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| **Authors** | þÿNiemczura, Ewa; Pigulski, Andrzej; KamiDska, Monika<br>Lehmann, Holger; et al. |
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# New photometric and spectroscopic observations of 53 Per

Ewa Niemczura[1], Andrzej Pigulski[1], Monika K. Kamińska[2], Krzysztof Kamiński[2], Holger Lehmann[3], Krzysztof G. Hełminiak[4], Giovanni Catanzaro[5], Ivanka Stateva[6], Mirela Napetova[6], Tomasz Różański[1] and the BRITE Team

1. Astronomical Institute, University of Wrocław, Kopernika 11, 51–622 Wrocław, Poland
2. Institute Astronomical Observatory, Adam Mickiewicz University, Słoneczna 36, 60–286 Poznań, Poland
3. Thüringer Landessternwarte Tautenburg, Sternwarte 5, D-07778 Tautenburg, Germany
4. Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rabiańska 8, 87–100 Toruń, Poland
5. INAF, Osservatorio Astrofisico di Catania, Via S. Sofia 78, 95123 Catania, Italy
6. Institute of Astronomy with NAO, Bulgarian Academy of Sciences, Tsarigradsko Chaussee 72, Sofia 1784, Bulgaria

We present the analysis of the variability of the SPB-type star 53 Per based on space photometry from BRITE-Constellation nano-satellites and SMEI-Coriolis experiment. The two photometries allowed us to detect 17 independent sinusoidal terms in the range $0.2-1.4\,\mathrm{d}^{-1}$ plus one combination, and one harmonic. The independent terms can be attributed to $g$ modes excited in this star. Only three of these modes have been known earlier. In addition, we gathered almost 3500 new mid- and high-resolution spectra of 53 Per, which were used to calculate radial velocities. The frequency spectrum of the time-series radial-velocity data revealed four independent terms and one combination, all consistent with the frequencies detected in BRITE and SMEI photometry. The high-resolution and high signal-to-noise averaged spectrum was used to obtain atmospheric parameters of 53 Per, $T_{\rm eff} = 15600 \pm 400\,\mathrm{K}$ and $\log(g/(\mathrm{cm\,s^{-2}}))= 3.85 \pm 0.10$.

## 1 Introduction

53 Per (d Per, V496 Per, HD 27396, B4 IV, $V = 4.85$ mag) is one of the first studied variable mid-B stars of the northern hemisphere. Its photometric and spectroscopic data have been gathered and analysed since the mid-1970s (see Chapellier et al., 1998; De Ridder et al., 1999, and references therein). The star was regarded as a prototype of a group of mid-B type stars showing variability in line profiles due to non-radial pulsations (Smith, 1977), later incorporated into SPB (Slowly Pulsating B-type) class of variables (Waelkens, 1991). The photometric variability of 53 Per was first detected by Percy & Lane (1977) and Africano (1977). Since the mid-1970s till late 1990s, 53 Per was frequently observed both photometrically and spectroscopically. The main goal of these investigations was to classify the variability of this star. However, pulsation frequencies obtained by different authors rarely agreed (see the review by Chapellier et al., 1998; De Ridder et al., 1999).

Summarising the past variability studies, most authors agreed on two frequencies, $f_1 \approx 0.46\,\mathrm{d}^{-1}$ and $f_2 \approx 0.60\,\mathrm{d}^{-1}$. First, Smith et al. (1984) found $f_1 = 0.464\,\mathrm{d}^{-1}$, and $f_2 = 0.595\,\mathrm{d}^{-1}$. Later on, Huang et al. (1994) obtained $f_1 = 0.462\,\mathrm{d}^{-1}$ and $f_2 = 0.603\,\mathrm{d}^{-1}$. Chapellier et al. (1998) analysed photometric and mid-resolution spectroscopic data obtained at Haute Provence Observatory with Aurelie spectrograph attached to the 1.5-m telescope. He found $f_1 = 0.462\,\mathrm{d}^{-1}$ and $f_2 = 0.597\,\mathrm{d}^{-1}$. Finally, De Ridder et al. (1999) investigated photometric Hipparcos and high-resolution

Table 1: BRITE and SMEI photometry of 53 Per.

