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The Magnetic δ Scuti Star β Cas

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Abstract. We study the pulsational, atmospheric, and magnetic properties of the evolved δ Scuti star β Cas using a combination of multiple seasons of BRITE-Constellation and SMEI space photometry and multiple-epoch spectropolarimetric observations conducted with the Narval instrument at the Télescope Bernard Lyot in France.

1. Introduction

With a V magnitude of 2.27, β Cas (HR 21, HD 432) is the second brightest object in the constellation of Cassiopeia. It was first identified as δ Scuti type star by Riboni et al. (1994) who found a single pulsation frequency of 9.6 d^{-1} corresponding to a period of 2.5 hours and described it as a radial pulsator near the Terminal Age Main Sequence (TAMS). Using observations obtained with the Center for High Angular Resolution Astronomy (CHARA) long baseline optical/IR interferometry array and the Michigan Infra-Red Combiner (MIRC) instrument, Che et al. (2011) found an inclination angle of 19.9 ± 1.9 for β Cas. Using the projected rotational velocity $\upsilon_\mathrm{e} \sin i$ of $70 \pm 1\,\mathrm{kms}^{-1}$, it can be deduced that β Cas rotates with 92% of its critical velocity (Che et al. 2011). This translates into a rotation rate of $1.12^{+0.03}_{-0.04}$ d^{-1} (Che et al. 2011). Consequently, there are inhomogeneous T_eff and $\log g$ distributions on its surface and β Cas' radius is ~24% larger on the equator than at the poles (Che et al. 2011).

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). They are typically multi-periodic oscillators that can show very rich pulsation frequency spectra (e.g., Poretti et al. 2009). Additionally, several physical processes act in δ Scuti type stars which challenge the theoretical asteroseismic interpretation of the observed pulsation frequencies. Among those are moderate to fast rotation which causes a splitting of the modes with same n and ℓ values but different m values and the presence of magnetic fields which is a rather recent discovery for δ Scuti stars (e.g., Kurtz et al. 2008; Neiner & Lampens 2015).

2. Observations and Data Analysis

2.1. BRITE-Constellation

The BRITE-Constellation nano-satellites (Weiss et al. 2014) obtained observations of β Cas first in field 11-CasCep-I-2015 from 23 July to 1 November, 2015, using BRITE-Austria (BAb), and BRITE-Lem (BLb) in the blue filter and BRITE-Heweliusz (BHr) and BRITE-Toronto (BTr) in the red filter. Subsequently, observations were taken in field 19-Cas-I-2016 from 7 August, 2016, to 1 February, 2017, using the satellites BAb and UniBRITE (UBr), and in the field 30-Cas-II-2017 from 7 August, 2017, to 3 February, 2018 only using BAb. Figure 1 shows a zoom into the BAb and UBr 2016 light curves binned to 5-minute intervals together with a two-sine fit using the two identified pulsation frequencies.

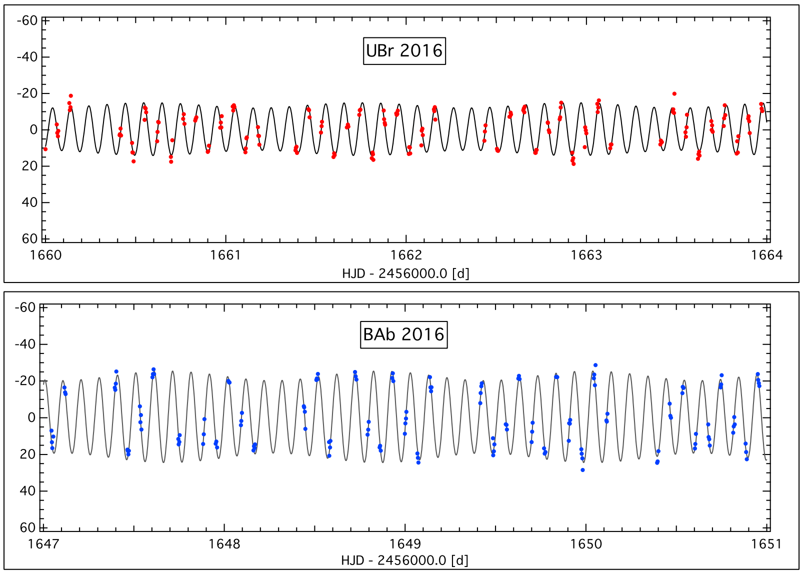

Figure 1. Zoom into the UniBRITE (UBr, top panel) and BRITE-Austria (BAb, bottom panel) light curves obtained in 2016. The solid line shows the fit with two sine functions based on the two identified independent pulsation frequencies.

