Magnetic field studies of massive main sequence stars

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We report on the status of our spectropolarimetric observations of massive stars. During the last years, we have discovered magnetic fields in many objects of the upper main sequence, including Be stars, β Cephei and Slowly Pulsating B stars, and a dozen O stars. Since the effects of those magnetic fields have been found to be substantial by recent models, we are looking into their impact on stellar rotation, pulsation, stellar winds, and chemical abundances. Accurate studies of the age, environment, and kinematic characteristics of the magnetic stars are also promising to give us new insight into the origin of the magnetic fields. Furthermore, longer time series of magnetic field measurements allow us to observe the temporal variability of the magnetic field and to deduce the stellar rotation period and the magnetic field geometry. Studies of the magnetic field in massive stars are indispensable to understand the conditions controlling the presence of those fields and their implications on the stellar physical parameters and evolution.

1 Introduction

Magnetic fields play an important role in astrophysical phenomena of the universe on various scales. For galaxies, dynamo models associated with various MHD instabilities occurring in the interstellar medium (ISM) are used to explain the formation of the galactic structure (e.g., Gomez & Cox 2004; Bonanno & Urpin 2008). Magnetic fields play a role in the evolution of interstellar molecular clouds and the star formation process, where the cloud collapse is probably taking place along the magnetic field lines (e.g. Alves et al. 2008). They are also present at all stages of stellar evolution, from young T Tauri stars and Ap/Bp stars to the end products: white dwarfs, neutron stars, and magnetars. On the other hand, the role of magnetic fields in massive O-type stars and Wolf-Rayet (WR) stars remains unknown. No definitive magnetic field has ever been detected in WR stars and presently only about a dozen O stars have published magnetic fields, while for early B stars magnetic field detections are more numerous. In our study of the open cluster NGC 3766, we found that seven out of the 14 observed early B-type stars showed magnetic fields (Hubrig et al. 2009). In addition, theories about the origin of magnetic fields in O- and early B-type stars remain poorly developed, mostly because the distribution of magnetic field strengths in massive

stars from the ZAMS to more evolved stages has not yet been studied. In our recent studies, we focused on magnetic fields of massive stars observed in different environments: in open clusters at different ages and in the field (Hubrig et al. 2009, 2011a, 2011b).

## 2 Magnetic field models for β Cephei and SPB stars

Using FORS 1/2 and SOFIN longitudinal magnetic field measurements collected in our recent studies (Hubrig et al. 2011c), we were able to determine the rotation period 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 with several kG the largest dipole strengths. In Fig. 1 we show periodograms and phase diagrams with the best sinusoidal fit for the longitudinal magnetic field measurements of ξ^1 CMa (left) and 15 CMa (right).

In our studies, V1449 Aql possesses so far the strongest longitudinal magnetic field of up to 700 G among the β Cephei stars. The resulting periodogram from our SOFIN and FORS1 measurements displays three dominant peaks with the highest peak at $f = 0.0720\,\mathrm{d}^{-1}$ corresponding to a period $P = 13.893\,\mathrm{d}$ (Hubrig et al. 2011d). This period was recently confirmed with seismic modeling based on CoRoT

