Magnetic fields of hot pulsating stars

S. Hubrig[1], I. Ilyin[1], M. Schöller[2], T. Morel[3], M. Briquet[4], P. de Cat[5]

[1] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
[2] European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
[3] Institute for Astrophysics and Geophysics, Liége University, Allee du 6 Août 17, 4000 Liége, Belgium
[4] Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200 D, 3001 Leuven, Belgium
[5] Koninklijke Sterrenwacht van België, Ringlaan 3, 1180 Brussel, Belgium

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 is not sufficiently studied yet. One 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 VLT. These measurements allowed us to carry out a search for rotation periods and to constrain the magnetic field geometry for a few stars in our sample.

Key words: stars: early-type — stars: magnetic field — stars: oscillations — stars: variables: general — stars: fundamental parameters — stars: individual (ξ^1 CMa, 15 CMa)

1. Introduction

Over several years, we undertook a magnetic field survey for main-sequence pulsating B-type stars, namely the slowly pulsating B (SPB) stars and β Cephei stars, with FORS 1/2 in spectropolarimetric mode at the VLT, allowing us to detect in four β Cephei stars and 16 SPB stars, for the first time, longitudinal magnetic fields of the order of a few hundred Gauss. For a few such stars we obtained multi-epoch magnetic field measurements to determine their magnetic field properties (strength, magnetic field geometry, and time variability) to study the impact of magnetic fields on rotation, pulsation, and diffusion. Here we report our results of monitoring a few targets.

2. Observations and magnetic field measurements

Multi-epoch time series of polarimetric spectra of the pulsating stars were obtained with FORS 2 on Antu (UT1) from 2009 September to 2010 March in service mode. Using a slit width of $0\farcs4$, the achieved spectral resolving power of FORS 2 obtained with the GRISM 600B was about 2000. The β Cephei stars ξ^1 CMa and 15 CMa were observed 11 and 13 times, respectively. 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

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

where V is the Stokes parameter which measures the circular polarisation, I is the intensity in the unpolarised spectrum, $g_{\rm eff}$ is the effective Landé factor, e is the electron charge, λ is the wavelength, m_e the electron mass, c the speed of light, $\mathrm{d}I/\mathrm{d}\lambda$ is the derivative of Stokes I, and $\langle B_{\rm z}\rangle$ is the mean longitudinal magnetic field. The measurements of the longitudinal magnetic field were carried out in two ways, using the whole spectrum ($\langle B_{\rm z}\rangle_{\rm all}$) and using only the hydrogen lines ($\langle B_{\rm z}\rangle_{\rm hyd}$). 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, and another one on 2010 January 01. SOFIN (Tuominen et al. 1999) is a high-resolution echelle spectrograph mounted at the Cassegrain focus of the NOT and equipped with three optical cameras providing different resolving powers of 30 000, 80 000, and 160 000. 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 10 000 Å with a length of the spectral orders of about 140 Å at 5500 Å. The polarimeter is located in front of the entrance slit of the spectrograph and consists of a fixed calcite beam splitter aligned along the slit and a rotating super-achromatic quarter-wave plate. Two spectra circularly polarized in opposite sense are recorded simultaneously for each echelle order, providing sufficient separation by the cross-dispersion prism below 7000 Å. Two such exposures with quarter-wave plate angles separated by 90° are necessary to derive circularly polarised spectra. The spectra were reduced with the 4A software package (Ilyin 2000).

A frequency analysis was performed on the longitudinal magnetic field measurements $\langle B_{\rm z}\rangle_{\rm all}$ (which generally show smaller sigmas) available from our previous work (Hubrig et al. 2006, 2009) and the current studies using a non-linear 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 (Ilyin 2010). The F-statistics allows to derive the false alarm probability of the trial period based on the F-test (Press et al. 1992). For four out of the studied six stars the resulting amplitude spectra displayed dominant peaks. The equivalent periods were 2.18 d for the β Cephei star ξ^1 CMa and 12.64 d for the β Cephei star 15 CMa. Phase diagrams of the data folded with the determined periods are presented in Fig. 1. The quality of our fits is described by reduced χ^2-values, which is 0.41 for ξ^1 CMa, 0.47 for 15 CMa.

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.

Using stellar fundamental parameters and asssuming that the studied stars are oblique dipole rotators, we obtain an obliquity angle β=79.1±2.8° for ξ^1 CMa and β=67.1±28.2° for 15 CMa.

3. Summary

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 by 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

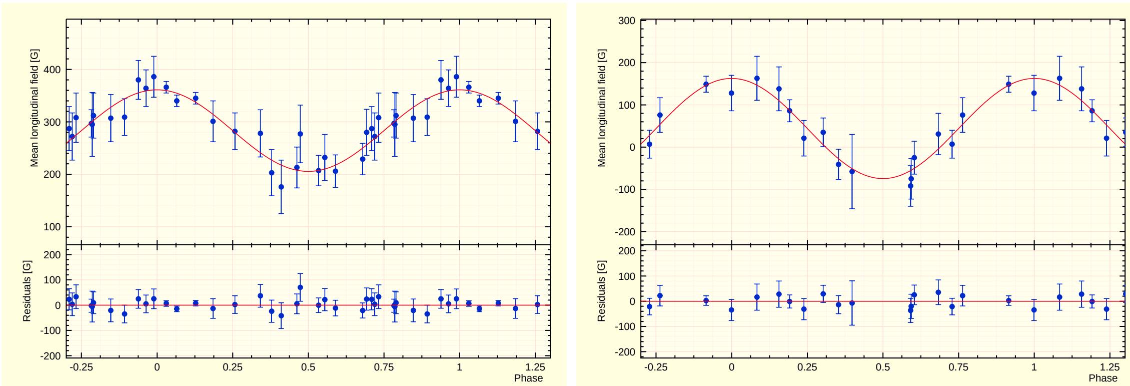

Figure 1: Phase diagrams with the best sinusoidal fit for the longitudinal magnetic field measurements. The residuals (Observed – Calculated) are shown in the lower panels. The deviations are mostly of the same order as the error bars, and no systematic trends are obvious, which justifies a single sinusoid as a fit function. The fits correspond to ξ^1 CMa (left) and 15 CMa (right).

a non-linear dominant radial mode (see also Saesen et al. (2006) for ξ^1 CMa). The presence of a magnetic field might consequently play an important role to explain such a distinct behaviour 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 slow 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. Interestingly, Silvester et al. (2009) used the LSD technique to measure magnetic fields in a small number of hot pulsating stars, but failed to detect magnetic fields in most of them. However, the majority of the stars in their sample were observed only once or twice during the same night, usually with poor signal-to-noise. Obviously, such results are rather misleading and give consequently a biased picture of the actual status of the presence of magnetic fields in massive stars.

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