 0.5-4$ h) oscillations, involving this time gravity (g-)modes, led to the identification of a second class of pulsators among hot B subdwarfs : the *V1093 Her* stars (Green et al. 2003). In both cases, a κ-mechanism triggered by an accumulation of heavy elements (in particular iron) in the stellar envelope caused by radiative levitation is driving the oscillations (Charpinet et al. 1996, 1997; Fontaine et al. 2003).

The nonradial oscillations observed in pulsating hot B subdwarfs of either p- or g-type offer, among other opportunities, the possibility to explore the dynamical properties of these stars through the very distinct signature that rotation leaves on their pulsation spectrum. However, despite this well known potential, seismic measurements of rotation remained relatively rare for sdB stars until quite recently, with the advent of high precision photometric monitoring from space. The main reason for this, as will become obvious below, is that the rotation periods involved are typically longer than the usual duration of ground-based observations that were carried out in the past. Even with space data spanning long time baselines now accessible, these measurements, when available, are rarely the main focus in the published literature and can often remain unnoticed.

In the present paper, we therefore decided to review the measured (or estimated) rotation rates currently available for sdB stars based on the study of their stellar pulsations. This exercise indeed turns out to be particularly enlightening, especially for topics related to the nature, origin, and fate of extreme horizontal branch stars, and may help answer important questions still debated in the field (see these proceedings).

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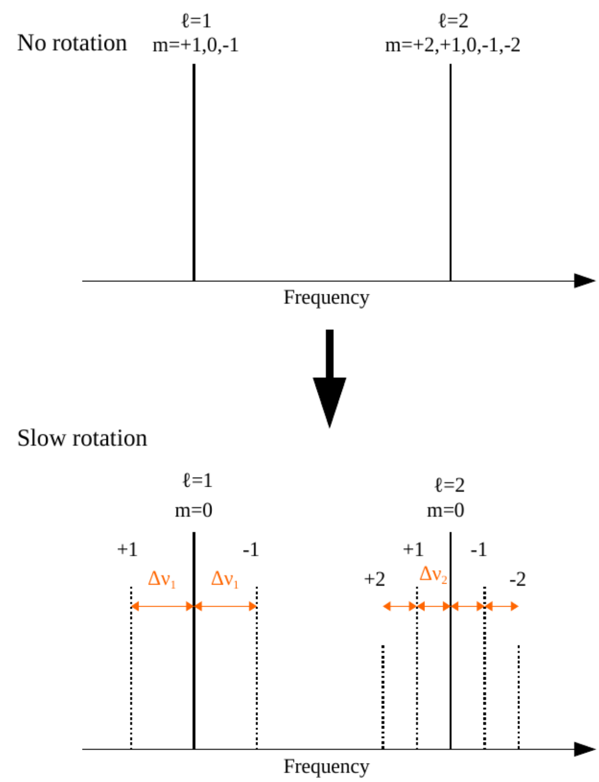

Figure 1. Schematic representation of the effect of slow rotation on oscillation modes. Without rotation, a mode is $(2\ell + 1)$-fold degenerate in m, all components having the same frequency. These components are separated when rotation is present, forming nearly symmetric triplets for $\ell = 1$, quintuplets for $\ell = 2$, and so-on. The frequency spacing between the components of a multiplet is easily measured and offers a direct way to estimate the average rotation rate of the star.

We propose in Section 2 a brief reminder of the effects induced by slow rotation on the pulsation frequencies, followed in Section 3 by a summary of the currently available measurements for the rotation rate of sdB stars. In Section 4, we discuss a connection with seismic results measuring the rotation rate of the core of He-burning red-giant stars that populate the red-clump. In Section 5, we make another connection, this time with white-dwarf stars that also have seismic measurements of their internal rotation rates. We then conclude in Section 6.

