

# Characterisation of the variability of the blue supergiant HD 14134

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## ABSTRACT

**Context.** The post-main-sequence evolution of massive stars encompasses phases in which the stars display high variability. One such class of objects are the blue supergiants. These objects may be in either the pre- or post-red-supergiant phase of their evolution. Their variability patterns might provide constraints for a proper classification of the objects.

**Aims.** The study aims to characterise the observed variability of the B-type supergiant HD 14134 and to investigate the imprint of a time-variable wind on the brightness variation of the star and its impact on the detectability of pulsation signals.

**Methods.** Spectroscopic data were collected over a five-month period and combined with space-photometry from the TESS mission. Stellar parameters were derived from a modelling of the time-averaged spectrum with CMFGEN and the spectral energy distribution and were confirmed with stellar evolution models computed with MESA. The light curves and radial-velocity curves of selected lines were analysed with various methods to determine pulsation signals. The wind variability and its imprint on the stellar brightness were investigated from an analysis of the H $\alpha$  line. Predictions of mode excitations were computed with the GYRE pulsation code and compared to the frequencies determined from the observations.

**Results.** A g mode with a period of  $\sim 19.2$  d and its harmonics are consistently detected in all datasets. The spectra unveil strong, non-periodic wind variability, and three frequency signals were identified as being due to this wind variability. The stellar parameters and age derived for HD 14134 together with the absence of radial pulsations classify the star as a post-main-sequence object evolving towards the red-supergiant stage, putting into question its classification as a  $\alpha$  Cyg variable.

**Conclusions.** The results reinforce that simultaneous long-term spectroscopic and photometric monitoring is indispensable for reliable frequency detections and for disentangling variabilities imprinted by a time-variable wind from those imposed by pulsations.

**Key words.** techniques: photometric – techniques: spectroscopic – stars: massive – stars: individual: HD 14134 – supergiants

## 1. Introduction

Blue supergiants (BSGs) are a class of massive stars whose evolutionary pathway is not well established. While they were supposed to be direct descendants of massive OB main-sequence stars, their relative numbers, especially for stars more massive than  $30 M_{\odot}$  (Castro et al. 2014), seem to be in conflict with this interpretation as the only formation channel and challenges stellar evolution theories.

The observed overdensity in BSGs might be explained by two diverse populations predicted from stellar evolution models of single stars (e.g. Ekström et al. 2012; Georgy et al. 2021): (i) shell-hydrogen-burning post-main-sequence stars; and (ii) core-He-burning post-red supergiants. On the other hand, there is growing evidence that the majority of massive stars are born in binary or multiple systems (Sana et al. 2012), but the number of confirmed binaries to date among BSGs is small (de Burgos et al. 2023; Simón-Díaz et al. 2024). This might suggest that binary interaction may have taken place and that a significant number of luminous BSGs might be merger remnants (Menon et al. 2024; Henneco et al. 2024). This scenario might also explain some of the surface abundance anomalies seen in BSGs (Sánchez Arias et al. 2023b; Menon et al. 2024). An apparent overpopulation of BSGs might also result from inaccuracies in stellar evolution models (core size, treatment of rotation, core overshooting

and mass loss) that can lead to shifts in the position of the end of the main sequence (e.g. Martinet et al. 2021). Each of these scenarios results in a different internal structure of the star. To distinguish BSGs resulting from the various formation channels, it is therefore necessary to gain insight into the stars' interiors.

High-precision space photometry and dedicated spectroscopic surveys revealed that many BSGs pulsate (e.g. Saio et al. 2006; Kraus et al. 2012; Aerts et al. 2017, 2018; Simón-Díaz et al. 2018; Bowman et al. 2020). Theoretical investigations found an instability strip of gravity-mode pulsations in the BSG domain (Saio et al. 2006; Daszyńska-Daszkiewicz et al. 2013) whose position and extent critically depend on the physical properties of the star during its main-sequence evolution (core overshooting, mass loss, mixing, etc; Godart et al. 2009; Ostrowski & Daszyńska-Daszkiewicz 2015). The type and amount of pulsation modes vary along the evolution and could be used to distinguish between BSGs in pre- and post-red-supergiant phases (Saio et al. 2013; Bowman et al. 2019b). Furthermore, differences in the internal structure of BSGs resulting from single-star and binary evolution (merger) channels may cause different pulsation patterns (Bellinger et al. 2024; Henneco et al. 2024). In addition to coherent pulsations, the amplitude spectra of many BSGs seem to contain stochastic low-frequency (SLF) variability (Bowman et al. 2019b, 2020; Ma et al. 2024; Kourniotis et al. 2025). The interpretation of this variability is yet unclear, with suggestions ranging from internal gravity waves generated by

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core convection (Bowman et al. 2019b) to subsurface convection zones (Cantiello et al. 2021), surface turbulences (Schultz et al. 2022), and line-driven wind instabilities (Krtićka & Feldmeier 2021).

Many BSGs display time-variable winds (Kaufer et al. 1996; Haucke et al. 2018; Cidale et al. 2023; Chamoun-Contreras et al. 2026), and a correlation between the occurrence of so-called strange modes and phases of enhanced mass loss was proposed from observations (Aerts et al. 2010; Kraus et al. 2015) and confirmed by theoretical modelling (e.g. for the BSG star 55 Cygni, Yadav & Glatzel 2016). Although strange-mode instabilities are predicted to occur in stars within the upper part of the Hertzsprung–Russell (HR) diagram spreading from hot to cool temperatures (Glatzel & Kraus 2024), not all excited modes automatically exceed the escape velocity and lead to mass loss (Yadav et al. 2021; Dasgupta et al. 2026).

We aim to investigate the variability of the photosphere and winds of BSGs, as well as their possible connection to pulsations. For this, we focused on the Galactic BSG HD 14134 (= 61 And; V520 Per,  $V = 6.57$  mag), which is classified as a B3 supergiant with luminosity class Ia (Johnson & Morgan 1955; Lennon et al. 1992; Negueruela et al. 2024). The star is known for its variability in (i) photometry (Rufener & Bartholdi 1982; Waelkens et al. 1990; Krzesiński et al. 1999; Adelman et al. 2000; Koen & Eyer 2002; Lefèvre et al. 2009; Laur et al. 2017); (ii) radial velocity measured in various photospheric lines (Kontizas & Kontizas 1981; Simón-Díaz et al. 2024); and (iii) its H $\alpha$  line, which displays a diversity of profile shapes such as P Cygni, inverse P Cygni, pure emission, pure absorption, and complete absence, i.e. compensation of absorption with emission (Morel et al. 2004; Maharramov & Jahangirova 2017; Maharramov 2017). It has been proposed to be a  $\alpha$  Cyg variable of variability type IA (Laur et al. 2017), meaning it is an irregular early-type star.

We conducted spectroscopic observations of HD 14134 and supplemented the data with space-based photometry. The paper is organised as follows. In Sect. 2 we describe the spectroscopic and photometric datasets. We determine the stellar parameters in Sect. 3 and analyse the line-profile, radial velocity, and wind variabilities detected in the spectroscopic time series in Sect. 4. The analysis of the photometric light curves is presented in Sect. 5. Our results are discussed in Sect. 6, and the conclusions follow in Sect. 7.

## 2. Observations and data reduction

### 2.1. Spectroscopy

Spectroscopic monitoring was carried out from 2017 October 11 to 2018 March 12 utilising the observing facilities of the Poznan Spectroscopic Telescope 2 (PST2, Kamiński et al. 2014), which is situated at the Winer Observatory, Arizona, USA. A total of 146 high-resolution ( $R \approx 40\,000$ ) spectra were obtained with a wavelength coverage of 3877–7114 Å. During three nights, the set-up was slightly shifted to longer wavelengths, covering a range of 4325–7725 Å. The exposure time per spectrum was in most cases 1200 s, in four nights with worse observing conditions it was increased to 1800 s. The spectra were reduced, heliocentric-velocity-corrected, and normalised to the continuum using standard IRAF<sup>1</sup> (Tody 1986, 1993) tasks. Whenever possible, two consecutive spectra were taken each night. These

were combined to correct for cosmic rays and to increase the signal-to-noise ratio (S/N). The final 73 individual spectra (see Table A.1 for details) have S/N values ranging from 30 to 110.

### 2.2. TESS photometry

The Transiting Exoplanet Survey Satellite (TESS) mission of NASA (Ricker et al. 2014) facilitates the high-precision photometric survey of the sky. It provides the time-series data products to study the variability of celestial objects. HD 14134 (TIC 264730431) was observed twice, in sector 18 (2019 November 2–27) and again, almost three years later, in sector 58 (2022 October 29–November 26). The time series were sampled with a cadence of 1800 s and 200 s, respectively. Both datasets were taken with camera 2 and CCD 4. We note that HD 14134 was also observed in sector 85; however, the data seem to be corrupted and did not allow us to construct a reliable light curve for our target. Hence, we omitted them from our analysis.

We downloaded  $20 \times 20$  pixel cutouts from the full frame images (FFIs) and utilised the python package LIGHTKURVE (Lightcurve Collaboration 2018) to extract the light curves from them. For these FFI cutouts, there are no pre-defined apertures available from the Science Processing Operations Center (SPOC, Jenkins et al. 2016). To avoid contamination of the light curves with close-by background (or foreground) stars (Higgins & Bell 2023; Pedersen & Bell 2023), we consulted the Gaia database (Lindegren et al. 2018) for precise positions and magnitudes of stars within our field of view (FOV). We used Gaia Data Release (DR) 2 instead of the more recent DR3, as the latter provides considerably fewer stars in our FOV.

The apertures were selected to maximise the flux while minimising contamination from other stars in the field. For the latter, we tested that background stars in the selected pixels do not add variable signals to the light curve of HD 14134. Background pixels were chosen to gauge background contamination (see Fig. B.1 for details). After subtraction of the background flux, the stellar flux was converted to magnitudes and normalised to the mean value of the entire light curve within one sector. The final light curves for both sectors are shown in Fig. B.2.

### 2.3. Gaia photometry

We obtained multi-band photometric data from Gaia DR3 (van Leeuwen et al. 2022). To date, 49 measurements have been released for HD 14134 (DR3 458374788336739200), spreading from 2014 August 30 to 2017 March 20. The observations were carried out in bands  $G$  (330–1050 nm),  $G_{BP}$  (330–680 nm), and  $G_{RP}$  (680–1050 nm). Figure B.3 displays the Gaia light curves in magnitudes in the different bands (top panel) and the temporal colour variation ( $G_{RP} - G_{BP}$ , bottom panel).

## 3. Stellar parameters

### 3.1. Atmospheric and spectral-energy-distribution modelling

Stellar and wind parameters of HD 14134 were determined in the literature based on non-LTE modelling using different codes, and Table 1 provides an overview of the most relevant studies. The values for the stellar parameters agree fairly well, except for the stellar rotation projected to the line of sight ( $v \sin i$ ). While older studies only used  $v \sin i$  to broaden the photospheric lines,

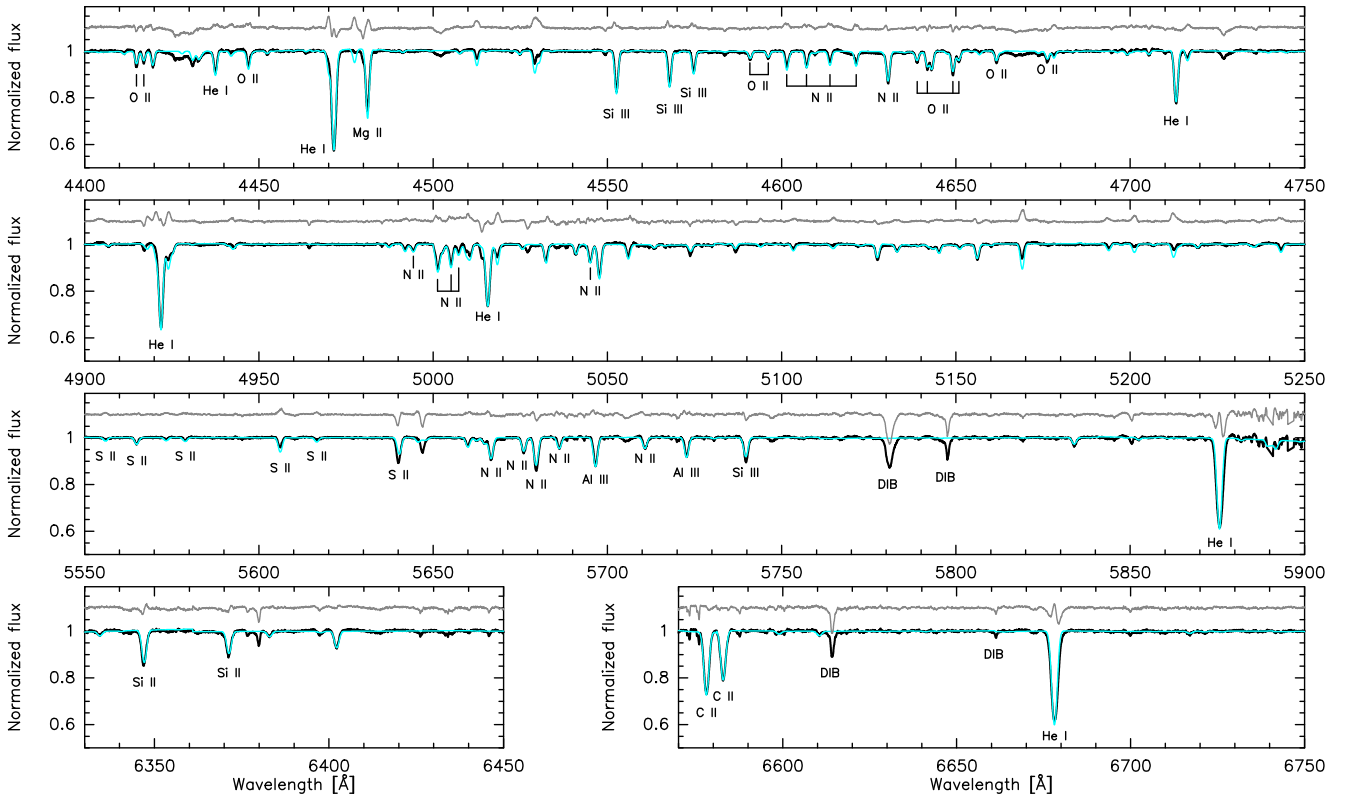
<sup>1</sup> IRAF was written at the National Optical Astronomy Observatory, which was operated by the Association of Universities for Research

