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

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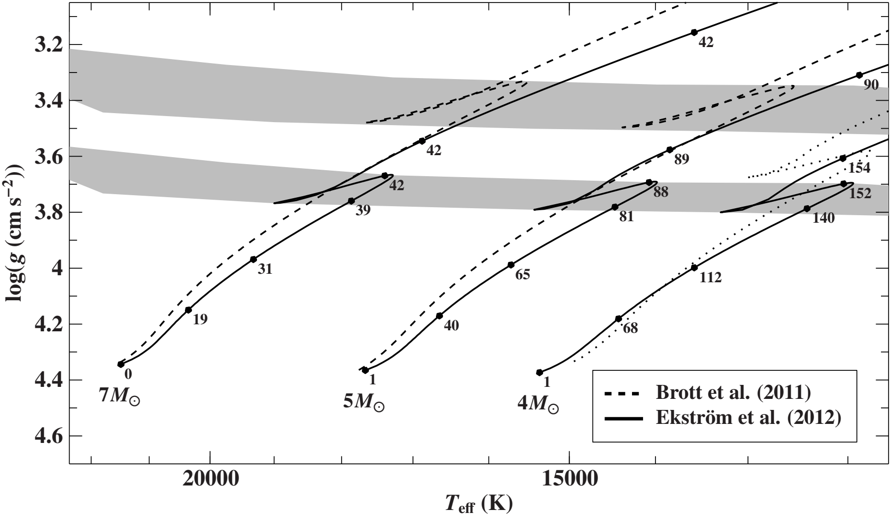
Convective overshooting – a longstanding challenge



Slowly pulsating B (SPB) stars

- The class of SPB stars was first introduced by Waelkens (1991) and consists of mid to late B-type stars that show photometric variability on the order of a few days
- Pulsations are thought to be driven by an “opacity bump” mechanism that excites multi-periodic, non-radial gravity modes with periods in the range 0.4–3 days and V-band amplitudes lower than 0.03 mag (Catelan & Smith 2015)
- In 2007, the number of confirmed plus candidate Galactic SPB stars was only 116 (De Cat 2007)
- The terminal-age main sequence is a hard boundary for the instability strip of SPB stars owing to the very strong damping of high-order gravity modes in the interiors of post main-sequence stars (Pamyatnykh 1999)

18 Peg: a not so standard "standard star"

Facts & beliefs

- Bright ($V = 6$ mag) mid B-type giant (B3 III) of relatively high Galactic latitude ($l = 65.80°$, $b = -36.51°$)
- Relatively nearby ($d = 372 \pm 25$ pc, Nieva & Przybilla 2012)
- Slow rotator ($\upsilon \sin(i_\mathrm{r}) = 15 \pm 3$ km s^{-1}, Nieva & Przybilla 2012)
- Normal chemical composition (Nieva & Przybilla 2012)
- Generally assumed to be a single star

⇒ Frequently used as a reference star for various different studies.

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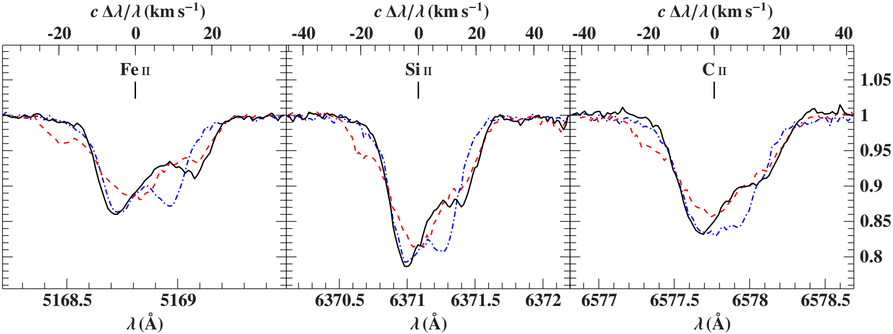
Two new facets (Irrgang et al. 2016)