| Satellite | Start date | End date | Reduced data points |
|---|---|---|---|
| UniBRITE (UBr) | 04-09-2014 | 18-02-2015 | 97783 |
| BRITE-Toronto (BTr) | 15-09-2016 | 07-03-2017 | 40613 |
| BRITE-Lem (BLb) | 14-09-2016 | 07-03-2017 | 30523 |
| Coriolis-SMEI | 06-02-2003 | 30-12-2010 | 24159 |

spectroscopic data made in Ritter Observatory. They obtained $f_1 = 0.461\,\mathrm{d}^{-1}$, $f_2 = 0.594\,\mathrm{d}^{-1}$ and third term at frequency $f_3 = 0.471\,\mathrm{d}^{-1}$, which was earlier proposed also by Mills & Dukes (1994).

Analysis of the space photometry obtained with the BRITE nano-satellites and the SMEI experiment onboard of the Coriolis satellite, supplemented by time-resolved high-resolution ground-based spectroscopy, enabled us to reveal a very rich frequency spectrum of 53 Per.

## 2 Photometric data

### *2.1 BRITE-Constellation photometry*

BRITE-Constellation (Weiss et al., 2014) consists of five nano-satellites, each hosting an uncooled CCD detector fed by a 30-mm diameter, f/2.3 telescope. Each satellite is equipped with either blue (390 – 460 nm) or red (545– 695 nm) filter. BRITE-Constellation satellites were launched into low-Earth orbits with orbital periods of the order of 100 min. The effective field of view of about $24 \times 20\,\mathrm{deg}^2$ allows to perform simultaneous monitoring of 15 – 30 stars brighter than about 6 mag in the $V$ band. A given field is observed typically over a 6 month time base. Details of the instrumentation and observing procedure were given by Weiss et al. (2014) and Pablo et al. (2016).

BRITE observations of 53 Per are summarized in Tab. 1. The star was observed during two runs, in the Perseus I and Auriga/Perseus I fields. The first run spanned between Sep. 2, 2014 and Feb. 18, 2015. The observations collected in the stare mode (see Pablo et al., 2016, for explanation of observing modes) were made by a single BRITE satellite, UniBRITE (UBr). In the second run, 53 Per was observed in the chopping mode with BRITE-Toronto (BTr) between Sep. 15, 2015 and Mar. 7, 2016 in the red filter, and with BRITE-Lem (BLb), between Sep. 14, 2015, and Mar. 7, 2016 in the blue filter. The images were reduced with the pipelines presented by Popowicz et al. (2017). Prior to the time-series analysis, BRITE photometry was corrected for instrumental effects. The corrections included outlier rejection and decorrelations with all available parameters, including centroid positions and CCD temperature. The final correction accounted for offsets between individual setups and satellites. After corrections, the combined red-filter (UBr+BTr) light curve consisted of 138 396 data points, whereas the blue-filter one comprised 30 523 data points.

The obtained light curves were used in the time-series analysis, which consisted

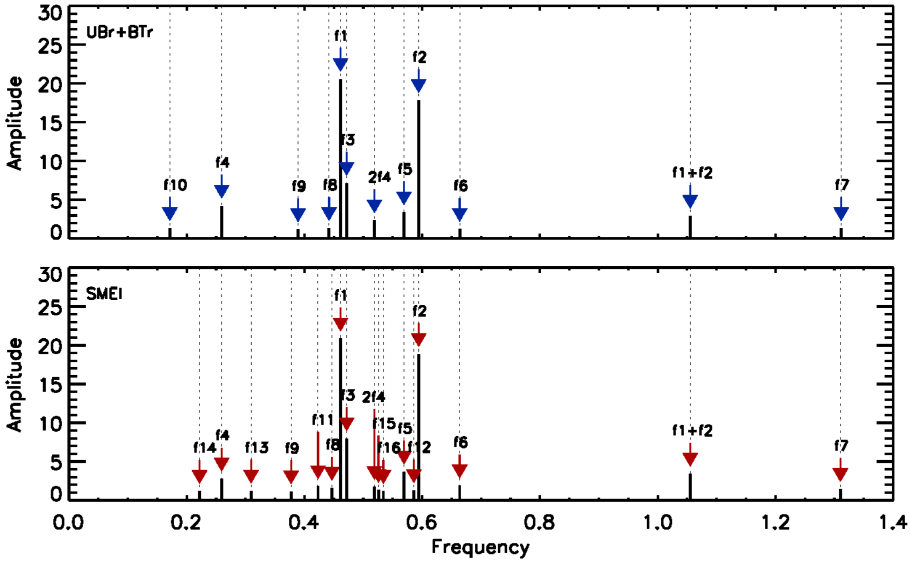

Fig. 1: A schematic frequency [$\mathrm{d}^{-1}$] spectrum [mmag] of 53 Per obtained from the analysis of BRITE red-filter (UBr+BTr) (upper panel) and SMEI (lower panel) data.