in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

**Table 1.** Stellar and wind parameters of HD 14134.

| Parameter                                | McErlean et al. (1999)<br>TLUSTY | Crowther et al. (2006)<br>CMFGEN | de Burgos et al. (2024)<br>FASTWIND | This Work<br>CMFGEN     |
|------------------------------------------|----------------------------------|----------------------------------|-------------------------------------|-------------------------|
| $T_{\text{eff}}$ (K)                     | $18\,000 \pm 1000$               | $16\,000 \pm 1000$               | $16\,700^{+400}_{-300}$             | $16\,100^{+260}_{-150}$ |
| $\log g$ (cgs)                           | $2.3 \pm 0.2$                    | 2.05                             | $2.17 \pm 0.05$                     | $2.09 \pm 0.04$         |
| $R$ ( $R_{\odot}$ )                      | 48.5                             | 56.7                             | —                                   | $48.6 \pm 1.0$          |
| $\log L/L_{\odot}$                       | 5.35                             | 5.28                             | —                                   | $5.16 \pm 0.03$         |
| $M$ ( $M_{\odot}$ )                      | —                                | 13.2                             | —                                   | $10.6 \pm 1.0$          |
| $v \sin i$ (km/s)                        | $60 \pm 20$                      | 66                               | 37                                  | $37 \pm 5$              |
| $v_{\text{mac}}$ (km/s)                  | —                                | —                                | 51                                  | $51 \pm 4$              |
| $v_{\text{mic}}$ (km/s)                  | $10 \pm 5$                       | 15                               | $14 \pm 1$                          | $14 \pm 3$              |
| $\beta$                                  | —                                | 2                                | 1                                   | 2–3                     |
| $v_{\infty}$ (km/s)                      | —                                | 465                              | —                                   | $590 \pm 40$            |
| $\log \dot{M}$ ( $M_{\odot}/\text{yr}$ ) | —                                | −6.28                            | —                                   | $−6.70 \pm 0.15$        |
| $\log Q$                                 | —                                | −12.9                            | $−13.3 \pm 0.1$                     | $−13.38 \pm 0.1$        |

**Notes.** The parameters to compute  $Q$  are  $\dot{M}$  ( $M_{\odot}/\text{yr}$ ),  $v_{\infty}$  ( $\text{km s}^{-1}$ ), and  $R$  ( $R_{\odot}$ ).



**Fig. 1.** Fit (blue line) to the averaged spectrum (black line) of HD 14134. The CMFGEN model was calculated with the photospheric and wind parameters listed in Table 1. For better visibility, the residuals (in grey) are offset by 0.1 in flux in each panel.

a combination of  $v \sin i$  and the so-called macroturbulent velocity ( $v_{\text{mac}}$ ) seems nowadays to be the better approach (Simón-Díaz & Herrero 2007, 2014). The cause of macroturbulence within the atmospheric layers of supergiants is still not fully understood but was proposed to be related to pulsation activity (Aerts et al. 2009; Simón-Díaz et al. 2010).

Our spectra of HD 14134 (see Fig. 1) display photospheric absorption lines in agreement with its classification as an early B-type supergiant (e.g. Walborn & Fitzpatrick 1990). In addition, we observe emission components of the hydrogen Balmer lines – particularly in the lower Balmer series. These show rapid and substantial changes likely due to wind variability, which is

further discussed in Sect. 4.3. We also observe line-profile variability in the photospheric lines, which we discuss in Sect. 4.1. Given these variabilities, we aim to reproduce the averaged spectrum of HD 14134 to derive average stellar parameters.

We utilised synthetic model atmosphere spectra calculated with the non-LTE radiative-transfer code CMFGEN (Hillier & Miller 1998). To limit the computational cost, several atmospheric parameters were fixed during the main analysis. The abundances of He, Ne, Mg, Al, Si, S, Fe, and Ni were initially set to solar values, and the microturbulent velocity ( $v_{\text{mic}}$ ),  $v_{\text{mac}}$ , and  $v \sin i$  were adopted from de Burgos et al. (2024); see Table 1. The free parameters include the effective temperature ( $T_{\text{eff}}$ ),

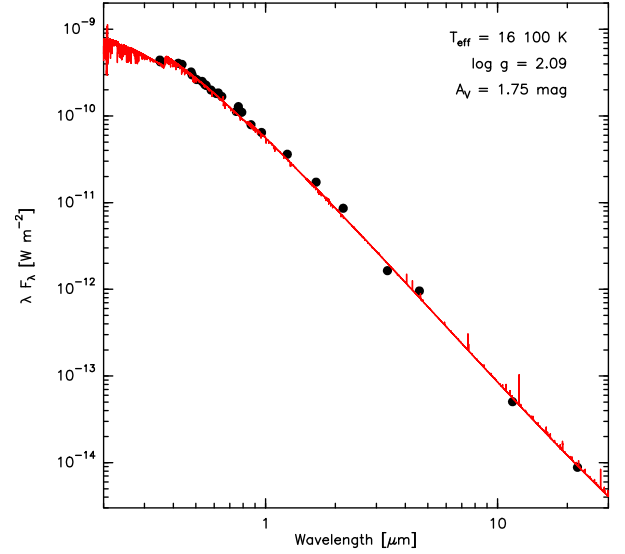
surface gravity ( $\log g$ ), CNO abundances, stellar radius ( $R$ ); and mass-loss rate ( $\dot{M}$ ). The wind structure follows a  $\beta$ -type velocity law with the terminal wind velocity ( $v_\infty$ ) and  $\beta$  as additional free parameters.

We initiated the spectral analysis using the parameter set of de Burgos et al. (2024) as listed in Table 1, adopting homogeneous winds throughout. The primary goal was to reproduce the observed photospheric variability, which requires a consistent treatment of the stellar wind. In contrast to the FASTWIND models computed by de Burgos et al. (2024), which parametrise the wind via the optical-depth invariant  $Q = \dot{M}(v_\infty \cdot R)^{-3/2}$ , CMFGEN treats  $\dot{M}$ ,  $v_\infty$ , and  $R$  as independent quantities. We started with the literature value for the terminal wind velocity of  $v_\infty = 465 \text{ km s}^{-1}$  obtained by Howarth et al. (1997). We derived the stellar radius from simultaneous fitting of the spectral energy distribution (SED) of HD 14134 with the spectrum computed with CMFGEN. The SED in the UV and optical spectral range is only sensitive to  $T_{\text{eff}}$  and  $\log g$ , so the extinction can be determined. Using the most recent distance estimate of  $2.11 \pm 0.21 \text{ kpc}$  (Pantaleoni González et al. 2025) delivers the stellar radius, luminosity, and mass of the star. These values serve as new inputs to CMFGEN. The entire process was iterated until both the spectrum and the SED were matched with a homogeneous set of parameters.

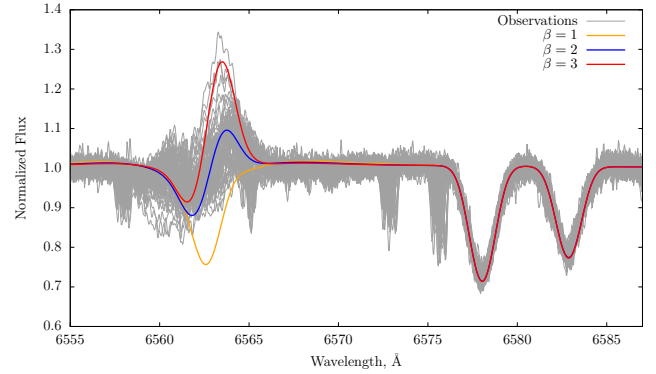
The spectral modelling was carried out using a steepest descent  $\chi^2$  minimisation procedure implemented in XTGRID (Németh et al. 2012; Németh 2019). New models were computed iteratively along the descent path, avoiding interpolation within pre-computed grids and allowing for the simultaneous optimisation of multiple parameters. The resulting spectra were broadened with the values of  $v_{\text{mac}}$  and  $v \sin i$  and convolved to the resolution of the observed spectra. We explored the degeneracy between macroturbulent and rotational broadening. A total broadening of  $63 \text{ km s}^{-1}$  reproduces the observed line profiles in the averaged spectrum, with the best agreement obtained for  $v \sin i = 37 \text{ km s}^{-1}$  and  $v_{\text{mac}} = 51 \text{ km s}^{-1}$  in agreement with the values found by de Burgos et al. (2024). Finally, we refined the abundances of Mg, S, and Fe, finding that slightly subsolar values ( $-0.1 \text{ dex}$ ) improve the quality of the fit. Slightly subsolar abundances were also found for the star's host cluster h Per (Dias et al. 2021), supporting our findings.

The parameters of our best-fitting model are included in Table 1. An inspection of Fig. 1 shows decent agreement between the synthetic (blue) and the observed (black) photospheric metal lines in the averaged spectrum. The goodness of the fit can also be assessed from the residuals (plotted in grey), which are shifted upwards in flux for better visibility. The fit to the SED is shown in Fig. 2. The observations were taken from the HIPPARCOS and TYCHO catalogues<sup>2</sup> (ESA 1997), Gaia DR3<sup>3</sup> (Gaia Collaboration 2023), the WISE All-Sky Data Release<sup>4</sup> (Cutri et al. 2012), and the Pan-STARRS1 release<sup>5</sup> (Chambers et al. 2016). We obtain an interstellar extinction value of  $A_V = 1.75 \pm 0.02$ , which is in good agreement with the value reported by Dias et al. (2021) for the cluster h Per in which HD 14134 resides.

From the spectral fitting, we find slightly lower values for the effective temperature and surface gravity compared to de Burgos et al. (2024) but more closely matching the results of Crowther et al. (2006). Crowther et al. (2006) derived  $[\text{N}/\text{C}] = +0.8$  and  $[\text{N}/\text{O}] = +0.9$  based on Asplund et al. (2006), while we obtain



**Fig. 2.** Fit of CMFGEN model to the spectral energy distribution of HD 14134.



**Fig. 3.** Comparison of models with varying  $\beta$ -parameter to the entire sample of observed  $\text{H}\alpha$  profiles.

slightly lower values of  $[\text{N}/\text{C}] = +0.6 \pm 0.1$  and  $[\text{N}/\text{O}] = +0.8 \pm 0.1$  using the solar abundances of Asplund et al. (2009). We observe an extra broadening of the He lines. This suggests that the He lines might require higher values of  $v_{\text{mac}}$  as observed in other B-type supergiants (Kraus et al. 2015; Haucke et al. 2018) or that  $v_{\text{mac}}$  is time-variable as found for 55 Cygnus (Cidale et al. 2023) or for the rapidly rotating massive star  $\zeta$  Oph (Kalita et al. 2025).

Furthermore, it became evident early in the analysis that  $\beta = 1$  does not reproduce the observed line profiles of the Balmer lines. This may be due to the fact that the average spectrum includes all (non-periodic) wind variations and, therefore, is inadequate to represent the stellar spectrum at any single (snapshot) time. Our model with  $\beta = 1$  results in an  $\text{H}\alpha$  line in absorption<sup>6</sup>, while most of our spectra show  $\text{H}\alpha$  in emission, often with a P-Cygni profile and sometimes a double-peaked profile (see Fig. D.1). Clearly, a higher value of  $\beta$  is needed to reproduce at least some of the individual observations (Fig. 3). For most epochs, the Balmer lines favour  $\beta \simeq 2$  in agreement with earlier findings by Crowther et al. (2006), while episodic

<sup>2</sup> <https://cdsarc.cds.unistra.fr/viz-bin/cat/I/239>

<sup>3</sup> <https://cdsarc.cds.unistra.fr/viz-bin/cat/I/355>

<sup>4</sup> <https://cdsarc.cds.unistra.fr/viz-bin/cat/II/311>

<sup>5</sup> <https://cdsarc.cds.unistra.fr/viz-bin/cat/II/349>

<sup>6</sup> We note that de Burgos et al. (2024) neither provided information on the profile shape of  $\text{H}\alpha$  of the spectrum they modelled nor stated whether they were able to achieve a decent fit to it with their best-fitting parameter set.

phases require significantly higher values ( $\beta > 3$ ), indicating variability in the wind acceleration. However, with such a highly dynamical wind as we observe for HD 14134, the approach of modelling any individual snapshot observation with a stationary atmosphere plus wind model – as computed with CMFGEN or comparable codes – to derive mass-loss rates and wind parameters seems to be at least questionable.

