FIRST MAGNETIC FIELD MODELS FOR RECENTLY DISCOVERED MAGNETIC β CEPHEI AND SLOWLY PULSATING B STARS[*]

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ABSTRACT

In spite of recent detections of magnetic fields in a number of β Cephei and slowly pulsating B (SPB) stars, their impact on stellar rotation, pulsations, and element diffusion has not yet been sufficiently studied. The reason for this is the lack of knowledge of rotation periods, the magnetic field strength distribution and temporal variability, and the field geometry. New longitudinal field measurements of four β Cephei and candidate β Cephei stars, and two SPB stars were acquired with FORS 2 at the Very Large Telescope. These measurements allowed us to carry out a search for rotation periods and to constrain the magnetic field geometry for four stars in our sample.

Key words: stars: early-type – stars: fundamental parameters – stars: individual (ξ^1 CMa, 15 CMa, α Pyx, ε Lup, 33 Eri, HY Vel) – stars: magnetic field – stars: oscillations – stars: variables: general

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1. INTRODUCTION

For several years, a magnetic field survey of main-sequence pulsating B-type stars, namely, the slowly pulsating B (SPB) stars and β Cephei stars, has been undertaken by our team with FORS 1 in spectropolarimetric mode at the Very Large Telescope (VLT), allowing us to detect in four β Cephei stars and in 16 SPB stars, for the first time, longitudinal magnetic fields of the order of a few hundred Gauss (Hubrig et al. 2006, 2009). β Cephei variables have spectral types B0–B2 and pulsate in low-order pressure and gravity modes with periods between 2 and 6 hr. SPB stars are mid-B-type (B3–B9) objects pulsating in high-order gravity modes with periods in the range of 0.5–3 days. Pulsating stars are currently considered as promising targets for asteroseismic analysis (e.g., Shibahashi & Aerts 2000), which requires as input the observed parameters of the magnetic field topology. Early magnetic field searches of β Cephei stars were mostly unsuccessful due to low precision (see Babcock 1958; Rudy & Kemp 1978). Before we started our systematic search for magnetic fields in pulsating B-type stars, a weak magnetic field was detected in two β Cephei stars, in the prototype of the class, β Cep itself, by Henrichs et al. (2000) and in V2052 Oph by Neiner et al. (2003a). The first detection of a weak magnetic field in the SPB star ζ Cas was reported by Neiner et al. (2003b). The detected magnetic objects for which we gathered several magnetic field measurements showed a field that varies in time, but no periodicity could be derived yet due to the limited amount of VLT observing time. Among these targets with a detected magnetic field, we selected two SPB stars, two β Cephei stars, and two candidate β Cephei stars with suitable coordinates, for successive VLT multi-epoch magnetic measurements. The list of the selected targets is presented in Table 1. In the four columns we list the HD number, another identifier, the spectral type retrieved from the SIMBAD database, the pulsating type, and membership in a spectroscopic

binary system. An asterisk in front of the HD number denotes candidate β Cephei stars (cf. Stankov & Handler 2005). This most recent study aimed at the determination of magnetic field properties for these stars, such as field strength, field geometry, and time variability. Here, we present the results of 62 new magnetic field measurements of the six selected stars and discuss the obtained results on their rotation periods and magnetic field geometry.

2. MAGNETIC FIELD MEASUREMENTS AND PERIOD DETERMINATION

Multi-epoch time series of polarimetric spectra of the pulsating stars were obtained with FORS 2[6] on Antu (UT1) from 2009 September to 2010 March in service mode. Using a slit width of $0\rlap{.}''4$, the achieved spectral resolving power of FORS 2 obtained with the GRISM 600B was about 2000. A detailed description of the assessment of the longitudinal magnetic field measurements using FORS 2 is presented in our previous papers (e.g., Hubrig et al. 2004a, 2004b, and references therein). The mean longitudinal magnetic field, $\langle B_z \rangle$, was derived using

$$\frac{V}{I} = -\frac{g_{\mathrm{eff}} e \lambda^2}{4\pi m_e c^2} \frac{1}{I} \frac{dI}{d\lambda} \langle B_z \rangle, \qquad (1)$$

