

β Cas: the first δ Scuti star with a dynamo magnetic field^{*}

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ABSTRACT

Context. F type stars are characterized by several physical processes such as different pulsation mechanisms, rotation, convection, diffusion, and magnetic fields. The rapidly rotating δ Scuti star β Cas can be considered as a benchmark star to study the interaction of several of these effects.

Aims. We aim to investigate the pulsational and magnetic field properties of β Cas. We also determine the star's apparent fundamental parameters and chemical abundances.

Methods. Based on photometric time series obtained from three different space missions (BRITE-Constellation, SMEI, and TESS), we conduct a frequency analysis and investigate the stability of the pulsation amplitudes over four years of observations. We investigate the presence of a magnetic field and its properties using spectropolarimetric observations taken with the Narval instrument by applying the Least Square Deconvolution and Zeeman Doppler Imaging techniques.

Results. β Cas shows only three independent p-mode frequencies down to the few ppm-level; its highest amplitude frequency is found to be a $n = 3$, $\ell = 2$, $m = 0$ mode. Its magnetic field structure is quite complex and almost certainly of a dynamo origin. β Cas' atmosphere is slightly metal deficient in iron peak elements and slightly overabundant in C, O, and heavy elements.

Conclusions. Untypically for δ Scuti stars, we can only detect three pulsation modes down to really low noise levels for β Cas. The star is also one of very few δ Scuti pulsators known to date to show a measurable magnetic field, and the first δ Scuti star with a dynamo magnetic field. These characteristics make β Cas an interesting target for future studies of dynamo processes in the thin convective envelopes of F-type stars, of the transition region between fossil and dynamo fields, and the interaction between pulsations and magnetic field.

Key words. Stars:individual: β Cas – Stars: variables: delta Scuti – Stars: atmospheres – Stars: magnetic field – Stars: abundances

1. Introduction

Stellar evolution is influenced by the interaction of several physical processes such as pulsations, rotation, magnetic fields, convection, and diffusion. The lifetimes of stars decrease or increase depending on how strong the impact of these effects is. The exact description and theoretical representation of all interacting physical processes remains one of the great challenges in stellar astrophysics. Through the analysis of suitable benchmark objects, we aim to learn more about these physical interactions and improve our theoretical concept.

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F-type stars can show three types of pulsations: (i) δ Scuti-type p-modes driven by the κ -mechanism acting in the He II ionization zone (Pamyatnykh 2000), (ii) γ Doradus type g-modes that are caused by the convective flux blocking mechanism (Guzik et al. 2000), and (iii) stochastic solar-like oscillations (e.g., Kjeldsen & Bedding 1995). In addition, hybrid stars showing both δ Scuti and γ Doradus pulsations have been detected and studied in detail in particular since the advent of space missions for high-precision photometry (e.g., Grigahcène et al. 2010).

Cool stars typically rotate slowly, while hotter stars mostly show fast rotation. A high rotation rate leads to strong centrifugal forces which make the star oblate. Consequently, the stars' surface temperatures vary across the latitudes due to the gravity darkening (von Zeipel 1924a,b). Also, the distribution of the chemical elements in the stellar atmosphere is affected by high rotation rates (Meynet & Maeder 2000).

In the massive and intermediate-mass O, B, and A stars on the main sequence, strong magnetic fields are found in $\sim 10\%$ of the cases. These are fossil fields that can exist in stars down to effective temperatures of about 6500 K (e.g., Kochukhov 2003). They are usually dipolar with a typical strength of 3 kG (Shultz

et al. 2019). At lower temperatures and up to effective temperatures of about 6700 K, observed magnetic fields have a dynamo character (e.g., Marsden et al. 2014). The exact transition between fossil and dynamo fields (Seach et al. 2020), and the possible interaction between these two types of fields (Featherstone et al. 2009), are not well known yet, but it is likely that some early F stars host both a fossil and a dynamo field observable at their surface.

β Cas (HD 432, HR 21, Caph) has an apparent magnitude of 2.27 in V and a spectral type of F2 III (Gray et al. 2003a). It is located at 16.8 pc (determined from the Hipparcos parallax of 59.58 ± 0.38 mas; van Leeuwen 2007), and its mass is estimated to be $2.09 M_{\odot}$ (Holmberg et al. 2007). β Cas is considered to be a rather evolved star located near the Terminal Age Main Sequence (TAMS) that was an A-type star during its main sequence lifetime.

Several measurements of β Cas' projected rotational velocity, $v_e \sin i$ can be found in the literature: The first determination dates back to Slettebak (1955) who reported a value of 70 km s^{-1} . This is rather consistent with several recent measurements that lie between 69 and 71 km s^{-1} (e.g., Glebocki et al. 2000; Schröder et al. 2009).

A detailed interferometric study of β Cas (Che et al. 2011) yielded its geometric properties, surface temperature distributions, mass, and age. β Cas rotates with more than 90% of its critical velocity, which causes significant radius and temperature differences between the poles and the equator: β Cas' radius is $\sim 24\%$ greater at the equator than at the poles and the temperature at the poles is $\sim 1000 \text{ K}$ higher than at the equator (Che et al. 2011). The authors also determined the inclination angle to be 19.9° , the rotation rate to be $1.12^{+0.03}_{-0.04} \text{ d}^{-1}$, the mass to be $1.91 \pm 0.02 M_{\odot}$, and the age to be $1.18 \pm 0.05 \text{ Gyr}$ (Che et al. 2011).

Millis (1966) discovered the brightness variability of β Cas and identified it as a member of the class of δ Scuti stars as it showed a period of 0.104 d (or 2.5 hours) with an amplitude of 0.04 mag in Johnson V . Yang et al. (1982) confirmed the photometrically discovered period in radial velocity variations of β Cas, which had the highest amplitude in the Ca II line at 8662 \AA . Antonello et al. (1986) refined the period to be 0.10101 days with full amplitude of 0.03 mag in V based on eight nights of observations at Merate Observatory, and speculated that β Cas would be a small-amplitude, mono-periodic δ Scuti star. Based on Strömgren $uvby\beta$ observations, Rodriguez et al. (1992) determined the pulsation frequency to $9.91 \pm 0.35 \text{ d}^{-1}$. The authors also determined the effective temperature, T_{eff} , of β Cas to be 7170 K, its $\log g$ to be 3.62, and its metallicity $[M/H]$ to be 0.2 from the Strömgren colors and calibrations. Based on these findings, Rodriguez et al. (1992) calculated the pulsation constant, Q , for the pulsation frequency to be 0.024 indicating first overtone radial pulsation, i.e., a p-mode with $\ell = 1$. These findings were reviewed by Riboni et al. (1994) who confirmed the presence of a single pulsation frequency at 9.899 d^{-1} , and found T_{eff} of $7000 \pm 200 \text{ K}$, $\log g$ of 3.55 ± 0.3 , but also reported that a firm mode identification could not be performed.

β Cas' chromosphere was studied using IUE spectra by Teays et al. (1989) who found that its chromospheric activity is modulated by the pulsation and that the mean level of chromospheric activity is comparable to other F-type stars.

At the beginning of the 20th century, it was speculated that β Cas could be a binary star with an orbital period of 27 days (Mellor 1917). However, a review of over 60 years of radial velocity data conducted by Abt (1965) revealed no sign of binarity. A recent catalog of δ Scuti stars in binary systems by Liakos

& Niarchos (2017) lists β Cas as a 'binary with an unspecified orbital period'.

In this work we combine photometric time series obtained by the BRITE-Constellation (Weiss et al. 2014), SMEI (Eyles et al. 2003; Jackson et al. 2004) and TESS (Ricker et al. 2015) satellites to investigate the suggested mono-periodicity of β Cas. We also obtained spectropolarimetric observations with the Narval spectropolarimeter at the Telescope Bernard Lyot and determine β Cas' magnetic properties. Based on these data, we also review the fundamental atmospheric parameters and chemical abundances of the star.

2. Observations

2.1. BRITE-Constellation observations and data reduction

β Cas was observed during four consecutive seasons with the BRITE-Constellation nano-satellites (Weiss et al. 2014): (i) in field 11-CasCep-I-2015 from 23 July to 1 November, 2015, using four of the five satellites: BRITE-Austria (BAb) and BRITE-Lem (BLb) with a blue filter, as well as BRITE-Heweliusz (BHR) and BRITE-Toronto (BTr) with a red filter, (ii) in field 19-Cas-I-2016 from 7 August, 2016, to 1 February, 2017, using the satellites BAb and UniBRITE (UBr, with a red filter), (iii) in field 30-Cas-II-2017 from 7 August, 2017, to 3 February, 2018 only using BAb, and (iv) in field 39-Cas-III-2018 from 7 August 2018 to 3 February 2019 using BAb and BTr. Table 1 summarizes the properties of the BRITE observations.

The BRITE raw data were extracted from the 2D images following the procedure described in Popowicz et al. (2017). The BRITE photometry was subsequently corrected for instrumental effects. The corrections included outlier rejection, and both one- and two-dimensional decorrelations with all available parameters, in accordance with the procedure described by Pigulski (2018). Figure 1 shows the full light curves obtained by UBr (panel a) and BAb (panel b) in 2016 as well as 4-days subsets of the data illustrating the pulsational variability. The corresponding light curves of the three other seasons are given in the Appendix (Fig. A.1).

2.2. Solar Mass Ejection Imager (SMEI) observations and data reduction

The Solar Mass Ejection Imager (SMEI) experiment (Eyles et al. 2003; Jackson et al. 2004), placed on-board the Coriolis spacecraft, aimed at measuring sunlight scattered by free electrons of the solar wind, but the images are also suitable to extract the photometry of bright stars. The β Cas data were obtained in the years 2003–2010 and are available through the University of California San Diego (UCSD) web page¹. The SMEI photometry is affected by long-term calibration effects, especially a spurious variability with a period of one year. We corrected the SMEI UCSD photometry of β Cas for this one-year variability by subtracting an interpolated mean light curve. Finally, the individual uncertainties were calculated for each data point using the scatter of the neighbouring data points, and the worst parts of the light curve (i.e., those with an uncertainty of 0.013 mag) and outliers were removed. The low-frequency instrumental variability was filtered out by subtracting detrended residuals of the fit. This procedure will have removed the intrinsic low-frequency (frequencies below $\sim 1 \text{ d}^{-1}$) variability, if present.

¹ http://smei.ucsd.edu/new_smei/index.html

Table 1. Properties of the BRITE-Constellation two-color observations, the SMEI and TESS data for β Cas.

Satellite	Field ID	Obs _{start}	Obs _{end}	Time base (d)	1/T (d ⁻¹)	N #	Res. noise (ppm)	f _{Nyq} (d ⁻¹)
BAb	11-CasCep-I-2015	29 Aug. 2015	26 Oct. 2015	58.034	0.017	14305	163.1	2117.33
BLb	11-CasCep-I-2015	29 Sep. 2015	17 Oct. 2015	18.067	0.055	8403	217.2	2119.62
<i>BAb + BLb</i>	<i>combined</i>	<i>29 Aug. 2015</i>	<i>26 Oct. 2015</i>	<i>58.034</i>	<i>0.017</i>	<i>22708</i>	<i>130.8</i>	<i>2133.35</i>
BHr	11-CasCep-I-2015	31 Aug. 2015	17 Oct. 2015	46.950	0.021	4552	215.4	2096.39
BTr	11-CasCep-I-2015	4 Dec. 2015	20 Jan. 2016	43.681	0.023	20609	50.8	1892.47
<i>BHr + BTr</i>	<i>combined</i>	<i>31 Aug. 2015</i>	<i>20 Jan. 2016</i>	<i>142.096</i>	<i>0.007</i>	<i>25161</i>	<i>62.8</i>	<i>1925.06</i>
BAb	19-Cas-I-2016	7 Aug. 2016	30 Dec. 2016	145.045	0.007	17728	114.4	2085.80
UBr	19-Cas-I-2016	13 Sep. 2016	1 Feb. 2017	141.072	0.007	23494	84.2	2120.99
BAb	30-Cas-II-2017	7 Aug. 2017	3 Feb. 2018	160.170	0.006	7253	227.2	2092.82
BAb	39-Cas-III-2018	8 Aug. 2018	14 Nov. 2018	96.587	0.010	1316	677.3	2075.96
BTr	39-Cas-III-2018	14 Sep. 2018	21 Jan. 2019	129.618	0.008	41757	92.4	2108.16
SMEI				2884.825	0.0003	28742	64.8	7.08
TESS	Sector 17	7 Oct. 2019	2 Nov. 2019	23.081	0.043	13134	-	-
	Sector 18	2 Nov. 2019	27 Nov. 2019	22.873	0.044	14961	-	-
	<i>combined</i>	<i>7. Oct. 2019</i>	<i>27 Nov. 2019</i>	<i>49.686</i>	<i>0.02</i>	<i>28516</i>	<i>2.4</i>	<i>359.39</i>

Notes. Satellite used to conduct the observations (Satellite), BRITE-Constellation field ID and TESS Sector number (Field ID), corresponding start (Obs_{start}) and end dates (Obs_{end}) of observations, total time base of the reduced data set (Time base), Rayleigh frequency resolution (1/T), number of data points (N), residual noise after prewhitening all frequencies (Res.noise) which is calculated over the complete frequency range relevant for δ Scuti pulsations from 0 to 100d⁻¹, and the Nyquist frequency (f_{Nyq}) for each data set. As the TESS data of sectors 17 and 18 were analyzed together, no individual values for the residual noise and Nyquist frequency are provided.