2 Seismic signature of slow rotation

The seismic signature of slow rotation is well understood within the framework of the linear theory of stellar pulsations (see, *e.g.*, Ledoux & Walraven 1958; Unno et al. 1989; Aerts et al. 2010). A mode is defined by three "quantum numbers" k, ℓ, and m, the first one giving the number of nodes in the radial direction of the eigenfunctions associated with that mode, and the others (ℓ and m) being the indices of the spherical harmonic function that specifies the angular geometry of the mode. Nonrotating (spherical) stars have eigenfrequencies that are $(2\ell + 1)$-fold degenerate in m. However, a slowly rotating star has en eigenmode spectrum that is not degenerate in m as a result of the destruction of the spherical symmetry. To first order, with slow rotation considered as a perturbation, one can show that

$$\nu_{k\ell m} \simeq \nu_{k\ell} - m\Delta\nu_{kl} \quad (1)$$

where ν_{klm} is the frequency of mode (k, ℓ, m), ν_{kl} is the frequency of the degenerate mode (k, ℓ) in the absence of rotation, and the separation between each component is

$$\Delta\nu_{kl} = \frac{1}{2\pi}\int_0^R K_{k\ell}(r)\Omega_{\rm rot}(r)dr. \quad (2)$$

This leads to a set of equally spaced frequencies with a splitting between adjacent frequency components given by $\Delta\nu_{kl}$. In the above expression, $\Omega_{\rm rot}(r)$ is the (assumed) spherically symmetric rotation law (expressed in units of angular frequency), and K_{kl} is the so-called first-order rotation kernel, which plays the role of a weight function. It is given by

$$K_{kl}(r) = \frac{\xi_r^2 - [\ell(\ell+1) - 1]\xi_h^2 - 2\xi_r\xi_h}{\int_0^R [\xi_r^2 + \ell(\ell+1)\xi_h^2]\rho r^2 dr}\rho r^2 \quad (3)$$

where ξ_r and ξ_h are, respectively, the real parts of the radial and horizontal components of the displacement vector

$$\vec{\xi} = \left[\xi_r(r), \xi_h(r)\frac{\partial}{\partial\theta}, \xi_h(r)\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\right] Y_\ell^m(\theta,\phi)e^{i\sigma t}. \quad (4)$$

These eigenfunctions for mode (k, ℓ) refer to the unperturbed configuration, *i.e.*, to a purely spherical (nonrotating) stellar model.

Hence, to first order, slow spherically symmetric rotation produces a set of $2\ell + 1$ equally spaced frequency components out of a degenerate mode with indices (k,ℓ) as illustrated in Figure 1. The spacing between two adjacent components of this multiplet (modes that differ by $|\Delta m| = 1$) can be computed from the unperturbed eigenfunctions. This fine structure within a multiplet is usually referred to as rotational splitting.

In the particular case of uniform rotation, $\Omega_{\rm rot}$ does not depend on the radial coordinate r, and the frequency spacing reduces to the expression

$$\Delta\nu_{k\ell} = \frac{\Omega_{\rm rot}}{2\pi}(1 - C_{k\ell}), \quad (5)$$

Table 1. List of pulsating sdB stars in close binary systems with a rotation period estimated from asteroseismology.

Star	P_{orb}	P_{rot}	Synchronized	Reference
PG 1336-018	2.42 h	2.42 h	yes	Charpinet et al. (2008)
KIC 11179657	9.6 h	7.4 d	no	Pablo et al. (2012)
KIC 2991403	10.6 h	10.3 d	no	Pablo et al. (2012)
B4 in NGC 6791	9.4 h	9.6 d	no	Pablo et al. (2011)
PG 1142-037	13 h	> 45 d	no	Reed et al. (2016)
KIC 7664467	1.56 d	35 d	no	Baran et al. (2016)
KIC 10553698	3.39 d	41 d	no	Østensen et al. (2014)
KIC 11558725	10d	45d	no	Telting et al. (2012)
KIC 7668647	14.16 d	47 d	no	Telting et al. (2014)
KIC 3527751	binary ?	43 d core, 15 d envelope ?	no	Foster et al. (2015)

where $C_{k\ell}$, the first-order solid-body rotation coefficient, is given by

$$C_{k\ell} = \frac{\int_0^R [\xi_h^2 + 2\xi_r\xi_h]\rho r^2 dr}{\int_0^R [\xi_r^2 + \ell(\ell+1)\xi_h^2]\rho r^2 dr}. \quad (6)$$

