

Central stars of newly discovered infrared nebulae: eruptive Be stars PY Gem and HD 253659

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ABSTRACT

The presence of a nebula around massive hot stars often works as an indicator that the object is either in an advanced evolutionary stage or a rare product of close binary interaction. Here, we focus on two Be stars – PY Gem and HD 253659 – whose nebulae were detected with the *Wide-field Infrared Survey Explorer*. We estimate their basic physical parameters from modelling the spectral energy distribution and examine their variability. We combine archival photometric data from several ground-based survey telescopes and from the *Transiting Exoplanet Survey Satellite* (TESS) with our own data from dedicated multicolour photometric and spectroscopic monitoring, and conclude that, despite having similar stellar properties, the photometric variability of the two objects is strikingly different. For HD 253659, we detect continuous eruptive variability and a major outburst that took place between 2016 and 2022 along with numerous flicker events seen in the TESS data. HD 253659 also exhibits loop-like behaviour in the colour–magnitude diagram, consistent with build-up and dissipation phases of a circumstellar disc seen close to pole-on. In contrast, during the past ~ 20 yr PY Gem has lost its eruptive variability and shows only small-amplitude p and g -mode pulsations classifying PY Gem as β Cephei hybrid pulsator. An incoherent low-frequency signal is identified as a Štefl frequency, which seems to be supported by the cyclic variation of the emission-line profiles. Detailed analysis of these stars indicates that both objects are inconsistent with evolved massive stars, and that the origin of their nebulae is more likely linked to the physics of the Be phenomenon.

Key words: circumstellar matter – stars: emission-line, Be – stars: evolution – stars: fundamental parameters – stars: individual: HD 253659 – stars: individual: PY Gem – stars: winds, outflows.

1 INTRODUCTION

Circumstellar nebulae and shells may be found around a variety of astrophysical objects. The formation of nebulae can have different origins but, in most cases, it is linked to mass ejections at late stages of stellar evolution, and various kinds of interaction in binary systems, such as wind collision, Roche lobe overflow or merging. The ejected matter typically expands and dilutes so that nebulae are only detectable during a certain amount of time. Their material is ionized by the radiation of the central star and the nebulae can be seen in recombination lines (such as the hydrogen series) and classical nebular lines, such as forbidden emission lines of ionized and neutral metals. Dust can form in cool nebulae, and its thermal emission can be observed at infrared wavelengths.

In contrast to nebulae, shells often result from the interaction between stellar winds and the surrounding interstellar medium (ISM). Such interactions often generate shocks in which the ma-

terial of both the wind and the ISM is compressed and heated. This may result in impressive shells and arc-like structures, such as the wind-blown bubbles around massive stars (e.g. V. V. Dwarkadas 2023, and references therein) and the bowshocks around OB-type runaway stars (e.g. C. S. Peri et al. 2012; C. S. Peri, P. Benaglia & N. L. Isequilla 2015; H. A. Kobulnicky et al. 2017).

Significant progress in the detection of new circumstellar nebulae was achieved with data from the *Spitzer* Space Telescope. Based on these multi-band images, several groups independently discovered many dozens of circumstellar shells (D. R. Mizuno et al. 2010; S. Wachter et al. 2010; V. V. Gvaramadze, A. Y. Knizhev & S. Fabrika 2010b). Other space missions, such as the *Midcourse Space Experiment* (MSX) and the *Wide-field Infrared Survey Explorer* (WISE), provided also useful images based on which nebulae around massive stars were detected, but the spatial resolution of these missions was significantly lower, hiding many structural details of the nebulae. Nevertheless, follow-up spectroscopy of the central stars of many of these shells led to the discovery of dozens of Wolf–Rayet (WR) stars, luminous blue variables (LBVs), and other massive stars (J. S.

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Table 1. Stars studied in this work. The photometry is taken from the Gaia DR3 Synthetic Photometry catalogue (Gaia Collaboration et al. 2023). Variability type is according to the AAVSO International Variable Stars Index (C. L. Watson et al. 2006). Spectral types are from: ^a H. H. Guetter (1968), ^b W. W. Morgan, A. D. Code & A. E. Whitford (1955). The distance to the objects is taken from C. A. L. Bailer-Jones et al. (2021), μ is the proper motion from Gaia Collaboration et al. (2021). The size corresponds to the full extent of the nebula on the sky along the longest axis.

Star	Sp. type	Var. type	Distance (pc)	μ (mas yr ⁻¹)	RUWE	<i>B</i> (mag)	<i>V</i> (mag)	<i>R</i> (mag)	Size (pc)
PY Gem	B1 Vne ^a	γ Cas	1401 ⁺⁴⁸ ₋₆₃	1.301	0.977	8.52	8.46	8.37	1.83
HD 253659	B0.5 V:nne ^b	γ Cas	1698 ⁺⁶⁶ ₋₅₈	1.002	1.106	9.59	9.16	8.86	1.48

Clark et al. 2003; V. V. Gvaramadze et al. 2009; J. C. Mauershan et al. 2010; S. Wachter et al. 2010; V. V. Gvaramadze et al. 2010a; V. V. Gvaramadze et al. 2010b; G. S. Stringfellow et al. 2012; Y. R. Cochetti et al. 2020) and the lists of Galactic bona fide and candidate LBVs have been significantly expanded (A. Kniazev & V. Gvaramadze 2015; A. Y. Kniazev, V. V. Gvaramadze & L. N. Berdnikov 2015; N. D. Richardson & A. Mehner 2018).

We continue to explore central stars of circumstellar nebulae and shells, a list of which is partially published in V. V. Gvaramadze et al. (2010a) and A. Kniazev & V. Gvaramadze (2015). In the current work, we analyse Be stars found in the sample, as circumstellar nebulae are not a typical feature of classical Be stars. Moreover, their presence is difficult to reconcile with the standard evolutionary picture, since main-sequence stars are not generally expected to undergo episodes of sufficiently strong mass-loss to produce extended circumstellar nebulae. The discovery of nebulae around rapidly rotating stars at or near the end of the main-sequence phase (V. V. Gvaramadze et al. 2018, and references therein) supported the hypothesis of Lamers et al. (2001) that the first significant mass loss in rotating stars can occur even before the end of the core hydrogen burning stage. In this context, Be stars, which are rapidly rotating main-sequence B-type stars, are particularly interesting because they have phases during which they are surrounded by ionized gaseous discs, most likely formed by their rapid rotation (e.g. J. M. Porter & T. Rivinius 2003), which by itself may lead already to mechanical mass-loss when reaching the critical value (J. Krtićka, S. P. Owocki & G. Meynet 2011; A. Granada et al. 2013). Or, mass ejections into (quasi-) Keplerian orbits may be triggered by rapid rotation paired with non-radial pulsations of the central star (T. Rivinius, D. Baade & S. Štefl 2003; T. Rivinius, A. C. Carciofi & C. Martayan 2013) that can cause discrete mass ejections known as ‘flickers’ (when occurring on short timescales) or ‘outbursts’ (e.g. A. C. Carciofi et al. 2025). Parts of the ejected (or disc) matter will certainly dissipate or interact with the ISM. On the other hand, recent simulations of Be binary systems have shown that material from the Be star disc can also end up revolving on circumbinary orbits (A. C. Rubio et al. 2025), which might form the base of a nebula around such systems.

We selected two objects – PY Gem and HD 253659 – that are plausible candidates for being associated with the discovered nebula. Both are visible in the northern hemisphere with brightness $V < 10$ mag, which allows us to study them using medium and high-resolution spectroscopy and several photometric survey facilities. The nebulae were not revealed in the large-scale study of infrared nebulae around bright massive stars (J. Bodensteiner et al. 2018), as the luminosities of their central stars are outside the magnitude limit in that study (which required a magnitude in V of less than 6.5), and they are not mentioned in other publications. Both stars are listed as eruptive variable stars of γ Cas

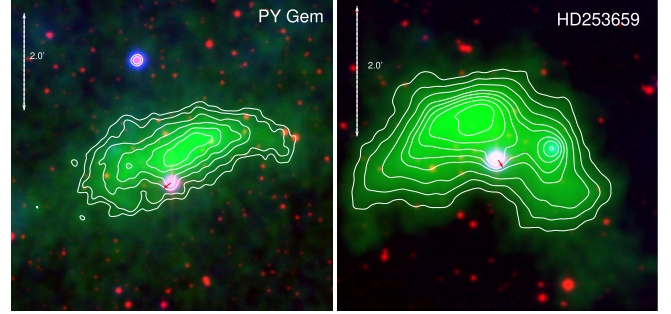


Figure 1. RGB images with optical DSS-2-red (red channel), *WISE* W4 22- μ m (green channel), and *WISE* W3 12- μ m (blue channel) bands showing structures of the discovered nebulae. Contour lines represent the isophotes of the intensity distribution in the *WISE* W4 22- μ m band. Red arrows indicate the direction and amplitude of the central star proper motions for 10 000 yr. The vertical arrow on the left defines the image scale and has a length of 2 arcminutes, which is 10 times larger than the *WISE* W4 band angular resolution (12 arcsec).

type (γ Cas variables) in the International Variable Star Index¹ (C. L. Watson, A. A. Henden & A. Price 2006). There are no X-ray sources associated with these stars, and therefore they are not included in the list of γ Cas analogues² by Y. Nazé & C. Motch (2018).

Table 1 lists spectral classification of the stars taken from the literature and their photometric magnitudes according to *Gaia* DR3 Synthetic Photometry catalogue (Gaia Collaboration 2023) i.e. they are the average values for the period of observations between July 2014 and May 2017. Also included are the distances (C. A. L. Bailer-Jones et al. 2021), proper motions (Gaia Collaboration 2021), and sizes of the nebulae. The values of the *Gaia* Renormalized Unit Weight Error (RUWE), which can be used as an indicator for unresolved binary systems (K. El-Badry 2024), is on the order of unity for both stars. However, with distances to both objects greater than 1 kpc, such an RUWE value does not exclude scenarios of either close or long-period binary systems (K. El-Badry 2024).

Fig. 1 shows pseudocolour images of the nebulae constructed from optical and infrared data. The nebula of PY Gem is extended, and the star is located at its edge, while the one around HD 253659 has an arc-like structure similar to a bow shock or a part of a

¹The General Catalogue of Variable Stars (GCVS; N. N. Samus’ et al. 2017) only lists PY Gem as a Be star, while HD 253659 is absent there.

²By definition in GCVS, γ Cas variables are stars that exhibit long-term photometric variability associated with the formation and dissipation of the disc. The similarly sounding but unrelated term ‘ γ Cas analogues’, which is outside the formal GCVS classification scheme, is becoming increasingly common to refer to a specific type of X-ray behaviour (see T. Rivinius & R. Klement 2026, and references therein).

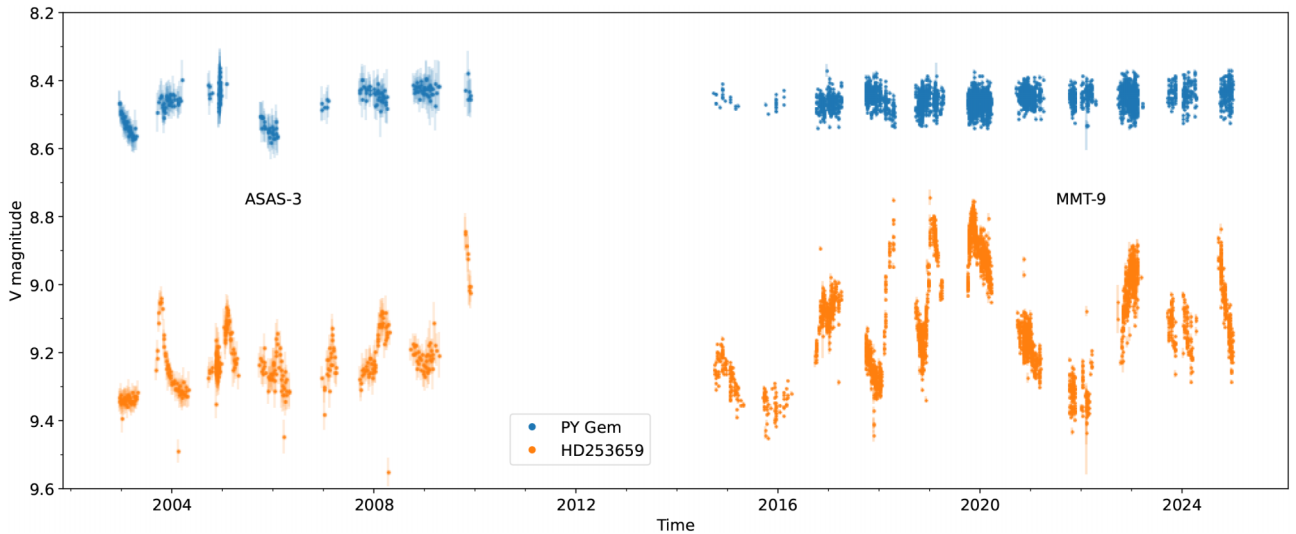


Figure 2. Light curves of PY Gem (blue dots) and HD 253659 (orange dots) from the ASAS-3 and Mini-MegaTORTORA sky survey archives. Formal photometric accuracy of individual measurements is represented with error bars, for most points it is comparable to the marker size.

circular nebula, probably indicating the heterogeneity of the ISM. Although the nebula near PY Gem is not perfectly centered on the star, no other possible sources are detected in the region. Moreover, the physical size of the nebula, estimated assuming the distance to PY Gem, supports its connection with the star.

With their classification as eruptive variables, HD 253659 and PY Gem are ideal objects to investigate their activity over a long temporal baseline to search for possible indications for a connection between disc formation processes and pulsational activity. Therefore, we have carried out a detailed photometric and spectroscopic study of these objects. The paper is organized as follows. In Section 2, we describe the long-term and short-term photometric variability of the objects using ground-based and space photometry. We present our spectroscopic observations in Section 3. In Section 4, we derive the stellar parameters, characterize the motion of HD 253659, in the colour–colour and colour–magnitude diagrams in terms of formation and dissipation of the disc, and analyse the detected frequencies. In Section 5, we discuss the outburst phases and disc-forming activity in relation to the observed nebulae, and we conclude our work in Section 6.

2 PHOTOMETRY

2.1 Optical counterpart

We conducted a search for possible optical counterparts of the discovered IR nebulae. The region around HD 253659 is covered by the publicly released data from the INT Photometric $H\alpha$ Survey (IPHAS; G. Barentsen et al. 2014). This survey is imaging the Northern Milky Way in visible light (r , i , and $H\alpha$ filters) using the Isaac Newton Telescope (INT) in La Palma, Spain. We downloaded and stacked the $H\alpha$ images around this star from the IPHAS data archive³, but did not detect any signs of extended emission on the scales comparable to the extent of infrared nebulae.