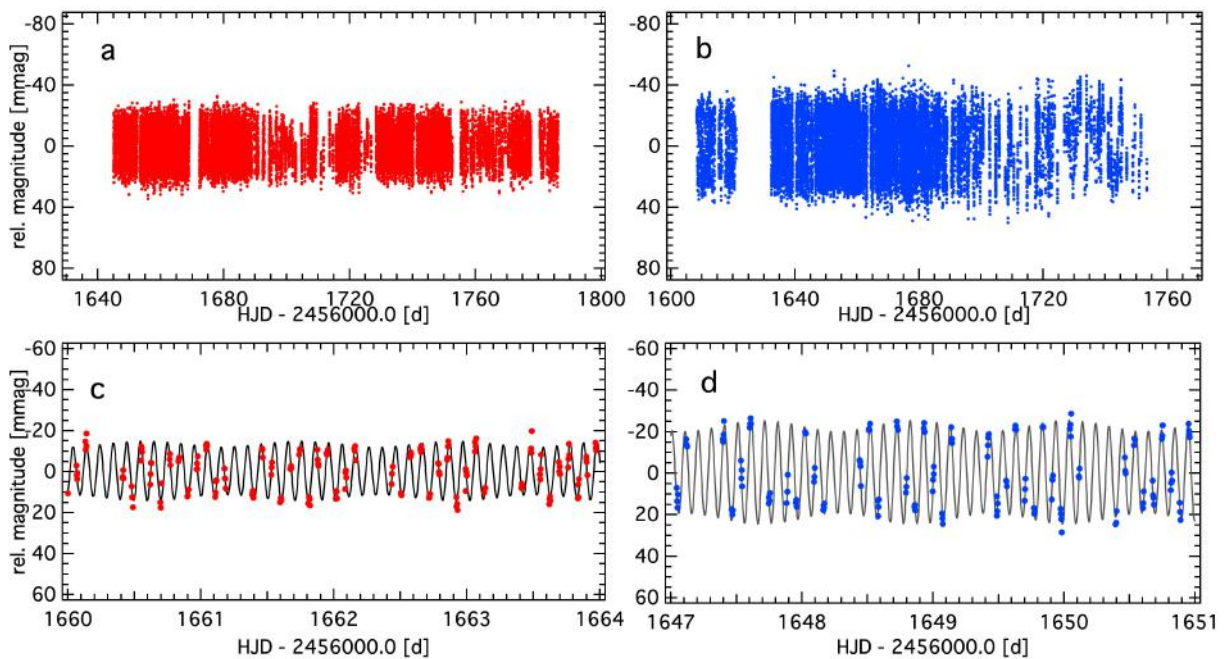


Fig. 1. BRITE photometric time series obtained by BAb (panel a) and UBr in 2016 (panels b). Panels c and d show 4-days subsets of the BAb and UBr 2016 light curves binned to 5-minute intervals and the corresponding multi-sine fit with the two identified pulsation frequencies.

The final SMEI data for β Cas comprise of 28742 data points obtained between 6 February 2003 and 31 December 2010 for a total time base of 2884.89537 days (~ 7.89841 years). This corresponds to a Rayleigh frequency resolution, $1/T$, of 0.0003d⁻¹. An overview of the properties of the SMEI data is given in Table 1.

2.3. TESS data

We combined the photometric data from BRITE-Constellation and SMEI with recent observations taken by the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) from 7 October to 27 November 2019 in Sectors 17 and 18. The total time base of the TESS data for β Cas (TIC 396298498, TESS magni-

tude $T = 2.041$ mag) is 49.686 days (see Table 1). β Cas is one of the preselected targets for 2-minute cadence observations.

The full TESS light curve and a zoom into a 4-day subset are given in Fig. 2. The beginnings and ends of the two Sectors are marked with a vertical dashed line. The obvious gaps within each Sector are caused by the data downlink at the perigee of the TESS orbit. β Cas was observed with CCD 1 of Camera 2 in Sector 17 and with CCD 2 of Camera 2 in Sector 18. Just before the end of the first orbit, the Moon entered Camera 1 and 2's field-of-view causing some strong arcs. No other instrumental effects were reported.

We used the 2-minute Simple Aperture Photometry (SAP) flux light curve, provided by the "Barbara A. Mikulski Archive for Space Telescopes" (MAST)² and the Python packages `lightkurve` (Lightkurve Collaboration et al. 2018) and `SMURFS`³ (Müllner 2020). We removed all measurements with a non-zero "quality" flag (see §9 in the TESS Science Data Products Description Document⁴), which marks anomalies like cosmic rays, instrumental issues or straylight from the Earth or Moon. Furthermore the light curve was sigma clipped, removing outliers outside of four σ . In a next step, we subtracted the median flux of the two sectors and combined them. We then applied a Gaussian filter using `scipy` (Virtanen et al. 2020) to remove the low frequency signal that is of instrumental origin and subtracted it from the lightcurve. This procedure could have removed any intrinsic low-frequency (i.e., frequencies below ~ 2 d⁻¹) variability, if present.

2.4. Narval spectropolarimetric observations

β Cas was observed with the Narval spectropolarimeter installed at the T lescope Bernard Lyot (TBL) in France. Narval provides spectra covering the wavelength range from 390 to 1050 nm with a resolving power of ~ 65000 , spread over 40 echelle orders recorded on a single detector. We used Narval in circular polarization mode to produce Stokes V and Stokes I spectra from a sequence of 4 sub-exposures. A Null polarization spectrum (N) is also produced by combining the 4 sub-exposures in a destructive way. N allows to check for signal due to instrumental effects or stellar phenomena unrelated to magnetism, such as pulsations.

β Cas was observed a first time on November 3, 2013, as part of the BRITePol survey (Neiner et al. 2016). BRITePol measures the potential magnetic field of all stars brighter than $V=4$, as a ground-based support to BRITe. The possible detection of a magnetic field in this first observation of β Cas led to a series of three additional observations obtained between September 24 and December 21, 2014, to confirm the presence of a magnetic field in β Cas. Finally, a complete series of follow-up observations was acquired between December 1 and 13, 2015, simultaneously with the BRITe observations.

The exposure time of the individual subexposures was kept very short (65 s) to avoid as much as possible contamination from expected short-period pulsations. To obtain a high signal-to-noise (S/N), several consecutive polarimetric sequences were then recorded and co-added after reduction (see Sect. 5.1).

The data were reduced with the LIBRE-ESPRIT software pipeline available at TBL. Each order of the intensity spectra was then normalized separately using SPENT (Martin et al. 2018)

Table 2. Journal of observations indicating the number of the averaged polarimetric measurement, the date of observations, the Heliocentric Julian Date at the middle of the observations (mid-HJD - 2450000), the number of polarimetric sequences times the exposure time in seconds, and the average signal-to-noise ratio of a (single) spectropolarimetric sequence per CCD pixel at ~ 500 nm.

#	Date	mid-HJD -2450000	T_{exp} s	S/N
1	Nov 3, 2013	6600.2627	4×65	818
2	Sep 25, 2014	6925.6165	3×4×65	1206
3	Dec 19, 2014	7011.2941	5×4×65	1258
4	Dec 21, 2014	7013.2990	5×4×65	1122
5	Dec 1, 2015	7358.3265	5×4×65	984
6	Dec 1, 2015	7358.3891	5×4×65	881
7	Dec 2, 2015	7359.3314	5×4×65	723
8	Dec 2, 2015	7359.3870	5×4×65	781
9	Dec 5, 2015	7362.2862	5×4×65	918
10	Dec 6, 2015	7363.2947	5×4×65	1100
11	Dec 6, 2015	7363.3535	5×4×65	1154
12	Dec 6, 2015	7363.4058	5×4×65	1160
13	Dec 7, 2015	7364.3514	5×4×65	1140
14	Dec 7, 2015	7364.4070	5×4×65	1058
15	Dec 9, 2015	7366.3073	5×4×65	1040
16	Dec 11, 2015	7368.3693	5×4×65	1093
17	Dec 12, 2015	7369.3194	5×4×65	991
18	Dec 12, 2015	7369.3734	5×4×65	889
19	Dec 13, 2015	7370.3799	5×4×65	995

and the normalization function was also applied to Stokes V and N.

The log of the Narval observations is available in Table 2.

3. Photometric analysis

The frequency analysis of the BRITe, SMEI and TESS photometric time series of β Cas was performed independently of each other using the software package `Period04` (Lenz & Breger 2005) that combines Fourier and least-squares algorithms. Frequencies were then prewhitened and considered to be significant if their amplitudes exceeded 3.9 times the local noise level in the amplitude spectrum (Breger et al. 1993; Kuschnig et al. 1997). Frequency, amplitude and phase errors are calculated using the formulae given by Montgomery & Odonoghue (1999). To verify the analysis, we use the frequency extraction tool `SMURFS`, which automates the search for significant frequencies in time series data by iteratively searching for the frequency with the maximum amplitude and removing it using curve fitting tools provided by `lmfit` (Newville et al. 2014) and `scipy` (Virtanen et al. 2020).

β Cas shows three frequencies that can be attributed to δ Scuti type pulsations: F_1 at 9.89708 d⁻¹ and F_2 at 9.04369 d⁻¹ are clearly dominating and can be identified in all data sets. The third independent δ Scuti type frequency is F_4 at 8.3847 d⁻¹, which can only be seen in the TESS data due to its relatively small amplitude of 0.055 mmag.

Frequency F_3 at 19.79221 d⁻¹ is only significant in those photometric time series that have a low enough noise level (i.e., in the BRITe 2015 and 2016 B & R observations and in TESS data). Additionally, F_3 is not an independent frequency, as it is identified to be two times F_1 . Similarly, frequency F_5 at 18.9409 d⁻¹ is actually a combination of F_1 plus F_2 ; its small amplitude of 0.038 mmag lets it also only appear in the TESS data.

² <http://archive.stsci.edu>

³ <https://github.com/MarcoMuellner/SMURFS>

⁴ <https://archive.stsci.edu/missions/tess/doc/EXP-TESS-ARC-ICD-TM-0014.pdf>

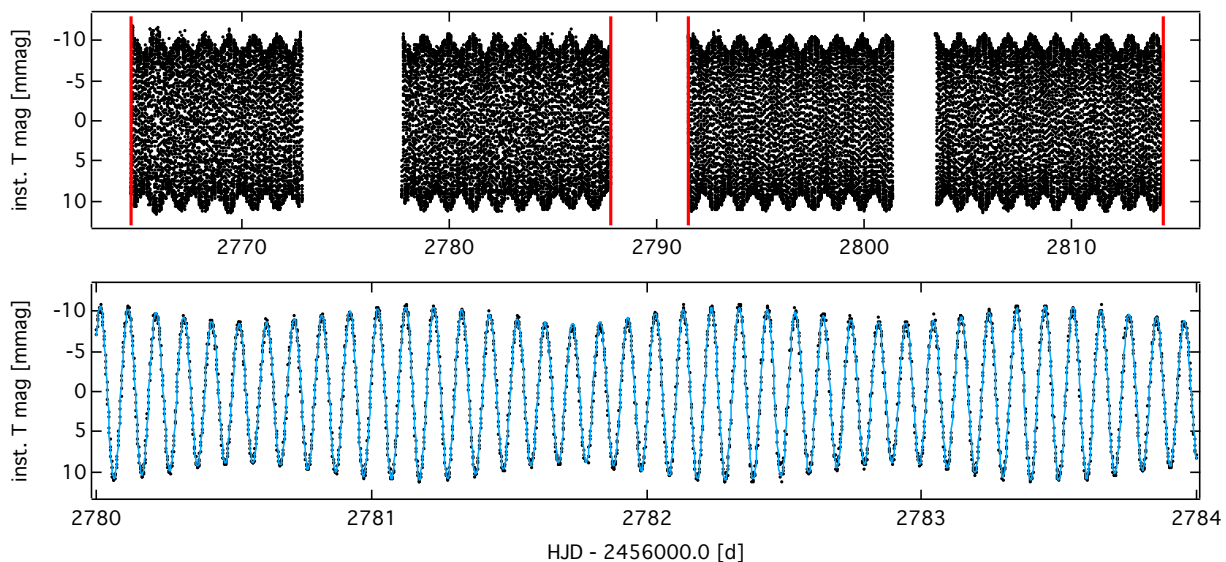


Fig. 2. Top panel: Complete TESS light curve . Start and end dates of Sectors 17 and 18 are marked with vertical red lines. Bottom panel: 4-days zoom illustrating the pulsational variability.

The latter also allow us to identify a frequency F_6 at 9.9000 d^{-1} that corresponds to F_1 within the Rayleigh frequency resolution. With the presently available data, we cannot decide unambiguously whether F_6 is an independent frequency or is dependent on F_1 . Future additional TESS observations of β Cas will hopefully contribute to finding an unambiguous solution.

