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Magnetic fields in massive stars

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Abstract. We review the recent discoveries of magnetic fields in different types of massive stars and briefly discuss strategies for spectropolarimetric observations to be carried out in the future.

Key words: stars: abundances – stars: chemically peculiar – stars: circumstellar matter – stars: emission-line, Be – stars: magnetic fields – stars: pulsations – techniques: polarimetric

1. Introduction

Massive stars end their evolution, with a final supernova explosion, as neutron stars or black holes. The initial masses of these stars range from $\sim 8 - 10 M_{\odot}$ to $100 M_{\odot}$ or more, which corresponds to spectral types earlier than about B2. While magnetic fields in the Sun and solar-like stars have been studied intensively, very little is known yet about their existence, origin and role in massive stars. In spite of considerable indirect evidence only very few direct magnetic field detections have been reported so far. Magnetic fields are accessible through the Zeeman effect. The Zeeman components of spectral lines are polarized and thus permit magnetic fields to be measured even in rapidly rotating massive stars where rotation broadening, etc., prevents the resolution of Zeeman components. Currently, direct measurements are achieved only in two O-type stars, θ^1 Ori C and HD 191612 with longitudinal magnetic field ($\langle B_l \rangle$) values of a few hundred Gauss (Donati *et al.*, 2002; 2006), and in a few early B-type stars. In Fig. 1 we demonstrate the excellent potential of FORS1 for measuring magnetic fields in massive stars. Our recent FORS1 observations with grism 600 R of the mean longitudinal magnetic field in θ^1 Ori C are compared with the measurements of Wade *et al.* (2006) obtained with the MuSiCoS spectrograph. This star was the first O-type star with a detected weak magnetic field varying with the rotation period of 15.4 days. It is obvious that the FORS1 measurements are much more accurate showing a smooth sinusoidal curve in spite of the phase gap between 0.60 and 0.88. However, our observations determine a magnetic geometry different from the one deduced by Wade *et al.* (2006). The maxima and minima of the measured longitudinal field as well as the phases of the field extrema appear to be completely different. Assuming an inclination of the rotation axis to the line-of-sight of i=45°, our modeling of the longitudinal field variation constrains the dipole magnetic field geometry of θ^1 Ori C to $B_d \approx 900$ G and $\beta \approx 80°$, where B_d is the dipole intensity and β is the obliquity angle. In the next sections we present the results of our recent surveys of magnetic fields in massive stars carried out with FORS1 at the VLT in recent years.

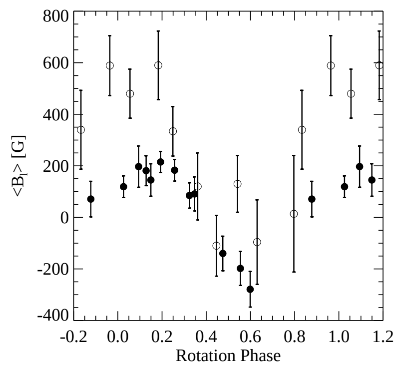

Figure 1. $\langle B_l \rangle$ vs. the rotation phase for θ^1 Ori C. Open circles: Wade *et al.* (2006) with MuSiCoS. Filled circles: Our FORS1 measurements in 2007.

2. Magnetic fields in SPB and β Cephei stars

We started a systematic search for magnetic fields in slowly pulsating B (SPB) and β Cephei stars with FORS1 in service mode in 2003 (Hubrig *et al.*, 2006 a). A weak mean longitudinal magnetic field of the order of a few hundred Gauss was detected in the β Cephei star ξ^1 CMa and in 13 SPB stars. The star ξ^1 CMa became the third magnetic star known among the β Cephei stars. It also shows the largest magnetic field and is the hottest magnetic β Cephei star. After the publication of these results we obtained two more observing runs allocated at the VLT. The new observations revealed the presence of magnetic fields in ten confirmed SPB and candidate SPB stars and in three β Cephei type stars. As an example, we present in Fig. 2 the acquired magnetic field measurements of ξ^1 CMa over the last 3.7 years. No strong variability or polarity change is detected although a slight increasing trend in the strength of the longitudinal field is apparent.

