The evolved slowly pulsating B star 18 Peg: A testbed for upper main sequence stellar evolution

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The bright B3 III giant star 18 Peg turns out to be a slowly pulsating B star in a long period binary with a main-sequence star or a neutron star as companion. Given that it is one of the most evolved members of this class of massive pulsating stars, an accurate determination of the location of 18 Peg in the Hertzsprung-Russell (H-R) diagram would provide a lower limit on the width of the upper main sequence and hence would reveal information about the efficiency of the convective overshooting. We explain why long-term space-based observations are needed and how BRITE could play a crucial role in the gathering of the mandatory ingredients to test the models of the upper main sequence evolution.

1 Introduction

18 Peg is a bright ($V = 6.0$ mag) B3 III giant star that has often been used as a telluric standard star and as a background source for the determination of the chemical composition of the interstellar medium. It is a slow rotator ($v \sin i = 15 \pm 3$ km s^{-1}; Nieva & Przybilla 2012) and hence an ideal object for a precise abundance determination and for differential abundance analyses to search for chemical peculiarities in other stars. Even though 18 Peg has often been used as reference star, recent results show that 18 Peg is not as innocent as it looks at first glance. Irrgang et al. (2016) looked at previously unexplored spectra from the ESO archive and some other observatories taken hours to years apart with many different instruments (UVES, FOCES, X-shooter, ESPaDOnS, ISIS, TWIN, FLECHAS, BACHES). They also studied photometric time series of 18 Peg: 59 HIPPARCOS H_p and 80 Tycho B_T/V_T observations with a time base of ∼1000 d (Perryman et al., 1997) and 85 ASAS V_A observations with a time base of 569 d (Pojmanski, 1997). 18 Peg turns out to be a long-period spectroscopic binary (Section 2) and an ideal asteroseismic target to test the upper main sequence stellar

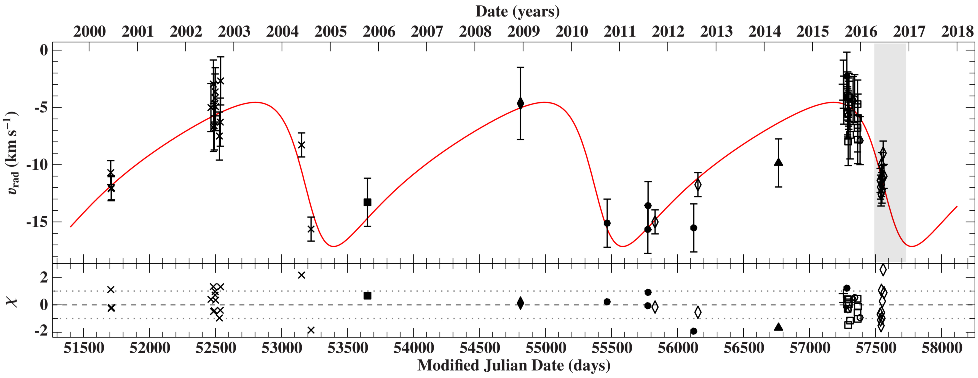

Fig. 1: Radial velocity curve of 18 Peg after inclusion of all the available HERMES spectra observed before 01/07/2016. The derived radial velocities are represented by black symbols with error bars while the best-fitting Keplerian model is visualized by the solid curve. Residuals χ are shown in the lower panel. The current observation season of 18 Peg at the Roque de Los Muchachos observatory is indicated with a grey area.

evolution (Section 3). We argue that complementary long-term space-based data are needed to reach our goals (Section 4). This paper serves as a proposal for observations with the BRITE-Constellation.

2 18 Peg as a binary

In Fig. 1, the radial velocities derived from all the spectra that were available at 01/07/2016 are represented by black symbols with an error bar. All of them, except those given with open diamonds, were used in the study of Irrgang et al. (2016). Long-term radial velocity variations with a peak-to-peak amplitude of the order of 10 km s^{-1} are clearly visible. The observed variations are compatible with the interpretation that 18 Peg is a spectroscopic binary with an orbital period of about 6 years and a high eccentricity. The parameters corresponding to the best-fitting Keplerian model published by Irrgang et al. (2016) are given in the left column of Table 2. This orbital solution, in combination with the absence of additional signatures of the secondary component in the spectroscopic data and the spectral energy distribution, lead to the conclusion that all the observations of 18 Peg are fully compatible with the assumption that the secondary component is most likely either a main-sequence star with a mass between 1 and 4 $M_\odot$ or a neutron star.