An overview of the pulsation frequencies, amplitudes and phases derived from the three seasons of BRITE-Constellation data, SMEI and TESS observations is given in Table 3.

As an example, the amplitude spectra from the 2016 BAb and UBr data are shown in Fig. 3: blue filter data are shown on the left, red filter data on the right side. The top panels illustrate the amplitude spectra of the original data with F_1 identified as well as two alias frequencies, which appear in the blue and the red filter data. $f_{alias,1}$ can be identified as the corresponding BRITE orbital frequency, f_{orb} , minus F_1 and $f_{alias,2}$ as 2 times f_{orb} minus F_1 . Both alias frequencies disappear after prewhitening F_1 as can be seen in the middle panels of Fig. 3 which shows the amplitude spectra after subtraction of F_1 where F_2 and two new alias frequencies $f_{alias,3}$ and $f_{alias,4}$ are marked. $f_{alias,3}$ is generated as f_{orb} minus F_2 , and $f_{alias,4}$ as 2 times f_{orb} minus F_2 . They again disappear when F_2 is prewhitened. The bottom panels show the amplitude spectra after prewhitening with F_1 and F_2 with $F_3 = 2 \cdot F_1$ and f_{orb} marked. The residual amplitude spectra for the 2016 blue and red filter data are shown in Fig. 4 and illustrate the corresponding average residual noise levels of 114.4 ppm for BAb and 84.2 ppm for UBr. The amplitude spectra for the 2015, 2017, and 2018 BRITE observations as well as all the residual amplitude spectra, and the spectral window functions are given in Appendix B (Figs. B.1, B.2, B.3, B.4, and B.5).

The Nyquist frequency for the SMEI data is at 7.08 d^{-1} because measurements were taken every ~ 1.7 hours. The frequencies of δ Scuti stars are typically higher than this value (e.g., Aerts et al. 2010). As it was shown for Kepler data by Murphy et al. (2013), it is possible to do super-Nyquist asteroseismology using the SMEI data because the real peaks remain as singlets even if they are above f_{Nyq} . Using the SMEI data, we could confirm the pulsation frequencies F_1 and F_2 (see Fig. 5). The residual amplitude spectrum after prewhitening F_1 and F_2 is shown in

the bottom panel of Fig. 5. Figure B.6 shows the SMEI spectral window.

The amplitude spectra obtained from the TESS data are illustrated in Fig. 6: following the prewhitening sequence, F_1 to F_6 are identified and marked in panels a to d. The residual amplitude spectrum after prewhitening the six frequencies is shown in Fig. 7. For completeness, Fig. B.7 illustrates the spectral window of the TESS data.

4. Spectroscopic analysis

4.1. Atmospheric parameters and chemical abundances

The spectropolarimetric time-series were averaged to produce one spectrum with $S/N=500$. This combined spectrum was used for the determination of the apparent atmospheric parameters and for a detailed abundance analysis conducted using the SME software (Spectroscopy Made Easy - version 503) written in the IDL language (Valenti & Piskunov 1996; Piskunov & Valenti 2017). In our analysis, we did not take into account the non-sphericity and gravity darkening due to rapid rotation, but constrain it to the apparent values.

For the fitting of the spectrum six intervals were chosen: 4400–4700, 5100–5250, 5570–5750, 6000–6220, 6400–6700 and 7700–7900 Å. The 6400–6700 Å region contains the $H\alpha$ line which is a good temperature indicator in the cool stars' domain and is still slightly sensitive to gravity variations at effective temperatures near 7000 K (see Ryabchikova et al. 2016). The 7700–7900 Å region contains the O I triplet which allows to estimate the oxygen abundance in non-local thermodynamic equilibrium (NLTE). In addition, the small spectral region from 5850–5910 Å with the Ba II line at a wavelength of 5853 Å and the resonance Na I D-lines were used for abundance determination. Atomic line parameters were extracted from the third version of the VALD database VALD3 (Ryabchikova et al. 2015; Pakhomov et al. 2017). Besides O, NLTE effects were taken into account for Na, Ca, Ba (Piskunov et al. 2017). Strong observed lines of these elements allow to get accurate abundances even in such a rapidly rotating star. The SME analysis was performed

Table 3. Pulsation frequencies (F), amplitudes (A), phases (ϕ), and signal-to-noise values (S/N) of β Cas derived from the BRITE-Constellation, SMEI and TESS data.

	F ₁	F ₂	F ₃ = 2·F ₁	F ₄	F ₅ = F ₁ + F ₂	F ₆ = F ₁ ± (1/T)	
Freq. <i>BRITE red</i>	9.89708(1)	9.0437(1)	19.7922(6)	-	-	-	d ⁻¹
A _R 2015	13.30(4)	1.51(4)	0.28(4)	-	-	-	mmag
A _R 2016	13.14(6)	1.43(6)	0.40(6)	-	-	-	mmag
A _R 2018	12.57(6)	1.34(6)	-	-	-	-	mmag
ϕ_R 2015	0.1911(5)	0.216(5)	0.4(2)	-	-	-	rad
ϕ_R 2016	0.1505(7)	0.769(6)	0.4(2)	-	-	-	rad
ϕ_R 2018	0.1566(7)	0.791(6)	-	-	-	-	rad
S/N _R 2015	21.47	21.94	4.38	-	-	-	
S/N _R 2016	23.81	17.57	4.98	-	-	-	
S/N _R 2018	32.54	14.46	-	-	-	-	
Freq. <i>BRITE blue</i>	9.89710(1)	9.0434(1)	19.7946(7)	-	-	-	d ⁻¹
A _B 2015	22.2(1)	2.5(1)	0.5(1)	-	-	-	mmag
A _B 2016	22.47(8)	2.62(8)	0.47(8)	-	-	-	mmag
A _B 2017	22.2(2)	2.38(2)	-	-	-	-	mmag
A _B 2018	23.7(4)	-	-	-	-	-	mmag
ϕ_B 2015	0.1719(7)	0.132(7)	0.49(3)	-	-	-	rad
ϕ_B 2016	0.1469(6)	0.82(5)	0.99(3)	-	-	-	rad
ϕ_B 2017	0.126(1)	0.78(1)	-	-	-	-	rad
ϕ_B 2018	0.625(3)	-	-	-	-	-	rad
S/N _B 2015	17.41	18.67	3.53	-	-	-	
S/N _B 2016	23.15	21.45	3.99	-	-	-	
S/N _B 2017	14.12	10.27	-	-	-	-	
S/N _B 2018	7.49	-	-	-	-	-	
Freq. <i>SMEI</i>	9.8971699(9)	9.044955(8)	-	-	-	-	d ⁻¹
A _{SMEI}	11.25(5)	1.24(5)	-	-	-	-	mmag
ϕ_{SMEI}	0.1301(7)	0.001(7)	-	-	-	-	rad
S/N _{SMEI}	120.65	21.41	-	-	-	-	
Freq. <i>TESS</i>	9.897098(2)	9.04391(2)	19.7942(1)	8.3847(4)	18.9409(6)	9.9000(5)	d ⁻¹
A _{TESS}	9.749(2)	1.035(2)	0.229(2)	0.055(2)	0.038(2)	0.025(2)	mmag
ϕ_{TESS}	0.77974(4)	0.4214(3)	0.304(2)	0.771(6)	0.260(9)	0.305(8)	rad
S/N _{TESS}	20.28	153.52	54.77	10.51	10.65	19.365	

Notes. Frequency, amplitude and phase errors are given as last-digit errors in parentheses and were calculated following Montgomery & Odonoghue (1999). Frequencies F₃, F₅, and F₆ are identified as linear combinations in the top line.

with the grid of plane-parallel MARCS atmospheric models (Gustafsson et al. 2008). The library of the departure coefficients for this grid was calculated based on the model atom developed for O by Sitnova et al. (2013), for Na by Alexeeva et al. (2014), for Ca by Sitnova et al. (2018) and for Ba by Mashonkina et al. (1999).

SME implements two methods for estimating parameter uncertainties when fitting stellar spectra. The first is a standard estimate of the confidence interval based on covariance matrix. This matrix is just the inverse of the Marquardt-Levenberg Hessian matrix approximation computed at the best fit solution (see, e.g. Press et al. 2002, Section 15 Modelling of Data). The covariance matrix is stored as part of the SME output structure. The main diagonal contains the squares of confidence intervals (1σ for normal distribution of uncertainties) for all free parameters of the fit. This is true under the assumption of perfect model (that is the residuals of the fit gradually go to zero as data accuracy improves). Such a situation will correspond to a reduced χ^2 reaching unity, which is seldom the case in spectral synthesis. In practice, for χ^2 values larger than 1 this method gives highly underestimated values of uncertainties. In our error estimates using method 1 we multiply the main diagonal numbers by the reduced χ^2 . The second more heuristic approach described in Piskunov

& Valenti (2017) and implemented in Ryabchikova et al. (2016) is based on the statistical analysis of the residuals. In this case, the focus is on the core of the distribution that, given good statistics, resembles a normal distribution. Therefore, the new method provides very reasonable uncertainty estimates for parameters that affect large number of data points (e.g., effective temperature, metallicity, velocities). The estimates are less robust in case only a small number of spectral elements is affected (e.g., surface gravity, individual abundances for species represented by one or a few lines etc.). For abundance estimates of Sr, Nd, and Eu we applied the spectrum fitting procedure used in the BinMag6 code (Kochukhov 2018).

Synthetic spectra are calculated with the model atmosphere and abundance table derived by the SME procedure, while Sr, Eu, Nd abundances are varied to reach the best fit. For the Sr and Eu abundance estimates, a fit of the synthetic spectrum to the observed one was performed in the 4200–4230 Å region which contains the Sr II λ 4215.52 Å and Eu II λ 4205.05 Å lines. Additionally, the Eu II line at λ 6645.11 Å was fitted. The spectral region 5200–5350 Å was examined for the Nd abundance. This region contains many Nd II and the strongest Nd III lines, which appear

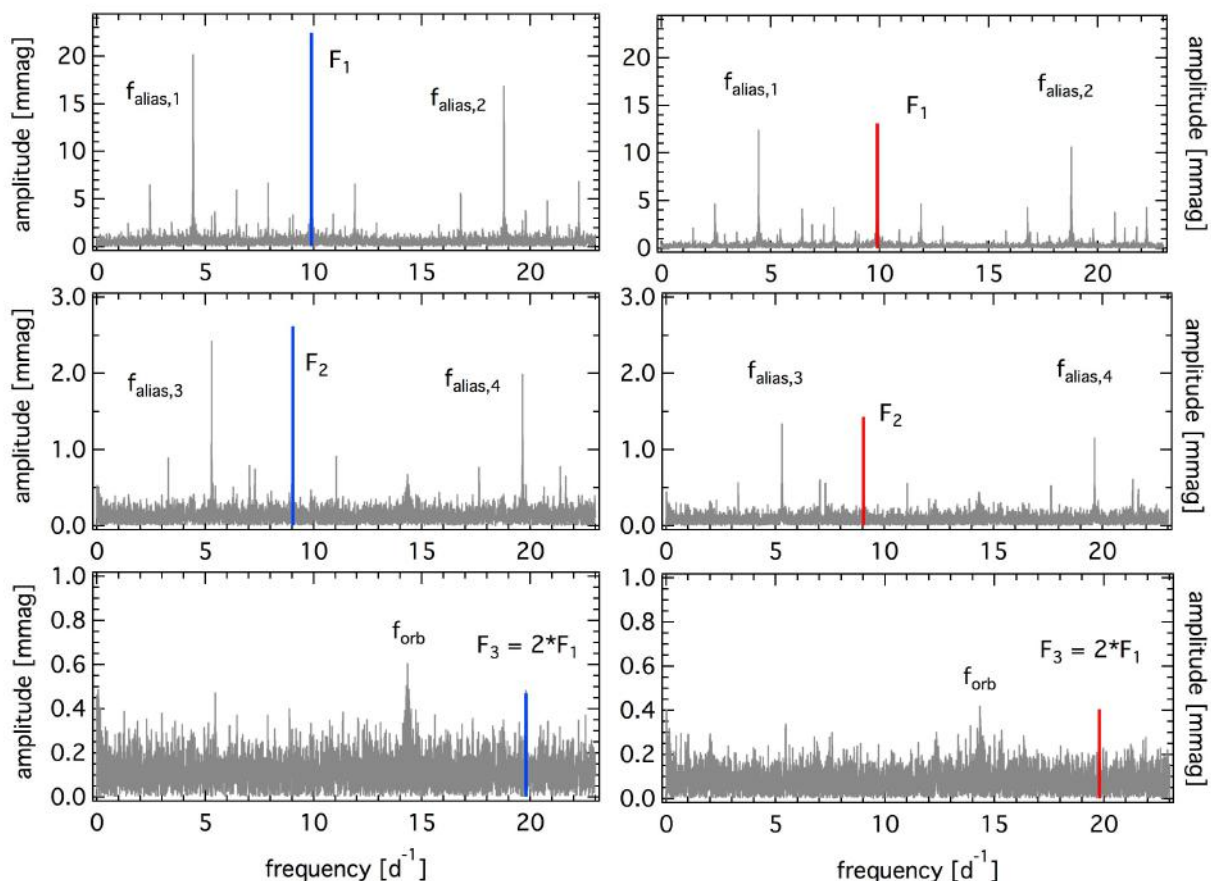


Fig. 3. Amplitude spectra of the BRITE-Constellation data obtained in 2016: BAB blue filter data are shown on the left side, UBr red filter data on the right side. Top panels show the amplitude spectra of the original data with F_1 identified, the middle panels illustrate the amplitude spectra after prewhitening F_1 , and the bottom panels those after prewhitening F_1 and F_2 . An explanation for the identified alias frequencies is given in the text.

