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The B fields in OB stars (BOB) survey is an ESO Large Programme collecting spectropolarimetric observations for a large number of early-type stars in order to study the occurrence rate, properties, and ultimately the origin of magnetic fields in massive stars. A total of 98 objects was observed over 20 nights with FORS2 and HARPSpol to July 2014. Preliminary results indicate that the fraction of magnetic OB stars with an organised, detectable field is low. This conclusion, now independently reached by two different surveys, has profound implications for any theoretical model attempting to explain the field formation in these stars. We also discuss some important issues addressed by our observations (e.g., the lower bound of the field strength) and the discovery of some remarkable objects.

Magnetic fields in OB stars

Magnetic fields affect the evolution and properties of massive stars in several ways; from redistributing the angular momentum in the stellar interior to the formation of a circumstellar magnetosphere through the channelling and confinement of their radiatively driven winds. In some cases, magnetic fields may also lead the stars to end their lives as exotic objects, such as magnetars (highly magnetised neutron stars with field strength up to 10^{14-15} Gauss) or gamma-ray bursts.

Yet it is only very recently that the number of known magnetic OB stars has reached a level that allows us to evaluate the field incidence, examine the properties of the fields, and critically test the various models proposed for their creation. The picture now emerging is that relatively strong fields (above, say, 100–200 Gauss at the surface) are only found in about 7 % of all massive stars (Wade et al., 2014) and that the field topology is rather simple (dipolar, or, in some rare cases, low-order multipolar). Moreover, the field strength is not directly linked to the stellar parameters (e.g., it does not scale up with rotation rate). While this is in sharp contrast with the situation for Solar-like stars with dynamo-generated fields, these characteristics are similar to those presented by intermediate-mass stars (the chemically peculiar Ap/Bp stars in the mass range 1.5–8 $M_{\odot}$). This similarity suggests a related origin of the field.

Despite these remarkable achievements and the promising progress made over the last few years, the answers to some important questions still elude us. For instance, the effects of magnetic fields on the internal rotational profile and on the transport of chemical species remain largely unknown. Even the mode of creation of the field in the first place is not completely settled. The magnetic field permeating the interstellar medium (ISM) is amplified during star formation and may naturally relax into a large-scale, mostly poloidal field emerging at the surface (e.g., Braithwaite & Spruit, 2004). The similarity between the magnetic properties of OB and Ap/Bp stars suggests that today we observe the remnant of the field frozen in from the ISM. However, recent studies indicate that a very significant fraction of OB stars may suffer a merger or a mass-transfer event during their evolution (Sana et al., 2012) and it cannot be ruled out that fields are created through such processes (e.g., Wickramasinghe et al., 2014). It has also been proposed that dynamo action can operate in either the radiative zone or in subsurface convection layers, and may lead to observable fields (unlike dynamo-generated fields in the convective core that take too long to reach the photosphere). Such a dynamo would presumably produce short-lived, spatially localised magnetic structures (e.g., Cantiello & Braithwaite, 2011) that are, however, much more challenging to detect.

A better understanding of the effects and origin of magnetic fields in massive stars requires a significant increase in the statistics of known magnetic OB stars (for instance, only in about ten O stars has a field been firmly detected). It is in this context that, building on our previous experience with ESO spectropolarimetric instruments (e.g., Hubrig et al., 2009a), we have launched the B fields in OB stars (BOB) survey[1].

The BOB survey

A total of 35.5 nights of observations were allocated during Period 91 to 96 as part of an ESO Large Programme (191.D-0255; Principal Investigator: Morel). A two-step approach was adopted: about 20 nights were dedicated to obtaining snapshot observations of a large number of OB stars, while the remaining nights are devoted to confirm the field detection for the candidate magnetic stars and to better characterise the field properties for those that are firmly identified as being magnetic. Two different state-of-the-art instruments with circular polarisation capabilities are used (with low and high spectral resolution, respectively): the FOcal Reducer and Spectrograph (FORS2) at the Very Large Telescope (VLT) for the fainter targets and HARPSpol (the polarimetric unit of the HARPS spectrograph) at the 3.6-metre telescope at La Silla for the brighter ones. About two thirds of the total observing time is allocated on HARPSpol (25 nights). As of July 2014, 20 nights of observations (8 with FORS2 and 12 with HARPSpol) have been completed. Only one night (with FORS2) was lost because of bad weather. About 85 % of the remaining 15.5 nights are scheduled on HARPSpol.

Previously known magnetic OB stars appear, on average, to have rotation speeds significantly lower than the rest of the population. We therefore mostly targeted stars with projected equatorial rotational velocities (v sin$i$) below 60 km s^{-1} to enhance the probability of detecting magnetic fields. Contrary to the Magnetism in Massive Stars survey (MiMeS; Wade et al., 2014), we concentrated on normal, main-sequence OB stars and did not consider, e.g., Be or Wolf–Rayet stars. The sample is composed in roughly equal parts of O (~ 40 %) and B (~ 60 %) stars; the vast majority are late O- and early B-type stars. BOB and MiMeS can be viewed as two complementary surveys in the sense that there are very few targets in common.

