The magnetic variability of the β Cep star ξ^1 CMa

S. P. Järvinen[a,*], S. Hubrig[a], M. Schöller[b], I. Ilyin[a]

[a] *Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany*
[b] *European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany*

Abstract

ξ^1 CMa is a known magnetic star showing rotationally modulated magnetic variability with a period of 2.17937 d. However, recent work based on high-resolution spectropolarimetry suggests that the rotation period is longer than 30 years. We compare our new spectropolarimetric measurements with FORS 2 at the VLT acquired on three consecutive nights in 2017 to previous FORS 1/2 measurements of the longitudinal magnetic field strength. The new longitudinal magnetic field values are in the range from 115 to 240 G and do not support the presence of a long period.

Keywords:
stars: magnetic fields, stars: oscillations, stars: individual (ξ^1 CMa)

1. Introduction

ξ^1 CMa is known to be a bright ($m_V = 4.3$) sharp-lined β Cephei variable with spectral type B0.5–B1 IV (e.g. Morel et al., 2008). β Cephei variables are massive (7 to 20 solar masses), B0–B3 main-sequence stars pulsating in several pressure and gravity modes with periods between 3 and 8 hours. Most uncertainties in the stellar structure of these massive stars are related to the amount of core convective overshooting and rotational mixing. The lack of knowledge on the internal structure of these progenitors of core-collapse supernovae has large consequences for the whole duration and the end of the stellar life, and, consequently, for any astrophysical results relying on it, such as the chemical enrichment of galaxies. The presence of large-scale organised magnetic fields in β Cephei stars is well established (e.g. Hubrig et al., 2006, 2009; Briquet et al., 2012). It is also generally accepted that these magnetic fields are frozen-in fields that were acquired during stellar formation on an early pre-main sequence stage. Pulsating stars with magnetic fields are considered as promising targets for asteroseismic analysis (e.g. Shibahashi & Aerts, 2000), which requires as input the observed parameters of the magnetic field geometry.

To determine the magnetic field geometry and its strength, the rotation period has to be known. However, only for very few β Cephei stars has the behaviour of the magnetic field been studied over the rotation cycle. Using low-resolution spectropolarimetric observations with the FOcal Reducer low dispersion Spectrograph (FORS 1/2; Appenzeller et al., 1998) in spectropolarimetric mode at the Very Large Telescope (VLT) and the Soviet-Finnish echelle spectrograph (SOFIN; Tuominen et al., 1999) installed at the 2.56 m Nordic Optical Telescope on La Palma, Hubrig et al. (2006, 2009) were able to detect magnetic fields in a few β Cephei stars. The first detection of a magnetic field in ξ^1 CMa was achieved by Hubrig et al. (2006).

Among the targets with detected magnetic fields, a few β Cephei variables were selected for follow-up VLT multi-epoch magnetic field measurements with the aim to detect their most probable periods and to put constraints on their magnetic field geometry (Hubrig et al., 2011a,b). The simplest models of the magnetic field geometry are usually based on the assumption that the studied stars are oblique dipole rotators, i.e. their magnetic field can be approximated by a dipole with the magnetic axis inclined to the rotation axis. Using the dipole approximation, Hubrig et al. (2011a) showed that ξ^1 CMa is a rather fast rotating star with a rotation period of 2.17937 ± 0.00012 d seen close to pole-on and having a rather strong dipole magnetic field of the order of 5.3 kG.

A few years later, Fossati et al. (2015) presented three additional measurements of ξ^1 CMa obtained with FORS 2 in 2013 and suggested a rotation period of 2.17950 d. On the other hand, Shultz et al. (2017)

*Corresponding author
Email address: sjarvinen@aip.de (S. P. Järvinen)