Hence, even in the case of solid-body rotation, each mode has a specific period spacing whose value differs from mode to mode due to the $C_{k\ell}$ coefficient. In practice, however, the effect of this coefficient is quite secondary. For p-modes, $C_{k\ell}$ tends to be very small compared to 1 and, to a good approximation, the frequency spacing of the rotational splitting simply reduces to

$$\Delta\nu_{k\ell} \simeq \frac{\Omega_{\rm rot}}{2\pi} = \frac{1}{P_{\rm rot}} \quad (7)$$

regardless of the ℓ and k indices, and where $P_{\rm rot}$ is the rotation period of the star. For g-modes, this frequency spacing still depends on ℓ but cluster near the asymptotic limit where $C_{k\ell} \simeq 1/[\ell(\ell+1)]$. Hence, rotational splittings for g-modes also obey, as a good approximation, simple relations such as

$$\Delta\nu_{k1} \simeq \frac{0.5}{P_{\rm rot}}, \quad \Delta\nu_{k2} \simeq \frac{0.82}{P_{\rm rot}}, \quad \Delta\nu_{k3} \simeq \frac{0.92}{P_{\rm rot}} \quad (8)$$

These expressions show that estimating the average rotation rate of the star from the measure of frequency spacings between rotationally split components of observed multiplets is straightforward and essentially model independent. A robust first estimate of the rotation timescale can thus be obtained without requiring a detailed seismic modeling. The latter would of course bring further information on the internal rotation and structure of the star, as shown by various detailed analyses carried out in the past (*e.g.*, Charpinet et al. 2008, 2009), but we will not discuss these in detail in the present context.

3 Rotation of sdB stars from asteroseismology

Several seismic inferences for the rotation rate of sdB stars can be found in the literature. We summarize below these various measurements, making a distinction between the sdB stars that are in close binary systems and those that are apparently single. This distinction is motivated by the fact that stars in binaries may have their rotation strongly influenced by the close companion, through tidal synchronization mechanisms (see Preece et al., in these proceedings). In contrast, the rotation of single sdB stars should reflect mainly their secular evolution, thus carrying the imprint of their past history.

3.1 sdB stars in close binaries

Table 1 lists all sdB pulsators known to be part of a close binary system and for which an estimate of the rotation period is available. The first in this list, PG 1336-018, has been one of the best studied systems in asteroseismology so far (Charpinet et al. 2008; Van Grootel et al. 2013). In particular, a thorough seismic investigation of its internal rotation has been carried out leading to the conclusion that the star rotation is synchronized to the orbital period from the surface down to at least 50% of its radius. Since this system has a rather short orbital period (2.42 h), this finding is not very surprising as strong tidal interactions are expected here. For completeness, we note that another system, Feige 48 (not listed in the table), was also claimed to be tidally locked (Van Grootel et al. 2008), but this case is currently under revision based on new data and we leave it aside for our present discussion.

In contrast, all the other systems listed in Table 1 are found to be unsynchronized, the sdB star rotating with a much longer timescale than the orbital period. Leaving

Table 2. List of single pulsating sdB stars with a rotation period estimated from asteroseismology.