One important aspect of our survey is that the data reduction and analysis are carried out entirely independently by two groups (one from the Argelander-Institut für Astronomie in Bonn and the other from the Leibniz-Institut für Astrophysik in Potsdam) to ensure that the results are robust. The two groups process both the FORS2 and HARPSpol data separately, and employ different tools and analysis techniques (for details, see Hubrig et al., 2014).

The occurrence of magnetic fields in massive stars

Previous results (e.g., Wade et al., 2014) indicated that only about 7 % of massive stars host a magnetic field detectable with current instrumentation (> 100 Gauss). We have so far observed 98 OB targets and only unambiguously detected five magnetic stars. For all the stars, the detection is not only confirmed by the two groups (Bonn and Potsdam), but the field measurements also systematically agree within the errors. In addition, the field is detected at a high significance level with both FORS2 and HARPSpol.

Therefore, our results tend to support those independently obtained by MiMeS and confirm that the incidence rate of strong magnetic fields is low in massive stars and is similar to that inferred for intermediate-mass stars. It should be emphasised, however, that a number of candidate magnetic stars are still being followed up and that the preliminary incidence rate that we obtain (~ 5 %) may eventually be revised upwards.

Regardless of the exact figures, the scarcity of strongly magnetic OB stars has far-reaching implications, from the interpretation of the statistical properties of stellar populations (e.g., X-ray characteristics and impact of magnetic braking on the rotational velocities) to their fate as degenerate objects following the supernova explosion (e.g., as magnetars).

The first magnetic stars discovered by BOB

A magnetic field in a multiple system in the Trifid Nebula

One of the aims of our survey is to uncover magnetic stars with specific and unusual characteristics that would allow us to discriminate between the various channels that could lead to field formation as outlined previously.

An interesting discovery in this context is the detection of a magnetic field in a multiple system in NGC 6514, the Trifid Nebula (Hubrig et al., 2014), which is a very young and active site of star formation. We first observed the three brightest components identified in the central part of the nebula (A, C and D; Kohoutek et al., 1999) with FORS2 and, as shown in Figure 1, clearly detected a circularly polarised signal in component C (HD 164492C). In contrast, no such features were visible for the two other components (an early O star and a Herbig Be star).

Further observations on two consecutive nights with HARPSpol confirmed the existence of a field with a longitudinal strength ranging from 400 to 700 Gauss (the strength of the disc-averaged, line-of-sight component of the surface magnetic field). These high-resolution observations reveal complex and variable line profiles pointing towards a multiple system (made up of at least two early B-type stars). The situation is complicated further by the possible existence of chemical patches on the surface of some components. We will continue to monitor this system with both FORS2 and HARPSpol in order to establish whether only one or more components are magnetic. Observing time has also been granted on UVES to determine the orbital parameters of this system and the properties of the individual components. A complete characterisation of this peculiar system may provide valuable information about the

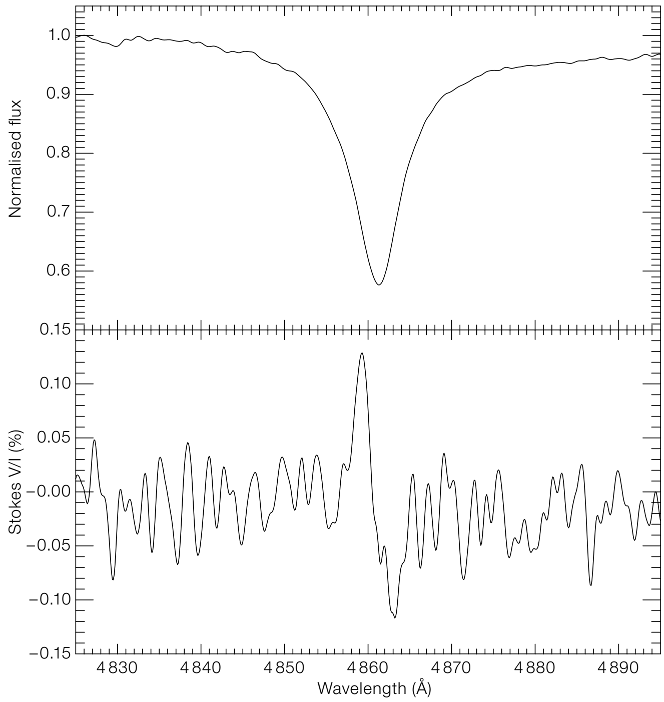


Figure 1. Stokes I (upper) and V/I (lower) FORS2 spectra of HD 164492C in the vicinity of the Hβ line (from Hubrig et al. 2014).