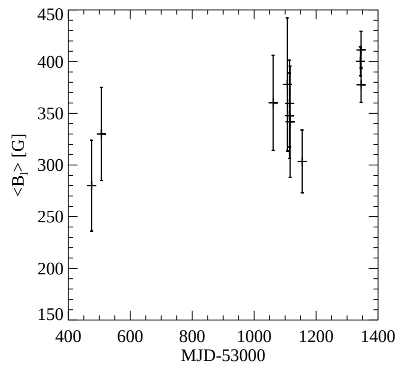

Figure 2. Longitudinal magnetic field measurements of ξ^1 CMa over the last 3.7 years.

Briquet *et al.* (2007) presented the evolution of the averaged quadratic effective magnetic field $\langle B_l \rangle$ in Bp and SPB stars over the main sequence (Fig. 3, left). The value $\log g$ was used as a proxy for the relative age and had the advantage of being a directly measured quantity. From this figure it is obvious that the strongest magnetic fields appear in very young Bp stars. The fact that strong magnetic fields are only observed in a restricted range of evolutionary states could be interpreted as a hint for a magnetic field decay in stars at advanced ages. On the other hand, Hubrig *et al.* (2007 a) studied a sample of Ap and Bp stars with accurate Hipparcos parallaxes and could show that the magnetic flux remains constant over the stellar life time on the main sequence (Fig. 3, right). This result is in full agreement with studies of magnetic fluxes in neutron stars which are similar to those in magnetic A and B stars and white dwarfs, suggesting that flux conservation during gravitational collapse may play an important role (Reisenegger, 2007).

Very recently, Morel *et al.* (2007) carried out an NLTE abundance study of a sample of slowly rotating early-type B dwarfs with detected weak magnetic fields. This sample includes among other stars also a number of SPB and β Cephei stars for which we carried out the magnetic field survey in recent years. The analysis strongly supports the existence of a population of nitrogen-rich and boron-depleted slowly rotating B stars. The presently available observational

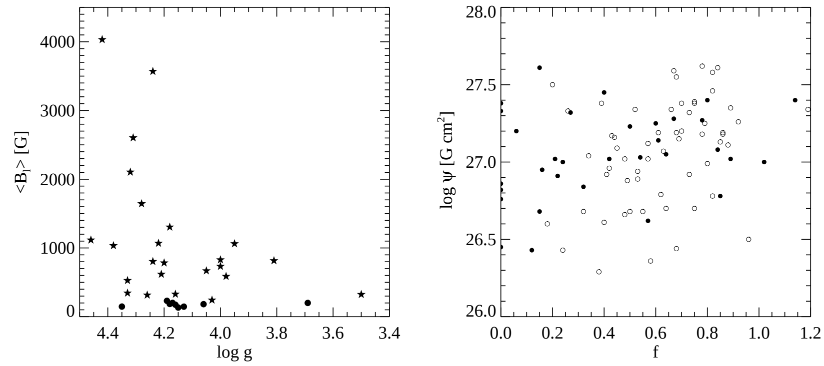

Figure 3. Left: Averaged quadratic effective magnetic field for Bp stars (filled stars) and SPB stars (filled circles) versus $\log g$. Right: Magnetic flux in Ap and Bp stars against elapsed time on the main sequence. Filled circles indicate stars with mass $M > 3\,M_{\odot}$, while open circles indicate stars with mass $M < 3\,M_{\odot}$.

data suggest a higher incidence of a nitrogen excess in stars with detected magnetic fields. These results open a new perspective for the selection of the most promising targets for magnetic field surveys of massive stars using chemical anomalies as selection criteria.

In summary, our recent observations of magnetic fields imply that β Cephei stars and SPBs can no longer be considered as classes of non-magnetic pulsators. However, the effect of the fields on the oscillation properties remains to be studied.