As PY Gem is not covered by IPHAS images, we performed a set of dedicated observations with the Small Binocular Telescope

(BART/SBT; J. Štrobl, M. Jelínek & R. Hudec 2019) at Ondřejov observatory of the Astronomical Institute of the Czech Academy of Sciences. BART/SBT is a robotic telescope system of two 0.2-m wide-field optical telescopes equipped with a set of Sloan and nebular filters. We acquired 200 180-s exposure frames (10 h in total) in $H\alpha$ over 4 nights in March 2025. We calibrated and stacked all the images, but also did not find any signs of extended $H\alpha$ emission around the star.

2.2 Long-term behaviour

In order to assess the long-term variability of the stars, we acquired their photometry from the data archive of Mini-MegaTORTORA (G. M. Beskin et al. 2017), which is a nine-channel wide-field optical monitoring system with high temporal resolution, operating since mid-2014 and located at the Special Astrophysical Observatory, Nizhny Arkhyz, Russia. It performs a systematic monitoring of the northern sky, covering every point of it on average several times per night in white light. The photometric measurements are then re-calibrated to Johnson V band by a dedicated pipeline that, apart from standard calibration steps, determines the effective photometric system of every frame, and then employs this information to derive the $(B - V)$ colours of every star (S. Karpov et al. 2018). The resulting measurements are published online on the dedicated portal⁴. The data for the stars have been extracted from the Mini-MegaTORTORA archive, and passed through quality cuts in order to filter out the points corresponding to bad weather intervals and images where photometric calibration was too noisy. This resulted in more than 3300 points with good quality V magnitudes for every star, spanning more than 10 yr since mid-2014 (Table A1). Additional photometric data covering the years 2003–2010 were also acquired from the archive of the northern observational station of the All Sky Automated Survey (ASAS-3; G. Pojmanski 1997).

Fig. 2 shows the light curves constructed from the Mini-MegaTORTORA and ASAS-3 data. HD 253659 shows long-term

³The IPHAS data archive is available online at <https://www.iphas.org>.

⁴<http://survey.favor2.info/>

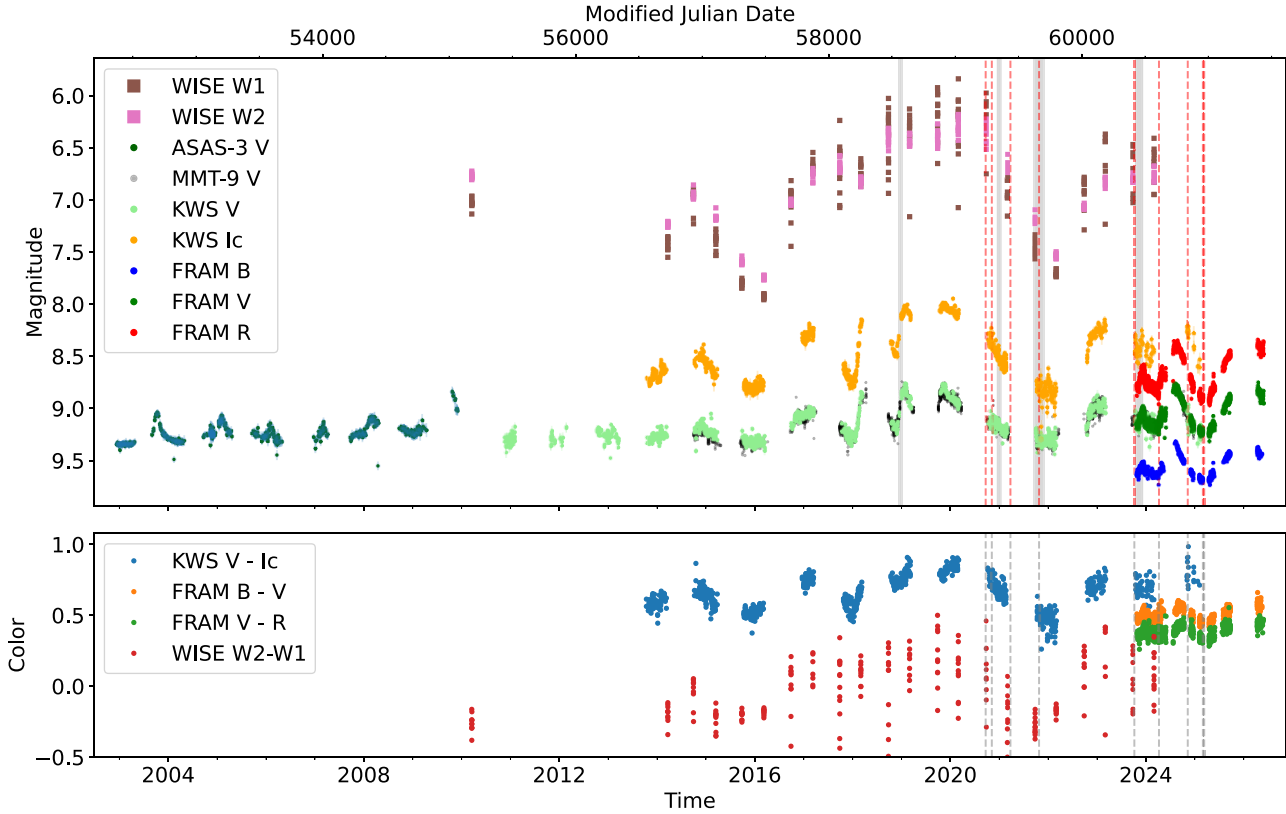


Figure 3. Upper panel: light curve of HD 253659 over the last 20 yr using the data from ASAS-3, KWS, and Mini-MegaTORTORA (MMT-9) sky surveys and our dedicated FRAM observations. Lower panel: variability of the colours of HD 253659. Vertical dashed lines mark the times of spectral observations, while grey bars indicate the intervals covered by *TESS*.

irregular variability with an amplitude of 0.4 mag. Such a photometric behaviour agrees with the classification of HD 253659 as a γ Cas variable. In contrast, the light curve of PY Gem, also classified as γ Cas variable, only shows noticeable variability about 20 yr ago between 2003 and 2008. In the last ~ 10 yr, PY Gem displays only low-amplitude (< 0.05 mag) variability.

With the aim of studying the colour behaviour of HD 253659, we initiated multicolour photometric observations at the end of October 2023 on FRAM-ORM, which is a 10-inch Meade f/6.3 Schmidt-Cassegrain telescope. The FRAM-ORM telescope is installed in the Roque de Los Muchachos Observatory, La Palma, and equipped by the Moravian Instruments G2-1600 CCD. Data were acquired in Johnson-Cousins *B*, *V*, and *R* filters with 30, 20, and 20 s exposures, respectively, to avoid saturation due to the brightness of the star, and then automatically processed by a dedicated PYTHON pipeline based on the STDPIPE package (S. Karpov 2021), which includes bias and dark current subtraction, flat-fielding, cosmic ray removal, astrometric calibration, aperture (with a 5-pixel radius) photometry, and photometric calibration using the catalogue of synthetic photometry based on *Gaia* DR3 low-resolution XP spectra (Gaia Collaboration 2023). The upper panel of Fig. A1 presents the light curves in the *B*, *V*, and *R* bands, while the lower panel shows the temporal variations of the colours *B* – *V* and *V* – *R*.

To complement these data, we used infrared photometry for HD 253659 from the AllWISE (R. M. Cutri et al. 2013) and NEOWISE Reactivation Mission (A. Mainzer et al. 2014) single ex-

posure catalogues based on *WISE* (E. L. Wright et al. 2010) observations in the W1 and W2 bands. We also found continuous observations of HD 253659 in the *V* and *Ic* bands in the Kamo-gata/Kiso/Kyoto Wide-field Survey (KWS; H. Maehara (2014)). Fig. 3 presents the combined light curve of HD 253659 since 2003, along with the evolution of several colours based on the data outlined above.

2.3 Short-term variability

PY Gem and HD 253659 have been monitored with *TESS* (G. R. Ricker et al. 2015) at various cadences (Table A2) and in different sectors simultaneous with the ground-based observations as shown in Figs 3 and 4 for HD 253659. We made use of the TESSCUT service (C. E. Brasseur et al. 2019) to extract cutout grids from the *TESS* full-frame images (FFIs). To optimize modelling of the background signal, we set the cutout size to 20×20 pixels. We then proceeded to extract the stellar flux and correct against the systematics, using the build-in methods from the dedicated Python package Lightcurve (Lightcurve Collaboration 2018). For measuring the target flux, we first defined an aperture of pixels with brightness exceeding 4σ that of the median value of the grid. Accordingly, a mask of pixels with brightness below the $10^{-4}\sigma$ level was used for measuring the background signal. The extracted background vectors were then subject of dimensionality reduction using three principal components, and the best-fitting noise models were subtracted from the flux of the two science objects. Fig. 4 shows a zoomed-in view of the light

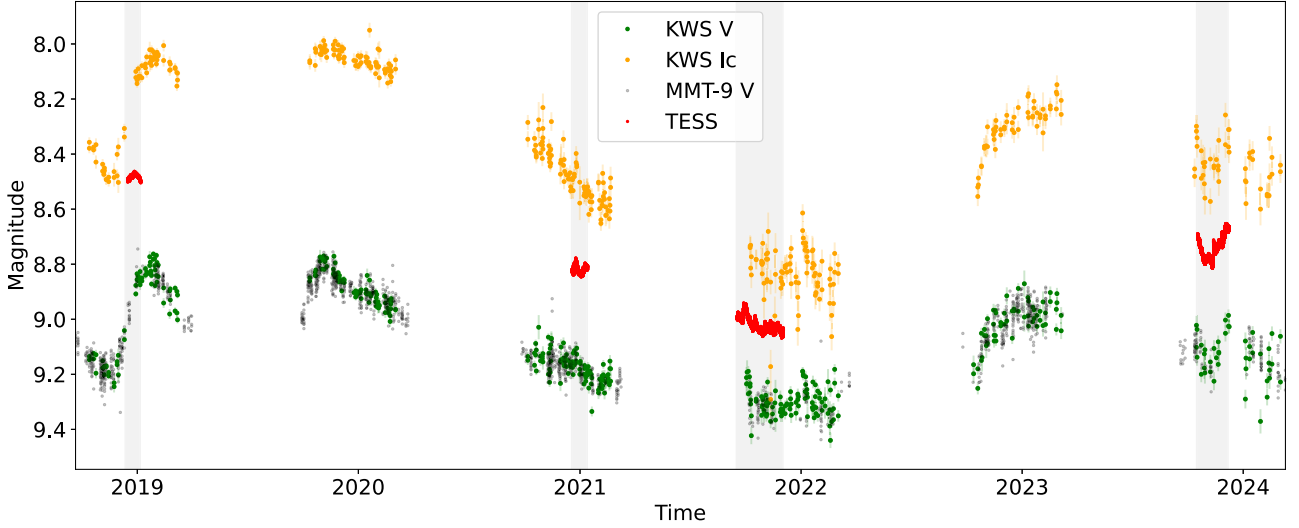


Figure 4. The light curves of HD 253659 in the V and Ic bands of KWS, and in the V band of Mini-MegaTORTORA (MMT-9), around the time intervals covered by *TESS* (grey vertical bars, like in Fig. 3). *TESS* light curves are presented in magnitudes directly derived from instrumental fluxes (see Section 2.3), and arbitrarily shifted vertically for better comparison.

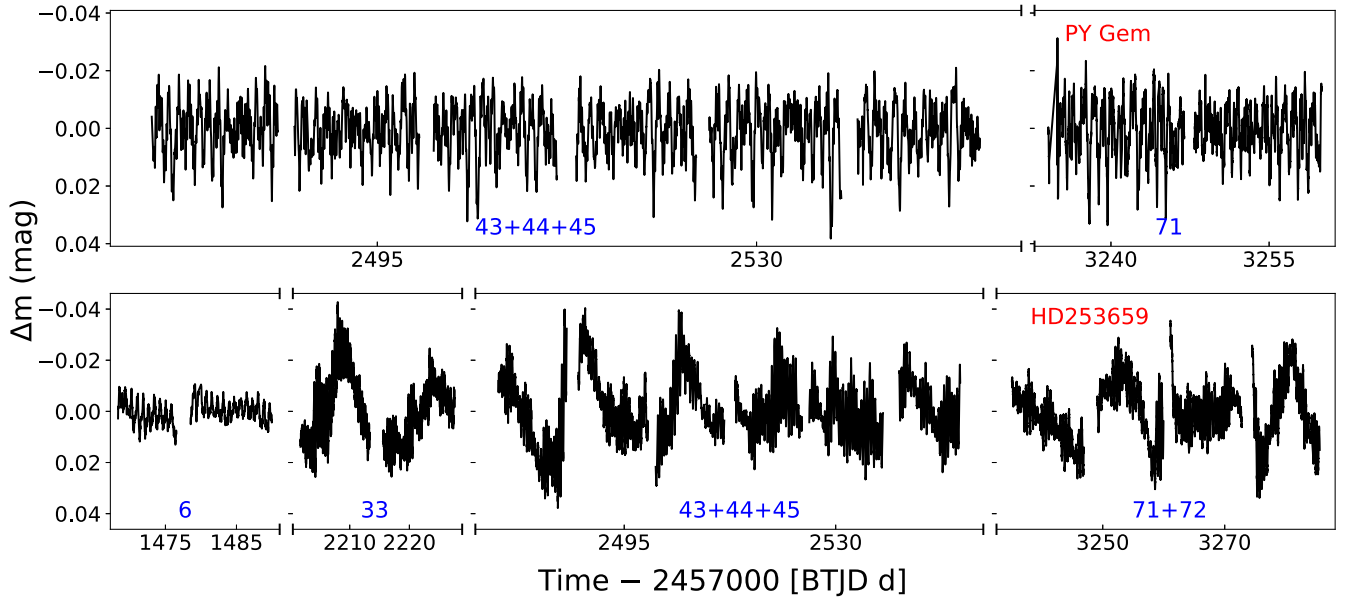


Figure 5. *TESS* light curves of PY Gem (upper panel) and HD 253659 (lower panel) in different sectors (blue labels).

curves in Fig. 3, including these *TESS* light curves, with fluxes converted to magnitudes with arbitrarily chosen zero point for easier visual comparison with other datasets. We can see that the *TESS* light curve follows a similar long term trend as the ground-based photometry. To facilitate the extraction of periodic signals, we correct for these long-term trends by additionally fitting and subtracting second-order polynomials from the fluxes in every sector of the data. The resulting light curves of our objects, in magnitudes relative to the fit baseline, are displayed in Fig. 5 and are used for further analysis.