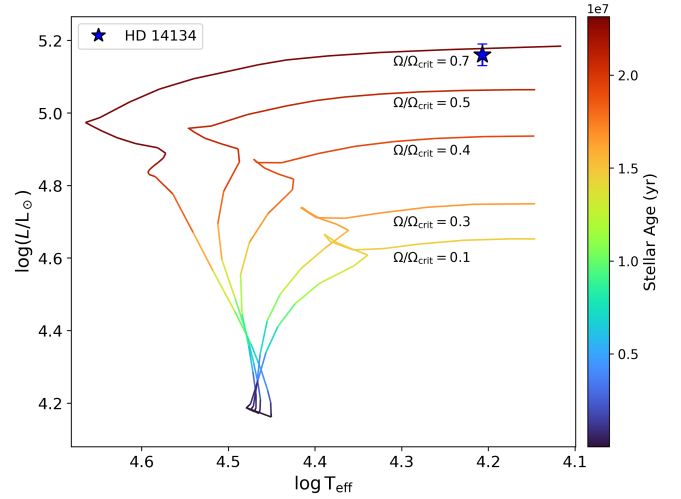
### 3.2. Stellar evolution model for HD 14134

The stellar parameters obtained from SED modelling and spectral fitting (temperature, luminosity, and mass; see Table 1), as well as the age of the star that is constrained by the age of the cluster, for which values in the 10–30 Myr range are reported (Dias et al. 2021; Taşdemir et al. 2026), are compared with the predictions from stellar evolution models. For this, we calculated evolutionary tracks with the Modules for Experiments in Stellar Astrophysics (MESA r23.05.1, Jermyn et al. 2023) for solar metallicity stars ( $Z = 0.0142$ ).

We first focused on a pre-red-supergiant scenario and developed the models from the zero-age main sequence beyond core-hydrogen burning and until the temperature of HD 14134 is reached. The setup of our models and values used for specific parameters, including numerical convergence constraints and time steps, is in line with other works on massive stars (see e.g. Paxton et al. 2013; He et al. 2025). More specifically, we used the Ledoux criterion for the treatment of convective boundaries. Convective mixing is addressed using the time-dependent convection theory with a mixing length parameter of  $\alpha_{\text{MLT}} = 1.5 H_p$ , where  $H_p$  is the pressure scale height at the outer boundary of the core. We employed step-overshooting for the hydrogen-burning convective core with an overshooting parameter of  $\alpha_{\text{ov}} = 0.18 H_p$ , which is similar to the value adopted by Martinet et al. (2021). Moreover, semi-convection was included with an efficiency of  $\alpha_{\text{sc}} = 0.01$ , allowing for moderate chemical mixing in Schwarzschild-unstable but Ledoux-stable zones. Furthermore, we used the updated and expanded OPAL equation-of-state tables from Rogers & Nayfonov (2002) and nuclear-reaction rates from the Nuclear Astrophysics Compilation of Reaction rates (NACRE; Angulo et al. 1999) and the Joint Institute for Nuclear Astrophysics Reaction Library (JINA REACLIB database; Cyburt et al. 2010). We included the solar heavy-elements mixture given by Asplund et al. (2009) and the OPAL opacity tables (Iglesias & Rogers 1996) for the higher temperature regime. For mass loss along the evolution, the prescriptions by Vink et al. (2001) and Nugis & Lamers (2002) were used with a scaling factor of 1.0. They are valid for temperatures of  $T_{\text{eff}} > 10\,000$  K and for surface hydrogen abundances of  $X(H) > 0.4$  and  $X(H) < 0.4$ , respectively.

As mentioned by Maeder & Meynet (2000), high initial rotation causes the star to evolve to higher luminosities. This means that fast rotators are over-luminous with respect to their actual masses. Accordingly, the high luminosity observed in HD 14134 compared to its relatively low mass could suggest that the star originally rotated rapidly. Therefore, we included rotation in our models. The chemical mixing and angular-momentum transport due to the rotationally induced instabilities were treated in a diffusion approximation (Paxton et al. 2013). For the efficiency of the total rotation-induced composition mixing we used  $f_c = 1/30$ , and for the sensitivity of the rotationally induced mixing to the mean molecular weight gradient we used  $f_\mu = 0.05$ , following Heger et al. (2000).

With this defined setup, we computed evolutionary tracks for stars in the 11–15  $M_\odot$  mass range and for a wide range of initial



**Fig. 4.** MESA evolutionary models for a  $14 M_\odot$  star with different initial rotation velocities.

rotation velocities. A general trend observed is that with higher initial rotation given in terms of the critical rotation ( $\Omega/\Omega_{\text{crit}}$ ), the star evolves to higher luminosities along the main sequence. Moreover, if the initial rotation velocity reaches (and exceeds) a value of  $\Omega/\Omega_{\text{crit}} \sim 0.5$ , the star starts to develop a chemically homogeneous evolution due to the strong mixing. As a consequence, it becomes hotter during the main sequence as can be seen in Fig. 4 for the example of models with increasing initial rotation and an initial mass of  $14 M_\odot$ . While the effect of chemically homogeneous evolution is considerably more pronounced at lower metallicities (Brott et al. 2011; Szécsi et al. 2015), it has also been reported to become dominant for rapidly rotating massive stars with solar metallicity using the Bonn models (Martins et al. 2013) and MESA (He et al. 2025); so, we can be confident in the validity of our results.

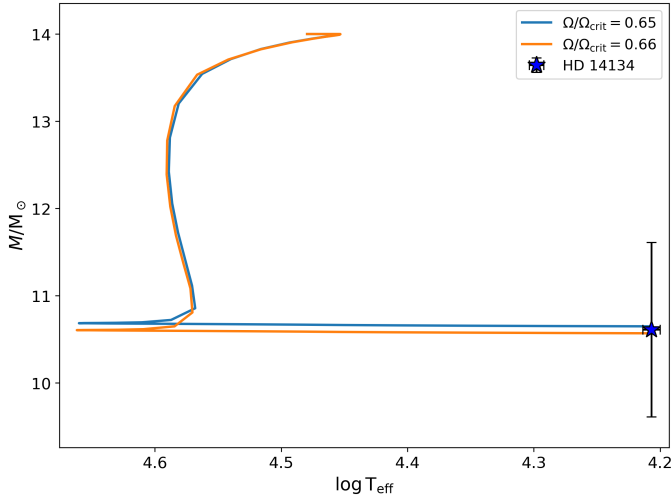
The stellar evolution models that most closely match all observed parameters of HD 14134 correspond to a star with an initial mass of  $\sim 14 M_\odot$  and a rotation rate of  $\Omega/\Omega_{\text{crit}} = 0.65$ – $0.66$ . The mass evolution of the two boundary models is shown in Fig. 5. And the extracted stellar parameters for them are listed in Table 2. These evolutionary models are further explored in Sect. 6.1, where they serve as input for the computations of pulsations. We also explored slightly higher or lower initial-mass models, but they matched either the luminosity of the star or its mass, but not both simultaneously. Therefore, we consider the models presented in Table 2 as representative for HD 14134.

We also explored whether HD 14134 could be in the post-red-supergiant evolution. To test this possibility, we developed MESA models for stars with higher initial masses and for a range of rotation velocities. We started from an initial mass of  $20 M_\odot$ , which serves as a lower limit for the post-red-supergiant evolution, because stars with initial masses of 8– $20 M_\odot$  end their lives as red supergiants and do not return (Smartt 2009; Ekström et al. 2012). However, we discarded the post-red-supergiant scenario for HD 14134, because all models evolved to significantly higher luminosities compared to the observed value.

## 4. Line-profile and radial-velocity variabilities

### 4.1. Equivalent-width (EW) variations

Photospheric lines in the stellar spectrum carry information about the star’s effective temperature and surface gravity.



**Fig. 5.** Evolution of stellar mass for models with an initial mass of  $14 M_{\odot}$  and two different rotation velocities that most closely reproduce the observed parameters of HD 14134.

**Table 2.** Parameters of stellar models.

| Parameter                         | M1<br>( $\Omega/\Omega_{\text{crit}} = 0.65$ ) | M2<br>( $\Omega/\Omega_{\text{crit}} = 0.66$ ) |
|-----------------------------------|------------------------------------------------|------------------------------------------------|
| Initial Mass ( $M_{\odot}$ )      | 14                                             | 14                                             |
| Current Mass ( $M_{\odot}$ )      | 10.65                                          | 10.57                                          |
| Age (Myr)                         | 22.99                                          | 23.04                                          |
| $T_{\text{eff}}$ (K)              | 16087.0                                        | 16099.6                                        |
| Radius ( $R_{\odot}$ )            | 50.18                                          | 49.52                                          |
| Luminosity ( $\log L/L_{\odot}$ ) | 5.18                                           | 5.17                                           |

**Notes.** Derived from MESA for a  $14 M_{\odot}$  star with different initial rotation rates.

Lennon et al. (1993) measured the EWs of hydrogen, helium, and metal lines (C, N, O, Mg, Si, Ne, and Fe, in different ionisation states) in the optical spectral range of late O-type to early A-type giants and supergiants and showed that they may change as functions of their spectral type. In a later work, Lefever et al. (2007) measured EWs of three selected photospheric lines (He I  $\lambda 4471$  Å, Si II  $\lambda 4128$  Å, Si III  $\lambda 4552$  Å) in synthetic spectra of B-type supergiants computed with FASTWIND and presented them in iso-contour plots as a function of  $T_{\text{eff}}$  and  $\log g$ . Both studies show that the EWs can be very sensitive even to small changes in effective temperature.

We measured the EWs of the photospheric lines Si II  $\lambda \lambda 4128, 6347$ , Si III  $\lambda 4568$ , N II  $\lambda 4601$ , and Mg II  $\lambda 4481$ , which are sensitive to the effective temperature of early B-type supergiants. Individual measurements are listed in Table C.1, and the mean values and their standard deviation are given in the bottom rows of Table C.1. To minimise the errors, we only considered spectra with local values of  $S/N \geq 50$  for the EW measurements. Errors are typically of the order of 5–10% for spectra with  $S/N$ s higher than  $\sim 70$ , and about 15% for the lower quality ones.

In Fig. 6, we show the values of Lennon et al. (1993) for B-type supergiants of luminosity class Ia (black circles). These authors also observed HD 14134, and their measurements are highlighted by filled red circles. Our measurements are added in blue. The mean values and their standard deviations are indicated

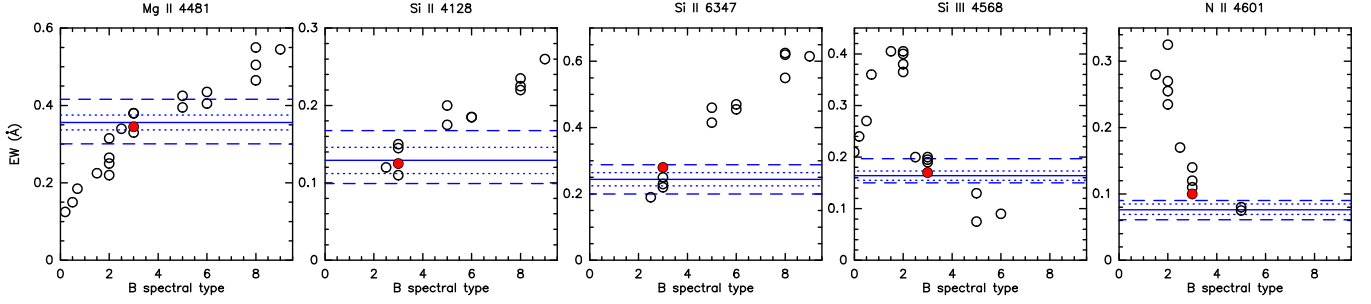
by solid and dotted lines, respectively. We also include the entire range of measured values, from minimum to maximum, which is marked by the dashed lines. Obviously, our individual measurements display a spread in values that is considerably higher than typical measurement errors.

The star HD 14134 was reported in several studies to be of spectral type B3Ia (Johnson & Morgan 1955; Lennon et al. 1992; Negueruela et al. 2024). However, inspection of the panels in Fig. 6 demonstrates that the various temperature-sensitive lines propose different (or a range of) spectral types<sup>7</sup>. Considering only the mean values and their standard deviation, the lines of Si II and Si III indicate a likely spectral type of B2.5–B3 whereas according to Mg II it might spread to B4. Most striking is that N II suggests a spectral type of B5. Inspecting the entire range of our measured values, the spread in spectral type (and hence in effective temperature) is even larger (from B2 to B6). Also, the measurements by Lennon et al. (1993) for the lines Si II  $\lambda 6347$  and N II  $\lambda 4601$  fall outside our average range, and for the latter line even outside the entire range of our measurements.

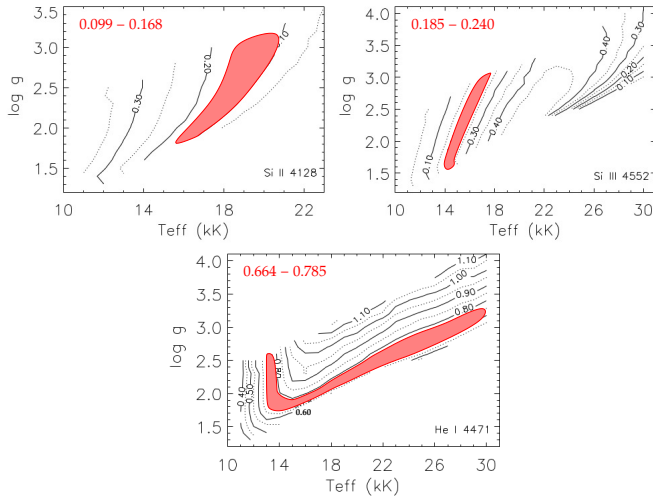
As pointed out by Lennon et al. (1993), the comparison with EWs measured from observations (that were also collected with lower resolution than our data) might bear some inaccuracies. Therefore, we also compared our measurements with predictions from the extensive grid of synthetic models computed by Lefever et al. (2007) for the temperature range of blue supergiants ( $T_{\text{eff}} = 10\,000$ – $30\,000$  K) and for a range of surface gravities ( $\log g = 1.3$ – $4.0$  in cgs units). In Fig. 7 we show the iso-contour levels of the EWs of the three modelled lines, Si II  $\lambda 4128$ , Si III  $\lambda 4552$ , and He I  $\lambda 4471$ . These diagrams were taken from the work of Lefever et al. (2007, their Figs. 2–4). In each panel, we indicate the range of our EWs and mark the parameter range for  $T_{\text{eff}}$  and  $\log g$  suggested by our measurements for these lines as red shaded areas. The most likely  $T_{\text{eff}}$  and  $\log g$  combination for our star would be at the common intersection of the three ranges. However, we note that He I has either a common intersection region with Si III for low temperatures ( $T_{\text{eff}} = 14\,000$ – $15\,000$  K) and surface gravities ( $\log g \sim 1.8$ – $1.9$ ) or with Si II for higher temperature ( $T_{\text{eff}} = 16\,000$ – $19\,000$  K) and surface gravity ( $\log g \sim 1.8$ – $2.45$ ) values. Surprisingly, the ranges of measured EW values for the line of Si III and Si II have no common area. While offsets between the parameters suggested from helium and silicon might be explained by different abundances of one (or both) of the elements, for which Lefever et al. (2007) used solar values, the clear mismatch between the suggested parameter combinations from the Si lines might be due to the assumed solar Si abundance. However, we also note that the grid of models was computed for a fixed value of  $10 \text{ km s}^{-1}$  for  $v_{\text{mic}}$ , while de Burgos et al. (2024) found a value of  $14 \text{ km s}^{-1}$  from their analysis of HD 14134, in agreement with the general trend of high  $v_{\text{mic}}$  values in blue supergiants (Haucke et al. 2018). A higher  $v_{\text{mic}}$  results in higher values of the EW of the lines and could indeed resolve the discrepancy, because the synthetic EWs for Si II  $\lambda 4128$  would shift to higher values of  $T_{\text{eff}}$  while those for Si III  $\lambda 4552$  would simultaneously shift to lower values.