In 2016, the binary system is in the phase where the orbital velocities are changing fast (Fig. 1). For an efficient fine-tuning of the orbital solution, it is crucial to obtain new spectroscopic observations right now. We therefore applied for observations with the high-resolution spectrograph HERMES (1.2-m Mercator telescope, La Palma, Spain; Raskin et al. 2011) at a three day cadence for the rest of the ongoing observational season of 18 Peg at the Roque de los Muchachos observatory (grey area on Fig. 1). Thanks to the scientific interest and the kind help of A. Tkachenko & C. Aerts, these observations could already start on 26/05/2016. The radial velocities derived from the HERMES spectra already available on 01/07/2016 are shown as open diamonds in Fig. 1. The new orbit found for the full data set is drawn with a solid curve in Fig. 1 and the corresponding orbital parameters are given in the right column

Parameter	Publised	This work
Period P	2245^{+25}_{-30} d	2190^{+11}_{-10} d
Epoch of periastron $T_{\mathrm{periastron}}$	57730^{+40}_{-60} MJD	57600^{+50}_{-70} MJD
Eccentricity e	$0.60^{+0.07}_{-0.08}$	$0.40^{+0.08}_{-0.09}$
Longitude of periastron ω	123^{+12}_{-7} deg	115^{+12}_{-17} deg
Velocity semiamplitude K_1	$7.7^{+1.9}_{-1.1}$ km s^{-1}	$6.3^{+0.9}_{-0.7}$ km s^{-1}
Systemic velocity γ	-9.9 ± 0.4 km s^{-1}	-9.8 ± 0.4 km s^{-1}
Derived parameter	**Published**	**This work**
Mass function $f(M)$	$0.054^{+0.035}_{-0.017}\,M_\odot$	$0.043^{+0.016}_{-0.012}\,M_\odot$
Projected semimajor axis $a_1 \sin(i)$	$1.27^{+0.23}_{-0.15}$ AU	$1.16^{+0.13}_{-0.11}$ AU
Projected periastron distance $r_{\mathrm{p}} \sin(i)$	$108^{+21}_{-17}\,R_\odot$	$149^{+22}_{-20}\,R_\odot$

Table 1: Comparison of the orbital solution of 18 Peg as published by Irrgang et al. (2016) ("Published"; left column) to the one derived after inclusion of all the available HERMES spectra observed before 01/07/2016 ("This work"; right column).

of Table 2. While most of the orbital parameters agree within the 1σ errors with those given by Irrgang et al. (2016), the revised values of the orbital period, the eccentricity and the epoch of periastron are (significantly) lower. Nevertheless, the conclusions about the nature of the secondary component remain the same.

3 18 Peg as an asteroseismic target

Irrgang et al. (2016) found a period of 1.38711±0.00014 d with a false alarm probability below 4% in the photometric time series of 18 Peg. The observed amplitudes of ~7 mmag in HIPPARCOS H_p, ~10 mmag in Tycho B_T, ~20 mmag in Tycho V_T, and ~10 mmag in ASAS V_A are typical for slowly pulsating B (SPB) stars. This class of pulsating stars consists of mid-to-late B-type stars in the main sequence oscillating in high-order gravity modes with periods from 0.3 to 3 d. These pulsations are driven by the κ mechanism acting in the iron opacity bump at around 200,000 K (e.g. Dziembowski et al. 1993). Also the low amplitude variations on a short timescale as seen in the residual radial velocities after subtraction of the orbit (Fig. 1) are compatible with the SPB suggestion.