Star	P_{rot} (d)	Reference
BAL 0090100001	6.3	Baran et al. (2009)
PG 1219+534	34.9	Van Grootel et al. these proc.
KPD 1943+4058	39.2	Charpinet et al. (2011)
KIC 10139564	27.5	Baran & Østensen (2013)
KIC 10670103	88	Reed et al. (2014)
KIC 1718290	96.5	BHB; Østensen et al. (2012)
KIC 02697388	42	Kern et al. (2017)
EPIC 211779126	16	Baran et al. (2017)
KIC 10001893	$\sim$ 289	See text

aside PG 1142-037, for which only a lower limit of the rotation period is proposed, and KIC 3527751, whose binarity is not clearly established, there seem to be two distinct groups among this small sample : 3 stars with orbital periods around 9 – 10 hours that rotate with periods of 7.4 – 10.3 days and 4 stars that have longer orbital periods (from 1.56 to 14.16 days) and rotation periods ranging from 35 to 47 days. Interestingly, the rotation timescale of this second group is comparable to the rotation periods typically found for single sdB stars (see next subsection). It is conceivable that tidal interactions in these wider binaries may have been unable to significantly affect the rotation period of the sdB star, which therefore rotate at a rate that would be representative of the outcome of its secular evolution. In contrast, the first group of more compact binaries (and faster rotating sdBs), even if still unsynchronized, may show the traces of the tidal synchronization mechanism speeding up the rotation of the sdB component. Hence, these objects offer a very interesting opportunity to test tidal synchronization timescales and theories (see Preece et al. in these proceedings).

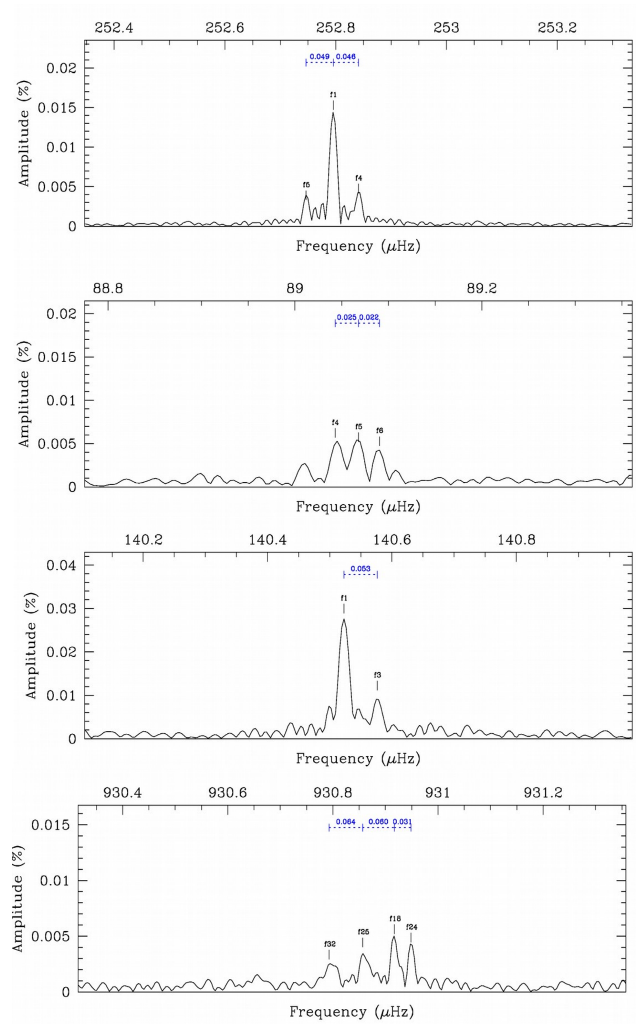

Figure 2. Hints of multiplet structures, possibly due to rotation, resolved just above the frequency resolution limit for several modes observed in the star KIC 10001893 monitored during 1111 days by the *Kepler* spacecraft (see text).

3.2 Single sdB stars

Table 2 lists all sdB pulsators with estimated rotation periods that show no evidence for the presence of a companion. Clearly, in all cases the measured rotation is extremely slow. This explains why the detection of rotational splittings have been relatively few before the advent of space observations, when ground based campaigns were simply not long enough to resolve rotation in most cases.