used high-resolution ($R \approx 67\,000$) spectropolarimetric observations made with the Multi-Site Continuous Spectroscopy (MuSiCoS; Baudrand & Bohm, 1992) between 2000 and 2002 and with the Echelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS; Donati, 2003; Donati et al., 2006) between 2008 and February 2017 and proposed that the longitudinal magnetic field is gradually decreasing since 2010. Correspondingly, the rotation period of ξ^1 CMa should be longer than 30 years. Notably, the determination of this long rotation period was partly based on the MuSiCoS observations that were carried out at an airmass never below 2.45. Only these observations show the presence of a longitudinal magnetic field with negative polarity, whereas all other measurements with both FORS 1/2 and ESPaDOnS exhibit positive polarity. To verify the proper operations of MuSiCoS during that period, Shultz et al. (2017) refer to observations of 36 Lyn. However, since 36 Lyn is an object that crosses Pic-du-Midi close to zenith, it is rather questionable if this star can actually support the validity of the results obtained on ξ^1 CMa. For example, Petit et al. (2011), who used NARVAL and ESPaDOnS spectropolarimetric observations for a sensitive magnetic field search in Sirius, dismissed all observations obtained at high airmass from their study. Therefore, it is not clear whether the detection of a magnetic field of negative polarity using MuSiCoS at high airmass can be considered genuine.

Since previous low-resolution FORS 2 observations did not show any hint at a long-term periodicity, we obtained three additional low-resolution FORS 2 observations for this target on three consecutive nights in October 2017, to investigate the possible presence of a much longer rotation period. In the following, we discuss the results of our analysis of these three new observations and compare all currently available FORS 1/2 measurements of ξ^1 CMa with those obtained using high-resolution spectropolarimetry.

2. Observations and magnetic field analysis

The FORS 2 multi-mode instrument is equipped with polarisation analysing optics comprising superachromatic half-wave and quarter-wave phase retarder plates, and a Wollaston prism with a beam divergence of 22″ in standard resolution mode. We used the GRISM 600B and the narrowest available slit width of 0.″4 to obtain a spectral resolving power of $R \approx 2000$. The observed spectral range from 3250 to 6215 Å includes all Balmer lines, apart from Hα, and numerous helium lines. For the observations, we used a non-standard readout mode with low gain (200kHz,1×1,low), which provides a broader dynamic range, hence allowing us to reach a higher signal-to-noise ratio (S/N) in the individual spectra.

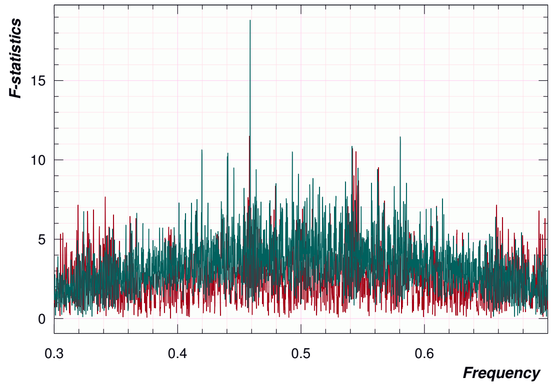

Figure 1: F-statistics periodogram for the longitudinal magnetic field measurements of ξ^1 CMa using the entire spectrum, published in the work by Hubrig et al. (2011a). The window function is presented in red.

A description of the assessment of the presence of a longitudinal magnetic field using FORS 1/2 spectropolarimetric observations was presented in our previous work (e.g. Hubrig et al., 2004a,b, and references therein). Rectification of the V/I spectra was performed in the way described by Hubrig et al. (2014). Null profiles, N, are calculated as pairwise differences from all available V profiles so that the real polarisation signal should cancel out. From these, 3σ-outliers are identified and used to clip the V profiles. This removes spurious signals, which mostly come from cosmic rays, and also reduces the noise. A full description of the updated data reduction and analysis will be presented in a separate paper (Schöller et al., in preparation, see also Hubrig et al., 2014). The mean longitudinal magnetic field, $\langle B_z \rangle$, is measured on the rectified and clipped spectra based on the relation following the method suggested by Angel & Landstreet (1970):

$$\frac{V}{I} = -\frac{g_{\rm eff}\, e\, \lambda^2}{4\pi\, m_{\rm e}\, c^2}\, \frac{1}{I}\, \frac{{\rm d}I}{{\rm d}\lambda}\, \langle B_z \rangle\ , \tag{1}$$

where V is the Stokes parameter that measures the circular polarization, I is the intensity in the unpolarized spectrum, $g_{\rm eff}$ is the effective Landé factor, e is the electron charge, λ is the wavelength, $m_{\rm e}$ is the electron mass, c is the speed of light, ${\rm d}I/{\rm d}\lambda$ is the wavelength derivative of Stokes I, and $\langle B_z \rangle$ is the mean longitudinal (line-of-sight) magnetic field.