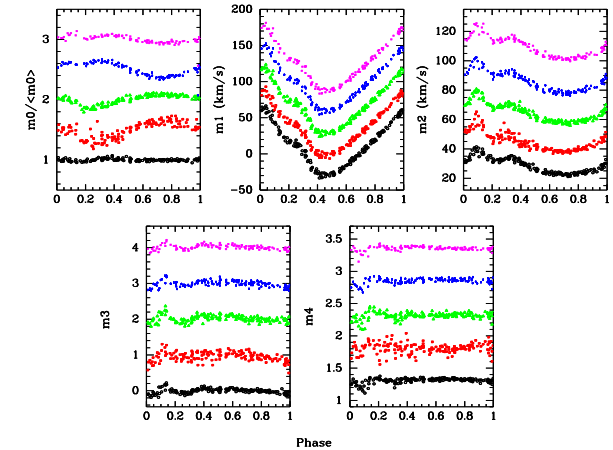* Corresponding author: e-mail: mschoell@eso.org
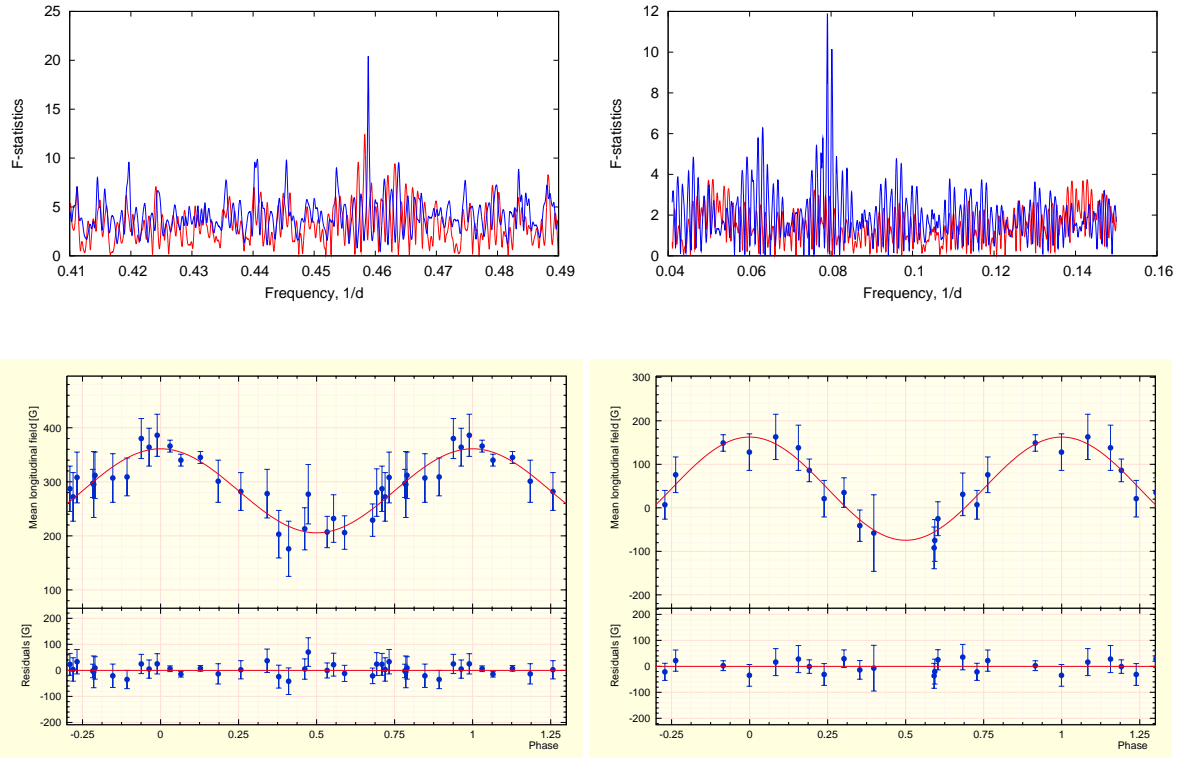
Fig. 1 Periodograms (top) and phase diagrams (bottom) with the best sinusoidal fit for the longitudinal magnetic field measurements of ξ^1 CMa (left) and 15 CMa (right). The residuals (Observed − Calculated) are shown in the lower panels.
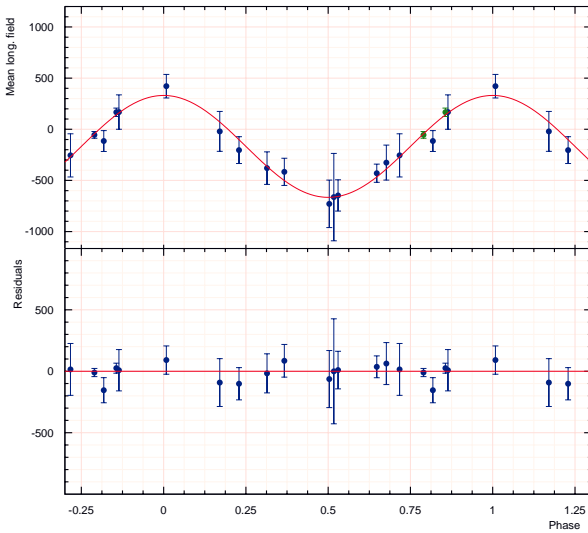
Fig. 2 Periodogram for the magnetic field measurements of V1449 Aql. The residuals (Observed − Calculated) are shown in the lower panel.