To further explore the impact of  $v_{\text{mic}}$  on the EWs of our strategic lines, we developed a grid of CMFGEN models with  $v_{\text{mic}}$  values of  $12 \text{ km s}^{-1}$  and  $14 \text{ km s}^{-1}$ . The models span the temperature range  $T_{\text{eff}} = 14\,000$ – $18\,000$  K, have surface gravities of around  $\log g = 2.0$  (with a spread from  $1.85$ – $2.3$ ) in cgs units, and are computed for solar abundances. In each synthetic

<sup>7</sup> The He I  $\lambda \lambda 4471, 6678$  lines, although included in Table C.1, were not used due to little or no variation of their EWs over several spectral sub-types (see Figs. 4 and 9 in Lennon et al. 1993).



**Fig. 6.** EWs of temperature-sensitive photospheric lines in Galactic B-type supergiants (limited to luminosity class Ia) from Lennon et al. (1993, open black circles) along with our measurements for HD 14134 (filled red circle). Shown are the mean values (solid blue lines) and their standard deviations (dotted blue lines), as well as the observed range limited by the minimum and maximum values (dashed blue lines). The red filled circles are the measurements for HD 14134 from Lennon et al. (1993).



**Fig. 7.** EW isocontour levels as function of  $T_{\text{eff}}$  and  $\log g$  of three photospheric lines computed by Lefever et al. (2007). The range in EW values covered by our measurements is indicated, and the likely parameter combination is marked by red shaded regions.

spectrum, we measured the EWs of the Si II  $\lambda$ 4128, Si III  $\lambda$ 4552, and Mg II  $\lambda$ 4481 lines and compared them with our measurements for HD 14134. In Fig. 8, we show the EWs for Si III  $\lambda$ 4552 (left) and Mg II  $\lambda$ 4481 (right) versus Si II  $\lambda$ 4128 for the two values of  $v_{\text{mic}}$  (different symbols) and for the temperature range, which is colour-coded. Our measurements for HD 14134 are depicted with black dots.

We note that EWs of the Si lines are very sensitive to the value of  $v_{\text{mic}}$ . The synthetic values for the investigated temperature range align along straight lines that are parallel in the diagram (left panel of Fig. 8). A comparison with the measurements for HD 14134 suggests that  $v_{\text{mic}}$  could on average even be slightly over  $14 \text{ km s}^{-1}$ . The extrapolation of the synthetic EW values would thus result in a range of stellar effective temperatures of 15 000–17 000 K. A similar temperature range is predicted from the EW values of the Mg II line (right panel of Fig. 8). Here, the curves for constant  $v_{\text{mic}}$  are not parallel but converge for higher temperatures. A slightly higher value for  $v_{\text{mic}}$  is needed here as well to match with some of the observed values, although most values cluster around  $14 \text{ km s}^{-1}$ .

The noticeable spread in the observed EW values, which is significantly larger than the errors of the individual measurements, in combination with the rather irregular photometric variability of the star might suggest real variations (fluctuations)

in stellar parameters<sup>8</sup>, possibly related to a highly dynamical stellar surface (respectively stellar atmosphere) due to pulsations<sup>9</sup>. Atmospheric motions also impact the line-forming regions (in particular the depth at which the lines are formed), which could explain the observed spread in  $v_{\text{mic}}$ . Moreover, they would explain why the EW values of Si III are rather stable, whereas those of Si II show a large scatter. If the variability in EW values were caused by (pure) temperature variations, the EW values of both lines would vary simultaneously.

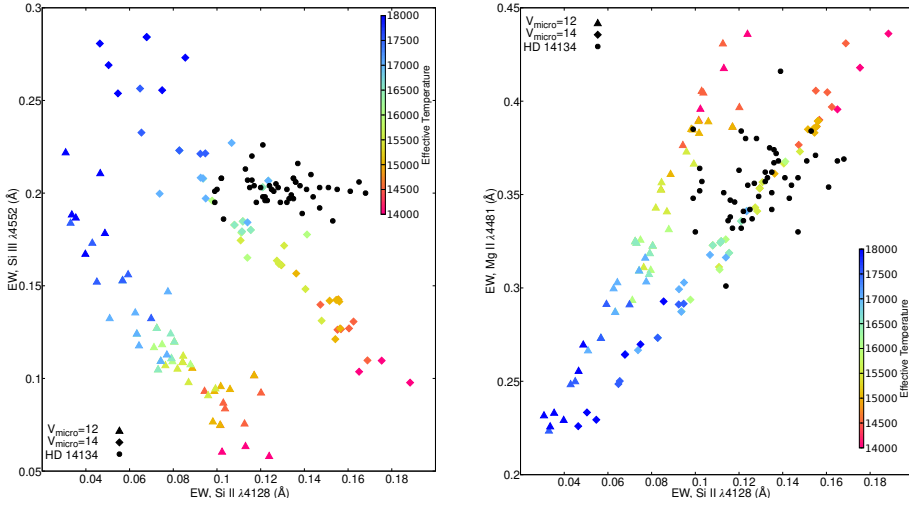
#### 4.2. Radial-velocity variations

The photospheric absorption lines of HD 14134 display temporal variations in radial velocity. Figure 9 depicts dynamic plots for the lines H $\beta$ , He I  $\lambda$ 4471, 6678, Si II  $\lambda$ 6347, Si III  $\lambda$ 4568, and Mg II  $\lambda$ 4481. The colour-code represents the flux normalised to the continuum value. The profiles change clearly in width, depth, and radial velocity. In many cases, we also observe asymmetric profile shapes, but no obvious periodic variability is seen. The asymmetry noticeable in the H $\beta$  line, in particular at the beginning of the time series, is caused by wind emission superimposed on the photospheric absorption line. Although the diverse spectral lines are formed in different layers of the stellar atmosphere, the patterns of radial-velocity variability are quite similar.

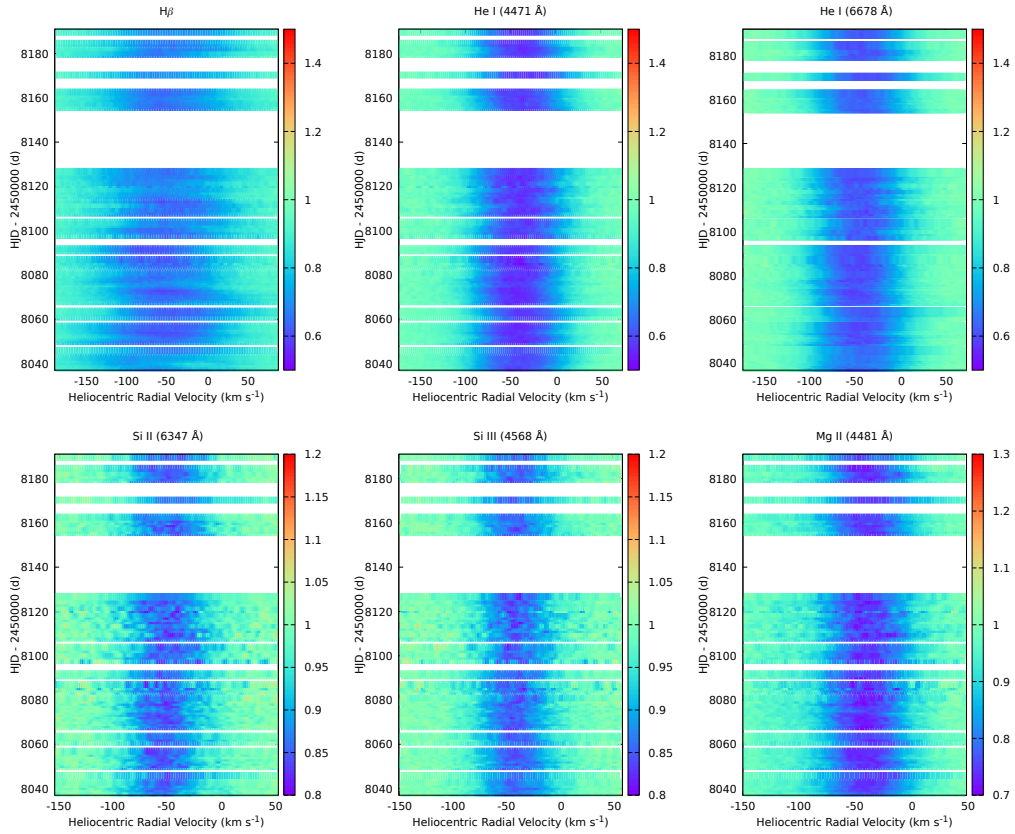
The object HD 14134 was included in the recent study by Simón-Díaz et al. (2024), whose authors analysed the Si III  $\lambda$ 4568 line and identified line-profile variability with a peak-to-peak amplitude in radial velocity of  $\leq 5 \text{ km s}^{-1}$ . To test whether this line-profile variation could be due to pulsation activity, we selected the same line and computed its moments (Aerts et al. 1992; North & Paltani 1994). We limited our analysis to spectra with S/N values  $\geq 70$  and integrated the fluxes below 0.98 in the normalised spectra. We are aware that for precise results from the moment method higher quality data (S/N  $\sim 300$ ) are required; however, our intention is not to determine pulsation modes but simply to check the global behaviour of the moments. For this, in the right panel of Fig. 10 we compare the temporal variation of the first (radial velocity, top panel) and third (line asymmetry, bottom panel) moments. These were corrected for the presumable radial velocity of the star (indicated in the top panel). From these plots, we note that the general behaviour of

<sup>8</sup> Although, some influence due to imperfect spectral normalisation cannot be excluded.

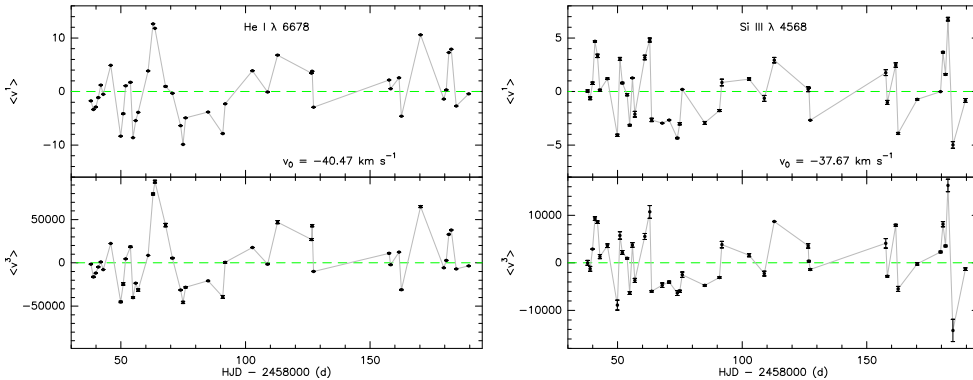
<sup>9</sup> That pulsations might lead to slight changes in stellar parameters was also recently proposed by Kalita et al. (2025) for  $\zeta$  Oph and shown based on theoretical models for the blue supergiants MWC 137 (Parida et al. 2024) and  $\epsilon$  Ori (Dasgupta et al. 2026).



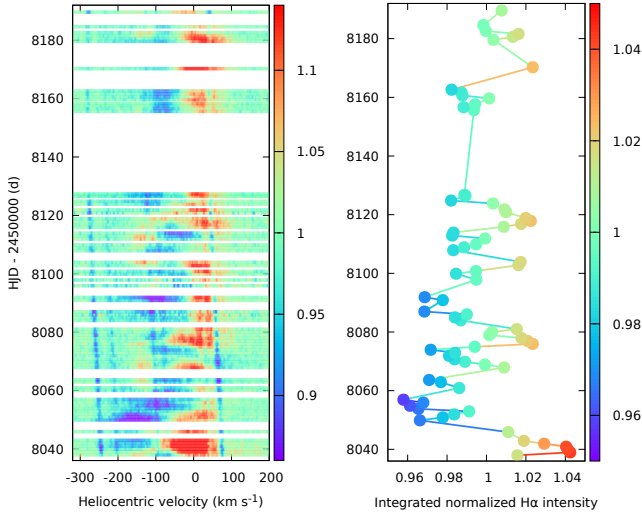
**Fig. 8.** Synthetic EWs for Si III  $\lambda 4552$  (left) and Mg II  $\lambda 4481$  (right) versus Si II  $\lambda 4128$  for the two values of  $v_{\text{mic}}$  (different symbols) and for the range of investigated temperatures (colour-coded). The measurements for HD 14134 are shown with black dots.