Table 4. Atmospheric parameters of β Cas.

Parameter	err ₁	err ₂	Che et al. (2011)		Gray et al. (2003b)	
			Model 1	Model 2		
T_{eff} [K]	6920	35	140	6825	6897	6915
$\log g$ [dex]	3.53	0.16	0.58	3.57	3.59	3.49
$[M/H]$	-0.11	0.04	0.12	-	-	-0.02
$v_e \sin i$ [km s ⁻¹]	73.6	8.1	7.0	72.4	79.8	-
v_{mic} [km s ⁻¹]	4.1	0.4	0.5	-	-	3.1

Notes. Apparent parameters from modelling by Che et al. (2011) are given in columns 5-6. The last column contains parameters derived by Gray et al. (2003b).

in stars with high overabundance of the rare-earth elements. The error estimates for Sr, Nd, Eu are obtained using method 1.

The final parameters of β Cas derived from our study are $T_{\text{eff}} = 6920$ K, $\log g = 3.53$, $[M/H] = -0.11$, $v_e \sin i = 73.6$ km s⁻¹, and microturbulent velocity, $v_{\text{mic}} = 4.1$ km s⁻¹. They are listed together with the error estimates from both methods (err₁ and err₂) and a comparison to literature values in Table 4.

As described above, our SME analysis was performed using a grid of plane-parallel atmospheric models. The surface integration implemented in SME assumes a spherical star with a homogeneous surface. However, according to Che et al. (2011), β Cas is a star rotating rapidly close to its critical velocity, and hence

has inhomogeneous temperature and gravity surface distributions. The authors modelled β Cas using two methods, and provided apparent effective temperatures, luminosities and masses. The corresponding effective temperatures and gravities for both models – the modified von Zeipel model (Model 1) and the Lucy model (Model 2) – are given in columns 5 and 6 of Table 4. Within the error limits our parameters agree with those obtained by Che et al. (2011). They also agree to the parameters derived by Gray et al. (2003b) from spectroscopy.

The results of the abundance analysis are presented in Table 5. Columns err₁ and err₂ list the errors of the abundances according to the two methods for error determination implemented in SME as described before. The last column shows relative to

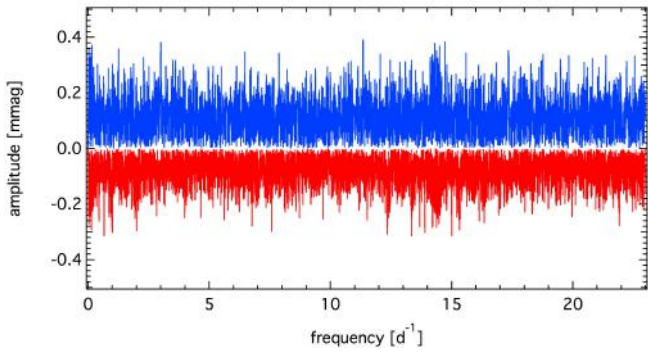


Fig. 4. Residual amplitude spectra for the 2016 BAB data (in blue pointing upwards) and UBr data (in red pointing downwards).

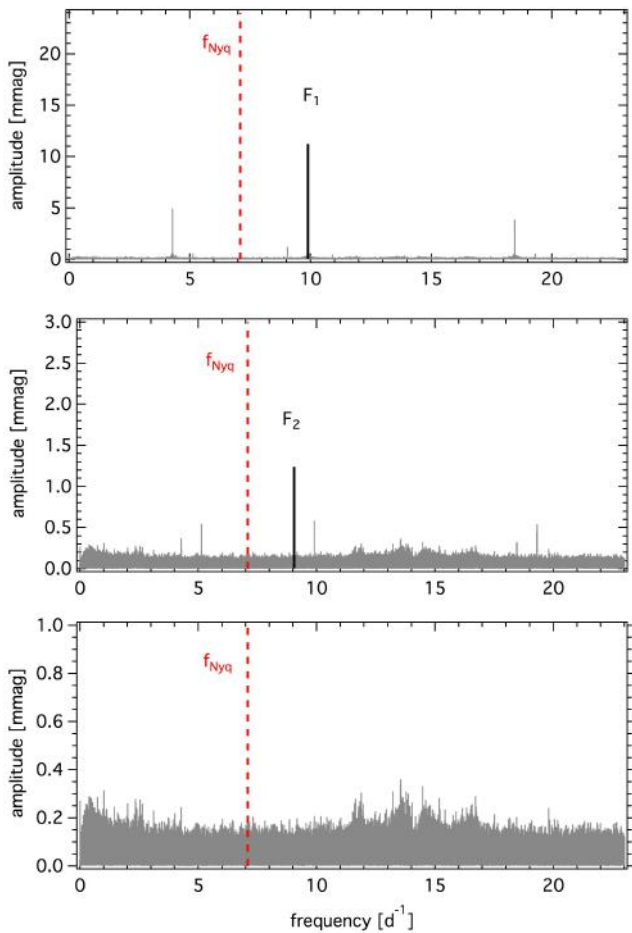


Fig. 5. Amplitude spectra of the SMEI data: original data with F_1 identified (top panel), amplitude spectra after prewhitening with F_1 and showing F_2 (middle panel), and residuals (bottom panel). The position of the Nyquist frequency is marked in red.

solar values. The solar abundances are taken from Scott et al. (2015b,a) and Grevesse et al. (2015).

Chemical species marked by asterisks in Table 5 have few lines in the analyzed parts of the spectrum, therefore their abundances are very uncertain. Sodium and barium also have few lines but they are strong enough to provide a reasonable abundance estimate. Abundances of heavy elements are rather uncer-

Table 5. Abundances in the atmosphere of β Cas.

Element	$\log(N_{el}/N_{tot})$	err ₁	err ₂	$[N_{el}/N_{tot}]$
C*	-3.52	0.10	0.26	+0.09
O	-3.19	0.02	0.06	+0.16
Na	-5.87	0.03	0.12	-0.04
Mg	-4.57	0.06	0.16	-0.12
Al*	-5.81	0.23	0.11	-0.20
Si	-4.55	0.07	0.19	-0.02
Ca	-5.84	0.05	0.15	-0.12
Sc	-8.93	0.10	0.15	-0.05
Ti	-7.14	0.03	0.17	-0.03
Cr	-6.54	0.05	0.22	-0.12
Fe	-4.76	0.02	0.13	-0.18
Ni	-6.05	0.08	0.29	-0.21
Sr*	-9.13	0.10		+0.08
Y	-9.75	0.09	0.18	+0.08
Zr	-9.40	0.19	0.37	+0.05
Ba	-9.74	0.03	0.06	+0.05
Nd*	-10.57	0.10		+0.05
Eu*	-11.40	0.10		+0.12

Notes. Columns err₁ and err₂ list the errors of the abundances according to the two methods for error determination implemented in SME. The last column shows the abundances relative to solar values. The solar abundances are taken from Scott et al. (2015b,a) and Grevesse et al. (2015).

tain, too, but obviously they are close to the solar values. The atmosphere of β Cas is slightly metal deficient in iron peak elements and slightly overabundant in both light elements C and O, and heavy elements. Overall, the observed abundance pattern of β Cas is similar to the atmospheric abundances of another δ Sc-type star HD 261711 (Zwintz et al. 2013).

Figures 8 and 9 illustrate our best fitting solution using the derived fundamental parameters and atmospheric abundances in the region around $H\alpha$ and in two selected regions.

5. Spectropolarimetric analysis

5.1. LSD profiles

We used the Least Square Deconvolution (LSD) technique (Donati et al. 1997) to create mean Stokes I, Stokes V, and N profiles of each Narval polarimetric sequence. The velocity step used for the LSD profiles is 2.6 km s^{-1} .

To perform LSD, a list of stellar lines present in the spectrum, together with their wavelength, depth, and Landé factor, is necessary. We started from a linelist extracted from the VALD3 atomic database for the effective temperature ($T_{\text{eff}} = 6920 \text{ K}$), gravity ($\log g = 3.53$), microturbulence (4.1) and chemical abundances of β Cas determined above, and restricted it to lines with depth larger than 1% of the continuum level. From this template list we rejected the hydrogen lines, as well as lines blended with hydrogen, that were not present in the spectrum, or that were contaminated by telluric or interstellar features. We then adjusted the line depths given in the linelist to the ones observed in the real spectrum. This method is described in more details in Grunhut et al. (2017). The final linelist includes 5104 lines, with a mean wavelength of 526.47 nm and a mean Landé factor of 1.2.

LSD profiles obtained on the same night were averaged. When 10 or 15 spectra were available for the same night, averages of the LSD profiles by group of 5 (as presented in Ta-

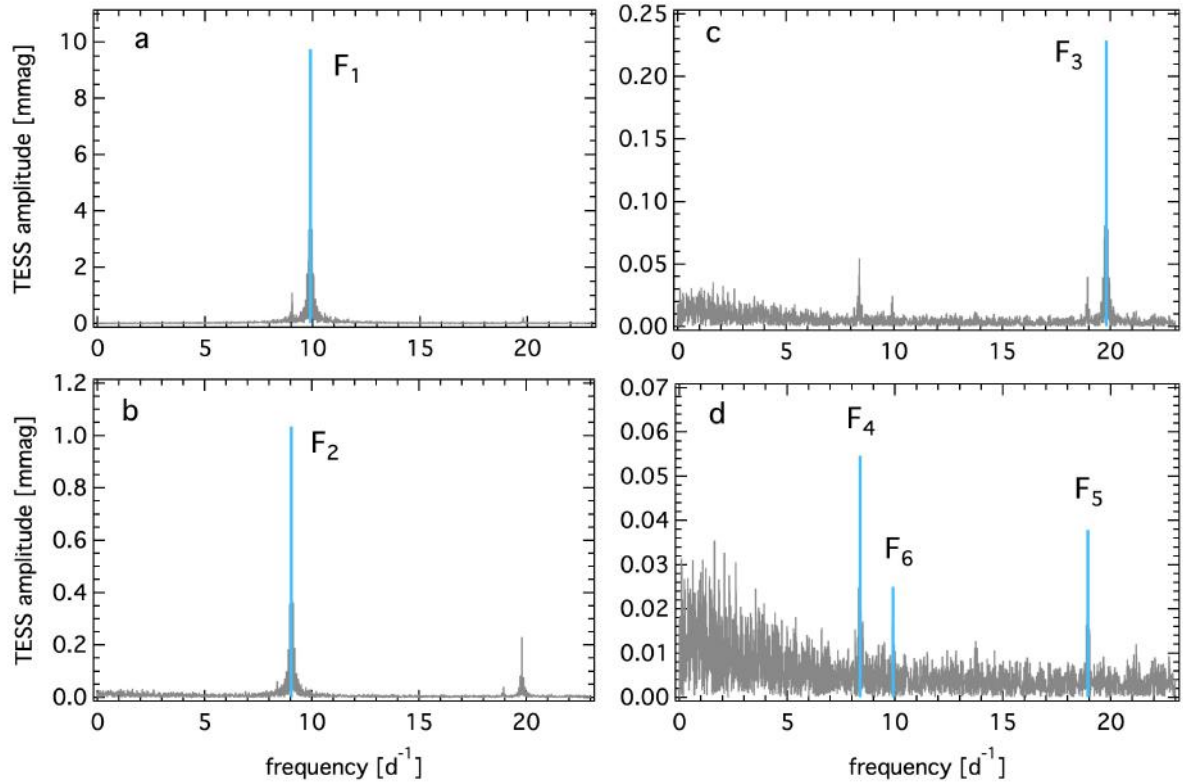


Fig. 6. Fourier analysis of the TESS data: The amplitude spectrum of the original data with F_1 identified (panel a), amplitude spectrum after prewhitening F_1 (panel b), amplitude spectrum after prewhitening F_1 and F_2 (panel c), and amplitude spectrum after prewhitening F_1 , F_2 , and F_3 .

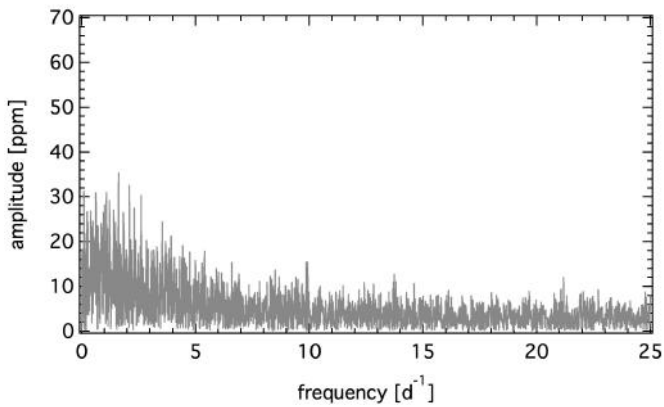


Fig. 7. Residual amplitude spectrum of the TESS data.