Fig. 3 Equivalent width (m0), radial velocity (m1), line width (m2), asymmetry (m3), and kurtosis (m4) from our SOFIN data of V1449 Aql.

data and ground-based time-resolved spectroscopy by Aerts et al. (2011), who also mention a somewhat high initial internal metallicity in their models, probably related to the presence of a magnetic field. The magnetic field geometry can likely be described by a centered dipole with a po-

lar magnetic field strength B_d around 3 kG. In Fig. 2 we show the periodogram for V1449 Aql and the residuals for our measurements. The line profiles undergo very significant pulsational variability and any rotational modulation of the observed profiles is completely masked by the pulsational modulation. The moment variations for five lines belonging to different elements, namely He I 4713.1, C II 5133.1, N II 5667.6, O II 4592.0, and Si III 4553.6 exhibit

Fig. 4   Combined IR Spitzer IRAC image of the bow shock around ζ Oph.

Fig. 5   Age distribution of probable cluster members from our study. Stars with magnetic fields are denoted by horizontal lines.
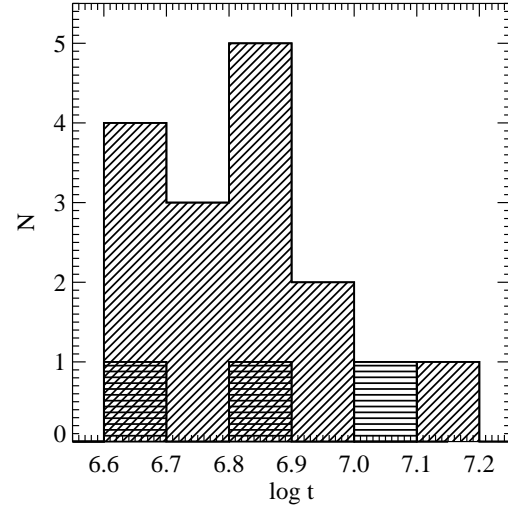
slight differences between the elements. In Fig. 3 we show the equivalent width (m0), radial velocity (m1), line width (m2), asymmetry (m3), and kurtosis (m4) from our SOFIN data of V1449 Aql.

3   O-type stars

To investigate statistically whether magnetic fields in O-type stars are ubiquitous or appear only in stars with a specific spectral classification, certain age, or in a special environment, we acquired new spectropolarimetric observations with FORS 1/2. A field at a significance level of 3σ was detected in eleven stars (Hubrig et al. 2011a, 2011e). The strongest longitudinal magnetic fields were measured in two Of?p stars: $\langle B_z \rangle = 381 \pm 122$ G for CPD–28 2561 and $\langle B_z \rangle = 297 \pm 62$ G for HD 148937. Both magnetic fields were detected by us for the first time, the latter in an earlier study (Hubrig et al. 2008).

The star ζ Ophiuchi of spectral type O9.5 V is a well-known rapidly rotating runaway star with extremely interesting characteristics. It undergoes episodic mass loss seen as emission in Hα, and it is possible that it rotates with almost break-up velocity with $v \sin i = 400 \, \mathrm{km \, s^{-1}}$ (Kambe et al. 1993). Our spectropolarimetric observations of ζ Oph with FORS 1 in 2008 revealed the presence of a mean longitudinal magnetic field $\langle B_z \rangle_{\mathrm{all}} = 141 \pm 45$ G. Additional nine spectropolarimetric observations were obtained with FORS 2 over the rotation period in 2011. The longitudinal magnetic field shows a change of polarity and its variation over the rotation cycle can be represented by a sinusoidal fit with a semi-amplitude of $\sim$160 G. Fig. 4 shows a combined IR *Spitzer* IRAC image of the bow shock around ζ Oph.