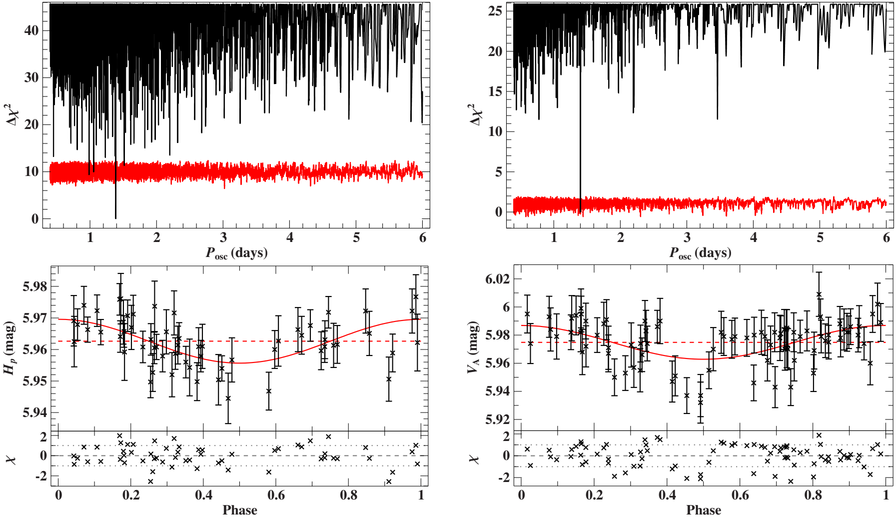
- Part of a single-lined spectroscopic binary system
- One of the most evolved slowly pulsating B stars discovered so far

Line-profile variations



The black solid, red dashed, and blue dash-dotted lines are observed UVES spectra with spectral resolutions $R = 107\,200$ taken three and two days apart (MJD $51\,707.23$, $51\,710.24$, and $51\,712.24$).

Light-curve analysis



Periodograms (*top*) and phased light-curves (*bottom*) for HIPPARCOS epoch photometry (*left*, 59 points in ~ 1000 days) and ASAS (*right*, 85 points in 569 days) data.

Oscillation parameters

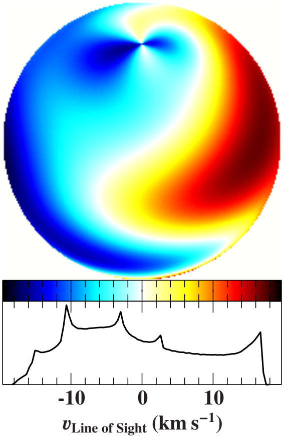
$$\mathrm{mag}_j(t) = \overline{\mathrm{mag}}_j + A_j \cos\left(2\pi\left[(t - T_{\mathrm{ref}})/P_{\mathrm{osc}} + \phi_{\mathrm{osc,ref}}\right]\right)$$

Parameter	Value
HIPPARCOS epoch photometry data:	
Period P_{osc}	1.38711 ± 0.00014 days
Reference epoch T_{ref} (fixed)	$47\,898.49$ MJD
Phase $\phi_{\mathrm{osc,ref}}$ at epoch T_{ref}	0.58 ± 0.05
H_p mean magnitude	5.9626 ± 0.0009 mag
H_p semiamplitude	0.0069 ± 0.0013 mag
ASAS light-curve:	
Period P_{osc}	1.39976 ± 0.00030 days
Reference epoch T_{ref} (fixed)	$54\,229.40$ MJD
Phase $\phi_{\mathrm{osc,ref}}$ at epoch T_{ref}	0.68 ± 0.05
V_{A} mean magnitude	5.9748 ± 0.0016 mag
V_{A} semiamplitude	0.0120 ± 0.0024 mag

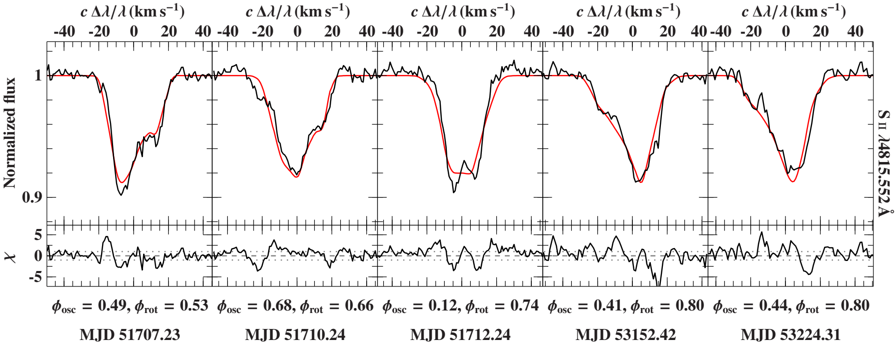
Spectral modeling of the line-profile variations

Schrijvers et al. (1997) provide a formulation for the surface velocity field of a rotating, adiabatically pulsating star:

- It is purely dynamical.
- The pulsational and rotational axes are aligned.
- It accounts for the effects of the Coriolis force ($\propto \Omega$) but not for the centrifugal force ($\propto \Omega^2$).
- It considers only mono-periodic modes although multiple modes are excited simultaneously in most pulsators.