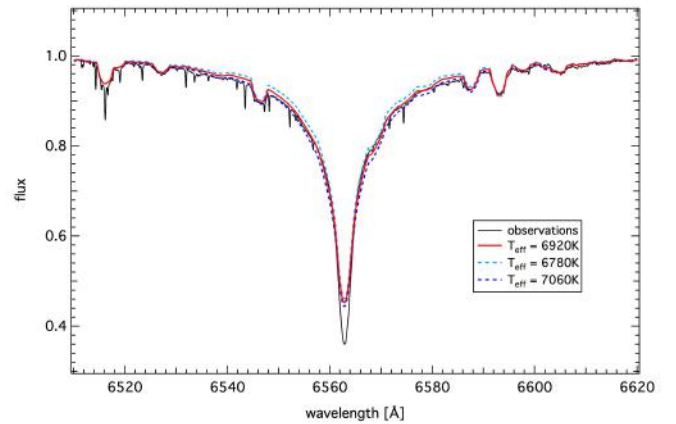


Fig. 8. Region of the $H\alpha$ line for β Cas: the observed spectrum is shown in black and the calculated synthetic spectrum with the final adopted parameters of $T_{\text{eff}} = 6920\text{ K}$ and $\log g = 3.53$ in red. The dashed light blue line represents a synthetic spectrum with a 140 K lower T_{eff} , and the dashed dark blue line a synthetic spectrum with a 140 K higher T_{eff} .

ble 2) have been computed. We finally obtained 19 LSD profiles. These averaged LSD profiles have a S/N ranging from 68000 to 125000 in Stokes V and N, and 5000 to 10000 in Stokes I. They are shown in Fig. 10.

The LSD Stokes I profiles show clear variations related to the δ Scuti pulsations. The LSD Stokes V profiles show weak and rather complex Zeeman signatures, while N does not show such signal. This is indicative of the presence of a magnetic field in β Cas.

5.2. Magnetic analysis

Using the LSD Stokes V and I, and a center-of-gravity method (Rees & Semel 1979; Wade et al. 2000), we calculated the longitudinal magnetic field value B_l corresponding to the observed Zeeman signatures in the velocity range defined by the Stokes I line width, i.e. $\pm 90\text{ km s}^{-1}$ around the line center. We applied the same calculation to the N profiles to obtain N_l . These values are reported in Table 6 for the averaged profiles. We find that

pulsational velocity amplitude and phase were adjusted to reproduce the observed RV curve. Based on this analysis, we inferred $v_e \sin i = 75 \text{ km s}^{-1}$, which is close to the value of 73.6 km s^{-1} found in Sect 4, and found that an axisymmetric quadrupolar mode provides a marginally better description of the pulsational Stokes I profile variability pattern compared to the radial or axisymmetric dipolar pulsation.

In a second step we used the previously determined broadening and pulsational parameters to reconstruct the magnetic field geometry of β Cas for different trial values of the stellar rotational period. This modelling was based on the 15 Stokes V averaged spectra obtained in 2015 (i.e. number #5 to #19 in Table 2).

Che et al. (2011) estimated the rotational period to be $1.12^{+0.03}_{-0.04} \text{ d}^{-1}$. This corresponds to $P_{\text{rot}} = 0.89^{+0.03}_{-0.02} \text{ d}$. For the ZDI modelling, we considered a P_{rot} interval of $0.847\text{--}1.174 \text{ d}$, which encompasses the $\pm 2\sigma$ rotational period range from Che et al. (2011) and extends all the way to 1.172 d corresponding to the difference between the two main frequencies present in the BRITE data. The resulting relative χ^2 of the fit to Stokes V profiles is illustrated as a function of trial rotation period in Fig. 11. We found that multiple rotation periods provide good description of our Stokes V observations of β Cas. Specifically, the lowest χ^2 of the fit to the observed LSD profiles is achieved with P_{rot} of 0.868 , 0.890 , and 1.145 d . All three rotation periods result in qualitatively similar magnetic field maps and a non-sinusoidal behavior of the B_l values. The ZDI field geometry and Stokes V profile fits corresponding to $P_{\text{rot}} = 0.868 \text{ d}$ are illustrated in Fig. 12 whereas the B_l values folded with this period are shown in Fig. 13.

The three rotation periods mentioned above result in a qualitatively different phase distribution of the 15 Stokes V observations. The period $P_{\text{rot}} = 0.868 \text{ d}$ yields three pairs of Stokes V profiles, obtained 7 nights apart, with very similar rotational phases. These profiles closely agree with each other both in the observations and in the model (see Fig. 12). This is unlikely to be a coincidence. On the other hand, periods $P_{\text{rot}} = 0.890 \text{ d}$ and $P_{\text{rot}} = 1.145 \text{ d}$ yield no pairs of close rotational phases. These periods might therefore represent aliases appearing due to a relatively sparse rotational phase sampling of our observations. For this reason, we consider $P_{\text{rot}} = 0.868 \text{ d}$ to be the most likely rotational period of β Cas. The ZDI inversion with this period also provides a magnetic map with 14% lower total energy compared to the reconstruction results for the other two periods. Formally, $P_{\text{rot}} = 0.890 \text{ d}$ cannot be excluded as it produces a low χ^2 and is consistent with the results of Che et al. (2011). However, it does not explain the observed repetition of Stokes V profile shapes. The period $P_{\text{rot}} = 1.145 \text{ d}$ has the same problem; in addition it is formally excluded (at 8.4σ level) by the interferometric results of Che et al. (2011).

For each of the three plausible periods we tested the possibility of the presence of a solar-like differential rotation. In all three cases equally good fits can be obtained with no differential rotation ($\alpha \equiv \Delta\Omega/\Omega_e = 0.0$) and with a combination of a shorter equatorial period and a moderate solar-like differential rotation ($\alpha = 0.01\text{--}0.02$). In other words, the existing observational data does not allow us to meaningfully constrain differential rotation.

Using the ZDI results obtained for $P_{\text{rot}} = 0.868 \text{ d}$, we find the maximum local field strength of 87 G and the mean field strength (averaged over the visible hemisphere) of 20 G . Considering the spherical harmonic description of the surface field topology implemented in INVERSLSD (see Kochukhov et al. 2014 for details), we infer that the magnetic field of β Cas is predominantly poloidal (65% of the field energy is concentrated in poloidal modes) and contains a comparable contribution of axisymmet-

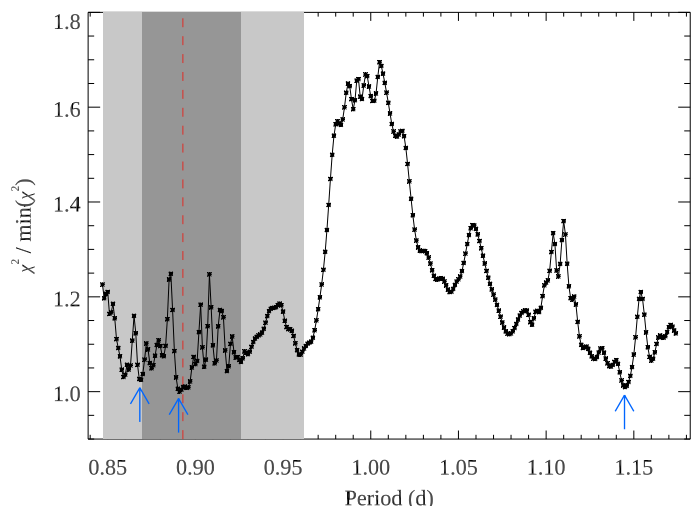


Fig. 11. Relative χ^2 of the fit to Stokes V LSD profiles as a function of rotational period. The vertical dashed line and the shaded regions correspond to the rotational period determined by Che et al. (2011) and the corresponding $1\text{--}2\sigma$ error bars. The arrows indicate the three rotational periods discussed in the text.

ric ($|m| < \ell/2$, 60%) and non-axisymmetric ($|m| \geq \ell/2$, 40%) harmonic components. In terms of its spatial scale, the field energy peaks at $\ell = 1$ (14% of the total energy) and then gradually diminishes until $\ell = 10$. Then, there is a prominent secondary maximum at $\ell = 12\text{--}15$, corresponding to the small-scale structure seen in the reconstructed magnetic maps. The energy contribution of all modes with $\ell \leq 27$ appears to be non-negligible ($\geq 1\%$ of the total magnetic field energy). Given the high $v_e \sin i$ of the star and the resolving power of our spectra, ZDI is potentially sensitive to modes with ℓ up to ≈ 100 (Fares et al. 2012).

6. Discussion

6.1. δ Scuti pulsations

δ Scuti pulsators are intermediate mass stars located in the lower part of the so-called classical instability strip with spectral types between A2 and F2 (Rodríguez & Breger 2001) that can be in the pre-main sequence, main sequence, or post-main sequence evolutionary stages. δ Scuti stars are typically multi-periodic oscillators that can show very rich pulsation frequency spectra (e.g., Poretti et al. 2009) that challenge asteroseismic analyses and the theoretical interpretation of the observed pulsation frequencies.

Two of the most prominent physical effects that complicate the asteroseismic analysis in δ Scuti stars, are (i) moderate to fast rotation which can cause a splitting of the pulsation modes with same n and ℓ values but different m values, and (ii) the presence of magnetic fields which is a rather recent discovery for δ Scuti stars (Neiner & Lampens 2015; Neiner et al. 2017).

β Cas is a special case in this context because observationally it shows only three independent p-mode pulsation frequencies and not several dozen to hundreds of modes. The reason might be connected to the inclination angle of only 19° (Che et al. 2011) and the presence of the magnetic field. And despite β Cas' rather high rotational speed, no sign of a rotational splitting can be detected in the present observational material. As β Cas is an F-type star, it could also show g -mode pulsations. But our investigation did not detect any pulsational signal in the g -mode regime.

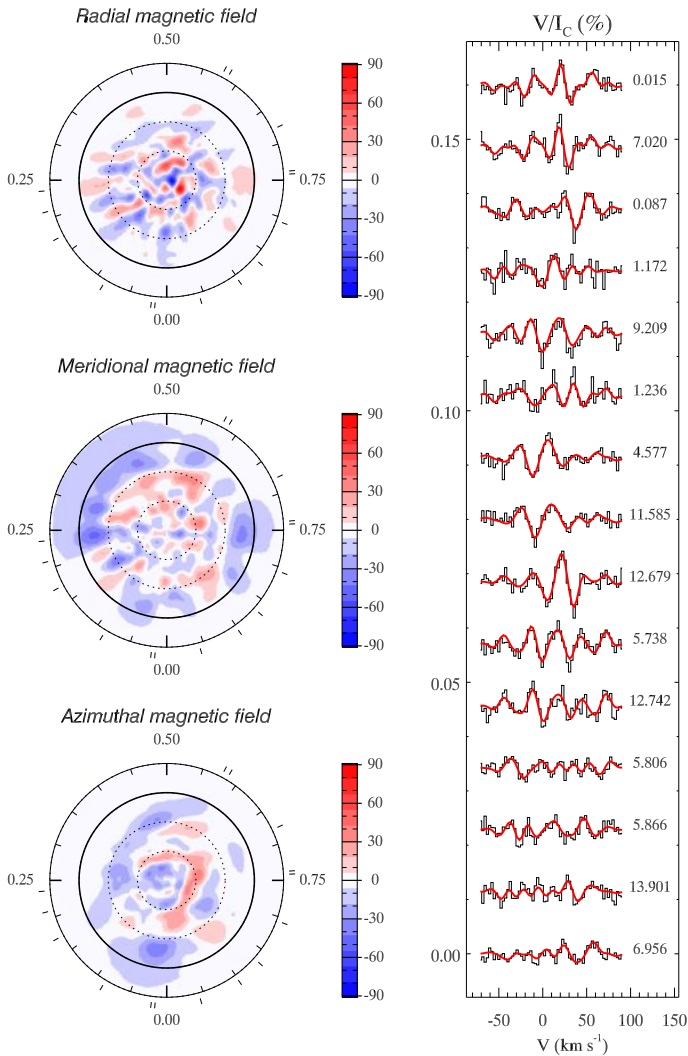


Fig. 12. Magnetic field maps of β Cas and corresponding Stokes V profile fits obtained with ZDI for $P_{\text{rot}} = 0.868$ d. The plots on the left side show the radial, meridional, and azimuthal magnetic field components in the flattened polar projection. The thick circle corresponds to the stellar equator. The colour bar indicates the field strength in gauss. The right panel shows the observed (histogram) and model (solid red curves) profiles, shifted vertically with an equidistant step. The rotational phases (calculated relative to $\text{HJD}_0 = 2457358.31370$) are indicated to the right of each line profile.