The available observations (Hubrig et al. 2011a, 2011b) seem to indicate that a magnetic field is more frequently
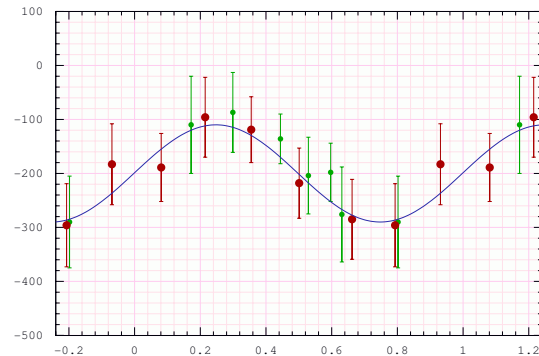
Fig. 6   Longitudinal magnetic field variation of HD 148937 over the 7.032 d period determined by Nazé et al. (2010). Red (large) symbols correspond to ESPaDOnS observations (Wade et al. 2011), while green (small) symbols are our FORS 1 and FORS 2 measurements (Hubrig et al. 2008, 2011a; Hubrig et al. in preparation).

detected in field stars than in stars belonging to clusters or associations. It is striking that most previously detected magnetic O-type stars are candidate runaway stars. Clearly, these findings generate a strong motivation to carry out a kinematic study of all stars previously surveyed for magnetic fields to search for a correlation between the kinematic status and the presence of a magnetic field. In Fig. 5 we show the age distribution of probable cluster members from our study. The three stars with magnetic fields, HD 155806, HD 156154, and HD 164794, are denoted by horizontal lines.

To demonstrate the excellent potential of FORS 2 for the detection and investigation of magnetic fields in mas-

sive stars, we present in Fig. 6 our FORS 2 observations collected between 2008 and May 2011 of the Of?p star HD 148937, together with the ESPaDOnS observations obtained at the CFHT (Wade et al. 2011). The measurement errors for both ESPaDOnS and FORS 1/2 observations are of similar order. One more measurement (not shown in this Figure) was obtained in 2010 on May 22, but ordinary and extraordinary beams in the FORS 2 setup were overlapping in this exposure due to slitlet problems.

4 Discussion

Early B-type pulsating stars had been a puzzle for a long time with respect to the presence of magnetic fields in their atmospheres. Only very few stars of this type with very weak magnetic fields were detected before we started our surveys of magnetic fields in B-type stars in 2004. We were the first to determine magnetic field strengths for a large sample of O-type stars, with an accuracy of a few tens of Gauss. Very few magnetic fields stronger than $300\,\mathrm{G}$ were detected in the studied sample, suggesting that large-scale, dipole-like magnetic fields with polar magnetic field strengths higher than $1\,\mathrm{kG}$ are not widespread among O-type stars. Our studies of massive stars revealed that the presence of a magnetic field can be expected in stars of different classification categories and at different evolutionary stages. We note that no physical properties are known that define these particular classes of stars as non-magnetic. The inability to detect magnetic fields in massive stars in previous studies could be related to the weakness of these fields, which can, in some stars, be as little as only a few tens of Gauss.

The results of our kinematic analysis of known magnetic O-type stars using the best available astrometric, spectroscopic, and photometric data indicates that a magnetic field is more frequently detected in candidate runaway stars than in stars belonging to clusters or associations (Hubrig et al. 2011b). As the sample of stars with magnetic field detections is still very small, a study of a larger sample is urgently needed to confirm the detected trend by performing dedicated magnetic field surveys of O stars in clusters/associations and in the field. The results obtained so far allow us to constrain preliminarily the conditions conducive to the presence of magnetic fields and derive the first trends for their occurrence rate and field strength distribution. This information is critical for answering the principal question of the possible origin of magnetic fields in massive stars.

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