Spectral modeling of the line-profile variations



Spectral modeling of the pulsationally driven line-profile distortions for five epochs (*columns*) and one exemplary line: the observations are indicated by a black line, the model by a red one, and the quality of the fit by the residuals χ. Oscillation and rotation phases are listed on the x-axes.

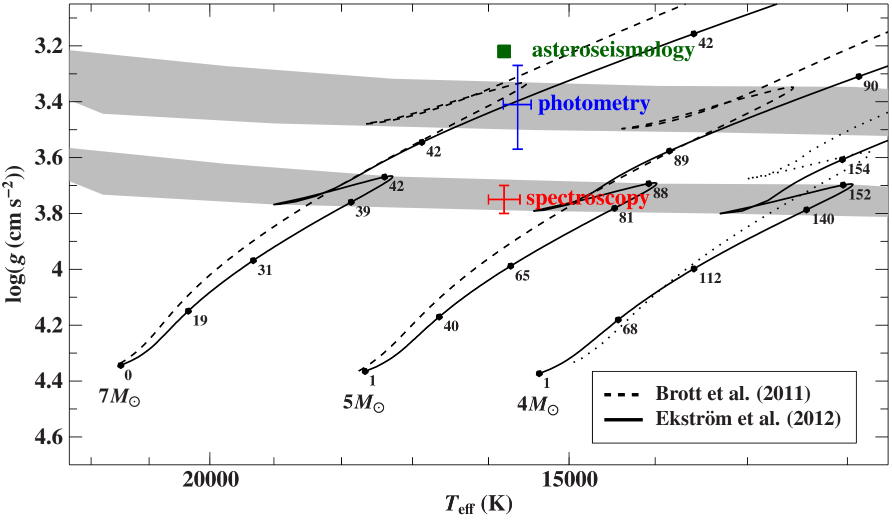
$\Rightarrow$ Line-profile variations can be well explained by stellar pulsations

Parameters and derived quantities for the best-fitting pulsational model with $l = 5$ and $m = 1$.

Parameter	Value	Derived quantity	Value
$k^{(0)}$	$0.792^{+0.006}_{-0.007}$	$a_{\rm sph}$	$0.2688^{+0.0016}_{-0.0009}\,R_\odot$
$P_{\rm osc}$	1.3818 ± 0.0001 days	$\omega^{(0)}$	4.5429 ± 0.0002 days^{-1}
$\phi_{\rm osc,ref}$	$0.4963^{+0.0020}_{-0.0015}$	$\Omega/\omega^{(0)}$	$0.0577^{+0.0010}_{-0.0001}$
$\phi_{\rm rot,ref}$	$0.5323^{+0.0018}_{-0.0020}$	η	$0.0042^{+0.0002}_{-0.0001}$
Ω/ω	$0.0576^{+0.0010}_{-0.0001}$	M	$7.3^{+0.2}_{-0.4}\,M_\odot$
$v\sin(i_{\rm r})$	$16.07^{+0.04}_{-0.03}\,{\rm km\,s^{-1}}$	$R_\star$	$10.9^{+0.1}_{-0.2}\,R_\odot$
$\langle v_{\rm v}^2\rangle^{1/2}$	$1.96^{+0.02}_{-0.01}\,{\rm km\,s^{-1}}$	$P_{\rm rot}$	$23.9801^{+0.0043}_{-0.3899}$ days
$i_{\rm r}$	$44.2^{+0.2}_{-0.3}\,^\circ$	$\log(g\,({\rm cm\,s^{-2}}))$	3.22 ± 0.01 dex

- η is the ratio of the centrifugal to the gravitational force at the equator
- $R_\star$ is derived from the identity $v\sin(i_{\rm r}) = \Omega R_\star \sin(i_{\rm r})$
- $M = k^{(0)}(\omega^{(0)})^2 R_\star^3/G$ (see Eq. (9) in Schrijvers et al. 1997)
- The surface gravity follows from $g = GMR_\star^{-2}$

Potential benchmark star for upper main sequence stellar evolution models



Conclusions

18 Peg is . . .

- a single-lined spectroscopic binary with an eccentric orbit of about 6 years with a main sequence or neutron star companion
- a slowly pulsating B star
  - low amplitude gravity mode observed in photometry and spectroscopy
  - evolved

    $\Rightarrow$ lower limit on the width of the upper main sequence

    $\Rightarrow$ information about the efficiency of convective overshooting

Follow-up observations are needed to perform a more sophisticated asteroseismic study and to fully exploit the star's potential as benchmark object:

- Spectroscopy: HERMES@1.2-m Mercator
- Photometry: BRITE? *TESS*?