where V is the Stokes parameter which measures the circular polarization, I is the intensity in the unpolarized spectrum, g_{eff} is the effective Landé factor, e is the electron charge, λ is the wavelength, m_e the electron mass, c the speed of light, $dI/d\lambda$ is the derivative of Stokes I, and $\langle B_z \rangle$ is the mean longitudinal magnetic field. The measurements of the longitudinal magnetic field were carried out in two ways, using the whole spectrum ($\langle B_z \rangle_{\mathrm{all}}$) and using only the hydrogen lines ($\langle B_z \rangle_{\mathrm{hyd}}$).

Two additional polarimetric spectra of ξ^1 CMa were obtained with the SOFIN spectrograph installed at the 2.56 m Nordic Optical Telescope on La Palma, one on 2008 September 13

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[6] The spectropolarimetric capabilities of FORS 1 were moved to FORS 2 in 2009.

Table 1
The Observed β Cephei and SPB Stars

HD	Other Identifier	Spectral Type	Comments
24587	33 Eri	B5V	SPB, SB1
46328	ξ^1 CMa	B1III	β Cep
50707	15 CMa	B1Ib	β Cep
*74575	α Pyx	B1.5III	β Cep
74560	HY Vel	B3IV	SPB, SB1
*136504	ϵ Lup	B2IV-V	β Cep, SB

and another one on 2010 January 1. SOFIN (Tuominen et al. 1999) is a high-resolution echelle spectrograph mounted at the Cassegrain focus of the NOT. The star was observed with the low-resolution camera with $R = \lambda/\Delta\lambda \approx 30{,}000$. We used the 2K Loral CCD detector to register 40 echelle orders partially covering the range from 3500 to 10000 Å with a length of the spectral orders of about 140 Å. Two such exposures with quarter-wave plate angles separated by $90°$ are necessary to derive circularly polarized spectra. The spectra were reduced with the 4A software package (Ilyin 2000).

A frequency analysis was performed on the longitudinal magnetic field measurements $\langle B_z \rangle_{all}$ (which generally show smaller sigmas) available from our previous (Hubrig et al. 2006, 2009) and the current studies using a nonlinear least-squares fit of the multiple harmonics utilizing the Levenberg–Marquardt method (Press et al. 1992) with an optional possibility of pre-whitening the trial harmonics. To detect the most probable period, we calculated the frequency spectrum for the same harmonic with a number of trial frequencies by solving the linear least-squares problem. At each trial frequency we performed a statistical test of the null hypothesis for the absence of periodicity (Seber 1977), i.e., testing that all harmonic amplitudes are at zero. The resulting F-statistics can be thought of as the total sum including covariances of the ratio of harmonic amplitudes to their standard deviations, i.e., as a signal-to-noise ratio. The F-statistics allows to derive the false alarm probability of the trial period based on the F-test (Press et al. 1992). Periodicity was found for four out of the studied six stars. The derived ephemeris for the detected periods are

$$\xi^1 \text{ CMa} : \langle V\&I \rangle^{max} = \text{MJD}55140.73332 \pm 0.03794$$
$$+ 2.17937 \pm 0.00012E$$

$$15 \text{ CMa} : \langle V\&I \rangle^{max} = \text{MJD}55168.09911 \pm 0.16667$$
$$+ 12.64115 \pm 0.00822E$$

$$\alpha \text{ Pyx} : \langle V\&I \rangle^{max} = \text{MJD}55144.59481 \pm 0.04105$$
$$+ 3.19779 \pm 0.00019E$$

$$33 \text{ Eri} : \langle V\&I \rangle^{max} = \text{MJD}55123.65285 \pm 0.03243$$
$$+ 1.27947 \pm 0.00005E.$$

The logbook of the new FORS 2 and the old, revisited, FORS 1 spectropolarimetric observations is presented in Tables 2 and 3. In the first column we indicate the MJD value at mid exposure. The phases of the measurements of the magnetic field, if available, are listed in Column 2. In Columns 3 and 4, we present the longitudinal magnetic field $\langle B_z \rangle_{all}$ measured using the whole spectrum and the longitudinal magnetic field $\langle B_z \rangle_{hyd}$ using only the hydrogen lines. Phase diagrams of the data folded with the determined periods are presented in Figure 1. The quality of our fits is described by a reduced χ^2-value which appears in the four panels of Figure 1.