The *TESS* data of PY Gem show high-frequency variability that is similar across all sectors. In contrast, HD 253659 displays rather erratic variations. The most remarkable is the abrupt change in the type of variability when comparing the *TESS* data from sector

6, where the light curve has a significantly lower amplitude⁵ and the behaviour resembles a bit that of PY Gem, with those of all other sectors, where the high-frequency variability appears to be superimposed on longer, more chaotic signals.

We used *TESS*-Localize (M. E. Higgins & K. J. Bell 2023) to verify the source of the detected variability. This software uses the observed frequencies as input parameters and calculates the best-fitting locations for the signal sources within the provided

⁵This finding is also confirmed by inspecting the instrumentally corrected products (so-called PDCSAP flux) produced by the Science Processing Operations Center (SPOC) pipeline, which are available at the Barbara A. Mikulski Archive for Space Telescopes.

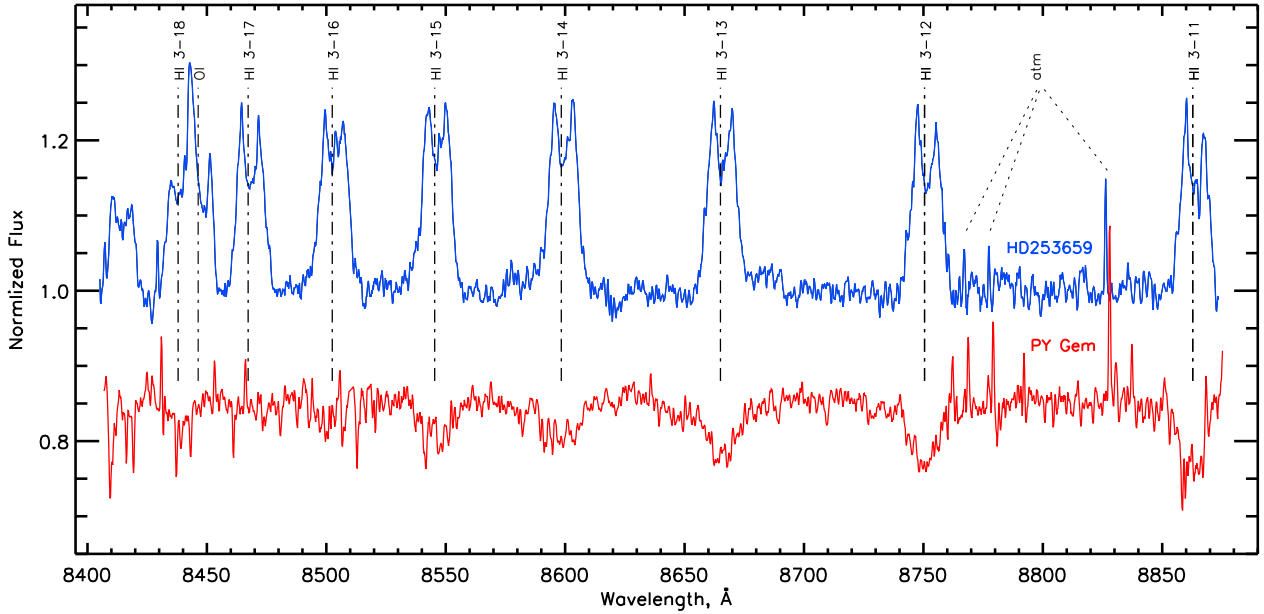


Figure 6. Near-IR spectra of PY Gem and HD 253659 obtained with the Perek 2-m telescope in October 2023 and April 2021, respectively.

Target Pixel File (TPF). Our analysis confirms that HD253659 is the most likely *Gaia* source with $G \leq 18$ mag that displays the observed variability within the 25×25 -pixel TPF, with a relative likelihood greater than 99 per cent.

3 SPECTRAL OBSERVATIONS

With the aim of investigating the $H\alpha$ line profile variability, we initiated spectral monitoring of the stars at the Perek 2-m telescope, operated by the Astronomical Institute of the Czech Academy of Sciences. Since 2020, we obtained 11 medium-resolution spectra ($R \simeq 13\,000$) covering the $H\alpha$ line for PY Gem and 8 spectra for HD 253659. Moreover, for both stars we acquired medium-resolution spectra in the near-IR range (8400–8880 Å) covering higher order lines of the Paschen series of hydrogen using the same coude spectrograph (Fig. 6) and one high-resolution spectrum ($R \simeq 50\,000$) covering the whole optical range for PY Gem using the Ondřejov Echelle Spectrograph (OES; P. Koubský et al. 2004; P. Kabáth et al. 2020). The spectra from both spectrographs were reduced using a dedicated IDL-based pipeline in the same way as it was done in O. V. Maryeva et al. (2022); O. Maryeva, P. Németh & S. Karpov (2023). After primary reduction, all spectra were normalized and corrected for barycentric velocity.

We complemented our data set with the spectra of HD 253659 and PY Gem retrieved from the BeSS data base (C. Neiner et al. 2011; C. Neiner 2018). The dates of all these spectral observations and the durations of exposures are summarized in Table B1.

Fig. 7 presents the variability of the $H\alpha$ and He I $\lambda 6678$ profiles in the spectra of PY Gem and HD 253659, while Tables B2 and B3 list the measured parameters of the $H\alpha$ lines (intensities of blue and red peaks, radial velocity). The distance between the red and blue peaks of the double peaked $H\alpha$ line shows that PY Gem has a significantly higher disc inclination to the line of sight compared to HD 253659, assuming the rough dependence of $v \sin i$ on the inter-peak distance from R. W. Hanuschik (1989) and that the

stars have similar values of v due to belonging to contiguous spectral types and comparable widths of their $H\alpha$ line wings ($\approx 800 \text{ km s}^{-1}$).

The positions of the red and blue peaks in the spectra of both stars vary from one observation to another (Tables B2 and B3). However, in the collected spectral data we do not detect any systematic radial-velocity variations that could be interpreted as evidence of binarity.

The central panel of Fig. 7 shows that, in the case of PY Gem, the He I $\lambda 6678$ profile is a superposition of photospheric absorption and double-peaked emission originating from the disc. Only in the spectrum obtained in January 2025 the disc contribution disappeared, and we observe pure photospheric absorption in He I $\lambda 6678$. We used this profile to measure the projected rotational velocity of PY Gem. For this, we applied the IACOB-BROAD IDL procedure developed by S. Simón-Díaz (S. Simón-Díaz & A. Herrero 2014), which simultaneously estimates both $v \sin i$ and the macroturbulent velocity v_m . The IACOB-BROAD routine is based on a combined Fourier Transform (FT) and goodness-of-fit (GOF) approach, where an intrinsic line profile is convolved with various broadening functions and compared to the observed profile using a χ^2 minimization method (S. Simón-Díaz & A. Herrero 2014). From this analysis, we derived a projected rotational velocity of $v \sin i = 303 \pm 15 \text{ km s}^{-1}$ and a macroturbulent velocity of $v_m = 154 \pm 15 \text{ km s}^{-1}$. The value of $v \sin i$ that we obtained is in good agreement with rotational velocities typical for Be stars (J. Zorec et al. 2016). We note, however, that the value for the macroturbulent velocity must be taken with caution and should be considered as an upper limit. Because the rotation is dominating the broadening of the profile, a possible contribution in form of a Gaussian profile (as is assumed for the macroturbulent velocity) will not be noticeable in the profile until it reaches a significant value.

In the spectrum of HD 253659 all hydrogen lines in the optical and near-IR ranges are in emission and have double-peaked profiles. The oxygen O I $\lambda 8446.3$ line is clearly visible in the spectrum – it also has a double-peaked profile and overlaps with the

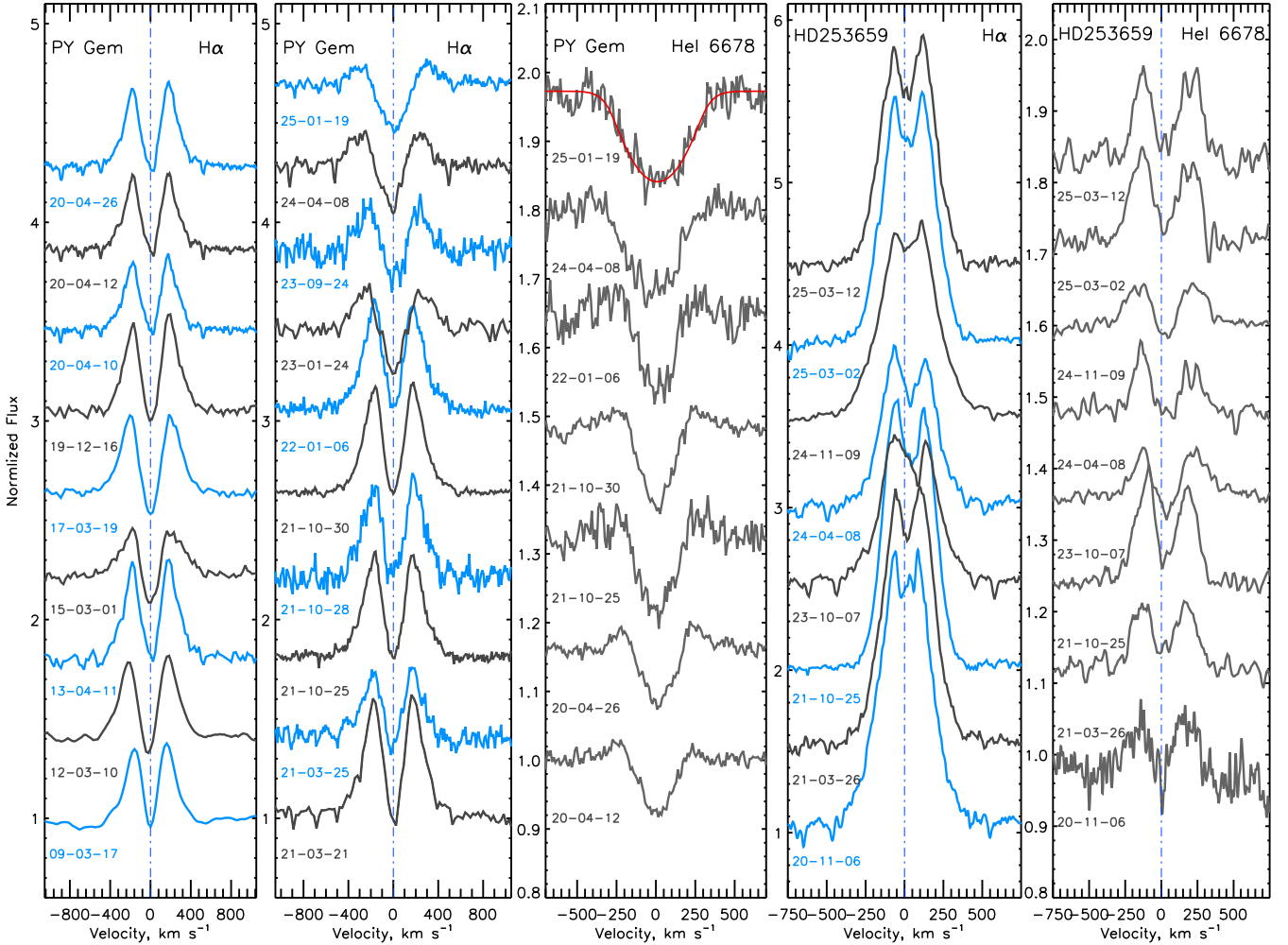


Figure 7. Variability of line profiles in the spectra of PY Gem (panels 1-3 from the left) and HD 253659 (panels 4-5). The red line in the third panel shows the result of the line-broadening analysis with the IACOB-BROAD routine. Dates of observations are given in the format (year-2000)-month-day.

hydrogen H I 3-18 line. In addition to the hydrogen and helium lines in the optical range, we also found a broad double-peaked line of Na I $\lambda 5688.2$. In the spectrum of HD 253659 there are no pure photospheric absorption lines, which can be used to estimate its projected rotational velocity.

It is important to note that we did not detect any signatures of nebular lines in the spectra of either of the two stars. This is consistent with the results presented in Section 2.1, where no evidence of extended H α emission was found.

4 RESULTS

4.1 Stellar parameters

In the spectra of both stars, we detect significant contribution from the circumstellar disc to the observed line profiles, which prevents a reliable determination of the stellar parameters through spectral line fitting. Therefore, we derived the stellar parameters using spectral energy distribution (SED) fitting. This approach is widely applied to Be and evolved massive stars (C. Arcos et al. 2018; M. Kouniotis et al. 2018).

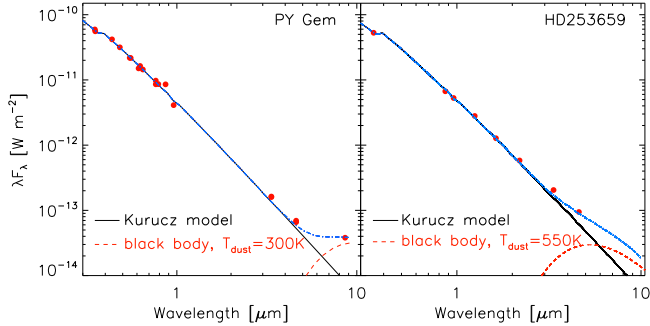
To construct the SEDs, we assembled multicolour photometric measurements spanning from the *U* band to the infrared us-

ing data from various photometric catalogues⁶ available through VizieR (F. Ochsenbein, P. Bauer & J. Marout 2000). We note that these measurements were obtained at different epochs and that both targets are photometrically variable. However, no simultaneous multi-wavelength observations are available. Therefore, for both stars, we compiled photometric measurements obtained at different epochs but corresponding to the same quiescent state. To represent the quiescent state of HD 253659, we used the *U*- and *B*-band measurements from 1973, 2MASS photometry obtained shortly before 2000, Pan-STARRS photometry (except the *g* band) obtained between 2010 and 2014, and the average *WISE* W1 and W2 fluxes from March 2016, corresponding to the global minimum of the *WISE* light curve. To represent the quiescent state of PY Gem, we excluded the 2MASS data from the analysis because, according to the ASAS-3 light curve, the star underwent a decrease in brightness in the early 2000s.

⁶The photometric measurements are taken from: *WISE* (R. M. Cutri et al. 2021); Two Micron All Sky Survey (2MASS) (R. M. Cutri et al. 2003); *Gaia* DR3 (Gaia Collaboration 2023); the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) DR1 (K. C. Chambers et al. 2016), J.-C. Mermilliod (1987).

Table 2. Derived sets of stellar parameters.

