The 19th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun
Edited by G. A. Feiden

Monitoring of the magnetic field topology and activity of the core helium-burning giant β Ceti in the period 2010-2013

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Abstract

β Ceti is a slowly rotating ($v \sin i = 3.5$ km s^{-1}) single giant. In our previous study (Tsvetkova *et al.* (2013)) we showed that it is in the core He-burning phase and we reconstructed two Zeeman Doppler imaging (ZDI) maps (using data from 2010 and 2011) revealing a simple large-scale magnetic field structure. We concluded that the magnetic field of β Ceti could have a fossil field origin. In addition, the study of Aurière *et al.* (2015) about the properties and origin of the magnetism of late-type giants, where β Ceti was a member of that sample, revealed that this star did not follow the general trends for dynamo-generated magnetic fields. Now, we present a new ZDI map of β Ceti and compare the new results with our previous study. This monitoring for several years of the magnetic field topology and line activity indicators variability supports our previous conclusion about the fossil field origin of the magnetic field of β Ceti.

1 Introduction

β Ceti (HD 4128) is a star of spectral class K0 with $V = 2.04$ mag and $B - V = 1.02$ mag. It is a single giant with the highest X-ray luminosity $\log L_x = 30.2$ erg s^{-1} (Maggio *et al.* (1998); Hünsch *et al.* (1996)) in the near solar neighborhood ($d \leq 30$ pc). Magnetic events such as coronal loops (Eriksson *et al.* (1983)) and flares (Ayres *et al.* (2001)) have been detected. It is a slowly rotating giant with $v \sin i = 3.5$ km s^{-1}.

In the previous study of Tsvetkova *et al.* (2013), we showed that β Ceti is a 3.5 $M_\odot$ giant in the core helium-burning phase with a radius of 18 $R_\odot$. The main sequence progenitor of β Ceti was a late B-type star. We were able to reconstruct two magnetic maps of the surface magnetic field topology of the star employing the ZDI technique. Both maps showed that the large-scale magnetic field of β Ceti was dominated by the poloidal component. The behavior of the line activity indicators Hα, CaII K, CaII IR (854.2 nm), and the radial velocity correlated rather well with the longitudinal magnetic field B_l. Our main conclusion was that the magnetism of β Ceti might be (at least partly) of fossil origin and inherited from a main sequence Ap/Bp star.

Here, we present a new dataset of β Ceti. We are able to reconstruct one more ZDI map and to compare the new results with the previous study.

2 Observations and data reduction [1]

Observational data were obtained with two twin fiber-fed echelle spectropolarimeters – Narval (Aurière (2003)), which operates at the 2-m Bernard Lyot Télescope (TBL) at Pic du Midi Observatory, France, and ESPaDOnS (Donati *et al.* (2006a)), which operates at the 3.6-m Canada-France-Hawaii Telescope (CFHT) of Mauna Kea Observatory, Hawaii. In polarimetric mode, both have a spectral resolution of about 65 000 and a nearly continuous spectrum coverage from the near-ultraviolet (at about 370 nm) to the near-infrared domain (at 1050 nm) in a single exposure, with 40 orders aligned on the CCD frame by two cross-disperser prisms. Stokes I (unpolarized light) and Stokes V (circular polarization) parameters are simultaneously obtained by four subexposures between which the retarders – Fresnel rhombs – are rotated in order to exchange the beams in the instrument and to reduce spurious polarization signatures (Semel *et al.* (1993)).

Seven spectra have been collected for β Ceti in the period June – November 2013. Reduced spectra were

[1] Based on observations obtained at the Bernard Lyot Télescope (TBL, Pic du Midi, France) of the Midi-Pyrénées Observatory, which is operated by the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique of France and Université de Toulouse, and at the Canada-France-Hawaii Telescope (CFHT), which is operated by the National Research Council of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

extracted using the automatic reduction software LibreEsprit, developed for Narval and ESPaDOnS (Donati *et al.* (1997)). The least squares deconvolution (LSD) multiline technique (Donati *et al.* (1997)) was applied to all observations. This cross-correlation technique enables averaging of about 12 700 absorption atomic lines in the case of β Ceti taken from one spectrum, which increases the signal-to-noise ratio (S/N) to the point where weak polarized Zeeman signatures can be detected. Mean photospheric Stokes I and V profiles were computed for each spectrum. Then, the surface-averaged longitudinal magnetic field B_l was computed using the first-order moment method (Donati *et al.* (1997); Rees & Semel (1979); Wade *et al.* (2000)).