Table 2
Magnetic Field Measurements of β Cephei Stars with FORS 1/2 and SOFIN (Marked with an Asterisk)

MJD	Rotation Phase	$\langle B_z \rangle_{all}$ (G)	$\langle B_z \rangle_{hyd}$ (G)
		ξ^1 CMa	
53475.046	0.702	282 ± 42	280 ± 44
53506.971	0.351	278 ± 43	330 ± 45
54061.325	0.715	287 ± 42	360 ± 45
54107.266	0.795	312 ± 43	319 ± 46
54114.028	0.898	309 ± 35	347 ± 38
54114.182	0.969	364 ± 35	382 ± 47
54116.108	0.853	307 ± 45	276 ± 58
54155.086	0.738	308 ± 47	349 ± 35
54343.371	0.132	345 ± 11	379 ± 15
54345.338	0.034	366 ± 11	400 ± 12
54345.414	0.069	340 ± 11	378 ± 18
54548.982	0.476	277 ± 55	297 ± 87
54549.995	0.941	380 ± 37	332 ± 55
*54722.274	0.991	386 ± 39	
55107.342	0.678	229 ± 30	302 ± 44
55109.325	0.589	206 ± 31	233 ± 52
55113.224	0.378	203 ± 44	320 ± 65
55135.200	0.461	213 ± 39	240 ± 59
55150.342	0.409	176 ± 51	322 ± 76
55153.340	0.784	295 ± 61	470 ± 94
55159.329	0.532	207 ± 29	254 ± 41
55163.085	0.256	282 ± 35	389 ± 56
55164.092	0.718	272 ± 45	416 ± 88
55165.106	0.183	301 ± 39	431 ± 64
55168.091	0.553	232 ± 44	174 ± 59
*55201.279	0.781	297 ± 26	
		α Pyx	
54082.341	0.816	142 ± 48	219 ± 60
54109.150	0.200	132 ± 50	184 ± 60
55107.378	0.362	5 ± 31	-29 ± 48
55118.347	0.792	120 ± 28	89 ± 34
55120.351	0.418	-14 ± 26	-35 ± 44
55168.167	0.371	24 ± 39	-26 ± 68
55171.162	0.308	40 ± 45	42 ± 69
		ϵ Lup	
54344.998		-156 ± 34	-128 ± 36
55225.268		-130 ± 94	-191 ± 129
55226.272		-33 ± 39	-40 ± 52
55227.285		-104 ± 44	-185 ± 69
55228.324		-7 ± 42	7 ± 51
55258.206		-147 ± 46	-162 ± 54
55259.260		-105 ± 41	-158 ± 66
		15 CMa	
54107.318	0.085	163 ± 52	157 ± 58
54345.372	0.917	149 ± 19	123 ± 27
55107.326	0.192	86 ± 26	113 ± 55
55109.371	0.354	-41 ± 36	-130 ± 52
55112.380	0.592	-92 ± 48	-88 ± 74
55150.330	0.594	-75 ± 54	-49 ± 78
55159.295	0.304	35 ± 34	13 ± 51
55163.101	0.605	-25 ± 39	-45 ± 58
55164.104	0.684	31 ± 49	-24 ± 61
55165.118	0.764	76 ± 41	19 ± 60
55168.104	0.000	128 ± 42	126 ± 65
55170.090	0.158	138 ± 52	90 ± 120
55171.133	0.240	21 ± 42	-12 ± 67
55173.143	0.399	-58 ± 88	-64 ± 122
55177.323	0.730	7 ± 33	0 ± 62