We calculated the pulsation constant, Q , based on our values for the three independent frequencies, F_1 at 9.89708d^{-1} , F_2 at 9.0437d^{-1} , and F_4 at 8.3847d^{-1} , and our fundamental parameters, $T_{\text{eff}} = 6920$ K and $\log g = 3.53$. The pulsation constant Q (Petersen 1976; Stellingwerf 1979) is defined as:

$$\log Q = -6.454 + \log P + 0.5 \log g + 0.1 M_{\text{bol}} + \log T_{\text{eff}}, \quad (1)$$

where P is the pulsation period in days, and M_{bol} is the bolometric magnitude, which is defined as $M_{\text{bol}} = M_V + \text{BC}$. The absolute magnitude of 1.14 mag is calculated from the distance of 16.8 pc, and the bolometric correction, BC, can be calculated from the relation given by Reed (1998).

$$\begin{aligned} \text{BC} = & -8.499 (\log T_{\text{eff}} - 4)^4 + 13.421 (\log T_{\text{eff}} - 4)^3 - \\ & 8.131 (\log T_{\text{eff}} - 4)^2 - 3.901 (\log T_{\text{eff}} - 4) - 0.438. \end{aligned} \quad (2)$$

The pulsation constant has a value of 0.033 for fundamental mode pulsation ($n = 0$), 0.025 for the first overtone ($n = 1$),

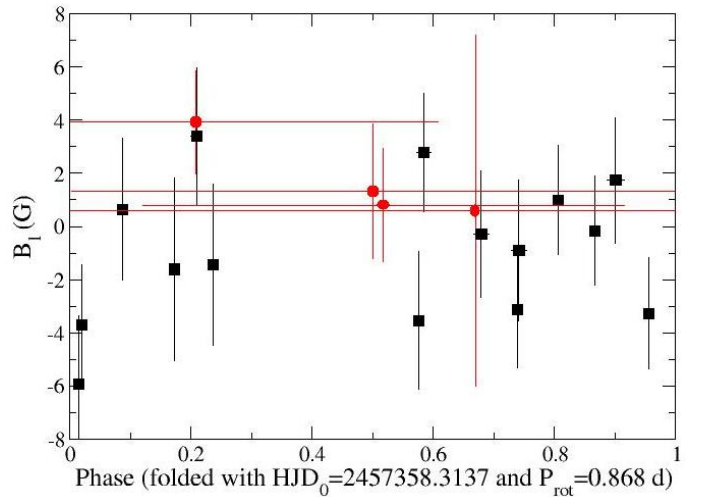


Fig. 13. Longitudinal magnetic field values folded with the rotation period 0.868 d, with phases calculated relative to $\text{HJD}_0 = 2457358.3137$ corresponding to the start of the 2015 observations. The red symbols indicate the data obtained in 2013 and 2014, which thus have a much larger phase error compared to the 2015 dataset.

0.020 for the second overtone ($n = 2$), and 0.017 for the third overtone ($n = 3$).

The corresponding Q values for F_1 at 9.89708d^{-1} , F_2 at 9.0437d^{-1} , and F_4 at 8.3847d^{-1} are 0.018, 0.020, and 0.022, respectively. The calculated Q value for F_4 lies between the first and second overtone pulsation mode; no clear identification of the radial order is therefore possible. F_2 can be identified as second overtone, and F_1 possibly as third overtone pulsation. The latter is in contradiction to earlier reports in the literature that identified F_1 as a first overtone pulsation mode (Rodríguez et al. 1992). Together with the results from our Stokes I LSD profile analysis (see Sect. 5.3), F_1 would then be a possible $n = 3$, $\ell = 2$, and $m = 0$ p-mode.

6.2. Amplitude variability

We have used data for β Cas obtained in four specific passbands: the BRITe blue filter (390 – 460 nm), the BRITe red filter (550 – 750 nm), the passband of SMEI (450 – 950 nm), and the passband of TESS (600 – 1000 nm). For each of the two pulsation frequencies that appear in data from all instruments, it is evident that the by far highest amplitude can be measured from the BRITe blue filter data, followed by the BRITe red amplitude and the amplitude in the SMEI passband. The pulsation amplitudes are smallest in the reddest passband of the TESS camera.

It has been reported several times in the past, that some of the pulsation amplitudes in δ Scuti stars show time-dependent behaviour (e.g., Breger et al. 1991; Breger & Bischof 2002; Zwintz et al. 2019). The origin of amplitude variability can be either intrinsic due to beating of unresolved frequencies, nonlinearity, or mode-coupling, or extrinsic due to binary and multiple systems. A detailed overview of the amplitude modulation in δ Scuti stars is given in Bowman et al. (2016).

We examined the amplitude variability of β Cas by first studying the annual behaviour in the BRITe red and blue filters based on the four years of consecutive observations (see Table 1). It can clearly be seen from Fig. 14 that there is no significant modulation of the amplitudes of F_1 and F_2 in both BRITe filters.

In a second step we used the longest and best BRITe-Constellation data obtained in single observing seasons to study

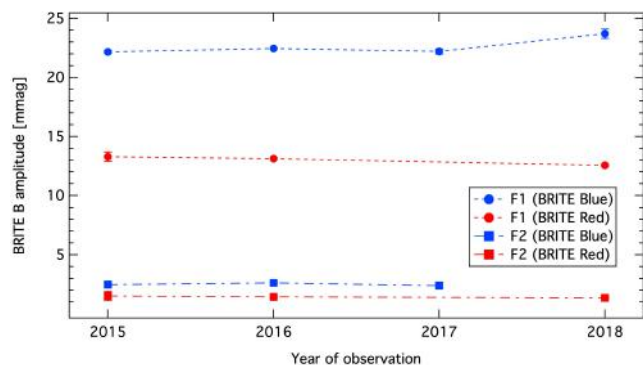


Fig. 14. Annual behaviour of the amplitudes of the two main pulsation frequencies, F_1 (filled circles) and F_2 (filled squares) based on the BRITE-Constellation observations in the B (blue) and R (red) filter conducted every year from 2015 to early 2019. The error bars in the figure are in some cases smaller than the symbol size.

the behaviour of the pulsation amplitudes on the shorter time scale of a few months. The first season of BRITE observations of β Cas in 2015 yielded too short time bases (i.e., ~ 58 days) for such an analysis. The BAb data obtained in 2017 and in 2018 have insufficient quality for such an analysis. Therefore, we restrained the analysis of shorter period amplitude variability on the BAb and UBr data obtained in 2016 and the BTr data from 2018. For each of the three data sets, we calculated 30-day subsets with 20-day overlaps, and find only very moderate modulations of the pulsation amplitudes of F_1 and F_2 (see Fig. 15).

Frequency F_1 seems to show some periodicity in the BAb 2016 and the BTr 2018 data. We therefore tried to see if a common period can be found that explains the moderate amplitude variability seen in Fig. 15. The amplitudes of F_1 in the BAb 2016 data vary with a period of ~ 91 days, the variability in the BTr 2018 data yields a period of ~ 101 days. As the BAb 2016 data set has a time base of 145 days and the BTr 2018 data set a time base of 129 days, the data only cover slightly more than one period of any potential amplitude variation. For completeness, we also calculated the period of a potential amplitude variability of F_1 using the UBr 2016 data, but no significant period was determined. Therefore, based on the available observational material, we cannot find an unambiguous value for a potential modulation of the pulsation amplitudes for F_1 .

As a final check, we used the TESS data set which is considerably shorter in time base, but has significantly less noise compared to the BRITE observations. Consequently, we split the light curve in the four blocks that are introduced by the visible gaps (see the top panel of Fig. 2). The blocks contain 8.24 d, 10.0, 9.9 d, and 10.5 d of uninterrupted data with nearly 100% of duty cycle. For each of the blocks, we determined the corresponding amplitudes of F_1 and F_2 . The third independent pulsation frequency, F_4 , has such a low amplitude that it does not appear in each of the four subsets. Hence, we had to discard it from our study of the pulsation amplitude behavior. Figure 16 again illustrates that the amplitudes of F_1 and F_2 do not vary much during the 49.686 days of TESS observations.

6.3. Non-binarity of β Cas

In the past, it was speculated several times that β Cas is actually a binary system. Although a detailed analysis by Abt (1965) illustrated the non-detection of a secondary component around β Cas,

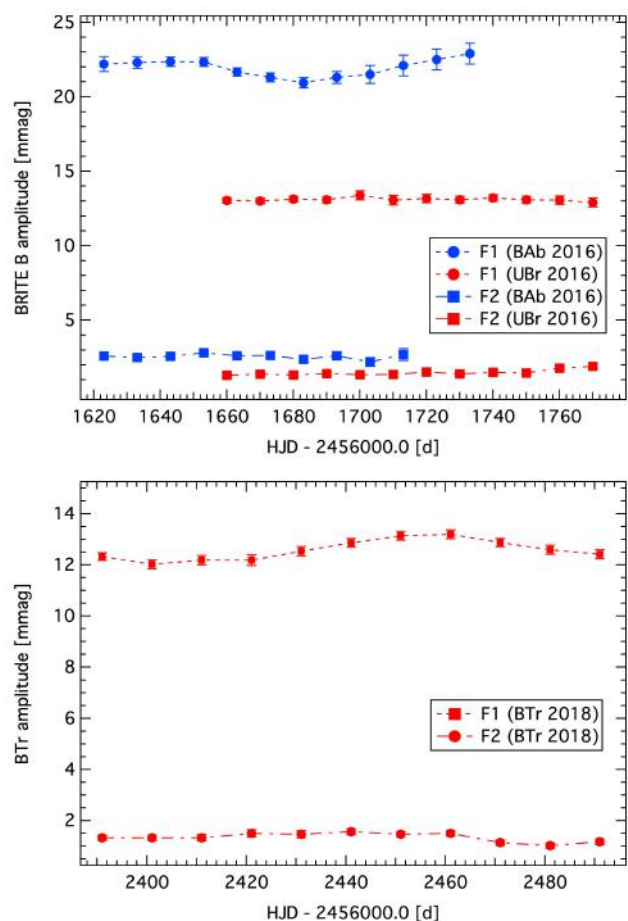


Fig. 15. Seasonal amplitude behaviour of the two main pulsation frequencies, F_1 (filled circles) and F_2 (filled squares). Top panel: 30-day subsets with 20-day overlaps for the BAb 2016 (blue) and UBr 2016 (red) data (top panel); bottom panel: 30-day subsets with 20-day overlaps for the BTr 2018 data (red). The error bars in the figure are in some cases smaller than the symbol size.

a recent study by Liakos & Niarchos (2017) again lists the star as a possible binary. Therefore, we applied the time delay method (Murphy & Shibahashi 2015) on our nearly four-years long photometric timeseries to check independently if a secondary can be detected.

The orbital movement of two components in a binary system introduces changes in the pulsation signal of δ Scuti pulsators throughout the orbit (Shibahashi & Kurtz 2012). This results in frequency modulation, where the amplitude spectrum shows additional peaks near the intrinsic pulsation frequencies and phase modulation, where the intrinsic pulsation signal arrives earlier (or later) depending on the orbital stage. This phase modulation is equivalent to the concept of light arrival time delays, i.e., the pulsation signal arrives later if the star is further away and vice versa. This time delays depend on the orbital parameters and it is therefore possible to constrain the orbit if time delays can be measured from the lightcurve (Murphy & Shibahashi 2015).

We used *maelstrom* (Murphy et al. 2020, under review) to investigate our data sets for any time delay signal. Neither data set shows significant time delays. We therefore exclude a binary signal with $a \sin(i)/c \lesssim 5$ s (see Fig. 8 in Murphy et al. 2020) and periods > 1000 days.

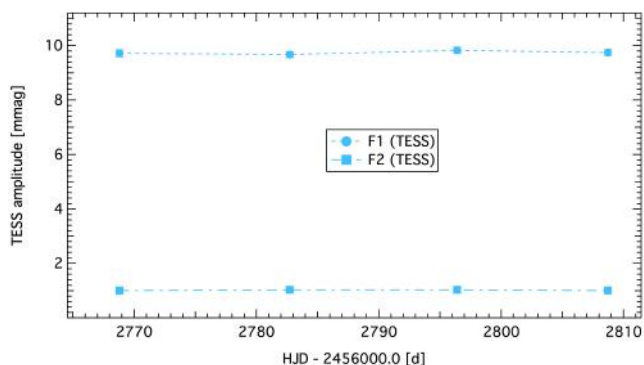


Fig. 16. Amplitude behaviour of the two main pulsation frequencies, F_1 (filled circles) and F_2 (filled squares) based on four subsets of TESS data. The error bars in the figure are in some cases smaller than the symbol size.