In this sample, two objects rotate somewhat faster with periods of 6.3 days (BAL 009100001) and 16 days (EPIC 211779126). However, the bulk of the distribution (so to speak as the sample is very small), seems to be in the range 27.5 – 96.5 days, which is similar to the rotation periods found for the second group of wider sdB binaries discussed in the previous subsection. There are hints, in particular from the very long *Kepler* time series, that some single sdB pulsators may in fact rotate at even slower rates. In a few cases, rotational splittings cannot be found even after months of observations, suggesting that the rotation may still be unresolved. Furthermore, the star KIC 10001893 observed continuously for 1111 days ($\sim$ 3 years) provides hints for a possibly very slow rotation of $\sim$ 289 days (9.6 months), since several peaks show fine structure just above the frequency resolution limit with spacings of $\Delta\nu \sim 0.02$ μHz and $\Delta\nu \sim 0.03$ μHz that could be consistent with rotational splittings of $\ell = 1$ and $\ell = 2$ g-modes (see Figure 2).

Since the rotation of single sdB stars is linked to secular evolution, without interference from any tidal effect,

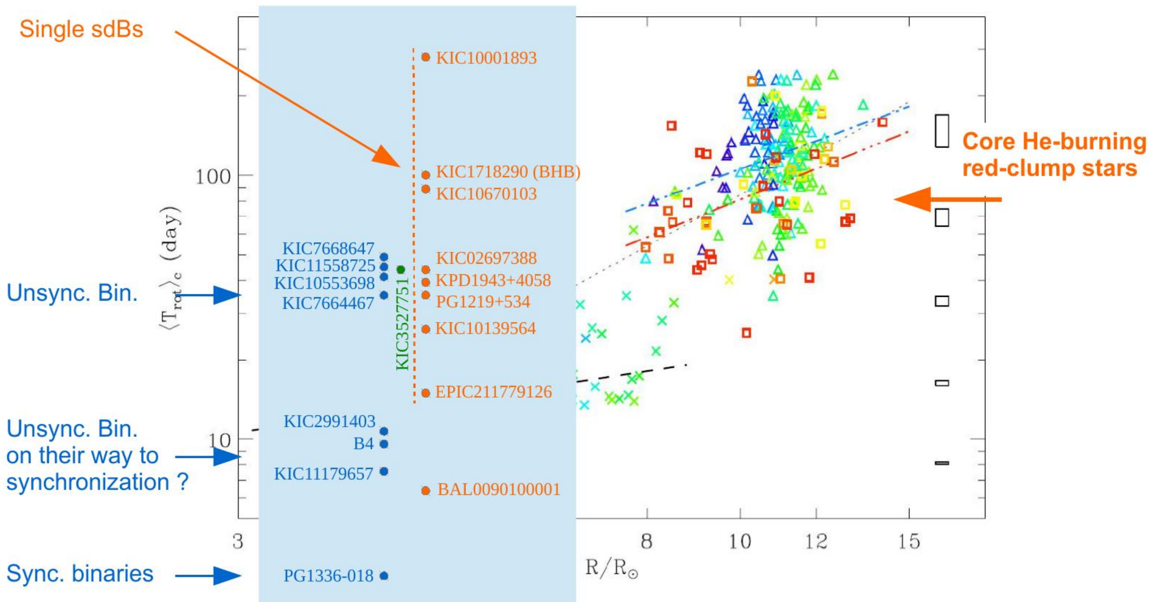

Figure 3. Comparison of the rotation periods derived for the sdB stars listed in Table 1 and Table 2 (left side of the figure) with the rotation periods measured for the cores of red-clump stars (from Figure 9 of Mosser et al. 2012). See text and Mosser et al. (2012) for further details.

comparing it with inferred rotation timescales in stars potentially connected from an evolutionary point of view is therefore particularly enlightening. We discuss such comparisons in next sections.