**Fig. 9.** Dynamic plots of selected absorption lines showing the temporal radial-velocity variations.



**Fig. 10.** First (radial velocity, top panels) and third moments (line asymmetry, bottom panels) of the He I  $\lambda 6678$  (left) and the Si III  $\lambda 4568$  (right) lines.



**Fig. 11.** Left: Dynamic plot showing the temporal evolution of the  $H\alpha$  profile. The sharp absorption features with radial-velocity drift are telluric lines. Right: Normalised intensity integrated over the  $H\alpha$  line. The colour bar gives the normalised intensity.

the two moments is very similar. We did the same analysis for the  $\text{He I } \lambda 6678$  line and show the results on the left side of Fig. 10. Also for this line, the two moments vary in phase and show a similar trend over the entire observing period as the  $\text{Si III } \lambda 4568$  line. This is a strong indication of pulsations being the cause of the variability rather than other effects such as stellar spots. We also see some differences between the two elements, which we interpret as being due to wind variability, that can influence the profile of the  $\text{He I } \lambda 6678$  line. The amplitude of the radial-velocity variation of the two lines is quite different. While a peak-to-peak amplitude of  $\sim 5 \text{ km s}^{-1}$  is found from  $\text{Si III}$  (with an exception of  $\sim 7 \text{ km s}^{-1}$  towards the end of our observing run), which is similar to what was found by Simón-Díaz et al. (2024), the velocity amplitude of  $\text{He I}$  is more than twice as high.

#### 4.3. Stellar wind variability

The winds of mid to late type-B supergiants imprint their signals mainly on the hydrogen Balmer lines – especially on  $H\alpha$ . HD 14134 is known for its highly variable  $H\alpha$  profile with pure absorption, P Cyg profiles, and the complete absence of  $H\alpha$ , likely due to compensation for the stellar photospheric-absorption line with wind emission (Morel et al. 2004; Maharramov & Jahangirova 2017; Maharramov 2017).

Our spectra collected over a period of five months reflect this diversity (see Fig. D.1). In the left panel of Fig. 11 we present a dynamic plot of the  $H\alpha$  line. Obviously,  $H\alpha$  had an intense and broad emission and a shallow absorption component at the beginning of our monitoring. Over the course of the observations, the absorption component shows strong variability in radial velocity, width, and intensity. On several dates the absorption and/or emission components are very weak or even disappear (almost completely) from the spectrum. At some phases, the emission displays an additional blue peak mimicking a double-peaked emission profile as is known for stars with disks (such as Be stars; see e.g. Porter & Rivinius 2003), and the profile eventually develops further into an inverse P Cygni, which might indicate that some material is falling back to the stellar surface.

No clear periodicity is found in the evolution of the  $H\alpha$  profile, but the strong variability in the emission and absorption components of  $H\alpha$  raises the question as to whether it can (significantly) influence the observed photometry. While both Gaia photometers cover the wavelength region of  $H\alpha$  (Evans et al. 2018), the colour (bottom panel of Fig. B.3) should not be influenced by the  $H\alpha$  line variability, and the colour changes of about 0.1 mag might trace temperature variability of the star<sup>10</sup>. The TESS detector bandpass is centred on the traditional Cousins  $I$  band and spans from  $6000 \text{ \AA}$  to  $1 \mu\text{m}$  including  $H\alpha$ . Therefore, to visualise the effect the time-variable wind of HD 14134 might imprint on photometric measurements, we integrated the spectra over the  $6557\text{--}6567.5 \text{ \AA}$  wavelength range and normalised them:

$$F_{\text{norm}} = \frac{\int_{\lambda_1}^{\lambda_2} F_{\lambda} d\lambda}{\int_{\lambda_1}^{\lambda_2} d\lambda}. \quad (1)$$

The results are shown in the right panel of Fig. 11. During the enhanced phase of wind activity at the beginning of the monitoring, the variability exceeds 4%, whereas during more quiescent phases it varies around 2–3%. The amplitude of the photometric variability seen in the TESS light curves (Fig. B.2) is of the same order of magnitude. This suggests that most of the photometric variability observed by TESS might be caused by the time-variable wind and that the variability due to pulsations might only play a minor role. We return to this in Sect. 6.1.

## 5. Analyses of the light curves

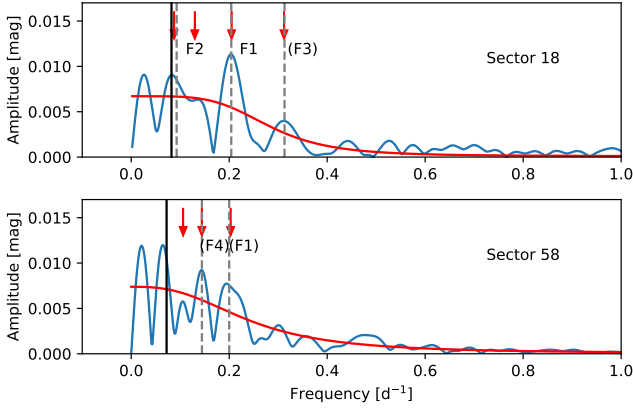
Although the wind seems to have a major impact on the light curve, the variability seen in the photospheric lines suggests the presence of pulsation activity. The sparse sampling of the Gaia data (Fig. B.3) is unsuitable to reliably identify periodic signals. Therefore, we focused on the TESS light curves (Fig. B.2), which display prominent but irregular variability along with some inherent variations on timescales considerably longer than the sector length. In the following, we analyse the light curves to search for signatures that might be related to pulsations.

### 5.1. Fourier analysis

We started to retrieve the frequencies of possible periodic signals in the classical way and used PERIOD04 (Lenz & Breger 2005) to compute the discrete Fourier transforms for non-uniformly sampled data. Figure 12 shows the first Fourier transform of the TESS data from both sectors. Our analysis is confined to the interval  $[0\text{--}24] \text{ d}^{-1}$ , below the Nyquist frequency of each sector. We found no strong signal beyond  $1 \text{ d}^{-1}$ . The amplitude and phase are calculated using a least-squares sine fit for each detected frequency. After obtaining the first frequency, the analysis was performed on the residuals in a standard pre-whitening procedure. The uncoupled uncertainties in the frequencies and amplitudes were calculated using Monte Carlo simulations following the procedure outlined in Sánchez Arias et al. (2023a).

To select the most likely frequencies from the obtained list, we applied the following criteria. We adopted a conservative  $\text{S/N} \geq 5$ , for each sector, to avoid spurious peak detection induced by noise, following the recommended values in

<sup>10</sup> Unfortunately, no effective temperature calibration for BSGs based on Gaia colours exists to date, so we cannot quantify the effective temperature of HD 14134 and its temporal changes based on the Gaia photometric measurements.



**Fig. 12.** Amplitude spectra of the first Fourier transform of the TESS light curves from sectors 18 (top) and 58 (bottom). Red curves represent the best-fit models for the Lorentzian function given by Eq. (2). Vertical black lines depict the lower limit for confident frequency detection. Dashed grey lines and red arrows mark frequencies identified using PERIOD04 and the Wavelet analysis (see Sect. 5.2), respectively.

Baran & Koen (2021). For the computation of the S/N value of each frequency, we considered a spectral window size of  $1 \text{ d}^{-1}$ . As was shown by Burssens et al. (2020), such a narrow window size prevents over-interpretation of the data for stars that have prominent SLF variability, as seems to be the case for our star. We further adopted  $1.5/\Delta T$  as resolution criteria as in Loumos & Deeming (1978), with  $\Delta T$  being the observation time span of the considered sector. For sectors 18 and 58 the time span is 24.33 d and 27.71 d, resulting in values of  $0.0616 \text{ d}^{-1}$  and  $0.0541 \text{ d}^{-1}$ , respectively, for the minimum separation distance of neighbouring frequencies. When comparing frequencies from different sectors, we adopted a conservative frequency separation of  $0.05411 \text{ d}^{-1}$ . A further constraint is that for a confident identification, the time span of the observations should spread over at least twice the period. This means that we considered only frequencies greater than  $2/\Delta T$ , i.e. greater than  $0.0822 \text{ d}^{-1}$  and  $0.0722 \text{ d}^{-1}$  for sectors 18 and 58, respectively.

The final frequencies are listed in Table B.1. Only two significant frequencies are obtained in sector 18, whereas the first two highest amplitude frequencies derived in sector 58 fall below our S/N threshold and are therefore not considered as reliable identifications. We list them, however, because (F1) seems to agree with F1 found in sector 18, although it displays a significantly lower S/N. (F4) is listed because it has a higher amplitude than (F1). Similarly, we list (F3) in sector 18. All these frequencies seem to be affected by the high level of the underlying noise.

To quantify this (red plus white) noise, we followed the approach of Bowman et al. (2019a) and fitted the amplitude spectra in Fig. 12 with a Lorentzian function of the form

$$\alpha(\nu) = \frac{\alpha_0}{1 + \left(\frac{\nu}{\nu_{\text{char}}}\right)^\gamma} + C_W, \quad (2)$$

where  $\alpha_0$  defines the amplitude at frequency zero,  $\gamma$  is the gradient of the linear part of the profile in a logarithmic presentation,  $\nu_{\text{char}}$  is a characteristic frequency representing the inverse of the mean duration of the dominant structures in the light curve, and  $C_W$  is the frequency-independent level of the white noise. To derive the best-fitting parameters, we performed a Monte Carlo simulation in the frequency range  $[0-24] \text{ d}^{-1}$ . Specifically, we calculated the standard deviations of the residuals after fitting our data with the Python package `curve_fit`

**Table 3.** Best-fit parameters for the Lorentzian functions (Eq. (2)).

| Parameters                              | Sector 18           | Sector 58          |
|-----------------------------------------|---------------------|--------------------|
| $\alpha_0$ ( $\mu\text{mag}$ )          | $6613.23 \pm 44.28$ | $735.31 \pm 49.51$ |
| $\nu_{\text{char}}$ ( $\text{d}^{-1}$ ) | $0.282 \pm 0.001$   | $0.239 \pm 0.002$  |
| $\gamma$                                | $4.52 \pm 0.29$     | $2.74 \pm 0.06$    |
| $C_W$ ( $\mu\text{mag}$ )               | $99.13 \pm 3.36$    | $37.63 \pm 2.78$   |

(Vugrin et al. 2007) and used them to create synthetic Gaussian noise. The noise was randomly generated in each iteration and added to the original data, creating the synthetic sample for each iteration. Finally, we computed the mean and the standard deviation after fitting Eq. (2) to our synthetic data 1000 times. The results are displayed in Table 3 and the fit curves are included in Fig. 12. We notice that the parameters considered to model the noise are different for the two sectors. Changes in the behaviour of SLF variability might indicate that its origin is linked to short-term variations that do not prevail from one sector to another and might be related (at least partially) to the previously identified wind variability. The drop in the level of white noise,  $C_W$ , by a factor of almost three is most likely due to the different cadences in the studied sectors.

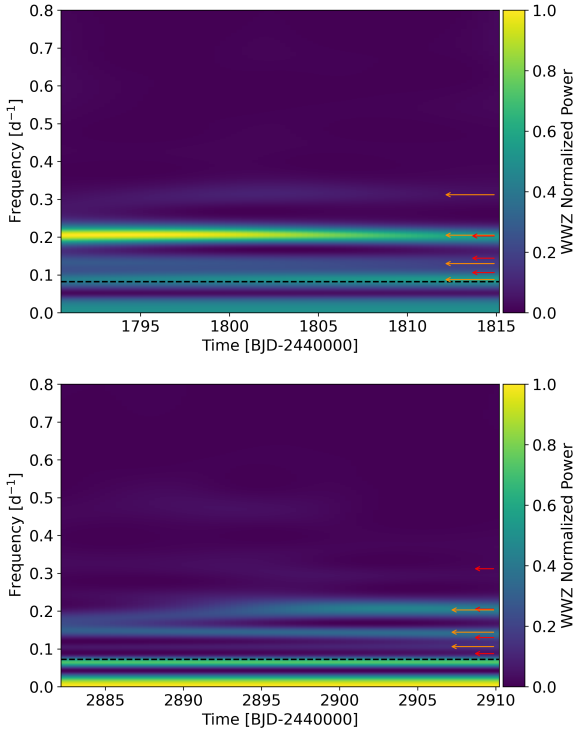
## 5.2. Wavelet analysis

Our Fourier analysis shows that the frequency with the highest amplitude, F1, identified in sector 18 is barely detectable in sector 58. F2 does not prevail over time and is not detected in sector 58. Similarly, (F4), which has the highest amplitude in sector 58, has no counterpart in sector 18. This suggests that the defining parameters of the signals (frequency, amplitude, phase) in the light curves are time variable. To study the changes in the frequencies and their amplitudes over the observing periods, we performed a wavelet analysis; more specifically, we employed the weighted wavelet Z-transform (WWZ, Foster 1996). In contrast to the classical wavelet method, WWZ is suitable to study unevenly sampled time series. It utilises a revised adaptation of the standard Morlet wavelet (Grossmann & Morlet 1984) to generate the local power spectra<sup>11</sup>, i.e. the energy distribution of the signal in the time-frequency domain. Figure 13 represents the WWZ scalograms obtained from the analysis of the data of both sectors using the Python package `libwwz`<sup>12</sup>.