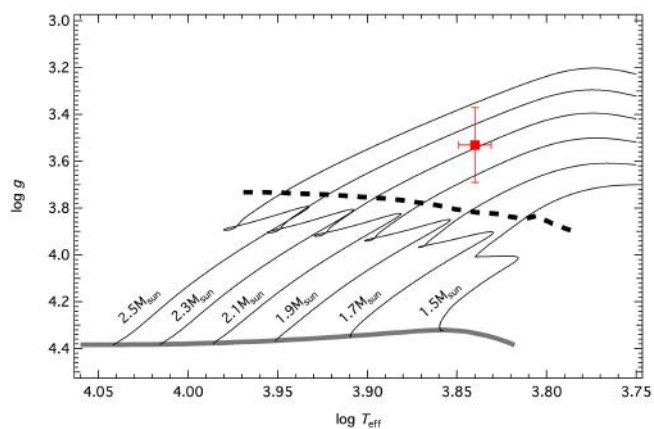


Fig. 17. Position of β Cas in the Kiel diagram based on our final adopted values for T_{eff} and $\log g$ (red square). Post-main sequence tracks have been calculated using MESA version r-12115 (Paxton et al. 2011, 2013, 2015, 2018, 2019). The location of the zero-age main sequence (ZAMS) is given as thick grey line, and the Terminal Age Main Sequence (TAMS) is marked as dashed line.

6.4. Evolutionary stage

Using the T_{eff} and $\log g$ values determined from our analysis and the errors taken from the second approach described in Sect. 4 (i.e., the err_2 values in Table 4), the position of β Cas in the Kiel diagram is shown in Fig. 17. From our analysis, we can confirm that β Cas' mass is around $2.1 M_{\odot}$, and that it has to be a rather evolved star moving away from the TAMS.

6.5. Structure of the magnetic field

Following the detection of a complex magnetic field on the surface of β Cas, we attempted to reconstruct the stellar field topology with the ZDI technique. The subset of 15 Stokes V averaged LSD profiles suitable for this analysis extends over about two weeks, corresponding to approximately 14 stellar rotations. These data alone are insufficient for an unambiguous determination of the rotational period and are not suitable for a refined investigation of, for example, latitudinal differential rotation, temporal field evolution, or variation of the field structure with pulsational phase. Nevertheless, we found a plausible rotational period, compatible with the period range suggested by the previ-

ous interferometric analysis, which phases the Stokes V profiles convincingly. Using this period we have successfully reproduced the circular polarisation observations with a fairly complex, yet static, magnetic field topology. The longitudinal field values follow a non-sinusoidal behavior, unlike dipolar fossil fields. Further high-cadence spectropolarimetric observations are required for probing the temporal evolution of this field and exploring its response to the global δ Scuti pulsations.

Finding such a complex surface magnetic field structure in a star with an effective temperature as high as 6920 K is very unusual. It is known that fossil magnetic fields exist in stars as cool as $T_{\text{eff}} \approx 6500$ K (Kochukhov 2003; Shulyak et al. 2010). On the other hand the hottest stars with dynamo magnetic fields were previously found with a temperature up to $T_{\text{eff}} \approx 6700$ K (Marsden et al. 2014; Seach et al. 2020). Judging by its complexity, the field of β Cas is almost certainly of dynamo origin. It is significantly more complex than any fossil fields of magnetic A, B, and O stars. Instead, its structure resembles the surface magnetic field topologies of well-studied cool, young, active stars such as AB Dor (Donati et al. 1999), V410 Tau (Kochukhov 2015), and Tap 26 (Yu et al. 2017). Thus, our study establishes that the dynamo fields can exist in stars with T_{eff} of up to ≈ 6900 K. It is possible that the rapid rotation of β Cas, by increasing the thickness of the surface convection layer at the equator, facilitates the dynamo action, allowing it to exist to a higher T_{eff} than in slowly rotating stars.

Finally, about $\sim 10\%$ of O, B and A stars host a fossil field on the main sequence with a typical dipolar field strength of 3 kG. The strength of these fields at the stellar surface has been shown to decrease with time due to magnetic flux conservation as the stellar radius increases, and probably to additional decay such as Ohmic decay (e.g. Shultz et al. 2019). Since β Cas is evolved, we cannot exclude that it hosts such a fossil field that has reached a faint strength at the surface and is interacting with the dynamo field in the surface layer. Therefore, β Cas is possibly also an interesting target for the study of the evolution of fossil field and for the interaction between fossil and dynamo fields.

7. Conclusions

For several reasons, β Cas is an unusual star that combines several physical properties:

- (i) It is a δ Scuti pulsator that shows only three independent pulsation frequencies even in multiple seasons of space photometry down to the few ppm-level. The highest amplitude mode, F_1 , can be identified as an $n = 3$, $\ell = 2$, $m = 0$ mode based on the pulsation constant and the ZDI analysis.
- (ii) It is one of the handful of δ Scuti stars known to date to show a measurable magnetic field.
- (iii) Additionally, β Cas' magnetic field structure is quite complex, which is unusual in a star with an effective temperature as high as 6920 K. According to its complexity, the field of β Cas is almost certainly of dynamo origin, which makes it the first δ Scuti object with a dynamo magnetic field. β Cas' rapid rotation may lead to a thicker surface convective layer and explain how a dynamo can exist.

Therefore, β Cas provides an interesting benchmark for the theoretical modelling of dynamo processes in thin convective envelopes of F-type stars and for the study of the transition region between fossil and dynamo fields..

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Appendix A: Additional BRITE and SMEI light curves

The data obtained by BAb and BLb as well as the data obtained by BHr and BTr in 2015 were combined to one blue filter and one red filter light curve, respectively. Their properties are described in Table 1. As can be seen in panels a and b of Fig. A.1, observations of BAb and BLb were conducted simultaneously, while BHr and BTr observed β Cas at distinct times. Figure A.1 also shows the BAb observations in 2017 (panel c) and the BTr and BAb observations in 2018 (panels d and e).

Figure A.2 shows the full light curve obtained by SMEI.

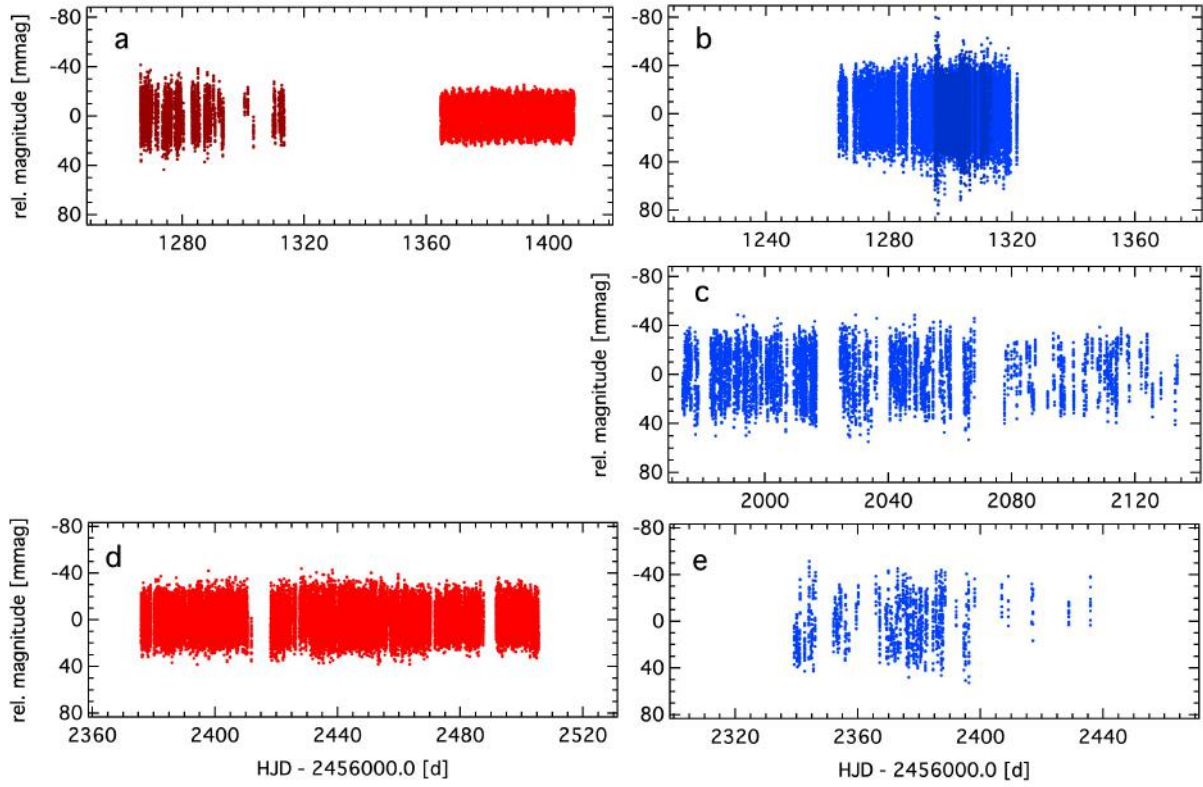


Fig. A.1. BRITE photometric time series obtained by BTr (brighter red in panel a), BHr (darker red in panel a), BAb (brighter blue in panel b) and BLb (darker blue in panel b) in 2015, by BAb in 2017 (panel c), by BTr (panel d) and BAb (panel e) in 2018.

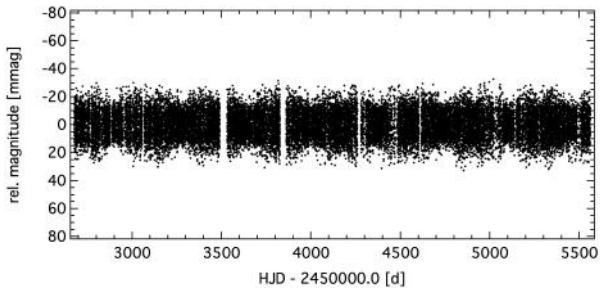


Fig. A.2. SMEI photometric time series.

Appendix B: Amplitude spectra and spectral windows

Below we provide additional figures illustrating the frequency analyses of the BRITE-Constellation 2015, 2017, and 2018 data as well as the spectral window functions for all data sets used in our analysis.

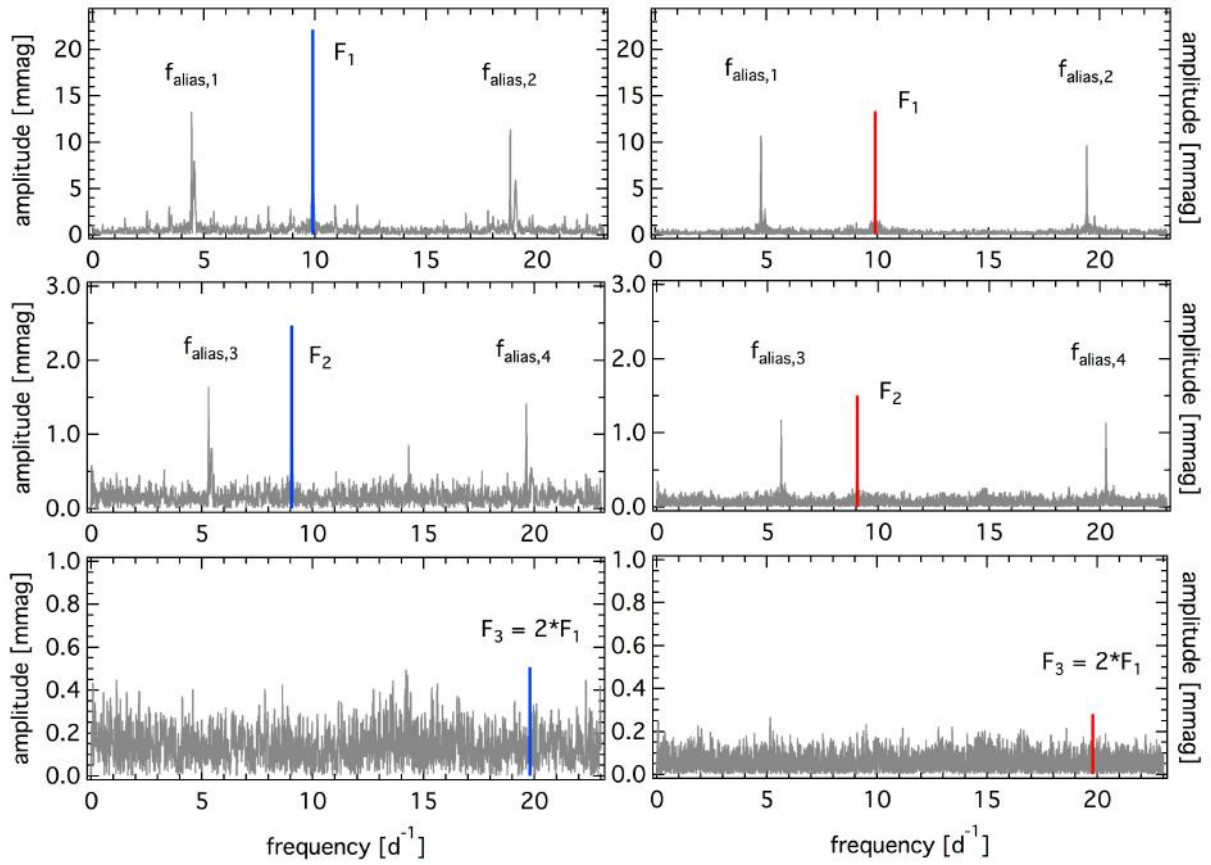


Fig. B.1. Amplitude spectra of the BRITE-Constellation data obtained in 2015: Combined blue filter data are shown on the left side, combined red filter data on the right side. Top panels show the amplitude spectra of the original data with F_1 identified, the middle panels illustrate the amplitude spectra after prewhitening F_1 , and the bottom panels those after prewhitening F_1 and F_2 . An explanation for the identified alias frequencies is given in the text.