of the calculation of the Fourier frequency spectrum, identification of the highest maximum in the spectrum, and pre-whitening the original light curve with all previously detected frequencies. In total, ten significant independent frequencies were identified in BRITE red-filter photometry (Fig. 1, upper panel). The spectrum is dominated by the three previously identified modes ($f_1 = 0.4612$, $f_2 = 0.5939$, and $f_3 = 0.4715\,\mathrm{d}^{-1}$), with amplitudes ranging from 7 to 20 mmag. The other modes have amplitudes lower than 5 mmag. In addition to the ten independent modes, one combination frequency, $f_1 + f_2$ and one harmonic $2f_4$, were found. The observations in the blue filter are less numerous and of lower quality allowing to detect only the two dominating modes, $f_1 = 0.4611$, and $f_2 = 0.5939\,\mathrm{d}^{-1}$ in accordance with the UBr+BTr results. Their amplitudes amount to about 20 mmag.

### *2.2 SMEI photometry*

The Solar Mass Ejection Imager (SMEI) was a high-precision photometer onboard of the Coriolis solar satellite (Jackson et al., 2004). Coriolis was launched in Jan. 2003 into a near-Earth orbit with a period of 101.6 min. SMEI was powered off in Sep. 2012, after more than nine years of continuous observations. The instrument has consisted of three baffled CCD cameras, each with a $3 \times 60\,\mathrm{deg}^2$ field of view, and has delivered observations of nearly the whole sky. The SMEI photometry of 53 Per was downloaded from the UCSD web page[1]. SMEI could detect changes in brightness in stars down to approximately 8th mag. Its photometric passband ranged from 450 to 950 nm with a maximum near 700 nm.

The SMEI observations of 53 Per spanned almost eight years, between Feb. 6,

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[1] http://smei.ucsd.edu/new_smei/data&images/stars/timeseries.html.

Table 2: Spectroscopic data collected for 53 Per.

| Telescope or spectrograph | Resolving power | No. of spectra | Wavelength range [Å] | Dates |
|---|---|---|---|---|
| TLS | 58 000 | 1428 | 4530 – 7540 | Nov. 2015 – Mar. 2016 |
| PST1 | 35 000 | 445 | 4320 – 7040 | Oct. 2015 – Mar. 2017 |
| PST2 | 35 000 | 1320 | 4320 – 7040 | Oct. 2016 – Mar. 2017 |
| HIDES | 50 000 | 50 | 4080 – 7520 | Feb., Mar. 2017 |
| CAOS | 45 000 | 16 | 3760 – 10700 | Nov. 2015 |
| BNAO | 22 000 | 24 | 3930 – 9020 | Nov., Dec. 2015 |

2003, and Dec. 30, 2010, hence the nominal frequency resolution is of the order of $0.0004\,\mathrm{d}^{-1}$. The process of preparing the stellar SMEI data for scientific analysis included the removal of extreme outliers from the raw light curve, the correction for one-year instrumental long-term variability, and the subsequent careful detrending and outlier rejection performed to eliminate effects resulting from the combination of data from different cameras, among others. The procedure affected the frequency spectrum only below $\sim 0.1\,\mathrm{d}^{-1}$, that is below the range in which the terms detected with BRITE data occured. After this step, the SMEI data comprised of 24 159 data points. The individual SMEI measurements have low accuracy, but their large number and long time span permitted to detect for 53 Per variabilities with amplitudes down to about 1 mmag. In total, 15 frequencies were identified in the SMEI data of 53 Per (Fig. 1, lower panel), including all but two ($f_9$ and $f_{10}$) found in the BRITE data.