For mapping the magnetic fields at the stellar surface from sets of rotationally modulated circularly polarised profiles we used the Zeeman Doppler Imaging tomographic method (ZDI; Semel (1989); Donati & Brown (1997); Donati *et al.* (2006b)). The surface vectorial magnetic field is modeled using a spherical harmonic expansion, in order to distinguish between the poloidal and toroidal components of the surface magnetic geometry (Donati *et al.* (2006b)). This method performs iterative fitting of the observed time series of LSD polarized profiles by a simulated set of Stokes V profiles computed for an identical sequence of rotational phases. The synthetic Stokes profiles are calculated from an artificial star whose surface is divided into a grid of 2 000 rectangular pixels of roughly similar area. Each surface pixel is associated with a local Stokes I and V profile. The local synthetic Stokes I line profile is assumed to possess a Gaussian shape, with a depth and width adjusted to achieve the best fit between synthetic and observed line profiles. Local Stokes V profiles are calculated under the weak-field assumption (Morin *et al.* (2008); Petit *et al.* (2010)). The linear limb darkening coefficient is set to 0.75, in agreement with Claret & Bloemen (2011). We limited the spherical harmonics expansion to $l \leq 10$, since no improvement was found for the fits between modeled and observed LSD profiles for higher values of l.

3 Results

We present a new dataset for the giant β Ceti for the period June – November 2013. The data from 2010 to 2012 have already been published (Tsvetkova *et al.* (2013)) and are also shown in Figs. 1 and 2. The new ZDI map and the fit of the corresponding Stokes V profiles are presented in Fig. 3. The input parameters for the ZDI model are the same as we used for the previous datasets – $v \sin i = 3.5\ \mathrm{km\,s^{-1}}$, inclination angle $i = 60°$, rotational period $P = 215$ days. All the three datasets were phased according to the following ephemeris:

$$HJD = 2454101.5 + 215\,\phi \qquad (1)$$

where HJD is the heliocentric Julian date of the observations and ϕ is the rotational cycle.

We also measured the classical line activity indicators Hα, CaII K, CaII IR (854.2 nm), and the radial velocity from the spectra. Their variability with time compared to the longitudinal magnetic field B_l for the three datasets is shown in Fig. 4.

The percentage of the magnetic energy stored in different components is shown in Table 1 for the three datasets.

4 Conclusions

We present a new dataset of spectropolarimetric observations for the giant β Ceti, which was obtained during the period June – November 2013. We compare these results with previous results already published by Tsvetkova *et al.* (2013). Our conclusions are:

- the large-scale magnetic topology of β Ceti does not change significantly for the three epochs, being dominated by the poloidal component (about 97%) and showing a mainly dipolar configuration.

- B_l remains of positive polarity for the whole period. It shows sinusoidal variations with time, which is consistent with a global dipole field configuration (Landstreet & Mathys (2000)).

- the new dataset confirms our previous conclusion of Tsvetkova *et al.* (2013) about the fossil field origin of the magnetic field of β Ceti. Even more, the study of Aurière *et al.* (2015) about the properties and origin of the magnetism of late-type giants, where β Ceti was a member of that sample, revealed that this star did not follow the general trends for a dynamo generated magnetic fields.

- According to our new results, there might be some evidence for a long-term variability of the magnetic features, but more observations are needed to confirm that conclusion.

Acknowledgments

We thank the TBL and CFHT teams for providing service observing with Narval and ESPaDOnS. The observations in 2010 with Narval were funded under Bulgarian NSF grant DSAB 02/3/2010. The observations in 2013 with Narval were funded under the contract BG051PO001-3.3.06-0047. S.Ts. acknowledges the financial support from the contract DFNP-104 A-1 to attend the 19th Workshop on Cool Stars, Stellar Systems, and the Sun (CS19). G.A.W. acknowledges support from the Natural Sciences and Engineering Research Council of Canada (NSERC).

References

Aurière, M. 2003, In *EAS Publications Series*, edited by J. Arnaud & N. Meunier, *EAS Publications Series*, vol. 9, p. 105.

Aurière, M., Konstantinova-Antova, R., Charbonnel, C., Wade, G. A., Tsvetkova, S., *et al.* 2015, A&A, 574, A90.

