The slowly pulsating B-star 18 Peg: A testbed for upper main sequence stellar evolution
Convective overshooting – a longstanding challenge

Ekström et al. (2012)
Brott et al. (2011)

\[ T_{\text{eff}} \text{(K)} \]

\[ \log(g \text{ (cm s}^{-2}) \]

- \( 7M_{\odot} \)
- \( 5M_{\odot} \)
- \( 4M_{\odot} \)

- Brott et al. (2011)
- Ekström et al. (2012)
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 ($d = 372 ± 25$ pc, Nieva & Przybilla 2012)
▶ Slow rotator ($v \sin(i_r) = 15 ± 3$ 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
The black solid, red dashed, and blue dash-dotted lines are observed UVES spectra with spectral resolutions $R = 107200$ taken three and two days apart (MJD 51707.23, 51710.24, and 51712.24).
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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HIPPARCOS epoch photometry data:</strong></td>
<td></td>
</tr>
<tr>
<td>Period $P_{\text{osc}}$</td>
<td>$1.38711 \pm 0.00014$ days</td>
</tr>
<tr>
<td>Reference epoch $T_{\text{ref}}$ (fixed)</td>
<td>47 898.49 MJD</td>
</tr>
<tr>
<td>Phase $\phi_{\text{osc,ref}}$ at epoch $T_{\text{ref}}$</td>
<td>$0.58 \pm 0.05$</td>
</tr>
<tr>
<td>$H_p$ mean magnitude</td>
<td>$5.9626 \pm 0.0009$ mag</td>
</tr>
<tr>
<td>$H_p$ semi-amplitude</td>
<td>$0.0069 \pm 0.0013$ mag</td>
</tr>
<tr>
<td><strong>ASAS light-curve:</strong></td>
<td></td>
</tr>
<tr>
<td>Period $P_{\text{osc}}$</td>
<td>$1.39976 \pm 0.00030$ days</td>
</tr>
<tr>
<td>Reference epoch $T_{\text{ref}}$ (fixed)</td>
<td>54 229.40 MJD</td>
</tr>
<tr>
<td>Phase $\phi_{\text{osc,ref}}$ at epoch $T_{\text{ref}}$</td>
<td>$0.68 \pm 0.05$</td>
</tr>
<tr>
<td>$V_A$ mean magnitude</td>
<td>$5.9748 \pm 0.0016$ mag</td>
</tr>
<tr>
<td>$V_A$ semi-amplitude</td>
<td>$0.0120 \pm 0.0024$ mag</td>
</tr>
</tbody>
</table>
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 $\chi$. Oscillation and rotation phases are listed on the x-axes.

⇒ Line-profile variations can be well explained by stellar pulsations
Parameters and derived quantities for the best-fitting pulsational model with $l = 5$ and $m = 1$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Derived quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k^{(0)}$</td>
<td>$0.792^{+0.006}_{-0.007}$</td>
<td>$a_{\text{sph}}$</td>
<td>$0.2688^{+0.0016}<em>{-0.0009} , R</em>{\odot}$</td>
</tr>
<tr>
<td>$P_{\text{osc}}$</td>
<td>$1.3818 \pm 0.0001 , \text{days}$</td>
<td>$\omega^{(0)}$</td>
<td>$4.5429 \pm 0.0002 , \text{days}^{-1}$</td>
</tr>
<tr>
<td>$\phi_{\text{osc,ref}}$</td>
<td>$0.4963^{+0.0020}_{-0.0015}$</td>
<td>$\Omega/\omega^{(0)}$</td>
<td>$0.0577^{+0.0010}_{-0.0001}$</td>
</tr>
<tr>
<td>$\phi_{\text{rot,ref}}$</td>
<td>$0.5323^{+0.0018}_{-0.0020}$</td>
<td>$\eta$</td>
<td>$0.0042^{+0.0002}_{-0.0001}$</td>
</tr>
<tr>
<td>$\Omega/\omega$</td>
<td>$0.0576^{+0.0010}_{-0.0001}$</td>
<td>$M$</td>
<td>$7.3^{+0.2}<em>{-0.4} , M</em>{\odot}$</td>
</tr>
<tr>
<td>$v \sin(i_{r})$</td>
<td>$16.07^{+0.04}_{-0.03} , \text{km s}^{-1}$</td>
<td>$R_{\star}$</td>
<td>$10.9^{+0.1}<em>{-0.2} , R</em>{\odot}$</td>
</tr>
<tr>
<td>$\langle v_{v}^{2} \rangle^{1/2}$</td>
<td>$1.96^{+0.02}_{-0.01} , \text{km s}^{-1}$</td>
<td>$P_{\text{rot}}$</td>
<td>$23.9801^{+0.0043}_{-0.3899} , \text{days}$</td>
</tr>
<tr>
<td>$i_{r}$</td>
<td>$44.2^{+0.2}_{-0.3} , \degree$</td>
<td>$\log(g , (\text{cm s}^{-2}))$</td>
<td>$3.22 \pm 0.01 , \text{dex}$</td>
</tr>
</tbody>
</table>

- $\eta$ is the ratio of the centrifugal to the gravitational force at the equator
- $R_{\star}$ is derived from the identity $v \sin(i_{r}) = \Omega R_{\star} \sin(i_{r})$
- $M = k^{(0)}(\omega^{(0)})^2 R_{\star}^3 / G$ (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

- Ekström et al. (2012)
- Brott et al. (2011)

![Graph showing stellar characteristics: Teff (K), log(g (cm s\(^{-2}\))), and masses (M\(_{\odot}\)).](image)
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
    ⇒ lower limit on the width of the upper main sequence
    ⇒ 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?
Despite various simplifications, the model is already a function of 10 parameters\(^1\): \(\Phi = \Phi(l, m, a_{\text{sph}}, k^{(0)}, \omega^{(0)}, \Omega/\omega^{(0)}, i, v \sin(i), \phi_{\text{osc}}, \phi_{\text{rot}})\)

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

\(^1\) 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\textsc{ii} lines.

*Right*: Interstellar K\textsc{i} and telluric lines are shown for reference.
The measurements are represented by black symbols with error bars while the best-fitting Keplerian model is indicated by the red solid curve. Residuals $\chi$ are shown in the lower panel.
### Orbital parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period $P$</td>
<td>$2190^{+11}_{-10}$ days</td>
</tr>
<tr>
<td>Epoch of periastron $T_{\text{periastron}}$</td>
<td>$57600^{+50}_{-70}$ MJD</td>
</tr>
<tr>
<td>Eccentricity $e$</td>
<td>$0.40^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>Longitude of periastron $\omega$</td>
<td>$115^{+12}_{-17}$ deg</td>
</tr>
<tr>
<td>Velocity semiamplitude $K_1$</td>
<td>$6.3^{+0.9}_{-0.7}$ km s$^{-1}$</td>
</tr>
<tr>
<td>Systemic velocity $\gamma$</td>
<td>$-9.8 \pm 0.4$ km s$^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Derived parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass function $f(M)$</td>
<td>$0.043^{+0.016}<em>{-0.012} M</em>{\odot}$</td>
</tr>
<tr>
<td>Projected semimajor axis $a_1 \sin(i)$</td>
<td>$1.16^{+0.13}_{-0.11}$ AU</td>
</tr>
<tr>
<td>Projected periastron distance $r_p \sin(i)$</td>
<td>$149^{+22}<em>{-20}$ $R</em>{\odot}$</td>
</tr>
</tbody>
</table>
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 $f(M)$. 
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)