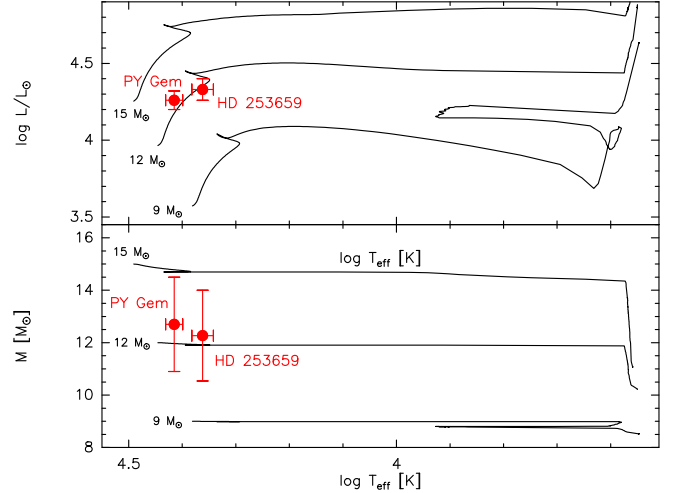
Star	T_{eff} (K)	$\log T_{\text{eff}}$ (K)	$\log g$ (cgs)	R ($R_{\odot}$)	$\log L/L_{\odot}$	M ($M_{\odot}$)	A_V (mag)
PY Gem	26300 ± 1200	4.42 ± 0.02	3.9 ± 0.1	6.62 ± 0.24	4.26 ± 0.06	12.7 ± 1.8	1.05 ± 0.02
HD 253659	23000 ± 1000	4.36 ± 0.02	3.6 ± 0.1	9.19 ± 0.32	4.33 ± 0.07	12.3 ± 1.7	1.92 ± 0.02

**Figure 8.** Stellar continuum fits (solid lines) to the observed, dereddened photometric data (red points) of PY Gem (left) and HD 253659 (right). The best-fitting parameters are listed in Table 2. Warm dust (red dashed line) contributes to the SEDs of both stars.

The photometric uncertainties adopted in the SED fitting were chosen to account not only for the quoted catalogue errors but also for the expected scatter introduced by the intrinsic variability of the stars. Under these assumptions, the assembled photometry provides a reasonable representation of the average SED of each target. We used the models from the grid of stellar continuum spectra provided by R. L. Kurucz (1992) and interstellar reddening with the extinction curve of J. A. Cardelli, G. C. Clayton & J. S. Mathis (1989) with a value of $R_V = 3.1$ to represent these SEDs. The distances used are listed in Table 1.

We followed the recipe of J. Maíz-Apellániz (2004) for obtaining the best-fitting models and the reddening. The sets of stellar parameters and the interstellar extinction values obtained from the fit are given in Table 2. The dereddened data along with the best-fitting models are shown in Fig. 8. The SED of PY Gem shows that dust emission becomes dominant at wavelengths closer to $10 \mu\text{m}$, corresponding to temperature of $T_d \sim 300 \text{ K}$. For HD 253659 the infrared excess emission is visible at wavelengths greater than $3 \mu\text{m}$ and can be represented with a Planck function with a temperature of $T_d \sim 550 \text{ K}$. We propose this excess emission to be due to warm dust, because in quiescence the star should not have a disc emitting free-free emission, but we cannot exclude that the mid-infrared emission might emerge from a disc remnant. Unfortunately, no *WISE* 3 and 4 band observations exist during quiescence, which could help discriminating between the two scenarios.

In the top panel of Fig. 9, we show the location of the objects in the Hertzsprung–Russell (HR) diagram together with stellar evolutionary tracks from S. Ekström et al. (2012) for rotating stars with initial masses in the range $9\text{--}15 M_{\odot}$ at solar metallicity. Although the derived $\log g$ is very sensitive, on the one hand, to the grid step of the models and, on the other hand, to the height of the Balmer jump and thus to the U -band flux, we find reasonably good agreement between the mass estimated from the SED and the one from evolutionary tracks (bottom panel of Fig. 9).

**Figure 9.** Positions of the stars in the HR diagram (top). A comparison of the obtained masses of the objects (dots) with evolutionary predictions (solid lines) is shown in the bottom panel. Evolutionary tracks are from S. Ekström et al. (2012) for rotating stars at solar metallicity.

4.2 Major outburst of HD 253659 and its disc evolution

Be stars may demonstrate major outbursts associated with the complicated process of circumstellar disc formation. Major outbursts are observed as brightenings in broad-band photometry (usually up to $0.5\text{--}0.6 \text{ mag}$) and may have different durations (K. Bernhard et al. 2018): from a few tens of days (for example BD+61 39; J. Labadie-Bartz et al. 2018) up to a few years [for example 2dFS0231; M. Kouniotis et al. 2014], $\omega \text{ Cma}$ (M. R. Ghereysy et al. 2018), KIC 9715425 (Q. Gao et al. 2025), EPIC 202060631 (Q. Gao & H. Yuan 2025)]. Numerical simulations have shown that Be stars should turn redder at the beginning of the major outburst phase due to the formation of a viscous decretion disc (see e.g. X. Haubois et al. 2012).

The light curve of HD 253659 (Fig. 3) clearly shows that the star experienced a series of minor outbursts between 2003 and 2010 with brightening in V band of $0.2\text{--}0.3 \text{ mag}$ during each event. These minor outbursts, when compared to theoretical predictions of X. Haubois et al. (2012), could be interpreted with (quasi-)periodic mass ejections with a (quasi-)period of $\sim 1.16 \text{ yr}$ and duty cycles (defined as the fraction of time spent actively ejecting mass) in the range $\sim 10 \text{ percent--}20 \text{ percent}$. The clear brightening in the V magnitude during these events speaks in favour of a more pole-on orientation ($i \lesssim 30^\circ$) of the disc.

The broad bump with a total brightness increase of $> 0.4 \text{ mag}$ observed between 2016 and 2022 may be interpreted as a major outburst. After 2016, we see two maxima in the light curve and a plateau from 2019 till 2021. The jagged plateau resembles those of $\omega \text{ Cma}$ during its major outbursts in 1982–1987 or 2009–2011 (M. R. Ghereysy et al. 2018). But in contrast to the cyclic outbursts of $\omega \text{ Cma}$ that show an instantaneous rise in magnitude (occasionally followed by a short series of brightness increase and dimming

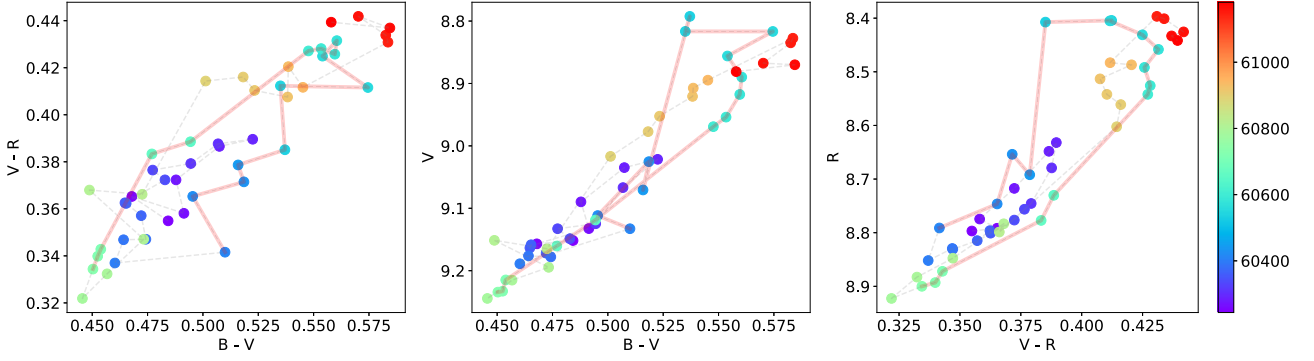


Figure 10. Colour–colour (left) and colour–magnitude (middle and right) diagrams of HD 253659 based on FRAM multiband photometry during the observing period 2022–2026. The colour bar shows Julian date of observations. The line in light red marks the outburst detected between April 2024 and April 2025.

episodes indicating alternating build up and dissipation phases) followed by a plateau phase of nearly constant brightness and a steep drop in magnitude that marks the onset of the subsequent quiescent (i.e. disc dissipation) phase, the event monitored in HD 253659 is less steep at both the beginning and the end of the event and shows deeper minima during the plateau phase, reaching even the pre-outburst level. This could indicate that the new disc that is formed has a lower viscosity than those reported for ω CMa, reaching even the pre-outburst level, indicating that the entire disc-formation process is non-continuous with intermediate phases of dissipation. In addition, the stage of quiescence following the outburst event is significantly shorter (less than two years) before the next minor outburst sets in (during 2023) compared to what was reported for ω CMa.

According to multiband photometry, HD 253659 becomes redder during the major outburst, which is consistent with theoretical expectations and was also seen during the cyclic outbursts of ω CMa (M. R. Ghoreysy et al. 2018). The major outburst is observed at all wavelengths and is more pronounced in the IR range, in agreement with the fact that longer wavelengths trace larger radii (and hence also a larger emitting area) within the disc, especially if it is seen close to pole-on (X. Haubois et al. 2012). The brightening in the *WISE* W1, W2 bands is about 1.5 mag. We do not see any delay of the IR maximum of brightness in comparison with the one in the optical range. However, the decline begins in the *V* band, while the infrared bands respond with a slight delay (see Fig. 4 around 2020). This delay produces an inversion in the relationship between *V* and $V - I_C$. It can be explained by the clearing of the innermost ($r \lesssim 2 R_*$) and densest disc region, in which the excess in *V*-band flux is generated.

To correlate the observed photometric variability with disc formation and dissipation activities, we follow the temporal evolution of HD 253659 in colour–colour and colour–magnitude diagrams. Fig. 10 shows the evolution at optical wavelengths based on the FRAM multi-band photometry collected between 2022 and 2026, which is the subsequent phase after the major outburst. During this period, HD 253659 moved across these diagrams with an increasing amplitude of variability, tracing three loop-like patterns and eventually returning to the upper-right region of the diagrams. The overall behaviour of HD 253659 is qualitatively consistent with the predictions of X. Haubois et al. (2012) for the build-up and subsequent dissipation of a circumstellar vis-

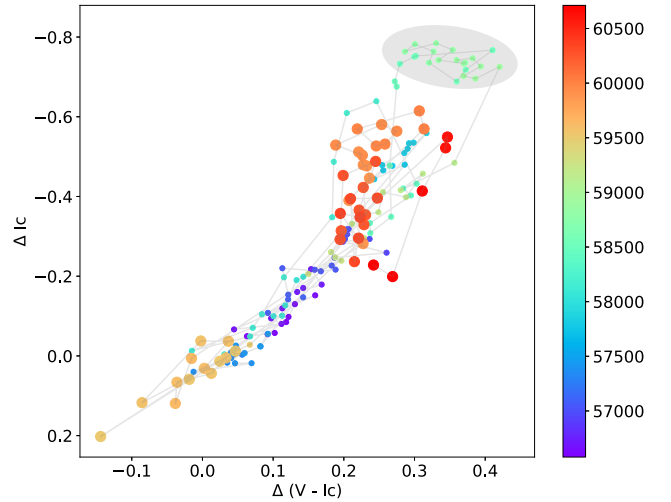


Figure 11. Colour–magnitude diagram of HD 253659 based on all KWS data (2014–2025). The small-sized symbols correspond to observations taken before October 2021. The zero points of magnitude and colour are the mean values over the light curve minimum around Jan 2022, which we consider to be most similar to the quiescent phase over the interval covered by KWS observations.

cous decretion disc. In this framework, the upward motion in the colour–magnitude diagram corresponds to disc growth, while the downward motion reflects disc dissipation. The observed hysteresis indicates that the disc properties are different in the formation and dissipation phases. A similar colour–magnitude behaviour was shown by δ Sco (C. E. Jones et al. 2013), which is explained by variation of the density of the inner and outer part of the disc, with density decreasing rapidly with increasing radius (M. W. Suffak et al. 2020). Interestingly, the object appears dimmer for some time beyond the end of the outburst (April 2025). This could indicate that mass accretion back onto the stellar surface does not occur exclusively within the disc plane but rather via some funnel flows, leading to temporary circumstellar extinction.

We also inspected the colour–magnitude behaviour including the I_C band. Fig. 11 presents the colour–magnitude diagram constructed from the full KWS photometric dataset spanning approximately 12 yr and including the whole major outburst. Comparison with theoretical predictions by A. L. Figueiredo et al. (2025)

confirms the repeated episodes of disc build-up and dissipation in a system viewed nearly pole-on. The narrowness of the loop suggests a relatively low base density at the inner edge of the disc. The points located in the upper-right corner (marked by the grey ellipse) correspond to the middle of the major outburst (≈ 2020), during which an inversion of the colour–magnitude relation was observed: the ($V-I_C$) colour increased while the object simultaneously dimmed in V . As mentioned previously, this can be explained by the clearing of the innermost disc region. The last group of dots forms broad loops, which corresponds to the phase after major outburst. Broadening of the loops is evidence of increasing of base density (A. L. Figueiredo et al. 2025) and its significant fluctuations over short time-scales, in agreement with the variations seen at optical wavelengths (Fig. 10).

Our regular spectroscopic monitoring of HD 253659 began in 2020, when the star was already recovering from the major outburst event (i.e. after the plateau phase). There is no clear correlation between the equivalent width (EW) measurements of the $H\alpha$ lines (last column of Table B3) and the brightness of the star. For similar stellar magnitudes, the EWs display a variety of values depending on whether they were measured during the recovery from the major outburst or during the post-outburst phase of less pronounced activity. This may indicate a delay in the $H\alpha$ response, similar to what was observed in the Be system EPIC 202060631 (Q. Gao & H. Yuan 2025). The intensities of the red and blue peaks of $H\alpha$ are similar ($I_b/I_r \sim 1$), indicating that the disc formation was already completed, and the shape of the $H\alpha$ line confirms a close to pole-on view of the disc. We detect clear variations in the absolute values of the intensities, suggesting a highly dynamical evolution of the disc, which is also supported by the variations seen in the velocities of the emission peaks. However, the lack of detailed spectral monitoring prevents us from drawing a more solid conclusion.

Multiband photometric observations covering major outbursts in Be stars are exceptionally rare but provide meaningful insight into the structure and evolution of the associated viscous decretion discs. As was shown in Figs 10 and 11, the colour–magnitude and colour–colour diagrams of HD 253659 trace disc formation and dissipation episodes, provide information on the disc density and viscosity, as well as on the inclination angle (X. Haubois et al. 2012; A. L. Figueiredo et al. 2025). Therefore, our data represent a valuable resource for detailed future modelling of the disc and for investigating its physical properties.

4.3 Quiescence of PY Gem

In the long-term photometric light curve of PY Gem, we detect a contradictory pattern (Fig. 2). The star’s well-defined photometric variability is only recorded until approximately 2008. Thereafter, the star seems to be in a continuous phase of quiescence with only low-amplitude variability. This is confirmed by the high-cadence *TESS* observations, which fall all into this quiet phase of the star.