The longitudinal magnetic field was measured in two ways: using the entire spectrum including all available lines or using exclusively hydrogen lines. Furthermore, we have carried out Monte Carlo bootstrapping tests. These are most often applied with the purpose of deriving robust estimates of standard errors (e.g. Steffen et al., 2014). The measurement uncertainties obtained before and after the Monte Carlo bootstrapping tests were found to be in close agreement, indicating the absence of reduction flaws. In Fig. 1 we show the periodogram calculated from the measurements presented by Hubrig et al. (2011a) using the entire spectrum and utilizing the Levenberg–Marquardt method (Press et al., 1992), and which was not presented in this previous work.

For the new observations, we present in Table 1 the heliocentric Julian date together with the observing date, followed by the achieved signal-to-noise ratio, and the results of the longitudinal magnetic field measurements obtained again in two ways: using the entire spectrum or exclusively the hydrogen lines. The measurements using the diagnostic null spectra N calculated using the entire spectrum and the rotational phases corresponding to $P_{\rm rot} = 2.17937$ d are presented in the last two columns.

We note that low-resolution spectropolarimetric observations are most appropriate for the detection of weak magnetic fields in β Cep pulsating stars, for which the impact of short-time variability on the magnetic field measurements can be quite significant. The work of Järvinen et al. (2017) indicated that ignoring the velocity shifts leads to an underestimation of the magnetic field strength roughly by a factor of two. Furthermore, the pulsational radial velocity amplitude of the order of 70 km s^{-1} for ξ^1 CMa is one of the largest known among β Cep stars (e.g. Saesen et al., 2006). While a full HARPS sequence of subexposures for ξ^1 CMa requires about 30 min, one FORS 2 observation of the same star lasts less than 10 min. Owing to the strong changes in the positions and shapes of line profiles in the spectra of pulsating stars, a method using high-resolution spectra averaged over all subexposures usually leads to erroneous wavelength shifts and thus to wrong values for the longitudinal magnetic field. Interestingly, Shultz et al. (2017) report on the detection of apparent scatter in the measurements of the mean longitudinal magnetic field with a standard deviation of up to 15 G. To explain this scatter, the authors suggest the presence of a modulation of the field with pulsation phase or some unidentified instrumental effect, but also consider the possibility of the impact of line profile variability.

In Fig. 2 we present the phase diagram for the magnetic field measurements of ξ^1 CMa, using the period of

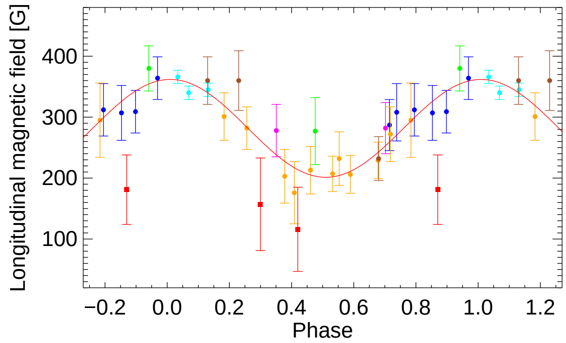

Figure 2: Phase folded measurements of the longitudinal magnetic field for ξ^1 CMa. The filled circles represent previously published values from Hubrig et al. (2006, 2011a) and Fossati et al. (2015). The different colors correspond to the different time bins presented in Fig. 3. The red filled squares are the new measurement values. The sinusoidal fit parameters and the ephemeris MJD55140.73332 $\pm$ 0.03794 + 2.17937 $\pm$ 0.00012E used for the folding of the phase are from Hubrig et al. (2011a).

2.17937 d, including the three recent FORS 2 measurements together with the results from Hubrig et al. (2006, 2011a) and Fossati et al. (2015). Our new measurements acquired on three consecutive nights in 2017 indicate a longitudinal magnetic field strength in the range from 115 to 240 G. Two measurements have rather large uncertainties and still fit the magnetic phase curve well. Only the measurement obtained on 2017 October 4 ($\langle B_{\rm z}\rangle_{\rm all} = 181 \pm 57$ G, ($\langle B_{\rm z}\rangle_{\rm hyd} = 240 \pm 77$ G) has a significance level of about 3σ. Therefore, the obtained new observations do not provide much evidence for the presence of the period of more than 30 years reported by Shultz et al. (2017).