4 Comparison with rotation rates of red-clump-star cores

The first interesting comparison is with the so-called red-clump stars. We update here, in light of most recent analyses, a discussion on rotation initiated in Charpinet et al. (2013) and continued in, *e.g.*, Reed et al. (2014) and Charpinet et al. (2016). Red-clump stars are evolved red-giant stars that have started helium burning in the core. They form the red part of the Horizontal Branch and their structure is generally made of a $\sim 0.5\ M_{\odot}$ helium burning core (in effect quite similar to a hot subdwarf star) surrounded by a thick hydrogen layer. With the advent of asteroseismology from space, it was discovered that red-giants develop rich oscillation spectra composed of many mixed modes. These modes either have a p-dominated or a g-dominated character, the former probing mainly the envelope of the star and the latter being concentrated in the core. As pointed out by O'Toole (2012), the g-dominated modes observed in red-clump stars show global properties, such as average period spacings, that are indeed similar to the period spacings measured in g-mode sdB pulsators, thus confirming the expected similarity of their core structure. The identification of rotational splittings around red-clump star's mixed modes offers the remarkable opportunity to estimate the rotation rate of these stars both in the envelope and in the core (see, *e.g.*, Mosser et al. 2012). The rotation of the core is, in particular, of direct interest for our comparison purposes since, in a context where sdB stars could be former cores of red-giant stars obtained from stripping out most of the envelope, the core of a red-clump star and a sdB star could have followed essentially the same structural and dynamical evolution.

Figure 3 shows, superimposed on Figure 9 of Mosser et al. (2012), all of the hot B subdwarf pulsators listed in Table 1 and Table 2, keeping the distinction between stars in close binaries (shown as blue dots) and single sdB stars (red dots). Clearly, the rotation timescale measured for the core of red-clump stars (between $\sim$ 20 and 300 days) appears remarkably similar to the timescale inferred for most single sdB stars. It is also comparable to the rotation rate found for hot subdwarfs in the group of wider binaries. This has fundamental implications in the context of the still debated formation channels that produce sdB stars, in particular the isolated ones.

The group of unsynchronized binaries with rotation periods for the sdB component around 40 days, *i.e.* comparable to the rotation periods of stellar cores in red-clump stars, strongly suggest that these stars evolved from the

Table 3. List of isolated pulsating white dwarfs with a rotation period derived from asteroseismology.

Star	Type	P_{rot} (h)	Comment	Reference
Ross 548	DAV	37.8 ± 2.0	Solid over ∼ 5% of the radius	Giammichele et al. (2016)
HL Tau 76	DAV	53		Pech et al. (2006)
GD 154	DAV	55		Pfeiffer et al. (1996)
GD 165	DAV	57.1 ± 0.6	Solid over ∼ 20% of the radius	Giammichele et al. (2016)
L19-2	DAV	13		Bradley (2001)
G 226-29	DAV	9		Kepler et al. (1995)
G 185-32	DAV	15		Pech & Vauclair (2006)
GD 358	DBV	29		Winget et al. (1994)
KIC 086626021	DBV	46.3 ± 2.5	Solid over ∼ 70% of the radius	Giammichele et al. (2017)
PG 0112+104	DBV	10.2 ± 0.3	Solid over ∼ 70% of the radius	Giammichele et al., these proc.
PG 0122+200	DOV	41.8 ± 2.1	Solid over ∼ 90% of the radius	Fontaine et al. (2013)
NGC 1501	DOV	28		Bond et al. (1996)
PG 1159-035	DOV	33.6 ± 0.6	Solid over ∼ 97% of the radius	Charpinet et al. (2009)
PG 1707+427	DOV	16 – 31		Kawaler et al. (2004)
PG 2131+066	DOV	5.15 ± 0.18	Solid over ∼ 90% of the radius	Fontaine et al. (2013)
RXJ 2117+3412	DOV	27.7 ± 1.8	Solid over ∼ 90% of the radius	Fontaine et al. (2013)

red-giant branch, thus sharing the same dynamical properties as typical cores of post-RGB stars. This is somewhat expected since the current paradigm is that sdB stars in close binaries are indeed produced through interacting binary evolution during which the stellar companion ultimately expels the envelope of the red-giant progenitor without affecting much the stellar core itself.