On the other hand, our spectroscopic data covering this quiet phase of PY Gem (from 2009 on) show clear variability in the $H\alpha$ intensity (i.e. equivalent width, see Fig. 7) and the velocities of the blue and red peaks (Table B2), implying a highly dynamical line-forming region, while the ratio of the emission peaks does not change significantly. An increase in the equivalent width indicates that more matter is located in the vicinity of the star. The subsequent decrease in equivalent width (sometimes within a couple of days, as seen in March 2021) implies that the region close to the stellar surface is being evacuated and the matter is

either dissipated or re-accreted to the stellar surface. This (maybe periodic or at least cyclic) behaviour of matter supply and dissipation occurs without any significant change in the stellar brightness. According to the theoretical predictions by X. Haubois et al. (2012), this could indicate a high inclination of the disc of $\sim 70^\circ$.

The last spectrum from 2025 shows a significantly weaker double-peaked emission profile of the $H\alpha$ line, whereas the emission in He I $\lambda 6678$ disappeared completely (see Fig. 7) revealing a pure, rotationally broadened photospheric profile. This could suggest that the matter supply from the star has stopped and the decretion disc might dissipate completely (although it might also be just an observational bias due to the sparse spectroscopic sampling).

4.4 Frequency analyses of the *TESS* light curves

The physical mechanism responsible for the Be phenomenon remains not completely understood. Since stellar pulsations are thought to play an important role in triggering mass ejection and disc formation, the analysis of *TESS* photometry offers a valuable opportunity to probe the internal structure of Be stars and better understand the nature of this phenomenon.

The frequency spectra of high-cadence light curves of Be stars can display four different features. These are (i) long-term trends with time-scales > 2 d which are usually associated with flickers or episodes of mass ejections, (ii) low-frequency stochastic variations, (iii) isolated frequencies, and (iv) frequency groups consisting of several closely spaced frequencies (for more details, see e.g. J. Labadie-Bartz et al. 2022). The occurrence of frequency groups can be linked to the rapid rotation of the star (see e.g. H. Saio et al. 2018), and frequency groups are seen in about 75 per cent of all Be stars (including γ Cas; J. Labadie-Bartz et al. 2021). Those groups with low frequencies (< 4 d $^{-1}$) are typically found to be g-mode pulsations, whereas higher frequency signals are consistent with p-modes (A.-L. Huat et al. 2009; T. Rivinius et al. 2013; D. Baade et al. 2016).

To investigate the frequency spectra of our objects, we combined the *TESS* light curves taken in consecutive sectors (i.e. sectors 43, 44, and 45 for both stars and sectors 71 and 72 for HD 253659). The frequency analysis was performed using an iterative pre-whitening procedure implemented in PYRIOD (K. J. Bell 2020; K. Bell 2022). A total of 43 and 48 frequencies were initially extracted for PY Gem and HD 253659, respectively. To avoid including unresolved peaks, frequencies separated by less than $1/T$, where T is the time span of the observations, were considered indistinguishable, and only the component with the highest amplitude was retained. The multi-sinusoidal fit was then repeated using this reduced set of frequencies. Statistical significance was assessed using a threshold of four times the local noise level in the residual periodogram. The local noise was estimated as the mean residual amplitude within a sliding window of width 2 d $^{-1}$, evaluated in steps of 2 d $^{-1}$. Only frequencies with $S/N > 4$ were retained for further analysis. The same $1/T$ criterion was also adopted when identifying harmonic and combination frequencies. The identified frequencies are listed in Tables C1 and C2 for PY Gem and HD 253659, respectively.

The temporal evolution of the frequency spectrum was investigated using the weighted wavelet Z-transform (WWZ; G. Foster 1996) and the PYTHON package LIBWWZ⁷. This method

⁷<https://github.com/ISLA-UH/libwwz>

combines time and frequency information, enabling the detection of transient oscillations and temporal changes in both frequency and amplitude. The resulting WWZ scalograms provide a two-dimensional representation of the variability, making them particularly useful for studying the non-stationary behaviour commonly observed in Be stars.

4.4.1 PY Gem

Starting with PY Gem, we distinguish four main groups of frequencies in the combined sectors 43-45. We label these groups as g_1 to g_4 in Table C1, following the notation of J. Labadie-Bartz et al. (2021). As observed in many Be stars, g_2 is located at approximately twice the frequency of g_1 (e.g. J. Labadie-Bartz et al. 2022). Moreover, g_3 and g_4 have about twice and three times the frequency of g_2 , which is also similar to what was found for γ Cas (J. Labadie-Bartz et al. 2021). The first three groups span the typical range of g-mode pulsations whereas g_4 , which is centered at $\sim 7 \text{ d}^{-1}$, fits better to the range of p-modes. A frequency similar to the dominant one of g_4 was also reported by J. Labadie-Bartz et al. (2017) who identified it in the light curve of PY Gem from the KELT photometric survey.

The remaining frequencies appear as individual frequencies and are marked with $f_0 - f_9$ in Table C1. Taking a closer look at these, we identify five combination frequencies ($f_3 = g_{43} - g_{18}$, $f_5 = 2f_1 - 2g_{19}$, $f_6 = 3g_{13} + g_{42}$, $f_8 = 2f_4 - g_{32}$ and $f_9 = 3f_7 - 3g_{34}$), leaving us with four individual frequencies (f_1 , f_2 , f_4 , and f_7) that might be identified as additional p-mode pulsations. Such high-frequency signals are less common in Be stars and are typically found in β Cephei pulsators. PY Gem might hence be classified as belonging to the class of Be stars that are β Cephei hybrid pulsators (similar to the Be star HD 49330, see A.-L. Huat et al. 2009). Only about 10 per cent-20 per cent of the sample (independent of whether these are early, mid, or late-type Be stars) studied by J. Labadie-Bartz et al. (2022) shows such isolated high frequencies, suggesting that hybrid pulsators are less common among Be stars and γ Cas analogs.

Sector 71 displays the same frequency groups. It also displays the frequency f_0 that we have not discussed yet. However, we find for f_0 a frequency of 0.4074 d^{-1} , which is slightly higher than the value of 0.3924 d^{-1} found in the combined sectors. Additionally, the frequency g_{43} has reduced its amplitude below the detection threshold in sector 71. This shift in frequency and amplitude changes have prompted us to examine the individual sectors more closely to check whether these observations might be real or an artifact, because of the single-sector observation with different cadence.

Fig. 12 shows the Fast Fourier Transform (FFT) centred at f_0 and g_{43} for each individual sector. We find that f_0 has slightly different values in each of them. In addition, its amplitude changes from sector to sector. The frequency f_0 might be a representative of g_0 , which is an additional frequency group in the domain $< 0.5 \text{ d}^{-1}$ often seen in Be stars. However, in that case, its frequency should remain constant. Instead, the incoherent frequency f_0 could be interpreted as the so-called Štefl frequency. In their studies of spectroscopic time series, S. Štefl et al. (1998) found that during phases of temporarily enhanced $H\alpha$ emission (outbursts), spectral lines that are formed in layers above the photosphere display variability with a frequency not related to stellar pulsations and with projected rotation velocities in agreement with a location above the photosphere. Later, D. Baade et al. (2016) have

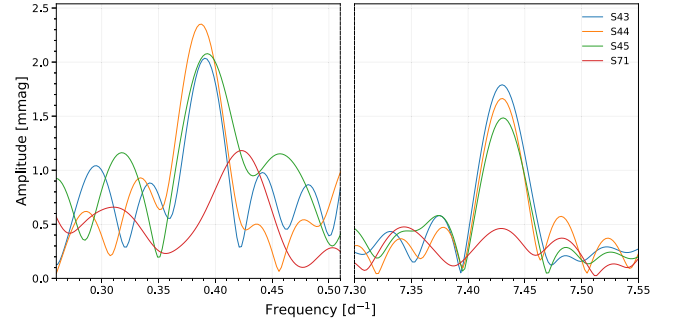


Figure 12. Comparison of the FFTs of the individual sectors of PY Gem centred at $f_0 = 0.3923 \text{ d}^{-1}$ (left) and $g_{43} = 7.4297 \text{ d}^{-1}$ (right).

proven that the same frequency can also be detected in the light curve of the star. Furthermore, these authors have shown that the Štefl frequency changes both its frequency and amplitude over time, in agreement with our findings for f_0 . They also proposed that for the detection of the Štefl frequency in photometry, the system must be seen under a high inclination angle, which was confirmed by numerical studies (A. C. Rubio et al. 2026). The presence of the Štefl frequency in PY Gem agrees with the high inclination suggested earlier.

As mentioned in Section 4.3, PY Gem is in a sort of quiescence state since 2008 with no indication of outbursts. Still, it is very actively pulsating with at least four frequency groups detected. Moreover, its cyclic (or periodic) changes in its emission spectrum speak in favor of a highly dynamical line-forming region of $H\alpha$ in the sense that matter is supplied cyclically and then dissolves, leading to an increase and a subsequent decrease in the equivalent width of the line. This region, which marks the interface between the star and its disc, is also the region in which the Štefl frequency is excited, for which D. Baade et al. (2016) speculate that the mass-loss process could be responsible.

For frequency g_{43} , interpreted as a p-mode, we also noticed unstable behaviour. This frequency displays similar values in sectors 43, 44, and 45, with a gradual decrease in amplitude (see Fig. 12). However, in Sector 71, it is no longer detected. The spectra obtained during sector 44 (October 2021), display a prominent double-peak $H\alpha$ emission, with normalized peak intensities of approximately 1.43 to 1.53. These values are among the highest measured during the monitoring and are clearly larger than the 1.21 peak intensity observed shortly before sector 71, in September 2023. This suggests that the pulsation amplitude of this mode may be modulated by changes in the outer layers of the star associated with disc feeding, while the Štefl frequency may independently trace the variability at the star-disc interface.

Our frequency analysis also revealed numerous linear combinations of independent frequencies. Among them, three stand out: $g_{17} = g_{42} - f_1$, $g_{24} = f_7 - g_{43}$ and $g_{10} = g_{23} - g_{15}$. For these cases, the amplitude of the ‘child’ frequency exceeds the sum of the amplitudes of its ‘parents’ modes. This amplification may indicate nonlinear coupling between pulsation modes rather than a simple linear beating. In Be stars, this interaction is particularly relevant to mass-loss, through which coupled modes may concentrate pulsation energy and angular momentum at the stellar surface, periodically facilitating the ejection of material into the circumstellar disc. A similar case was reported for η Cen, where a difference frequency associated with two non-radial pulsation modes reached approximately three

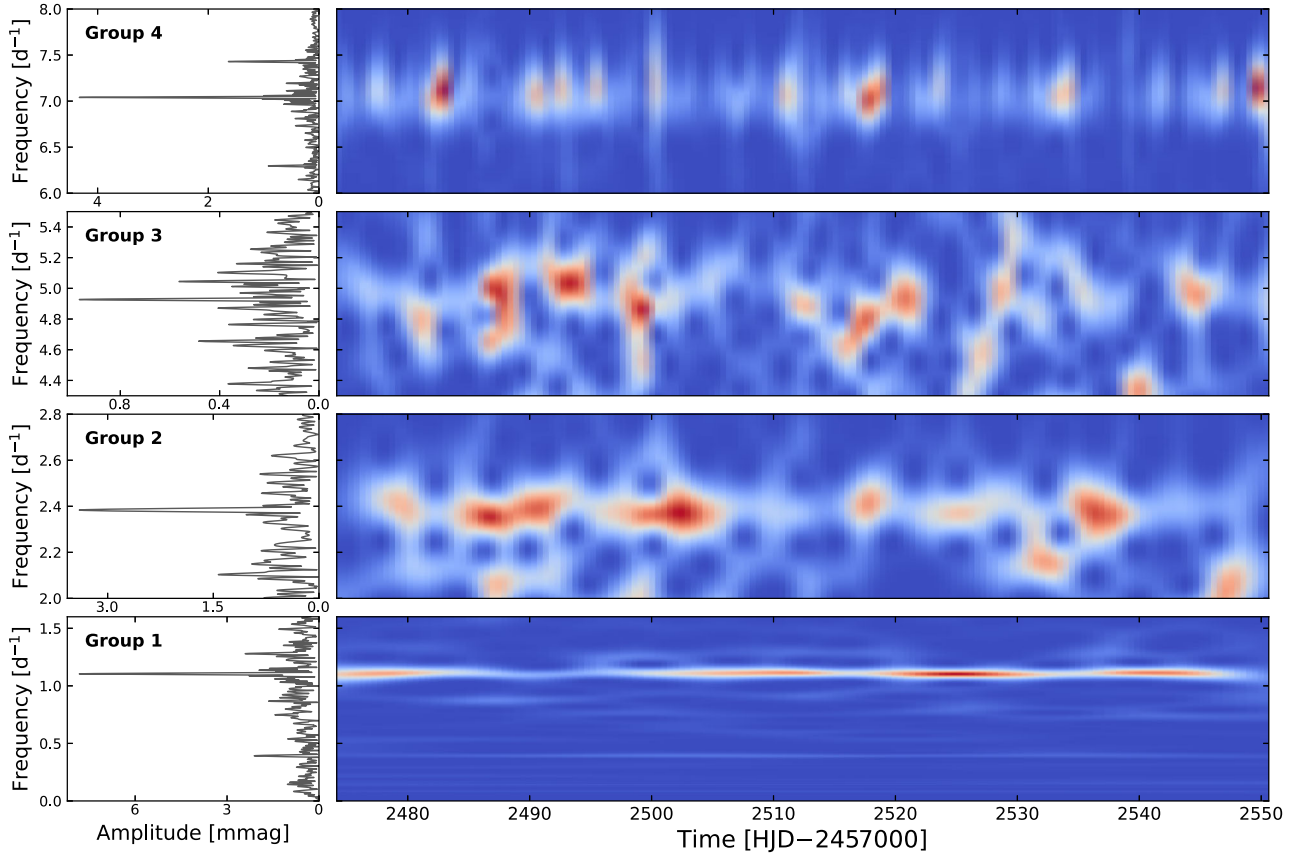


Figure 13. Amplitude spectra (left panels) and corresponding scalograms (right panels) for the four identified frequency groups (groups 1–4, from bottom to top) for the combined sectors 43 – 45 of PY Gem, normalized to the maximum power within each group.

times the sum of the parent-mode amplitudes and was linked to enhanced mass-loss (D. Baade et al. 2016). These three amplified combinations found could then trace pulsation-driven mass loss processes, although accidental numerical matches cannot be excluded.

Fig. 13 displays the amplitude spectra and scalograms for the four identified frequency groups in PY Gem, showing two distinct types of variability. The lowest-frequency group displays a more or less stable behaviour over the observing period, whereas the higher-frequency groups exhibit pronounced temporal changes with patchy patterns possibly due to beating phenomena of neighbouring frequencies within the densely populated groups (J. Labadie-Bartz et al. 2022).