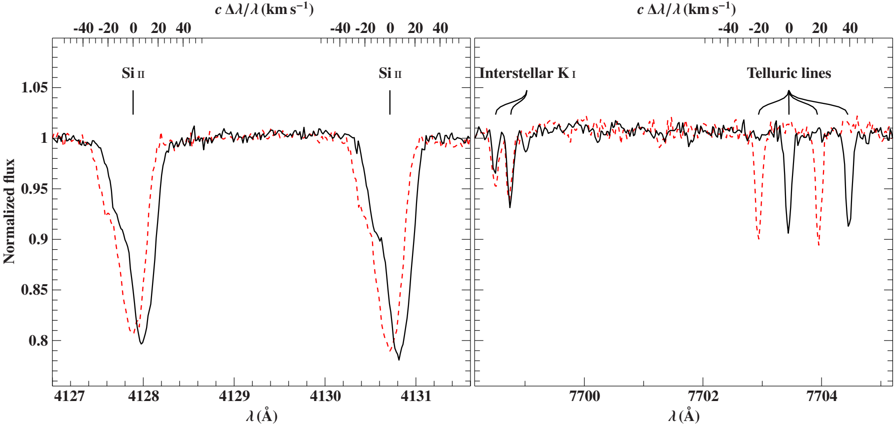
Pulsational broadening profile

Despite various simplifications, the model is already a function of 10 parameters[1]: $\Phi = \Phi(l, m, a_{\rm sph}, k^{(0)}, \omega^{(0)}, \Omega/\omega^{(0)}, i, v\sin(i), \phi_{\rm osc}, \phi_{\rm rot})$

- Angular degree: l
- Azimuthal order: m
- Vertical amplitude: $a_{\rm sph}$
- Ratio of the horizontal and vertical amplitude: $k^{(0)}$
- Angular oscillation frequency: $\omega^{(0)}$
- Ratio of the angular rotation frequency Ω and $\omega^{(0)}$: $\Omega/\omega^{(0)}$
- Inclination of the pulsational/rotational axis: i
- Projected rotational velocity: $v\sin(i)$
- Oscillation phase: $\phi_{\rm osc}$
- Rotation phase: $\phi_{\rm rot}$

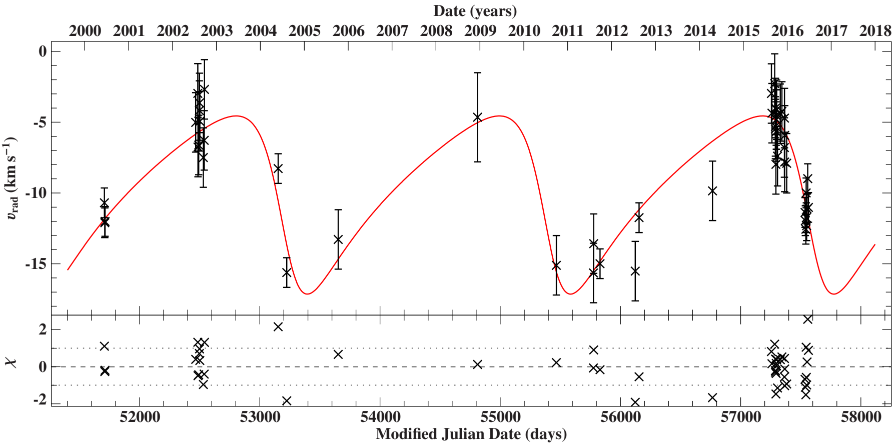
[1] Superscripts $^{(0)}$ refer to quantities in the non-rotating case.

Wavelength shifts



Observed Uves spectra with $R \approx 55\,000$ taken about 72 days apart.
Left: A clear wavelength shift is visible for the stellar Si II lines.
Right: Interstellar K I and telluric lines are shown for reference.