## 3 Spectroscopic data

The spectroscopic observations of 53 Per were carried out between Oct. 2015 and Mar. 2017, partly simultaneously with BRITE observations. The mid- and high-resolution spectra of this star were obtained with six different échelle spectrographs: attached to the 2-m telescope of the Thüringer Landessternwarte Tautenburg (TLS spectrograph, 1428 spectra), the 0.5-m and 0.7-m Poznań Spectroscopic Telescopes (PST1 and PST2, 445 and 1320 spectra, respectively), the 1.88-m telescope in Okayama (Japan) with the HIDES spectrograph (OAO, 50), the 91-cm telescope of the Osservatorio Astrofisico di Catania (OAC, 16), and the 2-m telescope of the Bulgarian National Astronomical Observatory (BNAO, 24). The spectra have an average signal-to-noise ratio of about 100. In total, 3497 spectra were collected for 53 Per (Tab. 2).

After the standard reduction and calibration procedures all spectra were normalised to continuum. To compute radial velocities (RVs), we extracted four He I lines (4713.15, 4921.93, 5875.62, and 6678.16 Å). RVs were calculated using the cross-correlation method. In total, four significant independent frequencies and one combination ($f_1 + f_2$), were identified. The two frequencies with the highest amplitudes were known before ($f_1$ and $f_2$). All spectroscopically obtained frequencies are consistent with the analysis of the BRITE and SMEI photometric data.

Table 3: Atmospheric parameters of 53 Per obtained by photometric methods and by fitting the data with synthetic spectra calculated with ATLAS9 and SYNTHE codes (see text for details).

| Method | $T_{\rm eff}$ [K] | $\log g$ | $\xi$, $\zeta$, $v \sin i$ [km s$^{-1}$] |
|---|---|---|---|
| Strömgren photometry | $16100 \pm 400$ | $3.80 \pm 0.10$ | – |
| Geneva photometry | $15300 \pm 300$ | $4.05 \pm 0.15$ | – |
| Spectroscopy<br>LTE (Balmer + Fe) | $15600 \pm 400$ | $3.85 \pm 0.10$ | $\xi = 1.0 \pm 0.5$<br>$\zeta = 5.0 \pm 5.0$<br>$v \sin i = 23.0 \pm 2.0$ |

### *3.1 Atmospheric parameters*

The collected high-resolution spectra were subsequently used to determine atmospheric parameters of 53 Per. The averaged spectrum, with the signal-to-noise of 1500 was prepared on the basis of the high-resolution TLS spectra, ranging from 4530 to 7540 Å, taking into account the computed RVs.

We determined effective temperature $T_{\rm eff}$ and surface gravity $\log g$ of 53 Per from the sensitivity of the hydrogen lines to these atmospheric parameters (see Tab. 3). From the investigation of the H$\beta$ profile and H$\alpha$ wings we derived $T_{\rm eff} = 15600 \pm 400$ K and $\log g = 3.85 \pm 0.10$. We used an iterative approach which minimises the differences between the observed and synthetic Balmer line profiles, following the method of Catanzaro et al. (2004). The atmospheric models and synthetic spectra were calculated with the ATLAS9 and SYNTHE codes (Kurucz, 2005), with the assumption of LTE (local thermodynamical equilibrium). Both codes, ATLAS9 and SYNTHE, were ported to GNU/Linux by Sbordone (2005). We used the line list introduced by Castelli & Hubrig (2004). For the detailed discussion of the method see Niemczura et al. (2015).

The obtained value of the effective temperature is in agreement with $T_{\rm eff} = 15300 \pm 300$ K derived from the Geneva photometry (Kunzli et al., 1997). Furthermore, from the analysis of iron lines, we obtained microturbulence $\xi = 1.0 \pm 0.5$ km s$^{-1}$, and macroturbulence $\zeta = 5.0 \pm 5.0$ km s$^{-1}$ velocities. Projected rotational velocity, $v \sin i = 23.0 \pm 2.0$ km s$^{-1}$, was determined from the investigation of all available spectral lines except of the hydrogen lines. These atmospheric parameters indicate that for many spectral lines non-LTE effect can be strong and should be taken into account. The full non-LTE analysis will be presented in the upcoming paper (Niemczura et al., in preparation).

## 4 Future work

The investigation of BRITE photometry has enabled us to identify many more frequencies than were known before, including one combination and one harmonic. Thanks to these results, the next step of our analysis will be mode identification and seismic modelling of the star. The full results of this study will be published elsewhere (Niemczura et al., in preparation).

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