4.4.2 HD 253659

In the combined sectors 43–45, HD 253659 displays two main groups of frequencies in the low-frequency range (see Fig. 14). The group with frequencies lower than 0.65 d^{-1} , we identify as g_0 , and the second group in the range $1.9\text{--}2.8 \text{ d}^{-1}$ as g_1 . We also found several combination frequencies within each group. Among the isolated frequencies, only f_2 is independent, suggesting that this frequency is a p -mode. Additionally, an amplified difference frequency ($g_{06} = g_{112} - g_{17}$) was also found in HD 253659, indicating a possible non-linear mode coupling and suggesting that the same pulsation-driven mass-loss mechanism may be operating in this object.

Fig. 15 shows a comparison of the FFTs for individual and combined sectors, showing that the same frequency pattern is found in sector 33 and in the combined sectors 71 + 72 with slight modulation of the relative amplitudes of the individual frequencies. However, inspecting sector 6, the situation is different. Sector 6 lacks the signal at 1.96 d^{-1} (identified as g_{11} in the later sectors), while the remaining pattern of group g_1 appears to be slightly shifted to higher frequencies. In addition, it shows the strongest signal at 1.234 d^{-1} . This frequency is absent in the observations of the later sectors.

To better understand the changes in the amplitude spectra of the different *TESS* light curves over time, we inspect the portions of the major outburst to which their observing periods correspond (see Figs 3 and 4). Sector 6 was observed in the middle of the major outburst and during the third brightening, i.e. the disc build-up phase. Sector 33 was obtained during the dissipation (or recovery) phase of the major outburst, while sectors 43–45 fall into the subsequent (relatively) quiescent phase. The sectors 71–72 also describe a recovery phase after the next (moderate) outburst.

In a study of continuous photometric monitoring of an entire moderate outburst in the early-type Be star HD 49330 with the CoRoT satellite, A.-L. Huat et al. (2009) found compelling evidence for changes in the Fourier spectrum over the event. In particular, a gradual emergence of frequency groups and individual frequencies during the precursor and outburst phases, which reach their maximum amplitude during the outburst. At the same time, frequencies that are prominent during quiescence are reduced. During the relaxation phase, the Fourier spectrum

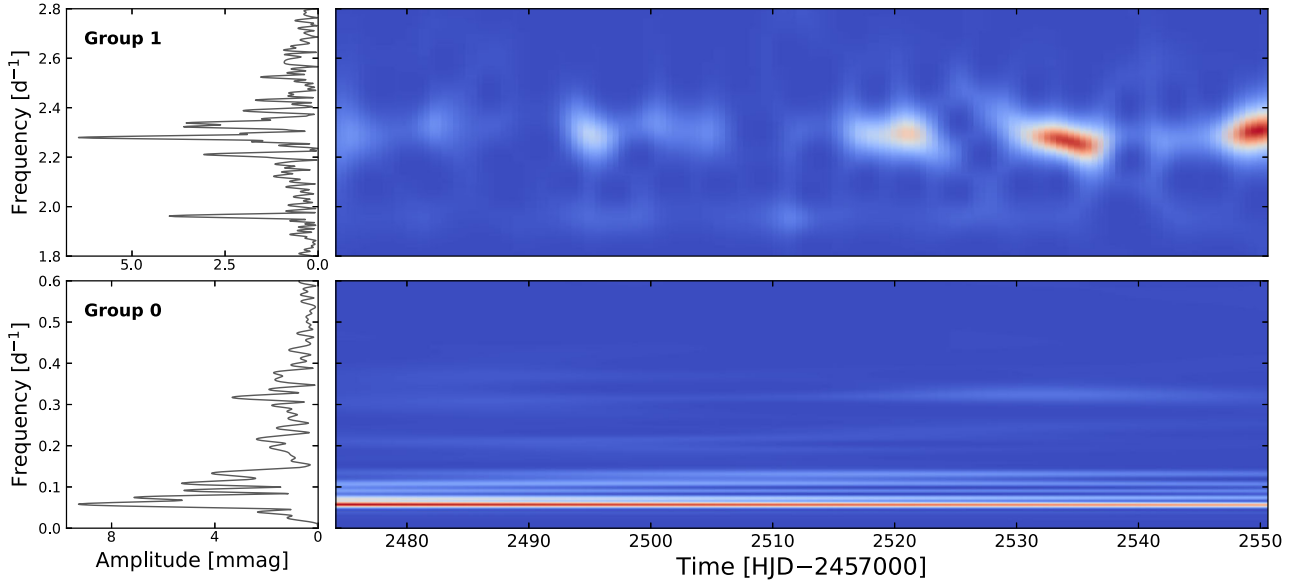


Figure 14. Same as Fig. 13 but for HD 253659.

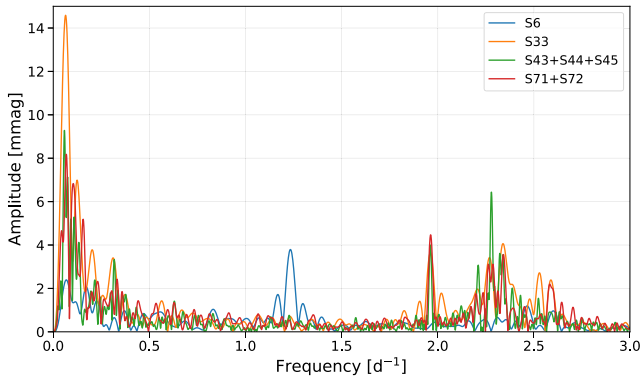


Figure 15. Comparison of the FFTs of individual (6, 33) and combined sectors (43-45, 71-72) of HD 253659.

seems to recover to the pre-outburst stage. In their study, A.-L. Huat et al. (2009) attribute the appearance of transient frequencies to rapid changes in the structure of the outer layers of the star during the outburst.

Our *TESS* data cover only small and individual portions of the events seen in the ground-based light curve of HD 253659 but the trend observed in our Fourier spectra is very similar. However, we also note a significant difference compared to HD 49330. The de-trended *TESS* light curves of all sectors but sector 6 show clear indications for recurrent flickers. These events with cycles of 10-20 d are most likely responsible for the high-amplitude low-frequency signals ($< 0.4 \text{ d}^{-1}$) in the corresponding Fourier spectra (which we tentatively labeled as group g0).

Similarly to PY Gem, the scalograms for HD 253659 (Fig. 14) reveal two distinct types of variability. The low-frequency signal (Group 0) remains coherent throughout the observations, whereas the higher-frequency signal (Group 1) exhibits pronounced temporal variations in amplitude and a lower degree of coherence, possibly connected to a beating phenomena.

5 DISCUSSION

Our investigation of HD 253659 and PY Gem was originally motivated by the discovery of nebulae surrounding them. But our current study presented above, including the determination of the positions of the objects in the HR diagram, reveals no unusual stellar properties that could naturally explain the origin of the nebulae. Thus, this raises the question of a possible connection between the formation of the observed circumstellar structures, the evolution of the decretion disc, and the variability properties of the central star. Since pulsations have been proposed as one of the possible mechanisms facilitating the ejection of material (see e.g. T. Rivinius et al. 2003; S. R. Cranmer 2009; T. Rivinius et al. 2013; D. Baade et al. 2017; T. Semaan et al. 2018) and its transfer into the circumstellar environment, it is particularly interesting to investigate whether changes in the pulsational activity of the star are related to episodes of disc formation and dissipation. Therefore, we investigated the photometric variability of the stars on different timescales, combining long-term light curves, which trace large-scale changes in the circumstellar discs, with high-cadence *TESS* photometry to study short-term variability and its frequency structure.

Despite being in a similar evolutionary state, the objects differ significantly in their photometric appearance. While on long time-scales HD 253659 exhibits quasi-periodic minor outbursts with low duty cycles followed by a high-amplitude major outburst event that lasted about six years with several disc formation and dissipation phases, PY Gem has ceased its typical γ Cas-type variability and instead displayed only small-amplitude variations over the past 20 yr.

The high-cadence *TESS* data clearly reveal the intrinsic properties of the targets and highlight differences between them. The frequency content observed in PY Gem remains relatively stable from sector to sector. With both g and p-mode pulsations, PY Gem might belong to the group of Be stars that are β Cephei hybrid pulsators. The object also shows an incoherent low-frequency signal, which we tentatively classify as a Štefl frequency originating from the interface region between the star and its disc (D. Baade et al.

2016). Support for such an interpretation is provided by the cyclic (or periodic) variability of emission lines like $H\alpha$ and He I that are formed in the same region. In contrast, HD 253659 exhibits substantial changes in its variability pattern, with the frequency structure undergoing significant reorganization during different phases of its activity. Its *TESS* observations reveal numerous g-modes and one p-mode as well as low-frequency variability that might be related to flickers and hence to possible density variations in the transition region between star and disc respectively the innermost disc region. Unfortunately, our spectroscopic coverage is insufficient for more solid conclusions. The individual sectors map different phases of the major outburst, and the general trend of the variabilities seen in the amplitude spectra agree well with those reported during outburst cycles (see e.g. A.-L. Huat et al. 2009).

Nevertheless, the mass-loss and disc-forming activity detected in HD 253659 could indicate that (some or certain) Be stars have the potential to create dusty nebulae. Support for this is provided by the SED of HD 253659, which contains a warm (~ 550 K) dusty component. Inspection of near-infrared images unveils no clear evidence of extended emission, so that this warm dust must be compact. Further support for high activity of Be stars that can lead to an accumulation of circumstellar material with conditions favouring the formation of molecules is provided by 12 Vul. This Be star was proposed by Y. R. Cochetti et al. (2021) to be in a transition phase between classical Be stars and B[e] supergiants, which are objects surrounded by dense molecular and dusty discs (see e.g. M. Kraus 2019). As such, outbursts and pulsation-triggered mass ejections from Be stars might also be related to instabilities similar to those recently proposed for B[e] supergiants (D. H. Nickeler & M. Kraus 2024).

The presumed lower mass-loss activity of PY Gem, which could be inferred from the absence of strong photometric variations, might simply be a misinterpretation of the actual conditions. As numerical computations have shown (X. Haubois et al. 2012), the detection of variability strongly depends on the inclination angle of the system. PY Gem might have an orientation ($\sim 70^\circ$) that suppresses the detection of (strong) photometric variability, while its activity is still traced in spectroscopy.

6 CONCLUSIONS

We studied the objects PY Gem and HD 253659 associated with nebulae that were discovered during the search for evolved massive stars with circumstellar structures in infrared images. Detailed study of the stars showed that they do not belong to evolved massive stars and are not related to the LBV phase, during which the formation of circumstellar nebulae is more natural. Instead, our analysis revealed that both stars are classical Be-stars, which have similar masses and luminosities.

The long-term light curves constructed from photometric data collected from various archives revealed the outburst activity of HD 253659 with major outburst between 2016 and 2022 and, in contrast, the prolonged quiescent state of PY Gem. For HD 253659 we traced disc formation and dissipation episodes in colour-magnitude and colour-colour diagrams. Collected data represent a valuable resource for detailed future modelling of the disc and for investigating its physical properties.

The high-cadence *TESS* observations reveal markedly different variability patterns in the two stars. PY Gem shows relatively stable frequency content across the observed sectors, with both g- and p-mode pulsations suggesting that it may be a β Cephei

hybrid pulsator; its additional low-frequency signal may represent a δ Scuti frequency associated with the star–disc interface. In contrast, HD 253659 exhibits substantial reorganization of its frequency spectrum between different phases of the major outburst, including numerous g-modes, a p-mode, and low-frequency variability that may be related to density variations in the star–disc transition region or the innermost disc. These results suggest a close connection between the changing pulsational/photometric variability and the evolution of the circumstellar disc during Be-star activity cycles.

All spectral lines observed in HD 253659 are in emission, whereas the spectrum of PY Gem contains absorption lines, which allowed us to determine its projected rotational velocity, $v \sin i = 303 \pm 15 \text{ km s}^{-1}$. Spectral monitoring of both stars did not detect any significant changes in radial velocity and thus provided no evidence for binarity.

Our investigation of these objects was originally motivated by the discovery of nebulae surrounding them. To conclude, we suggest that the nebulae detected around HD 253659 and PY Gem may be linked to the Be phenomenon itself. Testing this hypothesis requires a dedicated statistical analysis of a larger sample of Be stars and will be the subject of a forthcoming paper.

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We dedicate this publication to the memory of our dear colleague Vasilii Gvaramadze, who passed away on September 2nd, 2021. This is another article that would not have been possible without his idea, both studied stars are objects selected by him. The search for evolved stellar objects by means of the detection of their circumstellar nebulae in modern sky surveys was a topic that Vasilii successfully developed for the last years of his life.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Arcos C., Kanaan S., Chávez J., Vanzi L., Araya I., Curé M., 2018, *MNRAS*, 474, 5287