The raw 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).

2.2. Solar Mass Ejection Imager (SMEI)

The Solar Mass Ejection Imager (SMEI) experiment (Eyles et al. 2003; Jackson et al. 2004) placed on-board of the Coriolis spacecraft obtained time series photometry of β Cas from 6 February 2003 to 31 December 2010 for a total time base of 2884.9 days. The SMEI photometry is affected by long-term calibration effects which have to be corrected before the data can be used to study stellar light variations. As SMEI measured one data point every ~ 1.7 hours, the Nyquist frequency, $f_{\rm Nyquist}$, lies at only 7.08 $\rm d^{-1}$.

It is possible to do super-Nyquist asteroseismology with the SMEI data because the real peaks remain as singlets even if they are above f_{Nyquist}.

2.3. Narval Spectropolarimetry

Spectropolarimetric observations were conducted using the Narval instrument installed at the Télescope Bernard Lyot (TBL) in France as part of the so-called "BRITEPol Survey” which measured the potential magnetic fields of all stars brighter than $V = 4$ mag as a ground-based support program for BRITE-Constellation targets (Neiner & Lèbre 2014). Narval provides spectra in the wavelength range from 390 to 1050 nm with a resolution of of ~65000, spread over 40 echelle orders. In November 2013 one set of four exposures was taken, followed by a series of three sets of observations between 24 September and 21 December 2014 and a complete series taken in accordance with the BRITE-Constellation observations from December 1 to 13, 2015.

3. Frequency Analysis

The frequency analysis of the BRITE photometric time series of β Cas was performed 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). We verified the analysis using the iterative prewhitening method based on the Lomb-Scargle periodogram which is described by Van Reeth et al. (2015).

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, while the F_3 at 19.79221 d^{-1} was only discovered in the longest BRITE data sets with a low enough noise level for an amplitude lower than 0.5 mmag to be significant. F_3 is not an independent frequency, as it is identified to be two times F_1. Figure 2 shows the amplitude spectra of the 2016 data sets obtained by BAb and UBr as an example.

4. Spectroscopic Analysis

All data obtained with Narval were co-added to obtain a single spectrum with a total signal-to-noise ratio of 500. Using the Spectroscopy Made Easy (SME) tool (Valenti & Piskunov 1996; Piskunov & Valenti 2017) in combination with MARCS atmospheric models and atomic line data obtained from the third version of the VALD database (Ryabchikova et al. 2015; Pakhomov et al. 2017), we analyzed the atmospheric properties and chemical abundances of β Cas.

The final fundamental parameters of β Cas derived from our study are an effective temperature $T_{\mathrm{eff}} = 6920 \pm 140$K, $\log g = 3.53 \pm 0.16$, metallicity $[M/H] = -0.11 \pm 0.04$, projected rotational velocity at the equator $\upsilon_{\mathrm{e}} \sin i = 73.6 \pm 7.0$km s^{-1}, and microturbulent velocity, $\upsilon_{\mathrm{mic}} = 4.1 \pm 0.4$ km s^{-1}.

β Cas is slightly metal deficient in iron peak elements and overabundant in C, O, Y, Zr and Ba. Overall, the observed abundance pattern of β Cas is similar to the atmospheric abundances of another δ Scut-type star HD 261711 (Zwintz et al. 2013).