The high-resolution spectra of 18 Peg are of sufficient quality to reveal very prominent line-profile variations (LPVs) like those observed in the UVES spectra as shown in Fig. D.1. of Irrgang et al. (2016). The time evolution of these bumps and the amplitude of their Doppler shifts are not compatible with the assumption that the primary component of the long-period binary of 18 Peg would be a spectroscopic binary itself with an orbital period of the order of a few days. If the observed LPVs were to be caused by surface spots, it would require a very low value for the rotational inclination which is unlikely from a statistical point of view. Moreover, the star would be seen nearly pole-on and prominent LPVs would not be expected. Therefore, stellar pulsations are the most natural explanation for the observed short period spectroscopic variations. The LPVs can indeed be fitted in a satisfactory way with synthetic line profiles based on pulsational motion. Following Schrijvers et al. (1997), Irrgang et al. (2016) obtained the best fit for an $(\ell,m) = (5,+1)$ mode with 3.22 dex

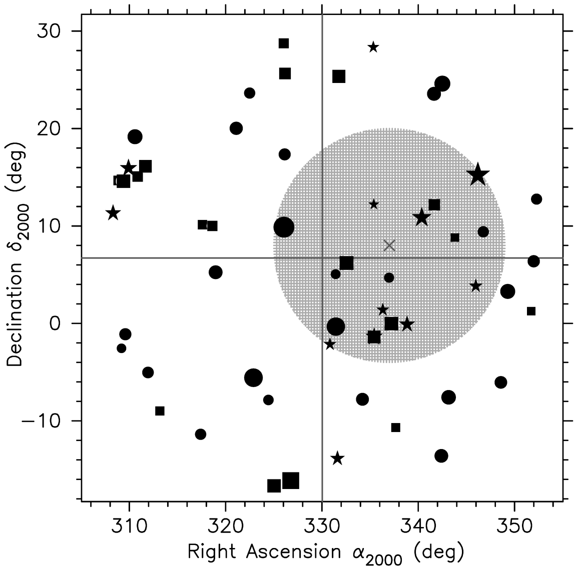

Fig. 2: SIMBAD objects with $V \leq 5$ mag within 24° around 18 Peg, whose location is marked by the dark grey cross-hair. The circular grey area represents the suggested field-of-view for BRITE-observations. Its center, located at $\alpha_{2000} = 22^{\rm h}28^{\rm m}00^{\rm s}$ and $\delta_{2000} = +08°00'00''$, is given by the dark grey cross. The symbols are related to the spectral type of the objects (stars for OB-type stars; squares for AF-type stars; circles for late-type stars) while their size is related to their brightness (bigger symbols for brighter stars).

as an asteroseismic estimation for $\log g$. This is low compared to the photometric value as found from the modelling of the spectral energy distribution ($3.41^{+0.16}_{-0.14}$ dex; Irrgang et al. 2016) and the spectroscopic value emerging from an abundance analysis ($3.75^{+0.05}_{-0.05}$ dex; Nieva & Przybilla 2012). All these analyses put 18 Peg close to the transition region between the main-sequence and post main-sequence phase in the H-R diagram (Fig. 4 of Irrgang et al. 2016). As the position of this region depends strongly on the amount of convective overshooting (and to a lesser extend on stellar rotation), an evolved SPB star such as 18 Peg is an ideal testcase for the evolutionary models in the upper main sequence.

4 18 Peg as a target for space missions

Follow-up observations are required to fully exploit the star's capability as benchmark object and to fine-tune the results given by Irrgang et al. (2016). As most SPB stars are multi-periodic, the observed variations have long beat periods and are generally complex. The large observational efforts required for in-depth asteroseismic studies leading to, e.g., accurate values of mass and age (and hence the evolutionary status) and an indirect measurement of the convective overshooting parameter are hard to achieve with ground-based observations. Complementary long-term space-based observations are generally needed to reach this goal.

So far, only one pulsation mode has been detected for 18 Peg, which is insufficient to derive an accurate position in the H-R diagram. The upcoming satellite mission TESS (to be launched in December 2017) will obtain time-series of high precision