- Baade D. et al., 2016, *A&A*, 588, A56
- Baade D. et al., 2017, in Zwintz K., Poretti E., eds, Second BRIT-Constellation Science Conference: Small Satellites-Big Science, Vol. 5. Polish Astronomical Society, Bartycka 18, 00-716 Warsaw, Poland, p. 196
- Bailer-Jones C. A. L., Rybizki J., Fousneau M., Demleitner M., Andrae R., 2021, *AJ*, 161, 147
- Barentsen G. et al., 2014, *MNRAS*, 444, 3230
- Bell K., 2022, Astrophysics Source Code Library, record ascl:2207.007
- Bell K. J., 2020, *Res. Notes Am. Astron. Soc.*, 4, 19
- Bernhard K., Otero S., Hümmerich S., Kaltcheva N., Paunzen E., Bohlens T., 2018, *MNRAS*, 479, 2909
- Beskin G. M. et al., 2017, *Astrophys. Bull.*, 72, 81
- Bodensteiner J., Baade D., Greiner J., Langer N., 2018, *A&A*, 618, A110
- Brasseur C. E., Phillip C., Fleming S. W., Mullally S. E., White R. L., 2019, Astrophysics Source Code Library, record ascl:1905.007
- Carciofi A. C., Bolzan G. P. P., Querido P. R., Rubio A. C., Labadie-Bartz J., de Amorim T. H., Fonseca Silva A. C., Schiavolim V. L., 2025, *Galaxies*, 13, 77
- Cardelli J. A., Clayton G. C., Mathis J. S., 1989, *ApJ*, 345, 245
- Chambers K. C. et al., 2016, preprint ([arXiv:1612.05560](https://arxiv.org/abs/1612.05560))
- Clark J. S., Egan M. P., Crowther P. A., Mizuno D. R., Larionov V. M., Arkharov A., 2003, *A&A*, 412, 185
- Cochetti Y. R., Kraus M., Arias M. L., Cidale L. S., Eenmäe T., Liimets T., Torres A. F., Djupvik A. A., 2020, *AJ*, 160, 166
- Cochetti Y. R., Arias M. L., Kraus M., Cidale L. S., Torres A. F., Granada A., Maryeva O. V., 2021, *A&A*, 647, A164
- Cranmer S. R., 2009, *ApJ*, 701, 396
- Cutri R. M. et al., 2003, VizieR Online Data Catalog, II/246
- Cutri R. M. et al., 2013, Explanatory Supplement to the AllWISE Data Release Products, Explanatory Supplement to the AllWISE Data Release Products, by R. M. Cutri et al.
- Cutri R. M. et al., 2021, VizieR Online Data Catalog, II/328
- Dwarkadas V. V., 2023, *Galaxies*, 11, 78
- Ekström S. et al., 2012, *A&A*, 537, A146
- El-Badry K., 2024, *New A Rev.*, 98, 101694
- Figueiredo A. L., Carciofi A. C., Labadie-Bartz J., Pinho M. L., de Amorim T. H., Ticiani dos Santos P., Soszyński I., Udalski A., 2025, *ApJ*, 994, 58
- Foster G., 1996, *AJ*, 112, 1709
- Gaia Collaboration, 2021, *A&A*, 649, A1
- Gaia Collaboration, 2023, *A&A*, 674, A33
- Gao Q., Yuan H., 2025, preprint ([arXiv:2503.15677](https://arxiv.org/abs/2503.15677))
- Gao Q. et al., 2025, *A&A*, 694, A131
- Ghoreyshi M. R. et al., 2018, *MNRAS*, 479, 2214
- Granada A., Ekström S., Georgy C., Krtićka J., Owocki S., Meynet G., Maeder A., 2013, *A&A*, 553, A25
- Guetter H. H., 1968, *PASP*, 80, 197
- Gvaramadze V. V. et al., 2009, *MNRAS*, 400, 524
- Gvaramadze V. V., Kniazev A. Y., Fabrika S., Sholukhova O., Berdnikov L. N., Cherepashchuk A. M., Zharova A. V., 2010a, *MNRAS*, 405, 520
- Gvaramadze V. V., Kniazev A. Y., Fabrika S., 2010b, *MNRAS*, 405, 1047
- Gvaramadze V. V., Kniazev A. Y., Maryeva O. V., Berdnikov L. N., 2018, *MNRAS*, 474, 1412
- Hanuschik R. W., 1989, *Ap&SS*, 161, 61
- Haubois X., Carciofi A. C., Rivinius T., Okazaki A. T., Bjorkman J. E., 2012, *ApJ*, 756, 156
- Higgins M. E., Bell K. J., 2023, *AJ*, 165, 141
- Huat A.-L. et al., 2009, *A&A*, 506, 95
- Jones C. E., Wiegert P. A., Tycner C., Henry G. W., Cyr R. P., Halonen R. J., Muterspaugh M. W., 2013, *AJ*, 145, 142
- Kabáth P. et al., 2020, *PASP*, 132, 035002
- Karpov S., 2021, Astrophysics Source Code Library, record ascl:2112.006
- Karpov S. et al., 2018, *Astron. Nachr.*, 339, 375
- Kniazev A., Gvaramadze V., 2015, in Buckley D., Schroeder A. eds, *SALT Science Conference 2015 (SSC2015)*. Stellenbosch Institute of Advanced Study, South Africa, p. 49
- Kniazev A. Y., Gvaramadze V. V., Berdnikov L. N., 2015, *MNRAS*, 449, L60
- Kobulnicky H. A., Schurhammer D. P., Baldwin D. J., Chick W. T., Dixon D. M., Lee D., Povich M. S., 2017, *AJ*, 154, 201
- Koubský P., Mayer P., Čáp J., Žďárský F., Zeman J., Pina L., Melich Z., 2004, Publications of the Astronomical Institute of the Czechoslovak Academy of Sciences, 92, 37
- Kourniotis M. et al., 2014, *A&A*, 562, A125
- Kourniotis M., Kraus M., Arias M. L., Cidale L., Torres A. F., 2018, *MNRAS*, 480, 3706
- Kraus M., 2019, *Galaxies*, 7, 83
- Krtićka J., Owocki S. P., Meynet G., 2011, *A&A*, 527, A84
- Kurucz R. L., 1992, in Barbuy B., Renzini A. eds, IAU Symposium, Vol. 149, The Stellar Populations of Galaxies. Kluwer Academic Publishers, Dordrecht, p. 225
- Labadie-Bartz J. et al., 2017, *AJ*, 153, 252
- Labadie-Bartz J. et al., 2018, *AJ*, 155, 53
- Labadie-Bartz J., Baade D., Carciofi A. C., Rubio A., Rivinius T., Borre C. C., Martayan C., Siverd R. J., 2021, *MNRAS*, 502, 242
- Labadie-Bartz J., Carciofi A. C., Henrique de Amorim T., Rubio A., Luiz Figueiredo A., Ticiani dos Santos P., Thomson-Paressant K., 2022, *AJ*, 163, 226
- Lightkurve Collaboration, 2018, Astrophysics Source Code Library, record ascl:1812.013
- Maehara H., 2014, Journal of Space Science Informatics Japan, 3, 119
- Mainzer A. et al., 2014, *ApJ*, 792, 30
- Maíz-Apellániz J., 2004, *PASP*, 116, 859
- Maryeva O., Németh P., Karpov S., 2023, *Galaxies*, 11, 55
- Maryeva O. V., Karpov S. V., Kniazev A. Y., Gvaramadze V. V., 2022, *MNRAS*, 513, 5752
- Mauerhan J. C., Wachter S., Morris P. W., Van Dyk S. D., Hoard D. W., 2010, *ApJ*, 724, L78
- Mermilliod J.-C., 1987, *A&AS*, 71, 413
- Mizuno D. R. et al., 2010, *AJ*, 139, 1542
- Morgan W. W., Code A. D., Whitford A. E., 1955, *ApJS*, 2, 41
- Nazé Y., Motch C., 2018, *A&A*, 619, A148
- Neiner C., 2018, in Di Matteo P., Billebaud F., Herpin F., Lagarde N., Marquette J. B., Robin A., Venot O., eds, SF2A-2018: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics. p. Di, preprint ([arXiv:1811.05261](https://arxiv.org/abs/1811.05261))
- Neiner C., de Batz B., Cochard F., Floquet M., Mekkas A., Desnoux V., 2011, *AJ*, 142, 149
- Nickeler D. H., Kraus M., 2024, *ApJ*, 963, 131
- Ochsenbein F., Bauer P., Marcout J., 2000, *A&AS*, 143, 23
- Peri C. S., Benaglia P., Brookes D. P., Stevens I. R., Isequilla N. L., 2012, *A&A*, 538, A108
- Peri C. S., Benaglia P., Isequilla N. L., 2015, *A&A*, 578, A45
- Pojmanski G., 1997, *AcA*, 47, 467
- Porter J. M., Rivinius T., 2003, *PASP*, 115, 1153
- Richardson N. D., Mehner A., 2018, *Res. Notes Am. Astron. Soc.*, 2, 121
- Ricker G. R. et al., 2015, *J. Astron. Telesc. Instrum. Syst.*, 1, 014003
- Rivinius T., Klement R., 2026, in *Encyclopedia of Astrophysics*. Elsevier, Amsterdam, Netherlands, p. 430
- Rivinius T., Baade D., Štefl S., 2003, *A&A*, 411, 229
- Rivinius T., Carciofi A. C., Martayan C., 2013, *A&A Rev.*, 21, 69
- Rubio A. C., Carciofi A. C., Bjorkman J. E., de Amorim T. H., Okazaki A. T., Suffak M. W., Jones C. E., Candido P. P., 2025, *A&A*, 698, A309
- Rubio A. C., Carciofi A. C., Baade D., Labadie-Bartz J., de Amorim T. H., Gabitova I. A., Suffak M. W., 2026, preprint ([arXiv:2607.05270](https://arxiv.org/abs/2607.05270))
- Saio H., Bedding T. R., Kurtz D. W., Murphy S. J., Antoci V., Shibahashi H., Li G., Takata M., 2018, *MNRAS*, 477, 2183
- Samus' N. N., Kazarovets E. V., Durlevich O. V., Kireeva N. N., Pastukhova E. N., 2017, *Astron. Rep.*, 61, 80
- Semaan T., Hubert A. M., Zorec J., Gutiérrez-Soto J., Frémat Y., Martayan C., Fabregat J., Eggenberger P., 2018, *A&A*, 613, A70
- Simón-Díaz S., Herrero A., 2014, *A&A*, 562, A135
- Štefl S., Baade D., Rivinius T., Stahl O., Wolf B., Kaufer A., 1998, in Bradley P. A., Guzik J. A., eds, ASP Conf. Ser. Vol. 135, A Half Century of

Stellar Pulsation Interpretation. Astron. Soc. Pac., San Francisco, p. 348

Štrobl J., Jelínek M., Hudec R., 2019, *Astron. Nachr.*, 340, 633

Stringfellow G. S., Gvaramadze V. V., Beletsky Y., Kniazev A. Y., 2012, in Richards M. T., Hubeny I. eds, IAU Symposium, Vol. 282, From Interacting Binaries to Exoplanets: Essential Modeling Tools. p. 267 (preprint ([arXiv:1112.2685](https://arxiv.org/abs/1112.2685)))

Suffak M. W., Jones C. E., Tycner C., Henry G. W., Carciofi A. C., Mota B. C., Rubio A. C., 2020, *ApJ*, 890, 86

Wachter S., Mauerhan J. C., Van Dyk S. D., Hoard D. W., Kafka S., Morris P. W., 2010, *AJ*, 139, 2330

Watson C. L., Henden A. A., Price A., 2006, Soc. Astron. Sci. Annu. Symp., 25, 47

Wright E. L. et al., 2010, *AJ*, 140, 1868

Zorec J. et al., 2016, *A&A*, 595, A132

APPENDIX A: PHOTOMETRIC MONITORING WITH GROUND-BASED ROBOTIC TELESCOPES AND SPACE MISSIONS

Table A1. Summary of photometric data used in the study. MMT-9 is Mini-MegaTORTORA, FRAM is FRAM–ORM. N is the number of measurements.

Star	Telescope	Observing interval	Filter	N
PY Gem	ASAS 3	2002-12-14-2009-11-30	<i>V</i>	262
	MMT-9	2014-09-23-2024-12-31	Clear	4012
HD 253659	ASAS 3	2002-12-13-2009-11-30	<i>V</i>	395
	<i>WISE</i>	2010-03-17-2024-03-02	W1, W2	250
	KWS	2010-12-04-2025-02-14	<i>V</i> , <i>Ic</i>	2038
	MMT-9	2014-09-30-2024-12-31	Clear	3348
	FRAM	2023-10-26-2026-05-27	<i>B</i> , <i>V</i> , <i>R</i>	3772

Table A2. Summary of *TESS* observations. Listed are the observing sector (S), corresponding time interval, and the cadence of observations.

Object	S	Observing interval	Cadence [s]
PY Gem	43	2021-09-16-2021-10-12	600
	44	2021-10-12-2021-11-05	600
	45	2021-11-06-2021-12-02	600
	71	2023-10-16-2023-11-10	200
HD 253659	6	2018-12-11-2019-01-07	1800
	33	2020-12-18-2021-01-13	600
	43	2021-09-16-2021-10-12	600
	44	2021-10-12-2021-11-05	600
	45	2021-11-06-2021-12-02	600
	71	2023-10-16-2021-11-11	200
	72	2023-11-11-2021-12-07	200

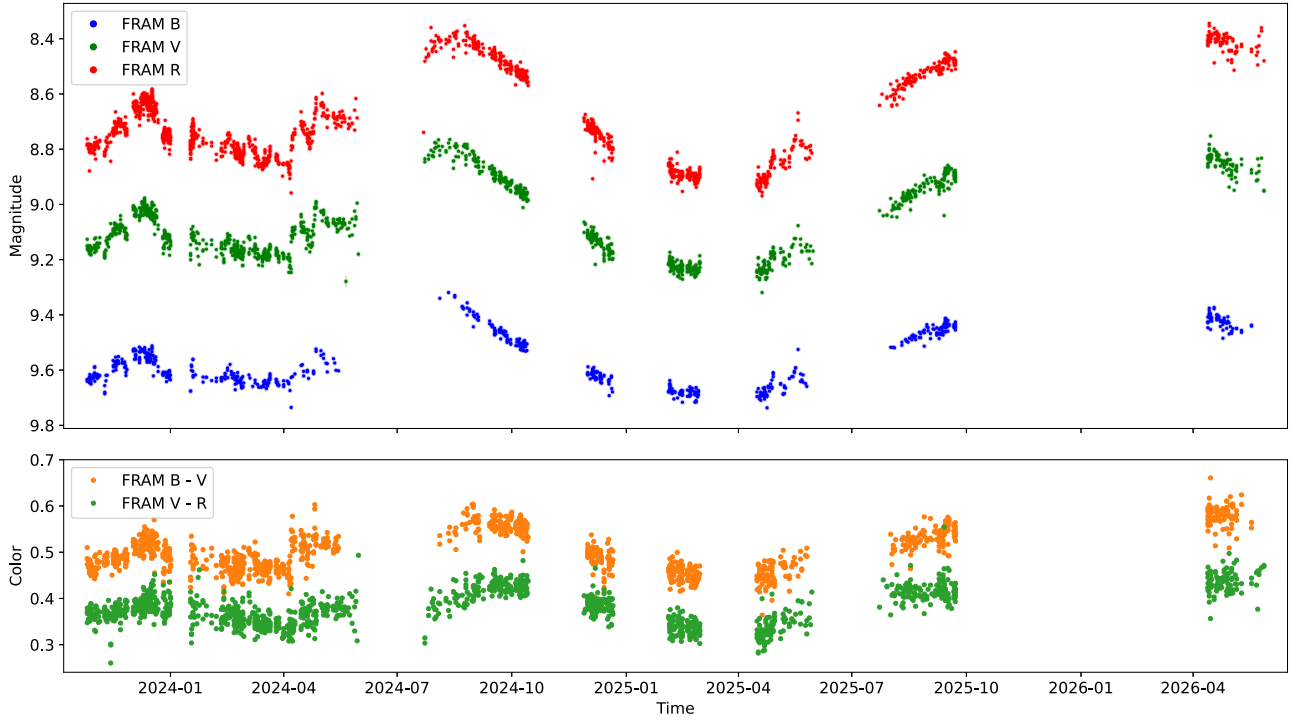


Figure A1. Upper panel: light curves of HD 253659 in the B (blue dots), V (green dots), and R (red dots) bands based on the FRAM multi-band photometry. Lower panel: behaviour of the corresponding colours.