The frequencies with the highest power obtained by the time integration of the local power spectra are listed in Table B.2 using lowercase letters but following the same numbering as before. These frequencies agree fairly well with those obtained from PERIOD04 (Table B.1). Deviations between the two are below  $0.052 \text{ d}^{-1}$  and are due to the different algorithms employed in each method. Frequencies f4 in sector 18 and f5 in sector 58 do not satisfy our selection criteria; however, they are clearly present in the amplitude spectrum (see Fig. 12). The scalograms demonstrate a decrease in amplitude of the main frequency, f1, in sector 18, whereas it is not present at the beginning of sector 58, but it appears and strengthens during the second half of that observing period. Frequency f2 seems to strengthen over sector 18, whereas in sector 58 it has no clear counterpart. It could either have turned into the signal seen at a lower frequency

<sup>11</sup> The tool we used computes normalised power spectra instead of amplitude spectra, so we use this notation throughout the paper when referring to WWZ results.

<sup>12</sup> <https://github.com/ISLA-UH/libwwz>



**Fig. 13.** Scalograms for the light curves of sectors 18 (top) and 58 (bottom). Orange (red) arrows indicate the frequencies obtained from the averaged power resulting from the scalogram of the same (other) sector. The dashed black lines mark the lower limit for reliable frequency identification in each sector.

(below the dashed line) but with considerably higher amplitude, or it could have shifted to a slightly higher frequency (identified as f5 in sector 58) but with significantly lower amplitude. Moreover, the frequencies f1 and f4 in sector 58 seem to be connected before the start of the observing run for sector 58 and separate shortly thereafter, with one component gradually converging towards f1 and notably matching the dominant frequency observed in sector 18. We also detected a broad but faint feature with time-variable intensity in sector 18 labelled f3, which lacks a counterpart in sector 58.

## 6. Discussion

The study presented here leverages high-cadence, space-based TESS photometric light curves and (albeit not simultaneously acquired) ground-based spectroscopic time series to probe the observed variability in HD 14134 and to constrain the evolutionary state of the object. With its reported spectroscopic and photometric variability, the star was proposed as belonging to the  $\alpha$  Cyg variables (Laur et al. 2017). Such objects display low-amplitude radial-velocity and brightness variations (van Leeuwen et al. 1998; Guzik et al. 2024) that can display alternating phases of quasi-periodic and erratic variability, as was reported by Guzik et al. (2026) for the prototype of this class, the star  $\alpha$  Cygni (Deneb). Studies of the pulsation properties of  $\alpha$  Cyg variables suggested that these objects might be post-red-supergiant stars (Saio et al. 2013). In the following, we discuss the plausible cause of the detected variabilities in HD 14134 and how our results may help to unveil the nature of the object.

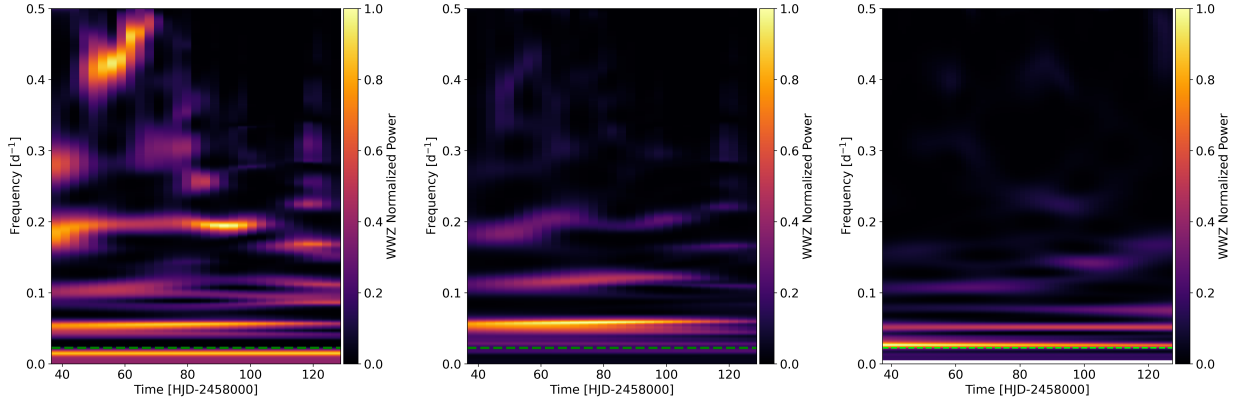
### 6.1. Pulsations versus wind variability

The object HD 14134 displays a variety of variabilities: in EW, radial velocity, stellar wind activity, and brightness. On the one hand, the moment analysis of the photospheric absorption lines of Si III and He I suggests that pulsations might cause the observed radial velocity and line-profile variability. The high value of macroturbulence needed to reproduce the line broadening is proposed as indicating pulsation activity, as was also reported for the BSG  $\rho$  Leo (Aerts et al. 2018). The EW measurements of temperature-sensitive lines display a large spread that might be interpreted with temperature fluctuations within the line-forming regions; this is likely due to a highly dynamical atmosphere. This again might indicate that pulsation activity is the main cause of the observed variations. On the other hand, the analysis of the TESS light curves provides no clear evidence of stable, coherent pulsation modes. Instead, the amplitude spectra are dominated by SLF variability, hampering a confident identification of periodic signals, and the identified signals show temporal variations in frequency, amplitude, or both. Furthermore, the H $\alpha$  line displays strong temporal line-profile variability due to time-variable winds that cause brightness variations of the same order of magnitude as the variations detected in the TESS light curves.

To explore whether the different observed variabilities might be pulsation induced or wind induced, we performed a wavelet analysis of the radial-velocity curves of the Si III and He I lines as well as of the integrated H $\alpha$  line using the WWZ method. We restricted the analysis to the spectra from the first three months to avoid artefacts in the scalograms due to the approximately one-month gap in the data. The resulting signals, normalised to their respective maximum power values, are shown in Fig. 14. No significant signals are found for frequencies over  $0.5 \text{ d}^{-1}$ . The dashed line in each panel marks the value of  $0.0225 \text{ d}^{-1}$ . This value indicates the confident identification threshold considering the observation time span of  $\Delta T = 88.78 \text{ d}$ .

The scalograms reveal a different frequency pattern compared to the TESS data (Fig. 13). Three categories appear in certain frequency domains and are present in all three datasets: (i) rather stable (or mildly variable in frequency and/or amplitude) signals in the low-frequency domain ( $< 0.08 \text{ d}^{-1}$ ); (ii) merging and splitting signals over long timescales ( $0.08\text{--}0.15 \text{ d}^{-1}$ ); and (iii) signals with strongly variable amplitude with patchy, sometimes recurrent, patterns ( $> 0.15 \text{ d}^{-1}$ ). We averaged the frequencies over the time span and calculated their errors as the weighted standard deviation over a small window around each detected peak. These are listed in Table 4 along with the frequencies obtained from the TESS light curves. In this table, the frequencies are ordered with increasing values from top to bottom, and we aligned frequencies from different data categories that agree within their error bars. The same information is provided in graphical form in Fig. 15, in which the symbol sizes additionally provide information about the power of the signals that were normalised to the highest power detected in the respective dataset, facilitating a direct comparison of relative signal strengths.

In addition, we tested whether pulsations are expected to be excited in HD 14134. For this, we used the GYRE stellar oscillation code (Townsend et al. 2018) and computed non-adiabatic radial ( $l = 0$ ) and non-radial modes ( $l = 1, 2, 3$ ) within the  $0.01 < f [\text{d}^{-1}] < 0.5$  range for the two MESA models matching closely with the parameters of HD 14134 (see Table 2). We found three excited non-radial modes in this frequency range for both M1 and M2. All predicted modes are included with their



**Fig. 14.** Scalograms of radial-velocity variation of the Si III (left) and He I lines (middle), and of the normalised integrated H $\alpha$  line (right). The horizontal dashed green lines indicate the threshold for the lowest confidence frequency identification.

**Table 4.** List of the frequencies.

| Si III              | Frequencies (d <sup>-1</sup> ) |                     | TESS                | M1<br>f (d <sup>-1</sup> ) ( <i>l</i> ) | M2<br>f (d <sup>-1</sup> ) ( <i>l</i> ) | Possible<br>Interpretation |
|---------------------|--------------------------------|---------------------|---------------------|-----------------------------------------|-----------------------------------------|----------------------------|
|                     | He I                           | H $\alpha$          |                     |                                         |                                         |                            |
| (–)                 | (–)                            | (–)                 | (–)                 | 0.0185 (1)                              | 0.0186 (1)                              | –                          |
| –                   | 0.0284 $\pm$ 0.0261            | 0.0263 $\pm$ 0.0040 | (–)                 | 0.0295 (1)                              | 0.0303 (1)                              | wind ?                     |
| –                   | –                              | –                   | (–)                 | 0.0452 (3)                              | –                                       | –                          |
| 0.0559 $\pm$ 0.0058 | 0.0585 $\pm$ 0.0094            | 0.0515 $\pm$ 0.0045 | (–)                 | –                                       | 0.0521 (2)                              | g-mode, $f_g$              |
| –                   | –                              | 0.0768 $\pm$ 0.0063 | 0.0875 $\pm$ 0.0227 | –                                       | –                                       | wind ?                     |
| 0.0978 $\pm$ 0.0197 | 0.1191 $\pm$ 0.0106            | 0.1076 $\pm$ 0.0115 | 0.1059 $\pm$ 0.0747 | –                                       | –                                       | 2 $\times$ $f_g$           |
| –                   | –                              | 0.1428 $\pm$ 0.0207 | 0.1368 $\pm$ 0.0586 | –                                       | –                                       | wind                       |
| 0.1680 $\pm$ 0.0298 | 0.1658 $\pm$ 0.0344            | 0.1663 $\pm$ 0.0436 | –                   | –                                       | –                                       | 3 $\times$ $f_g$           |
| 0.1953 $\pm$ 0.0111 | 0.1981 $\pm$ 0.0275            | 0.2276 $\pm$ 0.0221 | 0.2040 $\pm$ 0.0412 | –                                       | –                                       | 4 $\times$ $f_g$           |
| 0.2922 $\pm$ 0.0394 | 0.2931 $\pm$ 0.0806            | –                   | 0.3119 $\pm$ 0.0289 | –                                       | –                                       | –                          |
| 0.4249 $\pm$ 0.0514 | 0.3278 $\pm$ 0.1447            | 0.4064 $\pm$ 0.0337 | –                   | –                                       | –                                       | –                          |

**Notes.** Left: List of the frequencies obtained from the scalograms of the radial-velocity variation of the Si III and He I lines, the normalised integrated H $\alpha$  line, and the TESS photometry. For the latter, the entries for f1 and f4 in Table B.2 were averaged. Middle: Modes predicted by GYRE for the two stellar models in Table 2 with their frequencies and harmonic degree. Right: Possible interpretation. The entries (–) mark ranges below the lower limit for reliable frequency identifications; ‘–’ means no frequency detected in the observations respectively found from the theoretical models.

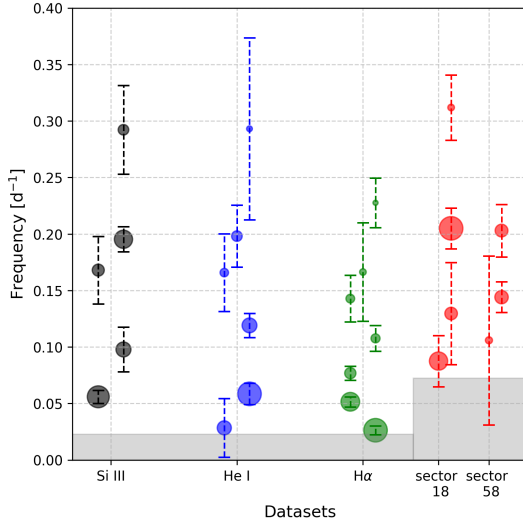
harmonic degree,  $l$ , in Table 4. The excited ones for  $l = 1$  in M1 have slightly lower frequencies but agree fairly well with those found for M2. The higher frequency modes predicted by the individual models do not match. The one for M1 has no observational counterpart within the error bars, whereas the one for M2 matches well with all the observations. Model M2 also has stellar parameters (mass, radius, luminosity) that fit closer to the observed ones (Table 1), so we consider the predictions from M2 to be representative for our object.

From model M2, we find one clear match for the theoretical frequency (0.0521 d<sup>-1</sup>,  $P \simeq 19.2$  d) with the values obtained from spectroscopy, which we identify as g modes (Saio et al. 2006). The mode is seen in the TESS data as well, but it aligns with our threshold value and is hence not listed in the table. Moreover, we find two more frequencies that match closely in the four data categories ( $\sim 0.1$  d<sup>-1</sup>;  $\sim 0.2$  d<sup>-1</sup>). They all have high power (see Fig. 15) but lack a theoretical counterpart. These frequencies seem to be multiples (harmonics) of the g mode (2 and 4  $f_g$ , but their frequencies and powers display modulations over the observing period). A third frequency is seen at least in the spectroscopic data ( $\sim 0.16$  d<sup>-1</sup>, although with lower powers) and might match with another harmonic (3  $f_g$ ). Inspection of the Fourier spectrum of the TESS data suggests that this signal is

also present (see Fig. 12), but its identification is suppressed by the high level of SLF variability in this frequency domain.

We consider two frequencies in our table as being most likely due to wind variabilities as they are only seen in H $\alpha$  and TESS. These signals have periods of  $\sim 7$  d and  $\sim 13$  d, respectively. The latter is similar to the  $\sim 12.8$  d signal reported by Morel et al. (2004) based on their analysis of the HIPPARCOS photometry and EW variations of the H $\alpha$  line. A third one with a period of  $\sim 38$  d is seen in H $\alpha$  and He I, but not in Si III. Therefore, we tend to assign it more to the wind rather than to a pulsation mode, although similar periods are predicted by both M1 ( $\sim 34$  d) and M2 ( $\sim 33$  d).