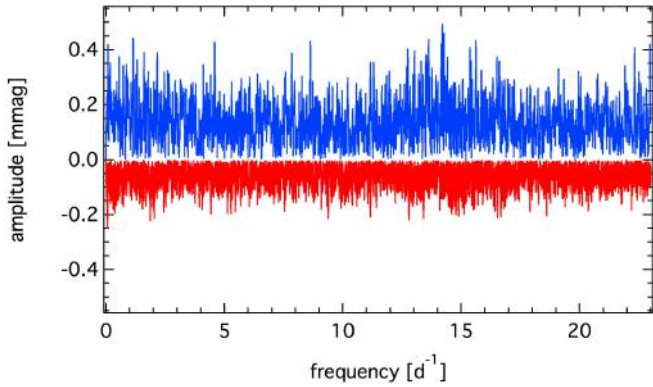


Fig. B.2. Residual amplitude spectra for the 2015 combined blue data (in blue pointing upwards) and combined red data (in red pointing downwards).

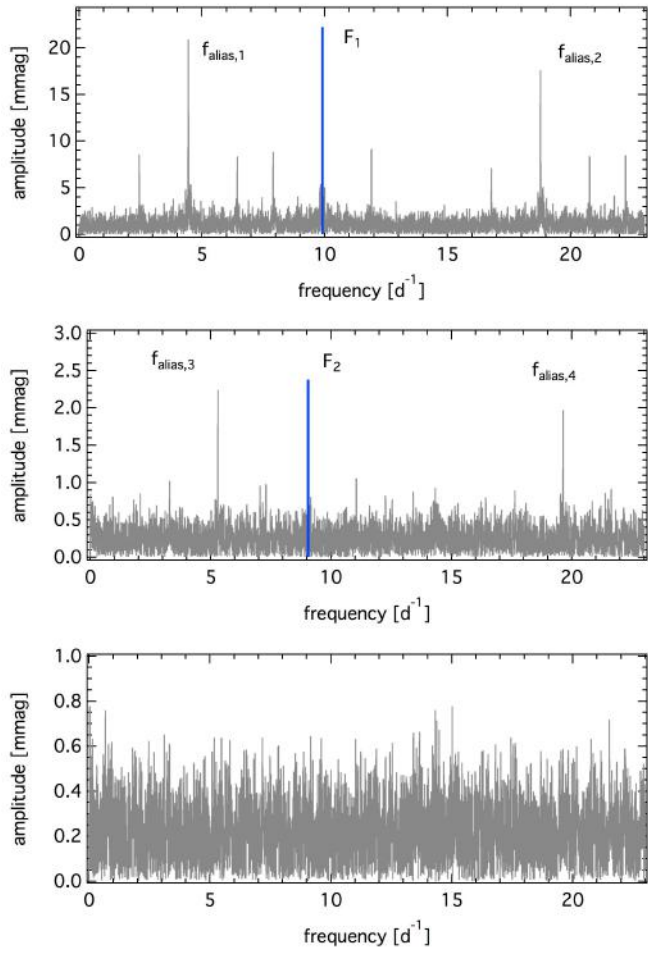


Fig. B.3. Amplitude spectra of the BRITE-Constellation data obtained in 2017 with BAb only: the top panel shows the amplitude spectrum of the original data with F_1 identified, the middle panel illustrates the amplitude spectrum after prewhitening F_1 , and the bottom panel shows the residuals. Please note that the noise of the 2017 BAb data is significantly higher than for all the other combined data sets, hence F_3 remains hidden in the noise.

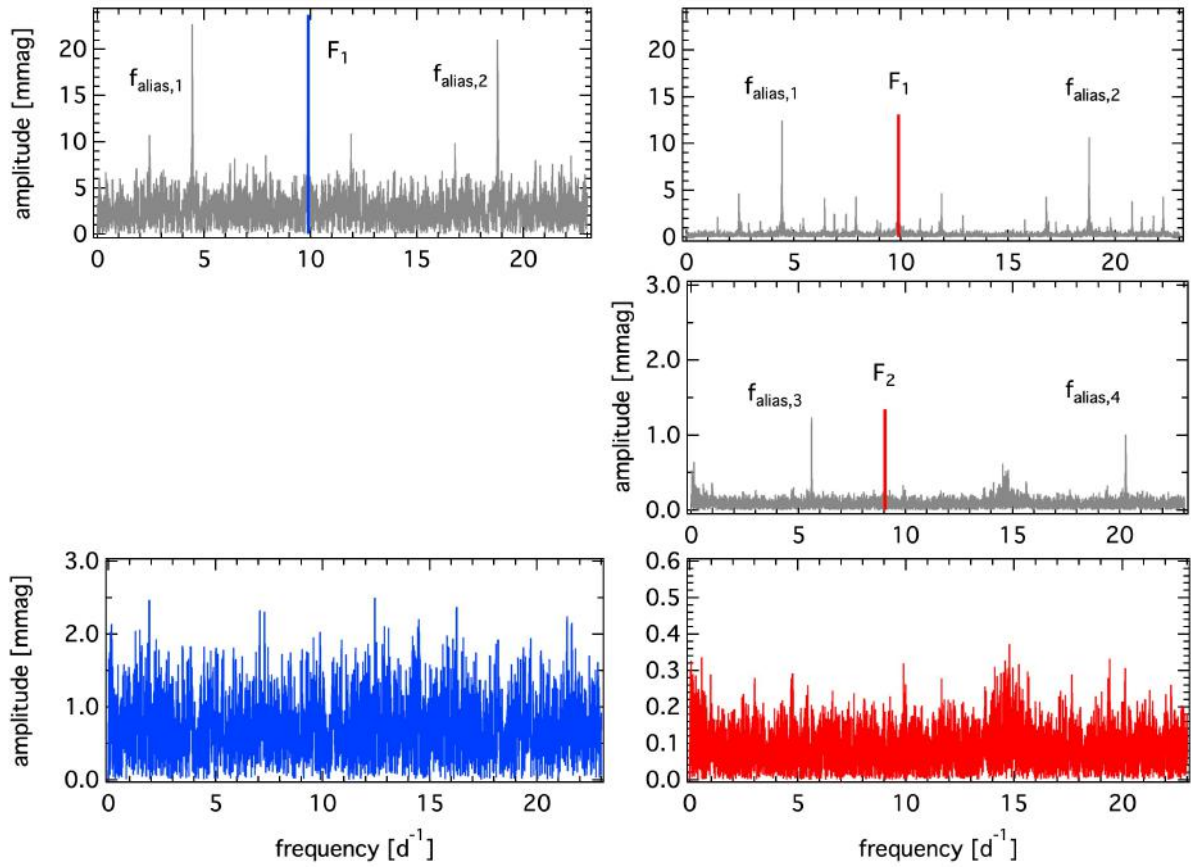


Fig. B.4. Amplitude spectra of the BRITE-Constellation data obtained in 2018: BAB data are shown on the left side, BTr data on the right side. Top panels show the amplitude spectra of the original data with F_1 identified, the middle panel (BTr only) illustrates the amplitude spectra after prewhitening F_1 , and the bottom panels the residuals after prewhitening all respective significant frequencies. An explanation for the identified alias frequencies is given in the text.

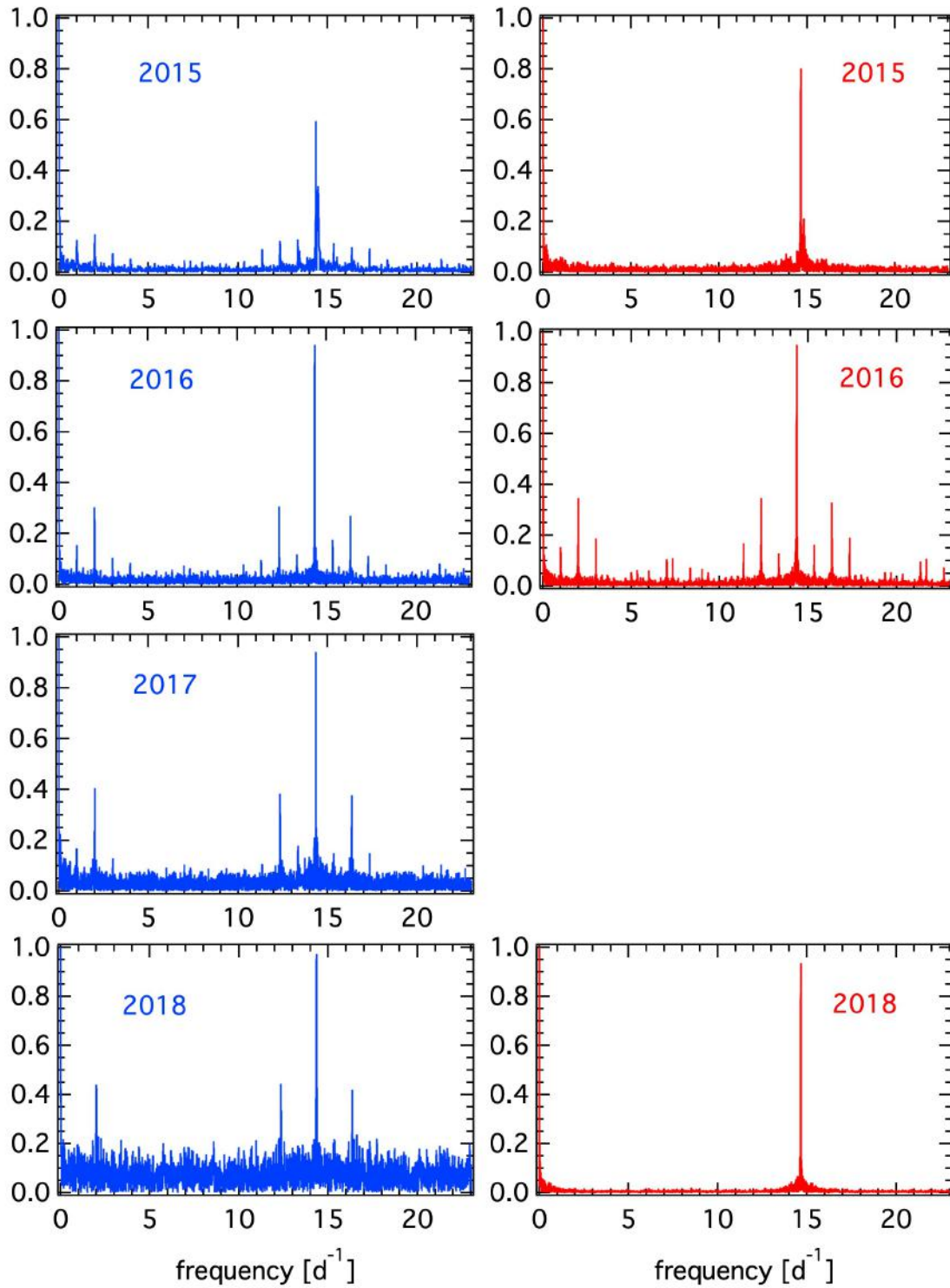


Fig. B.5. Spectral window functions for the BRITE-Constellation data obtained in 2015, 2016, 2017, and 2018 in the blue (left panels) and the red filter (right panels).

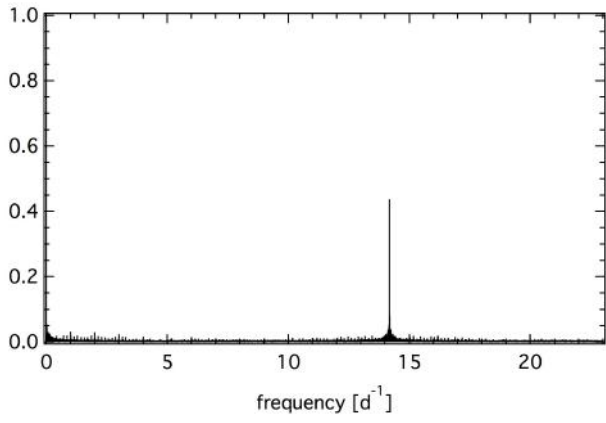


Fig. B.6. Spectral window function for the SMEI data.

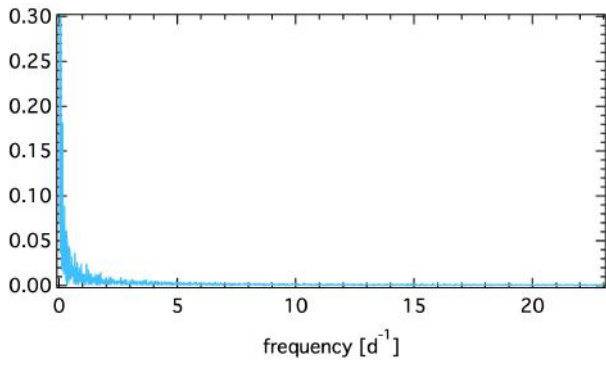


Fig. B.7. Spectral window function for the TESS data. Note the different Y-axis scale compared to the spectral window functions of the BRITE and SMEI data.