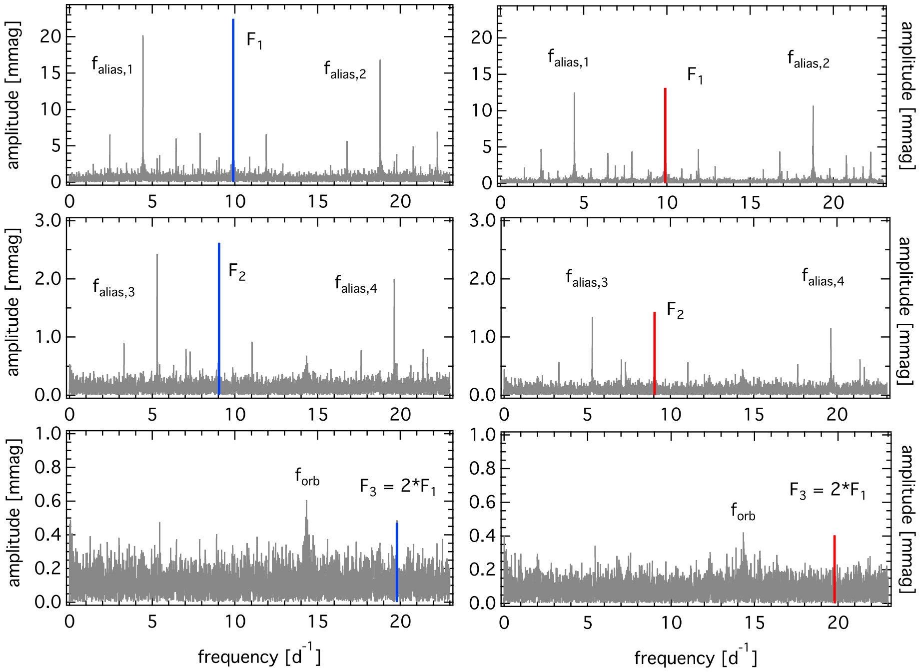

Figure 2. Amplitude spectra of the BRITE-Constellation data obtained in 2016: BRITE-Austria blue filter data are shown on the left side; UniBRITE red filter data on the right side. Top panels show the amplitude spectra of the original data with F$_1$ identified, the middle panels illustrate the amplitude spectra after prewhitening F$_1$, and the bottom panels those after prewhitening F$_1$ and F$_2$. Alias frequencies with the orbital frequencies of the satellites are indicated.

5. Spectropolarimetric Analysis

We used the Zeeman Doppler imaging (ZDI, Kochukhov 2016) technique to infer magnetic field topology of β Cas and to put constraints on the stellar rotational period. The tomographic mapping was carried out with the help of the magnetic inversion code InversLSD (Kochukhov et al. 2014), which was modified to include a non-radial pulsation velocity field. In the first analysis step we modelled the 75 individual Stokes I LSD profiles obtained in December 2015 in order to optimise $\upsilon_e \sin i$ together with the pulsational mode parameters using only F$_1$. The best description of the pulsational Stokes I profile variability pattern is accomplished with an $\ell = 2$, $m = 0$ pulsation mode identification. In a second step, we aim to reconstruct the magnetic field geometry of β Cas.

Best fits to the observed Stokes V LSD profiles can be achieved with three different rotation periods: 0.868, 0.890 or 1.145 days. As the rotation periods of 0.890 and 1.145 days do not explain the observed repetition of the Stokes V profile morphology, we consider $P_{\rm rot} = 0.868$ d to be the most likely rotational period of β Cas.

Using the ZDI results obtained for $P_{\rm rot} = 0.868$ d, we find the maximum local field strength to be 81 G and the mean field strength (averaged over the visible hemisphere) to be 16 G. Considering the spherical harmonic description of the surface field topology implemented in InversLSD, we infer that the magnetic field of β Cas is predominantly poloidal (68% of the field energy is concentrated in poloidal modes) and contains a comparable contribution of the axisymmetric ($m < \ell/2$, 58%) and non-axisymmetric ($m \geq \ell/2$, 42%) harmonic components.

6. Discussion

β Cas is an unusual star in several aspects:
(i) For a δ Scuti pulsator it is unusual that only two independent pulsation frequencies can be detected even in multiple seasons of BRITE observations and in two filters with a total time base of over 2.5 years and down to a residual noise level of ~60 ppm.
(ii) β Cas is one of the few 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 the 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. Therefore, β Cas provides an interesting benchmark for the theoretical modelling of dynamo processes in thin convective envelopes of F-type stars.

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