We do not have an easy way to interpret the two high-frequency signals. These non-coherent signals appear in the scalograms as patchy or recurrent signals with a complex frequency structure and might be related to damped lifetimes of stochastic gravity waves (e.g. Edelmann et al. 2019). We also have no explanation as to why none of the datasets show indications for the predicted low-frequency pulsation modes. Although the scalograms of Si III and He I seem to show some overlapping signals in this low-frequency domain, a clear separation into individual frequencies is difficult. Moreover, this frequency domain is most strongly impacted by the SLF variability. As we



**Fig. 15.** Graphical comparison of the frequencies and their errors (Table 4) obtained from the WWZ analysis of the different observational tracers. The frequencies from both TESS sectors (Table B.2) are shown. The grey box indicates the thresholds. The symbol sizes scale with the power of the signals, which are normalised to the maximum value.

have seen, the properties of the SLF variability also vary with time, suggesting that SLF variability is most likely connected to time-dependent processes in or close to the stellar surface layers. These could be caused by clumping and stellar wind inhomogeneities (Blomme et al. 2011; Nazé et al. 2021) or by rotational modulation of gravity modes and the excitation of Rossby waves, as was recently suggested for a sample of late O-type supergiants (Cidale et al. 2026). However, a detailed investigation of the origin of the SLF variability phenomenon in HD 14134, and BSGs in general, requires more sophisticated analyses, which are beyond the scope of this work.

## 6.2. Nature of HD 14134

Our analysis of the spectra and SED of HD 14134 revealed that its temperature, luminosity, radius, and current mass values are in good agreement with the predictions from the MESA model for a star with an initial mass of  $14 M_{\odot}$ . As such, it is a post-main-sequence object evolving towards the red-supergiant stage. This conclusion is in agreement with the age of the star that aligns with the one of its host cluster h Per (Dias et al. 2021; Taşdemir et al. 2026). Moreover, we do not detect radial pulsations in HD 14134, which is another argument for a pre-red-supergiant evolutionary state of the star (Saio et al. 2013).

The derived stellar parameters result in a luminosity-to-mass ratio of  $(L/M) = 1.4 \times 10^4 (L_{\odot}/M_{\odot})$ , which is in principle high enough for strange-mode instabilities to occur (e.g. Saio et al. 2013; Glatzel & Kraus 2024), and it seems plausible that a single-event or recurrent signals could be related to these instabilities. Strange modes were proposed to trigger phases of enhanced mass loss (Yadav & Glatzel 2016), which is certainly a suitable mechanism to explain the wind variability seen in HD 14134, in particular the strong activity that we recorded at the beginning of the spectroscopic monitoring.

## 7. Conclusions

We present an analysis of spectroscopic time series and photometric light curves from the TESS mission for the BSG star

HD 14134 with the aim of unveiling the nature of the star and the physical cause for the observed variabilities. Our analysis revealed that HD 14134 is a post-main-sequence object evolving towards the red-supergiant stage.

We found indications of stellar pulsations as well as wind-induced variability. In particular, we consistently detected a g mode with a period of  $\sim 19.2$  d and its harmonics in all datasets. The mode was also predicted from theoretical models (using MESA and GYRE) for the stellar parameters that we derived from the spectral and SED modelling. The presence of g-mode pulsations, including their harmonics, was found in several BSGs (e.g. Saio et al. 2006; Lefever et al. 2007; Aerts et al. 2017; Bowman et al. 2019b), supporting our identification.

The time-variable wind of the star is traced by the strong  $H\alpha$  line variability. This wind variability, when transformed to photometric signals, can reach amplitudes of the same order as those observed by TESS. This finding emphasises that variable stellar winds can have non-negligible contributions to light curves taken from broad-band (or white-light) filters that cover the wavelength region of the  $H\alpha$  line.

Despite significant progress based on the excellent data from the TESS mission, disentangling stellar pulsations and variability resulting from time-variable winds in BSGs remains a challenge. A considerable hindrance in our analysis were the single-sector TESS observations available for HD 14134, which do not allow us to derive all frequencies with the required precision. Longer cadence photometric observations, ideally paired with simultaneous spectroscopic monitoring, are clearly needed. The upcoming PLATO space mission (Rauer et al. 2025) that promises uninterrupted light curves and colour information is hence a very promising tool for future in-depth investigations.

## Data availability

Reduced and normalised optical spectra as well as information about the heliocentric julian dates of the observations are available at the CDS via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/714/A46>.

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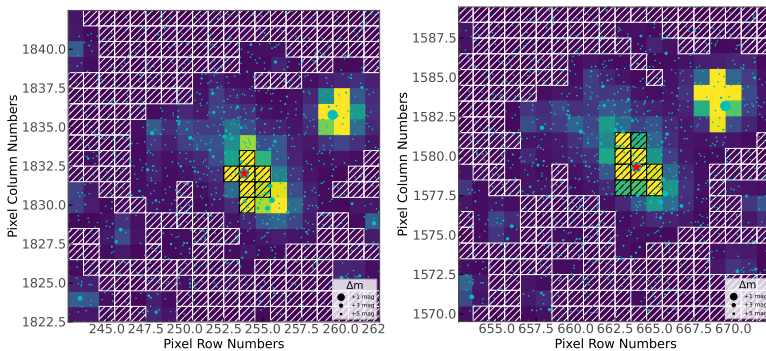
## Appendix A: Observation log

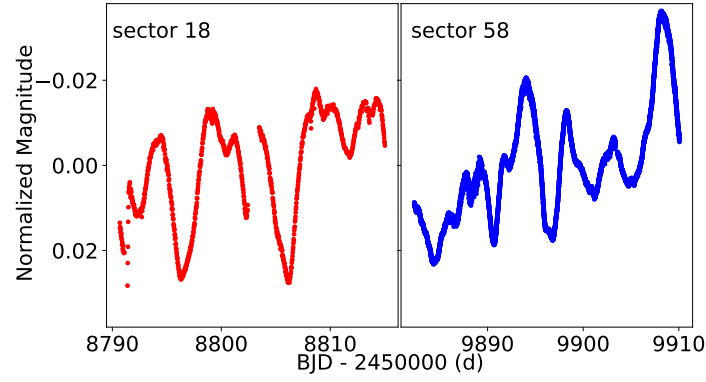
Table A.1: Observation log of spectroscopic data.

| UT date    | HJD<br>(day)     | S/N | UT date    | HJD<br>(day)     | S/N |
|------------|------------------|-----|------------|------------------|-----|
| 2017-10-11 | 2458037.96725645 | 70  | 2017-12-04 | 2458091.8739076  | 84  |
| 2017-10-12 | 2458038.96704434 | 80  | 2017-12-10 | 2458097.83683257 | 36  |
| 2017-10-13 | 2458039.91190416 | 98  | 2017-12-12 | 2458099.89595775 | 60  |
| 2017-10-14 | 2458040.91136581 | 102 | 2017-12-13 | 2458100.78801789 | 65  |
| 2017-10-15 | 2458041.95062805 | 84  | 2017-12-15 | 2458102.78720172 | 83  |
| 2017-10-16 | 2458042.90443349 | 97  | 2017-12-16 | 2458103.89687059 | 55  |
| 2017-10-19 | 2458045.90338126 | 94  | 2017-12-20 | 2458107.89722266 | 66  |
| 2017-10-23 | 2458049.90974458 | 96  | 2017-12-21 | 2458108.87702613 | 71  |
| 2017-10-24 | 2458050.90904115 | 77  | 2017-12-22 | 2458109.88607719 | 44  |
| 2017-10-25 | 2458051.90837908 | 87  | 2017-12-24 | 2458111.88316114 | 53  |
| 2017-10-26 | 2458052.95178009 | 48  | 2017-12-25 | 2458112.88285759 | 78  |
| 2017-10-27 | 2458053.82203571 | 93  | 2017-12-26 | 2458113.89954379 | 43  |
| 2017-10-28 | 2458054.85820033 | 101 | 2017-12-28 | 2458115.88628559 | 67  |
| 2017-10-29 | 2458055.91984851 | 73  | 2017-12-29 | 2458116.84177215 | 58  |
| 2017-10-30 | 2458056.93461986 | 79  | 2017-12-30 | 2458117.87768132 | 59  |
| 2017-11-03 | 2458060.91735185 | 71  | 2017-12-31 | 2458118.85603195 | 54  |
| 2017-11-05 | 2458062.91574058 | 77  | 2018-01-02 | 2458120.86309253 | 35  |
| 2017-11-06 | 2458063.67159516 | 96  | 2018-01-03 | 2458121.82700827 | 51  |
| 2017-11-10 | 2458067.91389092 | 78  | 2018-01-05 | 2458123.83509441 | 57  |
| 2017-11-11 | 2458068.91368308 | 66  | 2018-01-06 | 2458124.82401768 | 67  |
| 2017-11-12 | 2458069.87045822 | 69  | 2018-01-07 | 2458126.48530104 | 108 |
| 2017-11-13 | 2458070.69371944 | 80  | 2018-01-08 | 2458126.74506791 | 105 |
| 2017-11-14 | 2458071.91204849 | 62  | 2018-02-06 | 2458155.6321693  | 65  |
| 2017-11-15 | 2458072.91602665 | 62  | 2018-02-07 | 2458156.63251755 | 61  |
| 2017-11-16 | 2458073.95748005 | 82  | 2018-02-08 | 2458157.63297034 | 110 |
| 2017-11-17 | 2458074.95746185 | 83  | 2018-02-10 | 2458159.63416038 | 57  |
| 2017-11-18 | 2458075.95746916 | 75  | 2018-02-11 | 2458160.63759349 | 67  |
| 2017-11-19 | 2458076.95745086 | 67  | 2018-02-12 | 2458161.63474214 | 78  |
| 2017-11-20 | 2458077.95744755 | 46  | 2018-02-13 | 2458162.60357523 | 75  |
| 2017-11-21 | 2458078.95738346 | 60  | 2018-02-20 | 2458170.27277902 | 102 |
| 2017-11-22 | 2458079.98077465 | 50  | 2018-03-02 | 2458179.61132823 | 77  |
| 2017-11-23 | 2458080.98041942 | 50  | 2018-03-03 | 2458180.61180423 | 70  |
| 2017-11-26 | 2458084.00146832 | 49  | 2018-03-04 | 2458181.61212748 | 72  |
| 2017-11-27 | 2458084.99761594 | 70  | 2018-03-05 | 2458182.61249374 | 73  |
| 2017-11-28 | 2458085.99209371 | 30  | 2018-03-07 | 2458184.61347128 | 70  |
| 2017-11-29 | 2458086.97815903 | 44  | 2018-03-12 | 2458189.61559439 | 82  |
| 2017-12-03 | 2458090.87387006 | 78  |            |                  |     |

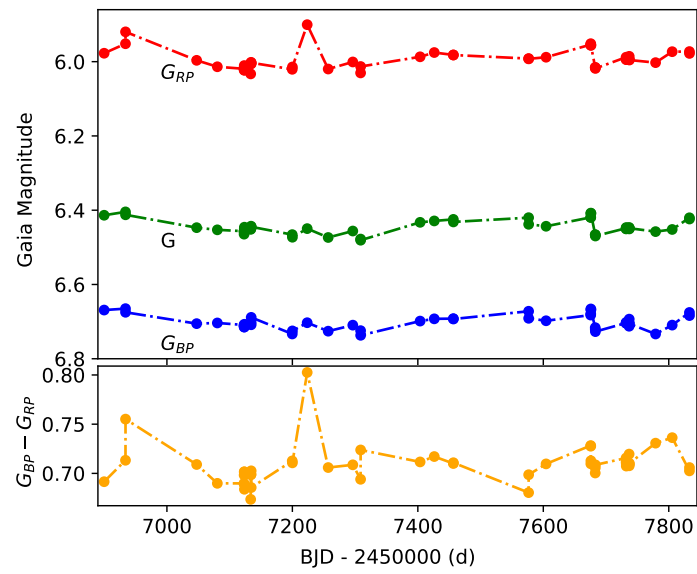
**Notes.** UT date is given in the format year-month-day. Heliocentric Julian Date (HJD) is computed in the middle of the (combined) exposures. S/N is measured in the vicinity of the H $\alpha$  line.

## Appendix B: Photometric light curves





**Fig. B.2.** Extracted, normalised TESS light curves of HD 14134 from sector 18 (*left*) and 58 (*right*).



**Fig. B.3.** Light curves from Gaia DR3 in the three different bands (*top*) and temporal colour variation (*bottom*).

Table B.1: List of identified frequencies their amplitudes, uncertainties, and S/N.

| ID        | Frequency<br>[d <sup>-1</sup> ] | $3\sigma_f$<br>[d <sup>-1</sup> ] | Amplitude<br>[mmag] | $3\sigma_A$<br>[mmag] | S/N  |
|-----------|---------------------------------|-----------------------------------|---------------------|-----------------------|------|
| Sector 18 |                                 |                                   |                     |                       |      |
| F1        | 0.2042                          | 0.0017                            | 12.311              | 0.781                 | 8.50 |
| F2        | 0.0927                          | 0.0024                            | 10.155              | 0.845                 | 6.47 |
| (F3)      | 0.3129                          | 0.0051                            | 3.757               | 0.822                 | 2.89 |
| Sector 58 |                                 |                                   |                     |                       |      |
| (F4)      | 0.1443                          | 0.0013                            | 9.175               | 0.002                 | 4.28 |
| (F1)      | 0.2000                          | 0.0012                            | 8.143               | 0.421                 | 4.07 |

**Notes.** Frequencies in brackets do not meet our S/N criterion. See text for more details on these.

Table B.2: Frequencies obtained from the WWZ analysis.