3. Magnetic fields in Be stars

Be stars are defined as rapidly rotating main sequence stars showing normal O or B-type spectra with superposed Balmer emissions. Until now, weak magnetic fields have been detected in only three Be stars. A sample of 15 Oe/Be stars was observed with FORS1 in April-September 2005 in service mode. A longitudinal magnetic field at a level larger than 3σ has been detected in four stars, HD 56014, HD 148184, HD 155806, and HD 181615 (Hubrig *et al.*, 2007 b). Also, an inspection of the Stokes V spectra of these four stars reveals noticeable Zeeman features at the position of numerous spectral lines. As an example, we present in Fig. 4 the Stokes I and V spectra for HD 148184 and HD 155806 in the spectral region around the line He I λ 4471.5 Å.

The star HD 155806 is the hottest star in our sample with a spectral type O7.5 IIIe and is currently the third O-type star with a magnetic field detected at

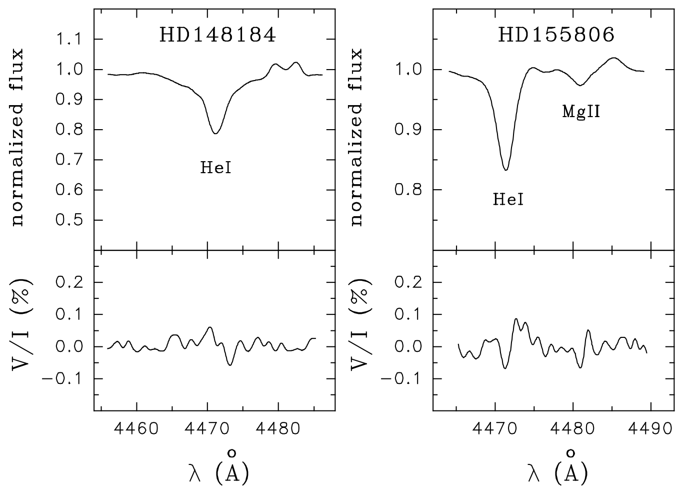

Figure 4. Stokes I and V spectra of HD 148184 and HD 155806 in the spectral region around the line He I λ 4471.5 Å.

a level larger than $3\,\sigma$: ($\langle B_z\rangle = -115\pm37$ G). Clear variations of Si IV, He I and other lines have been detected in FEROS and UVES spectra retrieved from the ESO archive (Hubrig *et al.*, in preparation). In Fig. 5 we present the variations of the He I 5016 Å line.

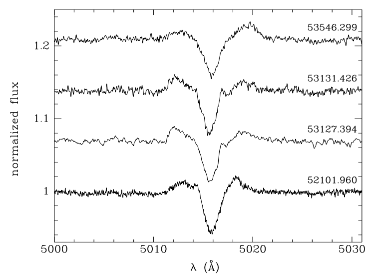

Figure 5. Spectral profile variability of the He I 5016 Å line in the FEROS and UVES spectra of HD 155806. Spectra are labeled with modified Julian Dates.

For three of early type emission stars, HD 58011, HD 117357, and HD 181615, we noticed the presence of distinctive circular polarization signatures detected in the Stokes V spectra of the Ca II H & K lines. The profiles of these Ca lines in the FORS1 spectra taken in integral light are deeper than predicted by synthetic spectra computed with the code SYNTH + ROTATE developed by

Piskunov (1992). Additional high-resolution high signal-to-noise spectroscopic observations are needed to study the Ca line profiles to be able to decide whether they are formed in the circumstellar disks around these stars. Interestingly, similar types of circumstellar components in Ca II H&K lines have recently been discovered by Hubrig *et al.* (2006 b; 2007 c) in Herbig Ae stars.

4. Discussion

Magnetic fields are indeed present in massive stars. For the case of magnetic fields in non-peculiar massive stars that are weaker in strength and likely more complex in their geometry than Bp stars, progress in their study may potentially come from detailed studies of polarized line profiles. It is not obvious to what extent magnetic fields can be directly discovered in circumstellar material. Previous detections of magnetic fields in circumstellar material include a detection of magnetic fields in the circumstellar disk of FU Ori (Donati *et al.*, 2005) and in circumstellar Ca lines of Herbig stars (Hubrig *et al.*, 2006 b; 2007 c). However, modeling diagnostics of magnetic fields in these environments are still under development (Ignace, Gayley 2007).

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