Note. All quoted errors are 1σ uncertainties.
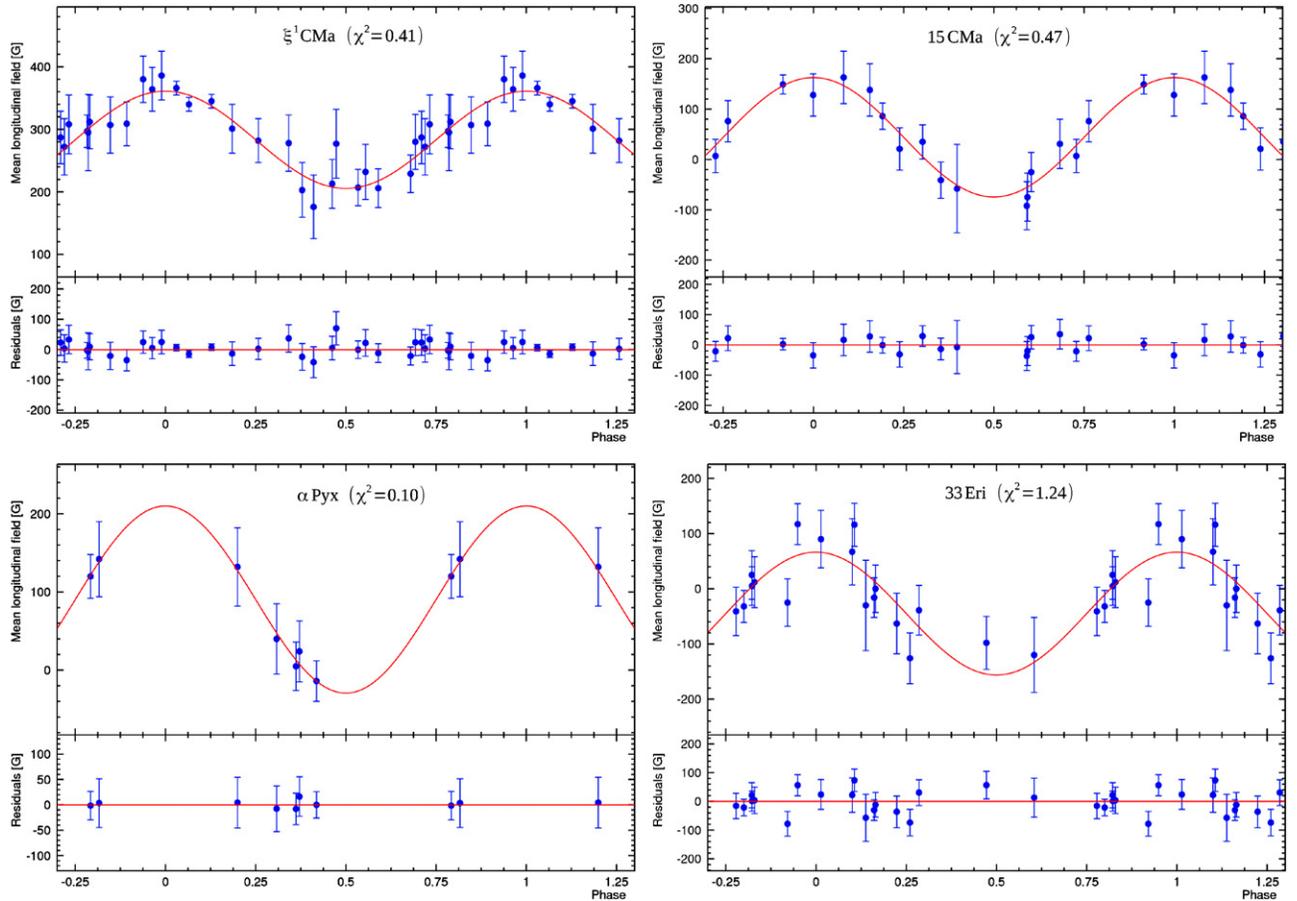
Figure 1. Phase diagrams with the best sinusoidal fit for the longitudinal magnetic field measurements. The residuals (Observed − Calculated) are shown in the lower panels. The deviations are mostly of the same order as the error bars, and no systematic trends are obvious, which justifies a single sinusoid as a fit function.

(A color version of this figure is available in the online journal.)