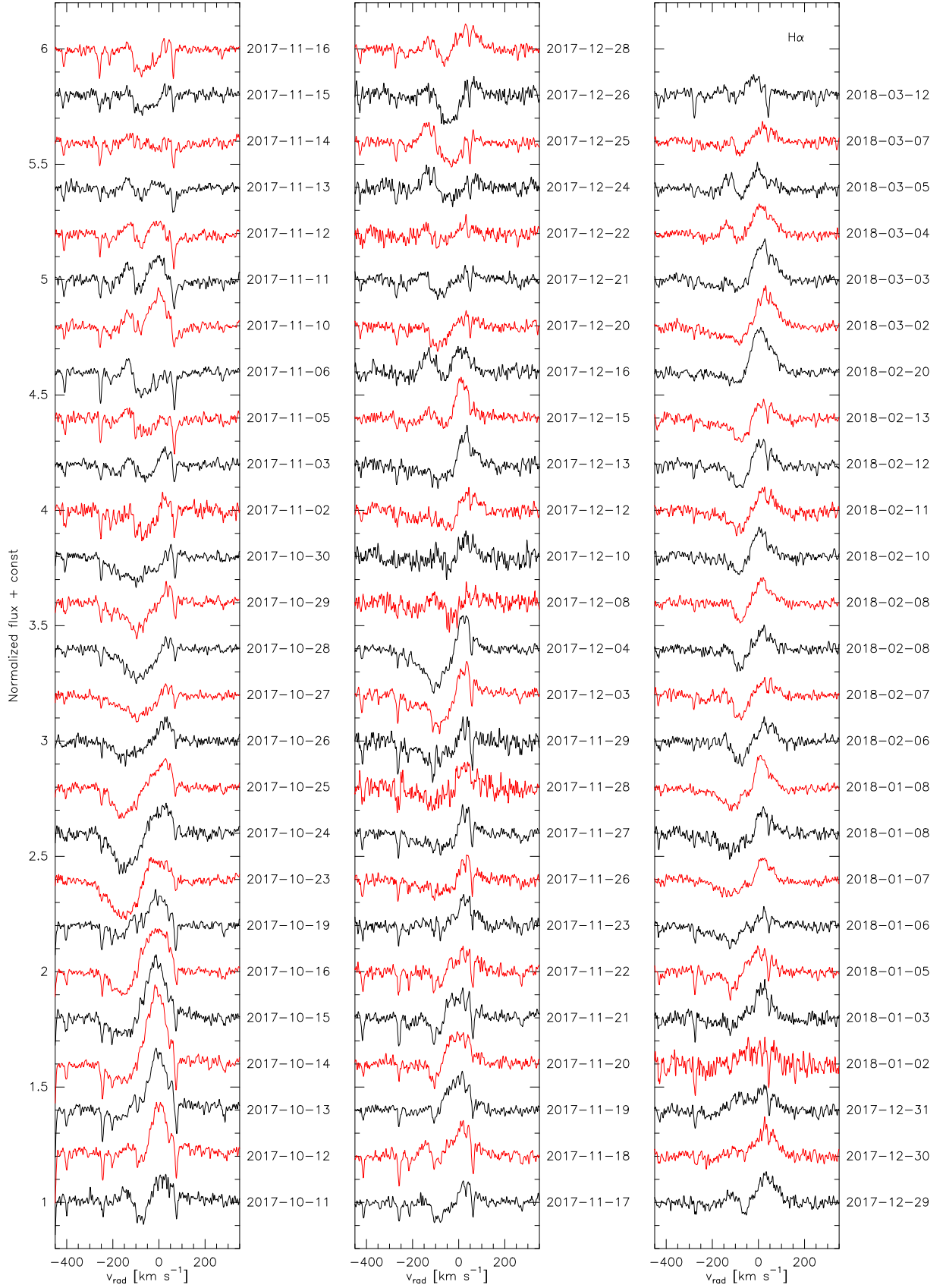
| ID | Frequency (Sector 18)<br>[d <sup>-1</sup> ] | Frequency (Sector 58)<br>[d <sup>-1</sup> ] |
|----|---------------------------------------------|---------------------------------------------|
| f1 | 0.2050                                      | 0.2030                                      |
| f2 | 0.0875                                      | -                                           |
| f3 | 0.3119                                      | -                                           |
| f4 | 0.1296                                      | 0.1441                                      |
| f5 | -                                           | 0.1059                                      |

## Appendix C: EW measurements

Table C.1: EW measurements of selected lines.

| UT data<br>(yyyy-mm-dd) | EW (Si II)<br>(4128 Å) | EW (Si II)<br>(6347 Å) | EW (Si III)<br>(4552 Å) | EW (Si III)<br>(4568 Å) | EW (He I)<br>(4471 Å) | EW (He I)<br>(6678 Å) | EW (Mg II)<br>(4481 Å) | EW (N II)<br>(4601 Å) |
|-------------------------|------------------------|------------------------|-------------------------|-------------------------|-----------------------|-----------------------|------------------------|-----------------------|
| 2017-10-12              | 0.114                  | 0.200                  | 0.207                   | 0.152                   | 0.664                 | 0.872                 | 0.301                  | 0.071                 |
| 2017-10-13              | 0.123                  | 0.217                  | 0.196                   | 0.160                   | 0.682                 | 0.876                 | 0.380                  | 0.064                 |
| 2017-10-14              | 0.136                  | 0.265                  | 0.206                   | 0.172                   | 0.699                 | 0.855                 | 0.374                  | 0.061                 |
| 2017-10-15              | 0.161                  | 0.235                  | 0.201                   | 0.150                   | 0.732                 | 0.894                 | 0.354                  | 0.074                 |
| 2017-10-16              | 0.139                  | 0.240                  | 0.189                   | 0.163                   | 0.705                 | 0.890                 | 0.416                  | 0.066                 |
| 2017-10-19              | 0.153                  | 0.288                  | 0.185                   | 0.160                   | 0.732                 | 0.950                 | 0.384                  | 0.063                 |
| 2017-10-23              | 0.120                  | 0.211                  | 0.203                   | 0.197                   | 0.758                 | 1.011                 | 0.363                  | 0.061                 |
| 2017-10-24              | 0.135                  | 0.243                  | 0.197                   | 0.165                   | 0.747                 | 0.984                 | 0.362                  | 0.070                 |
| 2017-10-25              | 0.102                  | 0.242                  | 0.208                   | 0.164                   | 0.732                 | 0.941                 | 0.352                  | 0.080                 |
| 2017-10-27              | 0.138                  | 0.248                  | 0.204                   | 0.168                   | 0.740                 | 0.986                 | 0.368                  | 0.081                 |
| 2017-10-28              | 0.143                  | 0.207                  | 0.210                   | 0.167                   | 0.725                 | 0.970                 | 0.348                  | 0.079                 |
| 2017-10-29              | 0.144                  | 0.250                  | 0.198                   | 0.170                   | 0.714                 | 0.928                 | 0.355                  | 0.090                 |
| 2017-10-30              | 0.151                  | 0.255                  | 0.203                   | 0.169                   | 0.747                 | 1.016                 | 0.368                  | 0.070                 |
| 2017-11-03              | 0.165                  | 0.233                  | 0.206                   | 0.168                   | 0.672                 | 0.861                 | 0.368                  | 0.088                 |
| 2017-11-05              | 0.137                  | 0.264                  | 0.216                   | 0.167                   | 0.762                 | 0.987                 | 0.372                  | 0.083                 |
| 2017-11-06              | 0.129                  | 0.228                  | 0.195                   | 0.171                   | 0.757                 | 1.046                 | 0.349                  | 0.071                 |
| 2017-11-10              | 0.134                  | 0.241                  | 0.199                   | 0.160                   | 0.728                 | 0.952                 | 0.375                  | 0.084                 |
| 2017-11-11              | 0.155                  | 0.227                  | 0.202                   | 0.170                   | 0.745                 | 0.992                 | 0.371                  | 0.084                 |
| 2017-11-12              | 0.127                  | 0.228                  | 0.205                   | 0.173                   | 0.726                 | 0.931                 | 0.356                  | 0.073                 |
| 2017-11-13              | 0.124                  | 0.265                  | 0.204                   | 0.161                   | 0.736                 | 0.952                 | 0.355                  | 0.081                 |
| 2017-11-14              | 0.128                  | 0.233                  | 0.203                   | 0.163                   | 0.744                 | 0.947                 | 0.380                  | 0.083                 |
| 2017-11-15              | 0.141                  | 0.250                  | 0.202                   | 0.160                   | 0.742                 | 0.971                 | 0.359                  | 0.086                 |
| 2017-11-16              | 0.147                  | 0.265                  | 0.203                   | 0.163                   | 0.726                 | 0.914                 | 0.359                  | 0.080                 |
| 2017-11-17              | 0.100                  | 0.230                  | 0.202                   | 0.163                   | 0.693                 | 0.914                 | 0.330                  | 0.074                 |
| 2017-11-18              | 0.121                  | 0.227                  | 0.198                   | 0.173                   | 0.670                 | 0.891                 | 0.332                  | 0.080                 |
| 2017-11-19              | 0.135                  | 0.218                  | 0.208                   | 0.159                   | 0.730                 | 0.975                 | 0.351                  | 0.080                 |
| 2017-11-21              | 0.132                  | 0.263                  | 0.202                   | 0.170                   | 0.717                 | 0.950                 | 0.362                  | 0.084                 |
| 2017-12-03              | 0.113                  | 0.257                  | 0.213                   | 0.160                   | 0.713                 | 0.924                 | 0.351                  | 0.077                 |
| 2017-12-04              | 0.168                  | 0.237                  | 0.200                   | 0.171                   | 0.737                 | 0.991                 | 0.369                  | 0.081                 |
| 2017-12-12              | 0.099                  | 0.243                  | 0.201                   | 0.160                   | 0.756                 | 0.997                 | 0.385                  | 0.083                 |
| 2017-12-13              | 0.122                  | 0.242                  | 0.196                   | 0.153                   | 0.681                 | 0.878                 | 0.336                  | 0.086                 |
| 2017-12-15              | 0.133                  | 0.246                  | 0.197                   | 0.156                   | 0.736                 | 0.905                 | 0.359                  | 0.067                 |
| 2017-12-20              | 0.136                  | 0.283                  | 0.206                   | 0.170                   | 0.734                 | 0.995                 | 0.367                  | 0.074                 |
| 2017-12-21              | 0.099                  | 0.270                  | 0.195                   | 0.159                   | 0.706                 | 0.930                 | 0.348                  | 0.072                 |
| 2017-12-25              | 0.103                  | 0.273                  | 0.186                   | 0.151                   | 0.703                 | 0.913                 | 0.357                  | 0.074                 |
| 2018-12-28              | 0.125                  | 0.252                  | 0.202                   | 0.168                   | 0.705                 | 0.885                 | 0.342                  | 0.090                 |
| 2018-01-06              | 0.121                  | 0.286                  | 0.226                   | 0.172                   | 0.777                 | 1.036                 | 0.384                  | 0.075                 |
| 2018-01-07              | –                      | 0.222                  | 0.198                   | 0.147                   | 0.734                 | 0.944                 | 0.345                  | 0.062                 |
| 2018-01-08              | –                      | 0.218                  | 0.200                   | 0.179                   | 0.766                 | 0.936                 | 0.345                  | 0.072                 |
| 2018-02-06              | 0.117                  | 0.266                  | 0.204                   | 0.168                   | 0.719                 | 0.908                 | 0.332                  | 0.072                 |
| 2018-02-07              | 0.118                  | 0.252                  | 0.195                   | 0.159                   | 0.707                 | 0.923                 | 0.346                  | 0.073                 |
| 2018-02-08              | –                      | 0.221                  | 0.202                   | 0.169                   | 0.708                 | 0.875                 | 0.334                  | 0.078                 |
| 2018-02-11              | 0.116                  | 0.260                  | 0.207                   | 0.154                   | 0.693                 | 0.880                 | 0.338                  | 0.069                 |
| 2018-02-12              | 0.132                  | 0.249                  | 0.195                   | 0.158                   | 0.696                 | 0.873                 | 0.357                  | 0.070                 |
| 2018-02-13              | 0.102                  | 0.239                  | 0.208                   | 0.163                   | 0.718                 | 0.926                 | 0.364                  | 0.079                 |
| 2018-02-20              | –                      | 0.256                  | 0.240                   | 0.171                   | 0.785                 | 1.044                 | 0.395                  | 0.072                 |
| 2018-03-02              | 0.116                  | 0.248                  | 0.220                   | 0.173                   | 0.702                 | 0.917                 | 0.347                  | 0.068                 |
| 2018-03-03              | 0.122                  | 0.246                  | 0.198                   | 0.153                   | 0.703                 | 0.884                 | 0.341                  | 0.075                 |
| 2018-03-04              | 0.126                  | 0.228                  | 0.201                   | 0.167                   | 0.699                 | 0.897                 | 0.337                  | 0.079                 |
| 2018-03-05              | 0.115                  | 0.245                  | 0.203                   | 0.173                   | 0.724                 | 0.910                 | 0.336                  | 0.067                 |
| 2018-03-07              | 0.135                  | 0.266                  | 0.208                   | 0.163                   | 0.706                 | 0.916                 | 0.342                  | 0.074                 |
| 2018-03-12              | 0.147                  | 0.228                  | 0.192                   | 0.151                   | 0.679                 | 0.895                 | 0.330                  | 0.082                 |
| <EW>                    | 0.129                  | 0.244                  | 0.203                   | 0.164                   | 0.721                 | 0.935                 | 0.356                  | 0.076                 |
| $\sigma$                | 0.017                  | 0.020                  | 0.009                   | 0.009                   | 0.027                 | 0.049                 | 0.019                  | 0.007                 |

## Appendix D: Line-profile variability

Fig. D.1. Temporal evolution of the H $\alpha$  profile.