To investigate the temporal evolution of the magnetic field strength in our data, we used time binned averages of the measured field strengths between 2005 and 2017. The distribution of the binned average field strengths and the number of measurements used in each bin is shown in Fig. 3 and the comparison of our field strength distribution with that of Shultz et al. (2017) is shown in Fig. 4. In contrast to the measurements presented by Shultz et al., we observe in both figures a slight decrease of the magnetic field strength in 2009. Comparing the identical colors between Figs. 2 and 3, it is obvious that the observed magnetic field decrease in the binned data is due to the rotational modulation of the magnetic field.

3. Discussion

Insufficient knowledge of the strength, geometry, and time variability of magnetic fields in hot pulsating stars prevented until now important theoretical studies on

Table 1: New longitudinal magnetic field measurements of ξ^1 CMa obtained using FORS 2 observations.

HJD 2 450 000+	Date	S/N at 4700Å	$\langle B_z\rangle_{all}$ [G]	$\langle B_z\rangle_{hyd}$ [G]	$\langle B_z\rangle_{N}$ [G]	Phase
8029.810749	2017–10–03	1875	116±69	115±102	−31±59	0.42
8030.790235	2017–10–04	2610	181±57	240±77	−56±61	0.87
8031.740386	2017–10–05	2720	157±76	207±95	45±65	0.30

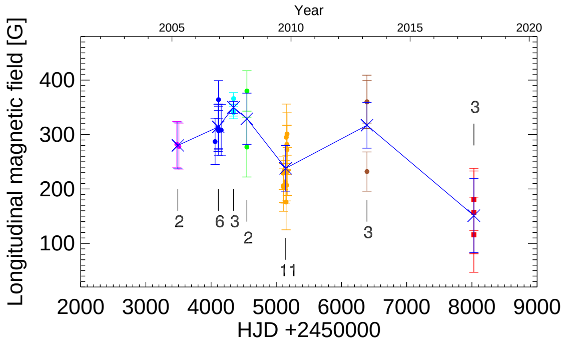

Figure 3: Temporal evolution of the longitudinal magnetic field. The time is given both in HJDs and years. Measurements belonging to different time bins are plotted with different colors. Identical colors are used in Fig. 2 for the phase folded points. The number of individual measurements in each bin is given in the plot. The blue line connects the time binned averages.

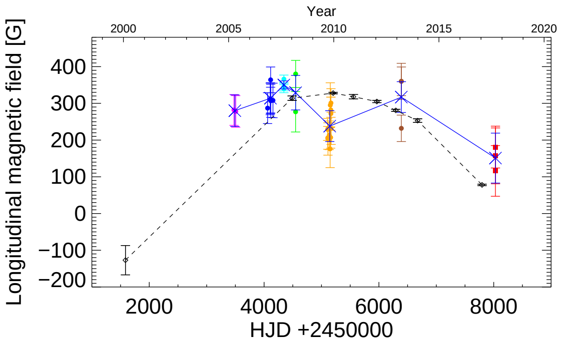

Figure 4: The same as Fig. 3. The black diamonds represent the annual weighted mean $\langle B_z\rangle$ measurements by Shultz et al. (2017), connected by the dashed line.

the impact of magnetic fields on stellar rotation, pulsation, and element diffusion. Morel et al. (2006, 2008) performed a NLTE abundance analysis of a sample of early-type B dwarfs with detected magnetic fields and low $v \sin i$–values, among them ξ^1 CMa. Their analysis strongly supported the existence of a population of nitrogen-rich and boron-depleted early B-type stars. It is of interest that the obtained abundance patterns for this group of stars are well-reproduced by the theoretical models of Heger & Langer (2000), but only assuming initial velocities exceeding $\sim$200 km s^{-1} which would imply strong rotational mixing and surface nitrogen enrichment. The existence of a rotation period of the length of more than 30 years in ξ^1 CMa would suggest an extreme loss of angular momentum over the fractional main-sequence lifetime of 0.76 reported in the study of Hubrig et al. (2006). Very long rotation periods of the order of decades are currently only known for a few chemically peculiar A-type (Ap) stars with kG magnetic fields. As evolutionary changes of the rotation periods of Ap stars during their main-sequence lifetime are at most of the order of a factor 2 (Hubrig et al., 2007), it is believed that the period differentiation took place already before Ap stars arrive at the main sequence. The typical rotation periods of more massive early B-type stars with much shorter main-sequence lifetimes are usually of the order of a few days and less and no early B-type star is known to have long rotation periods of the order of years or more.