Ayres, T. R., Osten, R. A., & Brown, A. 2001, ApJL, 562, L83.

Claret, A. & Bloemen, S. 2011, A&A, 529, A75.

Donati, J.-F. & Brown, S. F. 1997, A&A, 326, 1135.

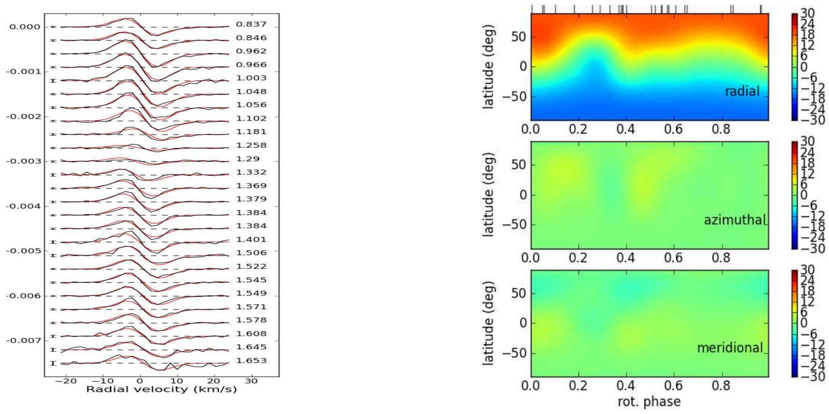

Figure 1: β Ceti in the period June 2010 – December 2010 (Tsvetkova *et al.* (2013)). Left panel: Normalized Stokes V profiles - observed profiles (black lines); synthetic profiles (red lines); zero level (dashed lines). All profiles are shifted vertically for display purposes. The rotational phases of observations are indicated in the right part of the plot and the error bars are on the left of each profile. Right panel: Magnetic map of β Ceti. The three panels illustrate the field components in spherical coordinates (from top to bottom – radial, azimuthal, meridional). The magnetic field strength is expressed in gauss. The vertical ticks on top of the radial map show the phases of observations.

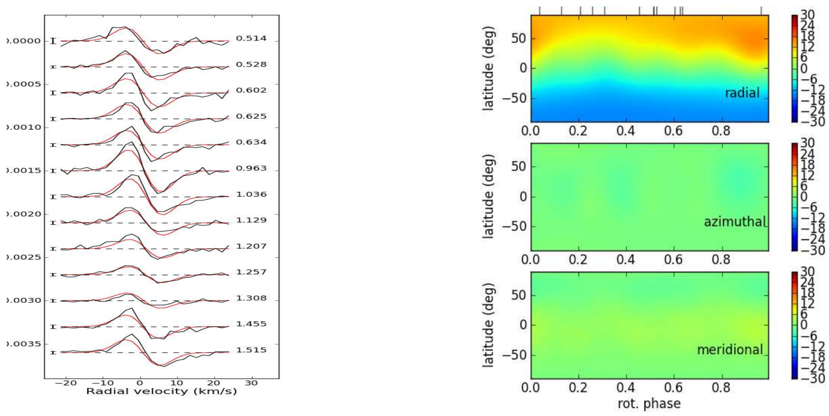

Figure 2: Same as Fig. 1, for the period June 2011 – January 2012 (Tsvetkova *et al.* (2013)).

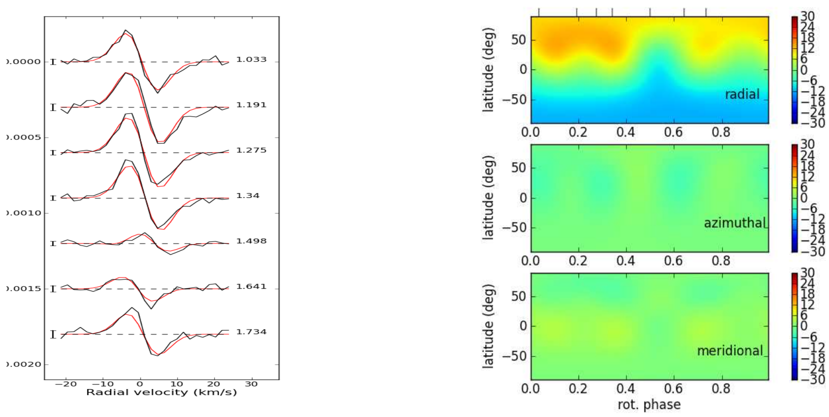

Figure 3: Same as Fig. 1, but for the new dataset of β Ceti, containing the period June – November 2013.