The situation for single sdB stars is more intriguing, because the formation scenario invoked in that case is usually the merger of two compact helium white dwarfs, *i.e.*, a completely different channel. In this context, the seismic measurements of the rotation rate of single sdB stars then raise at least two questions. The first one is : how could a merger event (storing by nature a large amount of orbital angular momentum) produce sdB stars with such slow rotations? And if it can, the second (perhaps even more puzzling) issue would then be : by which coincidence could this rotation rate end-up being very similar to the rates found for sdB stars in binaries and for the cores of red-clump stars, which both come from red-giant evolution ?

We point out that a natural explanation to this puzzle would be to consider these seismic measurements as evidence that most hot B subdwarf stars, including the single ones, originate from the evolution of red-giant stars stripped from their envelope, explaining their similar rotational properties. This would imply to develop alternatives to the merger scenario for producing isolated sdB stars, such as those, for instance, involving the presence of substellar companions (Soker 1998; Charpinet et al. 2011).

5 Connection with white dwarfs

Another interesting connection that can be made, is with the white-dwarf stars (see, *e.g.*, Charpinet et al. 2016). Hereafter, as a natural extension of the discussion carried out in the previous section, we consider hot B subdwarf stars to be representative of helium burning cores in horizontal branch stars in general. The dynamical similarities found with cores of red-clump stars justify this assertion, at least for the following discussion. Since white-dwarf stars are the ultimate outcome of the evolution of these helium burning cores, even though the hot subdwarf themselves would contribute only to a small fraction (∼ 2 %) of them, a comparison of their respective rotation rates is an important information to understand the general evolution of angular momentum in low-mass stars. In particular, we note that shrinking a sdB star (or more generally a typical helium-burning core) with the measured rotation rates to the size of a typical white dwarf, assuming total angular momentum (AM) conservation, would lead to white dwarfs rotating with periods between ∼ 2 – 70 hours.

Table 3 summarizes all the rotation periods obtained from asteroseismology that we are aware of for isolated white-dwarf stars. Some of these measurements derive from very detailed seismic analyses of the star, as described, *e.g.*, by Giammichele et al. in these proceedings, which provide insight on the internal fraction of the star that has been effectively probed. The others are usually based on a quick estimate of the rotation timescale from the average spacings observed in rotationally split multiplets. In any case, the range of rotation periods for typical white dwarfs derived from asteroseismology is be-