APPENDIX B: SPECTROSCOPIC DATA**Table B1.** Log of observations at the Perek 2-m telescope using the Coude and OES spectrographs, along with the dates of observations and instruments of the spectra from the BeSS data base that we used for spectral monitoring. R is spectral resolution, SMM is Santa Maria de Montmagastrell, UH is University Hills (Los Angeles), DW is Desert Wing, SJ is San Jose, ASJ is observatoire Antibes Saint-Jean, MR is Mill Ridge.

	Date	Exp 9s)	Instrument	R
PY Gem	2009-03-17	2428	BeSS/PIERA	6000
	2012-03-10	1818	BeSS/SMM	5000
	2013-04-11	3012	BeSS/PIERA	5866
	2015-03-01	3684	BeSS/MR	8756
	2017-03-19	3624	BeSS/MR	8810
	2019-12-16	7257	BeSS/UH	10 975
	2020-04-10	2794	Coude H α	13 000
	2020-04-12	4801	Coude H α	13 000
	2020-04-26	3601	Coude H α	13 000
	2021-03-21	12045	BeSS/DW	15 917
	2021-02-04	7200	OES	50 000
	2021-03-25	8202	Coude H α	13 000
	2021-10-25	4601	Coude H α	13 000
	2021-10-28	1582	Coude H α	13 000
	2021-10-30	1063	Coude H α	13 000
	2022-01-06	4801	Coude H α	13 000
	2023-01-24	3600	BeSS/SJ	—
	2023-09-24	2794	Coude H α	13 000
	2023-10-07	4801	Coude NIR	13 000
	2024-04-08	4801	Coude H α	13 000
	2025-01-19	1650	Coude H α	13 000
HD 253659	2020-09-21	3001	Coude H α	13 000
	2020-11-06	2407	BeSS/ASJ	12 000
	2021-03-26	3601	Coude H α	13 000
	2021-03-26	3601	Coude NIR	13 000
	2021-04-04	4001	Coude NIR	13 000
	2021-10-25	4801	Coude H α	13 000
	2023-10-07	5201	Coude H α	13 000
	2024-04-08	5201	Coude H α	13 000
	2024-11-09	5201	Coude H α	13 000
	2025-03-02	5201	Coude H α	13 000
	2025-03-02	4001	Coude NIR	13 000
	2025-03-12	4206	Coude H α	13 000

Table B2. Parameters of the H α line in the spectra of PY Gem. Vb and Vr are the velocities of the blue and red peaks, correspondingly, Va is the one of the central absorption. Ib , Ia and Ir are their relative intensities.

Date	JD-2400000	Vb (km s^{-1})	Va [km s^{-1}]	Vr (km s^{-1})	Ib	Ia	Ir
2009-03-17	54 908.4	-158.5 ± 22.8	1.3 ± 22.8	161.2 ± 22.8	1.32	1.00	1.34
2012-03-10	55 997.5	-226.4 ± 22.8	-20.8 ± 22.8	184.7 ± 22.8	1.35	0.95	1.38
2013-04-11	56 394.4	-180.5 ± 22.8	2.2 ± 22.8	184.9 ± 22.8	1.40	1.01	1.43
2015-03-01	57 082.7	-178.7 ± 22.8	4.0 ± 22.8	186.7 ± 22.8	1.20	0.88	1.20
2017-03-19	57 831.6	-204.3 ± 22.8	1.2 ± 22.8	206.8 ± 22.8	1.36	0.92	1.35
2019-12-16	58 833.9	-191.5 ± 22.8	14.0 ± 22.8	196.8 ± 22.8	1.38	0.98	1.44
2020-04-10	58 950.3	-171.8 ± 10.5	18.0 ± 10.5	176.3 ± 10.5	1.33	0.99	1.36
2020-04-12	58 952.3	-180.3 ± 10.5	20.1 ± 10.5	178.3 ± 10.5	1.35	0.97	1.37
2020-04-26	58 966.3	-177.0 ± 10.5	23.5 ± 10.5	181.7 ± 10.5	1.38	0.99	1.41
2021-03-21	59 294.7	-181.4 ± 22.8	1.3 ± 22.8	184.0 ± 22.8	1.54	1.03	1.56
2021-03-25	59 299.3	-169.7 ± 10.5	-22.0 ± 10.5	167.9 ± 10.5	1.32	0.94	1.35
2021-10-25	59 512.6	-168.1 ± 10.6	0.7 ± 10.6	169.5 ± 10.6	1.49	1.00	1.49
2021-10-28	59 516.4	-167.9 ± 10.6	-30.8 ± 10.6	180.3 ± 10.6	1.43	1.01	1.48
2021-10-30	59 517.6	-169.7 ± 10.6	-0.9 ± 10.6	178.5 ± 10.6	1.52	1.01	1.53
2022-01-06	59 586.3	-173.0 ± 10.5	-4.2 ± 10.5	164.6 ± 10.5	1.54	1.03	1.52
2023-01-24	59 968.7	-257.4 ± 22.8	-6.2 ± 22.8	245.0 ± 22.8	1.19	0.81	1.17
2023-09-24	60 211.5	-223.0 ± 10.6	-22.5 ± 10.6	241.3 ± 10.6	1.21	0.84	1.21
2024-04-08	60 410.0	-245.5 ± 10.5	-2.9 ± 10.5	260.7 ± 10.5	1.16	0.78	1.16
2025-01-19	60 695.4	-254.4 ± 10.5	19.9 ± 10.5	315.3 ± 10.5	1.09	0.77	1.11

Table B3. Parameters of the $H\alpha$ line in the spectra of HD 253659. Vb and Vr are velocities of the blue and red peaks, respectively, Va is the one of the central absorption. Ib , Ia and Ir are their relative intensities, and EW is the equivalent width.

Date	JD-2400000	V (mag)	$(V - I_c)$ (mag)	Vb (km s^{-1})	Va (km s^{-1})	Vr (km s^{-1})	Ib	Ia	Ir	EW [Å]
2020-09-21	59 113.8	9.12		-45.1 ± 10.5	44.5 ± 10.5	115.3 ± 10.5	1.29	1.26	1.30	
2020-11-06	59 159.6	9.15	0.78	-64.1 ± 10.5	35.9 ± 10.5	90.1 ± 10.5	2.68	2.54	2.69	15.79
2021-03-25	59 300.3	9.24		-50.0 ± 10.5	18.3 ± 10.5	100.3 ± 10.5	2.55	2.29	2.60	14.59
2021-10-25	59 512.8	9.32	0.52	-55.5 ± 10.5	40.1 ± 10.5	122.7 ± 10.5	2.62	2.25	2.54	13.57
2023-10-07	60 224.8	9.10	0.72	-60.0 ± 10.5	76.4 ± 10.5	142.1 ± 10.5	1.85	1.59	1.83	9.51
2024-04-08	60 409.3	9.15		-60.5 ± 10.5	39.3 ± 10.5	130.5 ± 10.5	2.01	1.69	1.94	8.32
2024-11-09	60 624.4	9.05	0.78	-30.8 ± 10.5	29.2 ± 10.5	129.3 ± 10.5	2.18	2.08	2.23	13.21
2025-03-02	60 740.0	9.23		-92.0 ± 10.5	9.9 ± 10.5	86.4 ± 10.5	2.51	2.24	2.54	13.40
2025-03-12	60 750.0	9.23		-94.9 ± 10.5	-12.5 ± 10.5	85.6 ± 10.5	2.3	2.02	2.38	11.46

APPENDIX C: TESS FREQUENCY TABLES

Table C1. List of frequencies and amplitudes detected, along with their errors, in the light curves of PY Gem in the combined TESS sectors 43, 44, and 45. Frequency groups are labelled following the notation of J. Labadie-Bartz et al. (2021, 2022), while isolated frequencies are labelled as f .

Id	Freq. (d^{-1})	σ_{Freq} (d^{-1})	Amp. (mmag)	σ_{Amp} (mmag)	Comb.
f_0	0.392 301	0.000 009	2.198 678	0.002 752	
g_{11}	0.747 429	0.000 015	1.493 956	0.002 831	
g_{12}	0.764 372	0.000 017	1.319 377	0.002 830	
g_{13}	0.865 053	0.000 015	1.292 551	0.002 777	
g_{14}	0.987 502	0.000 017	1.240 231	0.002 837	
g_{15}	1.047 756	0.000 017	1.220 930	0.002 870	
g_{16}	1.088 357	0.000 016	1.342 233	0.002 863	
g_{17}	1.104 142	0.000 003	7.791 497	0.002 871	$g_{42} - f_1$
g_{18}	1.136 812	0.000 015	1.450 272	0.002 900	
g_{19}	1.223 356	0.000 013	1.698 407	0.002 847	
g_{110}	1.278 970	0.000 008	2.490 439	0.002 816	$g_{23} - g_{15}$
g_{111}	1.493 178	0.000 016	1.231 250	0.002 764	$3g_{19} - 2g_{16}$
g_{21}	1.935 899	0.000 019	1.036 524	0.002 775	
g_{22}	2.103 877	0.000 015	1.315 188	0.002 783	$f_4 - g_{42}$
g_{23}	2.326 436	0.000 022	0.948 608	0.002 817	
g_{24}	2.383 455	0.000 006	3.405 144	0.002 816	$f_7 - g_{43}$
g_{31}	4.175 418	0.000 063	0.334 088	0.002 929	$f_2 - 2g_{14}$
g_{32}	4.203 657	0.000 050	0.418 726	0.002 958	
g_{33}	4.655 531	0.000 043	0.459 293	0.002 942	$2f_0 + 2g_{21}$
g_{34}	4.870 144	0.000 044	0.458 923	0.002 997	
g_{35}	4.927 180	0.000 020	1.015 686	0.003 036	$f_2 - g_{19}$
g_{36}	5.045 448	0.000 035	0.582 539	0.003 017	$f_0 + 2g_{23}$
g_{37}	5.102 287	0.000 040	0.495 948	0.003 009	$f_2 - g_{15}$
f_1	5.935 636	0.000 058	0.338 215	0.003 068	
f_2	6.150 013	0.000 057	0.346 288	0.003 117	
f_3	6.295 146	0.000 022	0.890 832	0.003 120	$g_{43} - g_{18}$
g_{41}	6.895 047	0.000 068	0.288 879	0.003 214	$3g_{11} + 2g_{23}$
g_{42}	7.039 972	0.000 005	4.295 556	0.003 238	
g_{43}	7.429 757	0.000 013	1.464 165	0.003 288	
f_4	9.142 417	0.000 102	0.189 828	0.003 641	
f_5	9.423 250	0.000 064	0.305 623	0.003 723	$2f_1 - 2g_{19}$
f_6	9.639 517	0.000 070	0.280 176	0.003 782	$3g_{13} + g_{42}$
f_7	9.813 083	0.000 053	0.369 789	0.003 832	
f_8	14.081 260	0.000 121	0.160 916	0.006 166	$2f_4 - g_{32}$
f_9	14.829 743	0.000 131	0.148 067	0.007 017	$3f_7 - 3g_{34}$

Table C2. Same as in Table C1 for HD 253659.

Id	Freq. (d ⁻¹)	σ_{Freq} (d ⁻¹)	Amp. (mmag)	σ_{Amp} (mmag)	Comb.
g0 ₁	0.014 067	0.000 015	1.685 331	0.003 789	
g0 ₂	0.057 852	0.000 003	10.328 896	0.003 628	
g0 ₃	0.112 008	0.000 005	5.158 962	0.003 404	
g0 ₄	0.139 303	0.000 008	3.873 643	0.003 739	
g0 ₅	0.196 875	0.000 011	2.688 889	0.003 788	3g0 ₃ – g0 ₄
g0 ₆	0.219 283	0.000 010	3.231 557	0.003 833	g1 ₁₂ – g1 ₇
g0 ₇	0.245 201	0.000 014	2.040 817	0.003 632	
g0 ₈	0.274 591	0.000 016	2.121 902	0.003 754	g1 ₁₄ – g1 ₆
g0 ₉	0.296 582	0.000 019	2.147 909	0.003 779	
g0 ₁₀	0.315 650	0.000 012	3.174 317	0.003 705	
g0 ₁₁	0.371 213	0.000 011	2.888 161	0.003 661	g0 ₂ + g0 ₁₀
g0 ₁₂	0.402 313	0.000 014	1.955 912	0.003 691	
g0 ₁₃	0.430 279	0.000 016	1.933 469	0.003 667	2g0 ₂ + g0 ₁₀
g0 ₁₄	0.477 989	0.000 019	1.523 685	0.003 714	2g0 ₉ – g0 ₂
g0 ₁₅	0.632 463	0.000 022	1.142 509	0.003 572	3g0 ₃ + g0 ₉
f0	0.891 314	0.000 039	0.610 999	0.003 370	3g0 ₁₂ – g0 ₁₀
f1	1.226 561	0.000 054	0.440 674	0.003 357	g1 ₁ – 3g0 ₇
g1 ₁	1.962 055	0.000 006	3.971 374	0.003 391	
g1 ₂	2.138 473	0.000 023	1.117 216	0.003 491	3g0 ₂ + g1 ₁
g1 ₃	2.173 656	0.000 027	0.923 906	0.003 474	g1 ₁₂ – g0 ₁₂
g1 ₄	2.212 520	0.000 009	2.841 390	0.003 818	
g1 ₅	2.278 367	0.000 005	6.007 756	0.003 646	g1 ₆ – g0 ₂
g1 ₆	2.336 542	0.000 007	3.554 191	0.003 506	
g1 ₇	2.358 879	0.000 020	1.455 452	0.003 754	
g1 ₈	2.390 903	0.000 013	2.152 668	0.003 639	
g1 ₉	2.430 207	0.000 025	1.106 695	0.003 711	3g0 ₁ + g1 ₈
g1 ₁₀	2.459 695	0.000 036	0.745 968	0.003 564	2g1 ₆ – g1 ₄
g1 ₁₁	2.522 384	0.000 027	1.010 086	0.003 635	
g1 ₁₂	2.578 433	0.000 031	1.094 429	0.003 625	
g1 ₁₃	2.598 238	0.000 033	1.133 767	0.003 647	g1 ₁₄ – g0 ₁
g1 ₁₄	2.612 865	0.000 036	0.814 589	0.003 619	
g1 ₁₅	2.635 155	0.000 030	0.919 697	0.003 693	2g1 ₁₂ – g1 ₁₁
g1 ₁₆	2.776 246	0.000 067	0.365 979	0.003 447	3g0 ₄ + g1 ₇
f2	7.936 386	0.000 056	0.427 891	0.004 113	
f3	9.898 140	0.000 081	0.292 558	0.004 691	g1 ₁ + f2

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