While rotational modulation with a short period of 2.18 d was previously clearly detected in FORS 1/2 data, the rotation period longer than 30 years reported by Shultz et al. (2017) based on high-resolution spectropolarimetric observations requires additional observational constraints. First of all, the impact of the strong pulsational variability on the magnetic field measurements in high-resolution spectropolarimetric observations has to be taken into account. Apart from spectropolarimetric monitoring of ξ^1 CMa in the coming years using circularly polarised spectra, a useful approach to proof the presence of an extremely long rotation could be to measure broad-band linear polarisation, which is caused by different saturation of the π and σ

components of a spectral line in the presence of a magnetic field. This differential effect is qualitatively similar for all lines, so that in broad-band observations the contributions of all lines add up. A model for the interpretation of such observations developed by Landolfi et al. (1993) does not allow to derive the field strength, but provides very useful constraints on the geometry of the magnetic field.

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References

Angel, J. R. P. & Landstreet, J. D. 1970, ApJL, 160, L147

Appenzeller, I., Fricke, K., Fürtig, W., et al. 1998, The Messenger, 94, 1

Baudrand, J. & Bohm, T. 1992, A&A, 259, 711

Briquet, M., Neiner, C., Aerts, C., et al. 2012, MNRAS, 427, 483

Donati, J.-F. 2003, in Astronomical Society of the Pacific Conference Series, Vol. 307, Solar Polarization, ed. J. Trujillo-Bueno & J. Sanchez Almeida, 41

Donati, J.-F., Catala, C., Landstreet, J. D., & Petit, P. 2006, in Astronomical Society of the Pacific Conference Series, Vol. 358, Astronomical Society of the Pacific Conference Series, ed. R. Casini & B. W. Lites, 362

Fossati, L., Castro, N., Schöller, M., et al. 2015, A&A, 582, A45

Heger, A. & Langer, N. 2000, ApJ, 544, 1016

Hubrig, S., Briquet, M., De Cat, P., et al. 2009, Astronomische Nachrichten, 330, 317

Hubrig, S., Briquet, M., Schöller, M., et al. 2006, MNRAS, 369, L61

Hubrig, S., Ilyin, I., Schöller, M., et al. 2011a, ApJL, 726, L5

Hubrig, S., Kurtz, D. W., Bagnulo, S., et al. 2004a, A&A, 415, 661

Hubrig, S., North, P., & Schöller, M. 2007, Astronomische Nachrichten, 328, 475

Hubrig, S., Schöller, M., Kharchenko, N. V., et al. 2011b, A&A, 528, A151

Hubrig, S., Schöller, M., & Kholtygin, A. F. 2014, MNRAS, 440, 1779

Hubrig, S., Szeifert, T., Schöller, M., Mathys, G., & Kurtz, D. W. 2004b, A&A, 415, 685

Järvinen, S. P., Hubrig, S., Ilyin, I., Schöller, M., & Briquet, M. 2017, MNRAS, 464, L85

Landolfi, M., Landi Degl'Innocenti, E., Landi Degl'Innocenti, M., & Leroy, J. L. 1993, A&A, 272, 285

Morel, T., Butler, K., Aerts, C., Neiner, C., & Briquet, M. 2006, A&A, 457, 651

Morel, T., Hubrig, S., & Briquet, M. 2008, A&A, 481, 453

Petit, P., Lignières, F., Aurière, M., et al. 2011, A&A, 532, L13

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical recipes in C. The art of scientific computing

Saesen, S., Briquet, M., & Aerts, C. 2006, Communications in Asteroseismology, 147, 109

Shibahashi, H. & Aerts, C. 2000, ApJL, 531, L143

Shultz, M., Wade, G. A., Rivinius, T., et al. 2017, MNRAS, 471, 2286

Steffen, M., Hubrig, S., Todt, H., et al. 2014, A&A, 570, A88

Tuominen, I., Ilyin, I., & Petrov, P. 1999, in Astrophysics with the NOT, ed. H. Karttunen & V. Piirola, 47