3. CHARACTERIZATION OF THE MAGNETIC FIELD GEOMETRY FOR THE STARS WITH DETERMINED PERIODS

The determination of the fundamental parameters and the description of the pulsating properties of all studied stars were presented by Hubrig et al. (2009, Tables 1(a), (b), and 4). The most simple modeling of the magnetic field geometry is 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.

The magnetic dipole axis tilt β is constrained by

$$r = \frac{\langle B_z \rangle^{\min}}{\langle B_z \rangle^{\max}} = \frac{\cos\beta \cos i - \sin\beta \sin i}{\cos\beta \cos i + \sin\beta \sin i}, \qquad (2)$$

so that the obliquity angle β is given by

$$\beta = \arctan\left[\left(\frac{1-r}{1+r}\right)\cot i\right]. \qquad (3)$$

In Table 4, we show for each star with detected periodicity in Rows 2 and 3 the mean value $\overline{\langle B_z \rangle}$ and the amplitude of the field variation $A_{\langle B_z \rangle}$. In Row 4, we present $v \sin i$ values published recently by Lefever et al. (2010) for ξ^1 CMa and 15 CMa and from Hubrig et al. (2009) for α Pyx and 33 Eri. The radius values in Row 5 were taken from Hubrig et al. (2009). The radius of 15 CMa ($R = 10.0 \pm 1.5\ R_\odot$) was derived in the same way as in Hubrig et al. (2009) by adopting the values of T_{eff} and $\log g$ from

Lefever et al. (2010). In the last four rows, we list the v_{eq} and the parameters of the magnetic field dipole models. The polar field strength B_d in the last row was calculated following Preston (1969) using limb darkening parameters from Diaz-Cordovés et al. (1995).

4. DISCUSSION

Using FORS 1/2 and SOFIN longitudinal magnetic field measurements collected in our recent studies, we were able to determine rotation periods and constrain the field geometry of two β Cephei stars, one candidate β Cephei star and one SPB star. The dipole model provides a satisfactory fit to the data and among the very few presently known magnetic β Cephei stars, ξ^1 CMa and α Pyx possess the largest magnetic fields, with a dipole strength of several kG. Briquet et al. (2007) discussed the position of SPB and chemically peculiar Bp stars in the H-R diagram indicating that the group of Bp stars is significantly younger than the group of SPB stars. A similar conclusion was deduced by Hubrig et al. (2007), who studied the evolution of magnetic fields in Ap and Bp stars with definitely determined magnetic field geometries across the main sequence. The vast majority of Bp stars exhibit a smooth, single-wave variation of the longitudinal magnetic field during the stellar rotation cycle. These observations are considered as evidence for a dominant dipolar contribution to the magnetic field topology. It is of interest that the study of Hubrig et al. (2007) indicates the prevalence of larger obliquities β, namely, $\beta > 60°$, in more

Table 3
Magnetic Field Measurements of SPB Stars with FORS 1/2

MJD	Rotation Phase	$\langle B_z \rangle_{\rm all}$ (G)	$\langle B_z \rangle_{\rm hyd}$ (G)
		33 Eri	
52971.071	0.599	-122 ± 64	-120 ± 68
53574.415	0.157	-14 ± 33	-16 ± 36
53630.250	0.796	-34 ± 27	-32 ± 29
54086.175	0.135	-30 ± 54	-45 ± 61
54343.301	0.098	67 ± 60	83 ± 65
55107.154	0.105	116 ± 39	166 ± 49
55108.197	0.929	-25 ± 43	-43 ± 56
55109.350	0.822	5 ± 35	10 ± 49
55110.181	0.471	-98 ± 48	-138 ± 70
55111.222	0.284	-39 ± 45	-52 ± 69
55112.347	0.164	0 ± 43	-20 ± 72
55113.188	0.821	25 ± 44	62 ± 73
55120.099	0.223	-63 ± 55	-177 ± 79
55135.184	0.013	90 ± 52	112 ± 64
55149.176	0.948	117 ± 37	119 ± 44
55150.302	0.829	12 ± 46	-7 ± 72
55161.089	0.259	-126 ± 46	-168 ± 55
55163.031	0.777	-41 ± 44	-18 ± 59
		HY Vel	
53002.141		-180 ± 57	-199 ± 61
53143.986		-48 ± 60	-53 ± 66
54108.348		-198 ± 55	-191 ± 58
55107.361		34 ± 59	-61 ± 79
55112.367		-25 ± 51	-58 ± 69
55118.320		133 ± 62	162 ± 83
55120.324		63 ± 33	59 ± 48
55168.150		-99 ± 38	-147 ± 64
55169.349		47 ± 41	78 ± 73
55171.150		40 ± 59	-11 ± 88
55173.269		17 ± 51	-19 ± 68
55177.341		117 ± 35	160 ± 49
55181.141		42 ± 36	35 ± 54
55182.280		67 ± 38	144 ± 53
55189.176		19 ± 44	30 ± 68