Name	α_{2000} (°)	δ_{2000} (°)	V (mag)	SpT	V	D	SB	EM
π Aqr	336.3192749	1.3773985	4.640	B1 III-IVe			SB	EM
31 Peg	335.3794861	12.2051840	4.990	B2 IV-Ve				EM
β Psc	345.9692078	3.8200462	4.520	B6 Ve				EM
o Aqr	330.8285217	-2.1553631	4.690	B7 IVe				EM
η Aqr	338.8390808	-0.1174969	4.030	B8/9 V				
42 Peg	340.3655396	10.8312893	3.410	B8 V				
α Peg	346.1902161	15.2052670	2.480	B9 III	V			
γ Aqr	335.4140625	-1.3873342	3.847	A0 V				
ρ Peg	343.8069763	8.8161650	4.900	A1 V				
θ Peg	332.5499268	6.1978631	3.550	A1 Va	V			
ζ Aqr	337.2079468	-0.0199428	3.650	F3 III-IV		D		
20 Peg	330.2722778	13.1198235	5.613	F4 III				
ξ Peg	341.6732483	12.1728849	4.200	F6 V				
α Aqr	331.4459839	-0.3198500	2.940	G2 Ib				
35 Peg	336.9646912	4.6956668	4.800	G8 IV				
ϵ Peg	326.0464783	9.8750086	2.390	K2 Ib-II	V			
ν Peg	331.4197998	5.0585332	4.840	K4 III	V			
55 Peg	346.7510681	9.4094915	4.520	M1 III	V			

Table 2: All the SIMBAD objects with $V \leq 5$ mag inside the suggested field-of-view for BRITE observations of 18 Peg. They are sorted from early-type (top) to late-type (bottom) stars. The objects classified as a variable star, a double or multiple star, a spectroscopic binary or a star with emission are indicated with V, D, SB, and EM, respectively.

photometry in a single broad band with a cadence of 30 minutes (Ricker et al., 2015). However, TESS observations with a time-base of 27 d only can be expected at the ecliptic lattitude of 18 Peg (except if we are in the unlucky situation that the ecliptic longitude of 18 Peg would fall into one of the few small strips that will not be observed with TESS). Such a time base is too short for a typical SPB star. We therefore apply for observations with the BRITE-Constellation. The center of the suggested field-of-view is located at $\alpha_{2000} = 22^{\rm h}28^{\rm m}00^{\rm s}$ and $\delta_{2000} = +08°00'00''$ and is presented in Fig. 2. Apart from 18 Peg, this field contains 18 SIMBAD objects[1] with $V \leq 5$ mag, including five, one, one, and four stars classified as a variable star, a double or multiple star, a spectroscopic binary, and a star with emission, respectively (Table 4). However, for a star as faint as 18 Peg, accurate BRITE photometry can only be obtained in the red band and long-term one-band observations with the BHr satellite alone will not be sufficient for our purposes either. The requested observations will therefore be further complemented with high-resolution HERMES spectra (guaranteed access) and with Strömgren u and y photometry with a cadence of ~18 minutes obtained with the 0.75-m T6 APT at Fairborn Observatory (Arizona, USA; kindly offered by G. Handler). However, the inclusion of long-term BRITE observations is crucial to allow us to:

• get the right values of the pulsation frequencies. The time-sampling of the BRITE observations will be very different from the one of the ground-based follow-up observations. Hence, they will give us crucial information to allow to separate the physical frequencies from the alias frequencies. Moreover, their long time-base will increase the accuracy of the pulsation frequencies.

[1] This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France

• get a better view on the full pulsational content of 18 Peg as we will be able to detect lower amplitude modes.

• calculate accurate pulsation amplitudes in the red filter of the BHr satellite. In combination with the observed amplitudes in the passbands of the ground-based photometry, we will be able to get constraints on the degree ℓ of the pulsation modes. These will be used as input for an in-depth mode identification for the highest amplitude modes that are simultaneously present in the LPVs. Note that the ongoing ground-based follow-up observations with HERMES with a three day cadence already allow a rough monitoring of the LPVs provided that the quality of the spectra is high enough (S/N>200 in the V-band). However, for a detailed seismic modelling of the main pulsation mode, A. Tkachenko observed 18 Peg with a higher cadence of five spectra well-spread throughout the night during four consecutive nights (04-07/08/2016). These observations are currently being investigated.

• detect in the best case scenario quasi-regular period spacings. It would give a severe constraint on the fraction of hydrogen in the core and hence on the evolutionary status of 18 Peg.

5 Conclusions

The requested BRITE observations for 18 Peg are a crucial step to get the mandatory ingredients to test the models describing the upper main sequence evolution.

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