Table 1: Magnetic characteristics inferred from the three datesets of β Ceti. The first to the last columns list the fraction of the large-scale magnetic energy reconstructed in the poloidal field component, the fraction of the poloidal magnetic energy stored in the dipolar ($l = 1$), quadrupolar ($l = 2$) and octopolar ($l = 3$) components, and the fraction of the energy stored in the axisymmetric component ($m = 0$).

Epoch	pol. comp. (% tot)	dipole comp. (% pol)	quad. comp. (% pol)	oct. comp. (% pol)	axi. comp. (% tot)
2010	96.7	83.2	20.8	6.2	77.1
2011/2012	96.5	85.4	11.3	4.0	74.4
2013	97.5	89.1	17.8	10.3	69.4

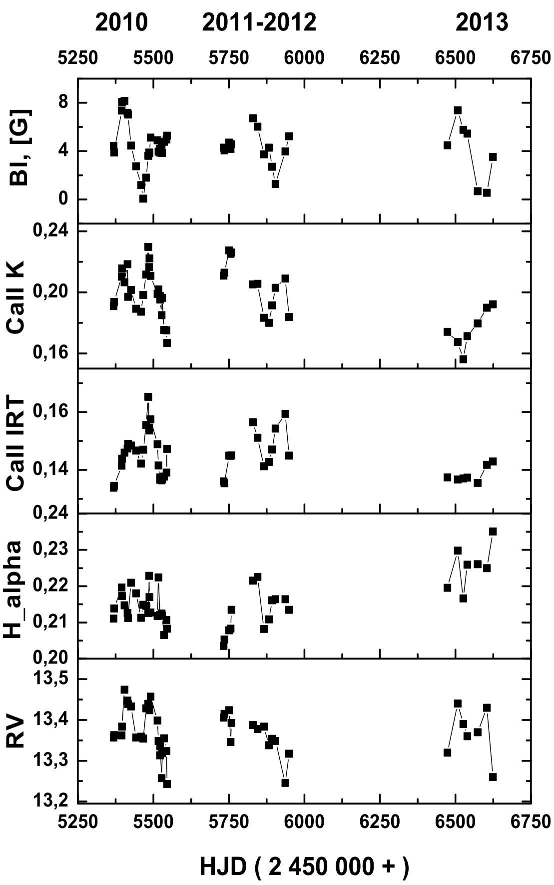

Figure 4: From top to bottom are presented the variations of B_l and the activity indicators CaII K, CaII IR, Hα, and the radial velocity for all the three datasets.

Donati, J.-F., Catala, C., Landstreet, J. D., & Petit, P. 2006a, In *Astronomical Society of the Pacific Conference Series*, edited by R. Casini & B. W. Lites, *Astronomical Society of the Pacific Conference Series*, vol. 358, p. 362.

Donati, J.-F., Howarth, I. D., Jardine, M. M., Petit, P., Catala, C., *et al.* 2006b, MNRAS, 370, 629.

Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, MNRAS, 291, 658.

Eriksson, K., Linsky, J. L., & Simon, T. 1983, ApJ, 272, 665.

Hünsch, M., Schmitt, J. H. M. M., Schröder, K.-P., & Reimers, D. 1996, A&A, 310, 801.

Landstreet, J. D. & Mathys, G. 2000, A&A, 359, 213.

Maggio, A., Favata, F., Peres, G., & Sciortino, S. 1998, A&A, 330, 139.

Morin, J., Donati, J.-F., Petit, P., Delfosse, X., Forveille, T., *et al.* 2008, MNRAS, 390, 567.

Petit, P., Lignières, F., Wade, G. A., Aurière, M., Böhm, T., *et al.* 2010, A&A, 523, A41.

Rees, D. E. & Semel, M. D. 1979, A&A, 74, 1.

Semel, M. 1989, A&A, 225, 456.

Semel, M., Donati, J.-F., & Rees, D. E. 1993, A&A, 278, 231.

Tsvetkova, S., Petit, P., Aurière, M., Konstantinova-Antova, R., Wade, G. A., *et al.* 2013, A&A, 556, A43.

Wade, G. A., Donati, J.-F., Landstreet, J. D., & Shorlin, S. L. S. 2000, MNRAS, 313, 851.