Note. All quoted errors are 1σ uncertainties.

Table 4
Magnetic Field Models for the Stars with Detected Periods

Object		ξ^1 CMa	15 CMa	α Pyx	33 Eri
$\langle B_z \rangle$	(G)	281.6 ± 4.3	45.3 ± 7.1	90.3 ± 5.1	-44.1 ± 15.3
$A_{\langle B_z \rangle}$	(G)	80.3 ± 5.8	116.3 ± 12.1	119.7 ± 12.8	112.0 ± 25.5
$v \sin i$	(km s^{-1})	9 ± 2	34 ± 4	11 ± 2	25 ± 4
R	($R_\odot$)	7.1 ± 0.9	10.0 ± 1.5	6.3 ± 1.0	2.5 ± 0.3
$v_{\rm eq}$	(km s^{-1})	165 ± 21	40 ± 6	100 ± 16	99 ± 12
i	($^\circ$)	3.1 ± 0.8	58.1 ± 17.6	6.3 ± 1.5	14.6 ± 3.0
β	($^\circ$)	79.1 ± 2.8	57.9 ± 18.3	85.2 ± 1.3	84.1 ± 2.7
B_d	(G)	5300 ± 1100	570 ± 50	3800 ± 500	1500 ± 350

massive stars. The magnetic field models for the three β Cephei stars and the one SPB star presented in this work confirm this trend.

The insufficient knowledge of the strength, geometry, and time variability of magnetic fields in hot pulsating stars prevented until now important theoretical studies on the impact of magnetic fields on stellar rotation, pulsations, and element diffusion. Although it is expected that the magnetic field can distort the frequency patterns (e.g., Hasan et al. 2005), such a perturbation is not yet detected in hot pulsating stars. Splitting of non-radial pulsation modes was observed for 15 CMa

(Shobbrook et al. 2006), but the identification of these modes is still pending. The magnetic β Cephei star sample indicates that they all share common properties: they are N-rich targets (e.g., Morel et al. 2008) and, as discussed by Hubrig et al. (2009), their pulsations are dominated by a nonlinear dominant radial mode (see also Saesen 2006 for ξ^1 CMa). The presence of a magnetic field might consequently play an important role to explain such a distinct behavior of magnetic β Cephei stars. More precisely, chemical abundance anomalies are commonly believed to be due to radiatively driven microscopic diffusion in stars rotating sufficiently slowly to allow such a process to be effective. However, we need an additional clue to account for the fact that both normal and nitrogen-enriched slowly rotating stars are observed. The presence of a magnetic field is a very plausible explanation, as it can add to the stability of the atmosphere, allowing diffusion processes to occur (Michaud 1970). On the other hand, among the studied stars, apart from the star 15 CMa with rather low $v_{\rm eq} = 40 \pm 6$ km s^{-1}, the other three magnetic pulsating stars rotate much faster up to $v_{\rm eq} = 165 \pm 21$ km s^{-1} for ξ^1 CMa with the strongest magnetic field, indicating that these stars are not truly slowly rotating stars, but seen close to pole-on. Obviously, the topic of mixing signatures is not understood theoretically yet and more computational work as well as future additional observational validation of our results are needed to understand the link between the presence of a magnetic field, rotation, pulsating characteristics, and abundance peculiarities.

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