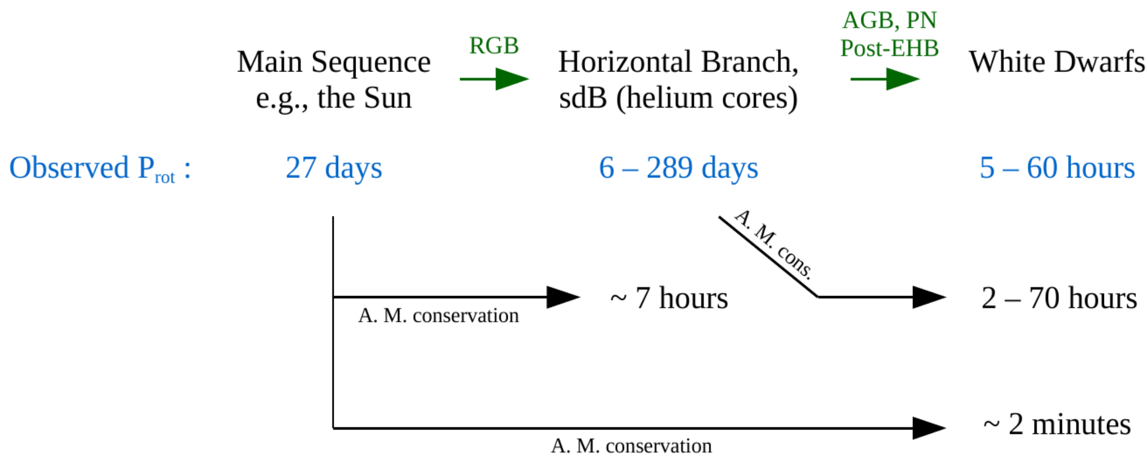

Figure 4. Schematic view of the angular momentum evolution in low-mass stars as revealed by seismic observations (source : Charpinet et al. 2016). Clearly, strong braking and loss of almost all of the initial angular momentum occurs before or during the Red Giant Branch (RGB) phase. During post-RGB evolution, the angular momentum in stellar cores is essentially preserved (see text).

tween 5 and 57 hours, which corresponds to the predicted rates if angular momentum is conserved from the core helium burning phase to the white-dwarf cooling track. This clearly indicates that no angular momentum is lost (or gained) by stellar cores during HB and post-HB evolution. The core evolves disconnected from the envelope of the star.

Figure 4 schematically summerizes the picture that can be drawn regarding the evolution of angular momentum for low-mass stars from main sequence to white dwarfs. If we take the Sun as a reference for main sequence stars, then assuming again angular momentum conservation, its rotation period when shrunk to the size and mass of a helium core and of a white dwarf would be $\sim$ 7 hours and $\sim$ 2 minutes, respectively. This is a lot faster than the observed rotations, as we have shown previously. Therefore, a massive loss of the original angular momentum (by a factor of $\sim$ 200 – 300 relative to the Sun) must have occurred before the star settles as an object burning helium in the core. Most likely, this strong braking in the star rotation happens during the red-giant phase itself, as asteroseismology of red-giant stars seems to indicate. Viewed differently, this means that practically all the angular momentum stored in the core must transit through the red-giant envelope during that phase, a mechanism that may have some influence on the common envelope ejection process needed to produce hot B subdwarfs.

6 Conclusion

As illustrated in previous discussions, learning about the internal rotation rate of hot B subdwarf stars is important to address several unanswered questions in the field and beyond. When they are found in close binary systems, their rotation is potentially influenced by tidal interactions, thus making these stars ideal test-beds for testing tidal synchronization physics. In contrast, the rotation of single sdB stars should solely reflect their secular evolution. In this context, asteroseismology is a rather straightforward and secure means to, at least, estimate rotation timescales, when such stars pulsate and rotational splittings are identified in their oscillation spectra. Several such measurements have indeed been gathered over the years, which show that isolated sdB stars rotate very slowly, implying that strong braking has occurred during the previous phases of evolution. Moreover, their rotation timescale is found similar to the rotation periods derived from asteroseismology both for the helium burning cores of red-clump stars and for the slowest rotating sdB stars found in unsynchronized close binaries. This strongly suggests that some (most?) isolated sdB stars follow the typical red giant-branch evolution and are not produced by a merger event, although, of course, one cannot completely rule out that a fraction of the single hot subdwarfs could still be formed through this channel. This raises again the question of the mechanism involved for a red-giant to expel most of its envelope if there is no stellar companion present in the vicinity. A solution might be to consider common envelope evolution involving substellar companions (brown dwarfs, planets), as has already been suggested in the past.

Finally, isolated white dwarfs also rotate very slowly (and mostly as solid bodies) at rates indicating that stellar core dynamics past the red giant branch no longer drastically evolve, *i.e.*, no further massive loss of angular momentum occurs in the core which is therefore well disconnected from the outer envelope layers (during the AGB phase, for instance).

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