18 Peg: A single-lined spectroscopic binary system



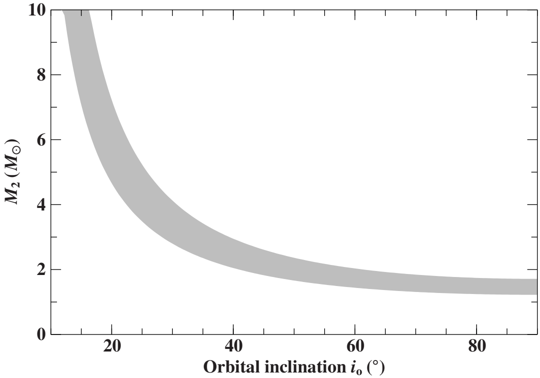
The measurements are represented by black symbols with error bars while the best-fitting Keplerian model is indicated by the red solid curve. Residuals χ are shown in the lower panel.

Orbital parameters

Parameter	Value
Period P	2190^{+11}_{-10} days
Epoch of periastron $T_{\rm periastron}$	57600^{+50}_{-70} MJD
Eccentricity e	$0.40^{+0.08}_{-0.09}$
Longitude of periastron ω	115^{+12}_{-17} deg
Velocity semiamplitude K_1	$6.3^{+0.9}_{-0.7}\,{\rm km\,s^{-1}}$
Systemic velocity γ	$-9.8 \pm 0.4\,{\rm km\,s^{-1}}$

Derived parameter	Value
Mass function $f(M)$	$0.043^{+0.016}_{-0.012}\,M_\odot$
Projected semimajor axis $a_1 \sin(i)$	$1.16^{+0.13}_{-0.11}$ AU
Projected periastron distance $r_{\rm p} \sin(i)$	$149^{+22}_{-20}\,R_\odot$

The nature of the companion

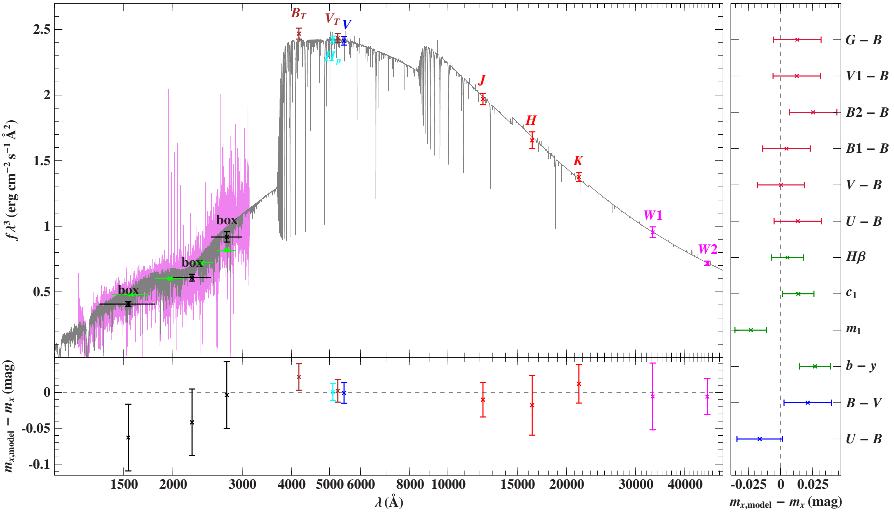


Mass of the secondary component as a function of the orbital inclination: a fixed primary mass of $M_1 = 5.8\,M_\odot$ (Nieva & Przybilla 2014) is used to solve the mass function

$$f(M) := \frac{M_2 \sin^3(i_o)}{(1 + M_1/M_2)^2} = (1 - e^2)^{3/2} \frac{K_1^3 P}{2\pi G}$$

numerically for M_2. The width of the shaded region reflects the 1σ-uncertainties of $f(M)$.

The nature of the companion



Spectral energy distribution. No signatures of an infrared excess/cool companion.

The nature of the companion

All constraints on the nature of the companion are indirect and not very tight:

- Mass function: $M_2 \geq 1\,M_\odot \Rightarrow$ no substellar object
- Single-lined system $\Rightarrow L_2 \leq 0.07\,L_1 \Rightarrow M_2 \leq 4\ M_\odot$ if the companion is a main-sequence star
- No binary signatures in the spectral energy distribution

Possible candidates:

- Main-sequence star with $1\,M_\odot \leq M_2 \leq 4\,M_\odot$
- Compact object (white dwarf, neutron star, or a black hole)