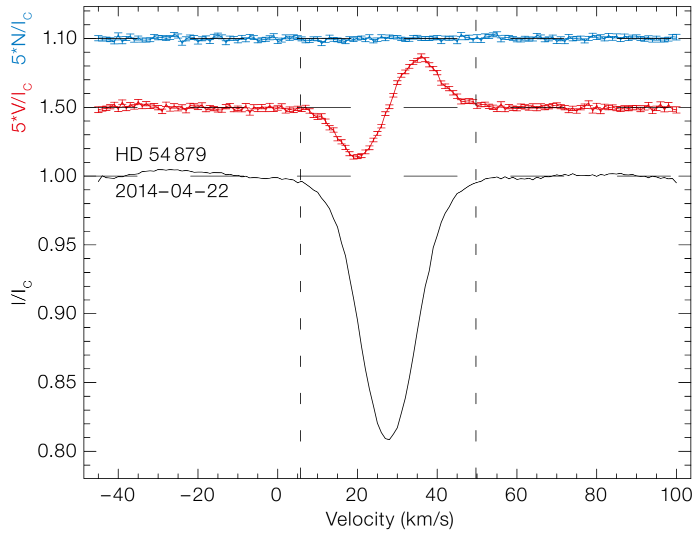


Figure 2. Stokes I (black), Stokes V (red) and diagnostic null N (blue) profiles of HD 54879 obtained through least squares deconvolution (LSD) techniques with HARPSpol (from Castro et al., 2014).

interplay between binarity and magnetic fields in massive stars (e.g., through a mass-transfer episode).

A new magnetic, He-rich star with a tight age constraint

The rare magnetic, helium-rich stars (some 30 are known) are the most massive chemically peculiar stars. These main sequence stars of spectral type ~ B2 display spectral, brightness and magnetic variability that can be accommodated by models where the dipolar field is tilted with respect to the rotational axis. Their photospheric abundance anomalies are believed to arise from the competition between radiative levitation and gravitational settling in the presence of a stellar wind.

While the surface abundance inhomogeneities give rise to the observed variability in some stars of this kind, a rigidly co-rotating circumstellar magnetosphere can result in variability in other cases, like in the prototype He-rich star σ Ori E. These objects have traditionally been used to study the interaction of the stellar wind with the (strong) magnetic field. Some stars have been shown to undergo rapid rotational braking (e.g., Mikulášek et al., 2008), which presents the opportunity to study angular momentum extraction from massive stars virtually in real time. This has stimulated magnetohydrodynamical simulations of angular momentum loss in magnetically channelled line-driven winds, which provided, for instance, first estimates of spin-down times (ud-Doula et al., 2009). Magnetic, He-rich stars can therefore be viewed as extreme laboratories where the still poorly understood effects of magnetic fields on the evolution of massive stars can be studied in detail. Of importance is the understanding of how the properties of He-rich stars develop during their main sequence evolution.

Our spectropolarimetric observations of the B1 star CPD −57° 3509 in the young (~ 10 Myr) open cluster NGC 3293 with FORS2 and HARPSpol reveal a strong and rapidly varying field (by up to 900 Gauss for the longitudinal component between two consecutive nights). The field is found to change polarity, which shows that both magnetic hemispheres are visible as the star rotates. The polar field exceeds 3 kiloGauss assuming a dipole geometry. A preliminary spectral analysis, assuming non-local thermodynamic equilibrium, indicates that CPD −57° 3509 is helium-rich (about three times solar) and has evolved through about one third of its main sequence lifetime (Przybilla et al., 2014). This makes CPD −57° 3509 one of the most evolved He-rich stars with a tight age constraint, promising to provide crucial information on the evolution of stars with magnetically confined stellar winds. Observing time has recently been granted on FORS2 and the Ultraviolet and Visual Echelle Spectrograph (UVES) to study this object in greater detail and to eventually reconstruct the abundance maps at the surface through Doppler imaging.

A non-peculiar magnetic O star

The few magnetic O stars known are very often peculiar. Their strong magnetic fields are believed to give rise to spectral peculiarities and/or to drive periodic line-profile variations (e.g., the Of?p stars or θ^1 Ori C). In contrast, we have discovered a narrow-lined O9.7 V star (HD 54879) hosting a strong field (with a dipole strength above 2 kiloGauss; see Figure 2), yet displaying no evidence, in the few optical spectra taken over five years, of any spectral peculiarity or variability (Castro et al., 2014). Only the broad and emission-like Hα profile is variable. This might be related to the presence of a centrifugal magnetosphere where wind material is trapped in closed magnetic loops and prevented from falling back to the star by centrifugal forces. Further observations

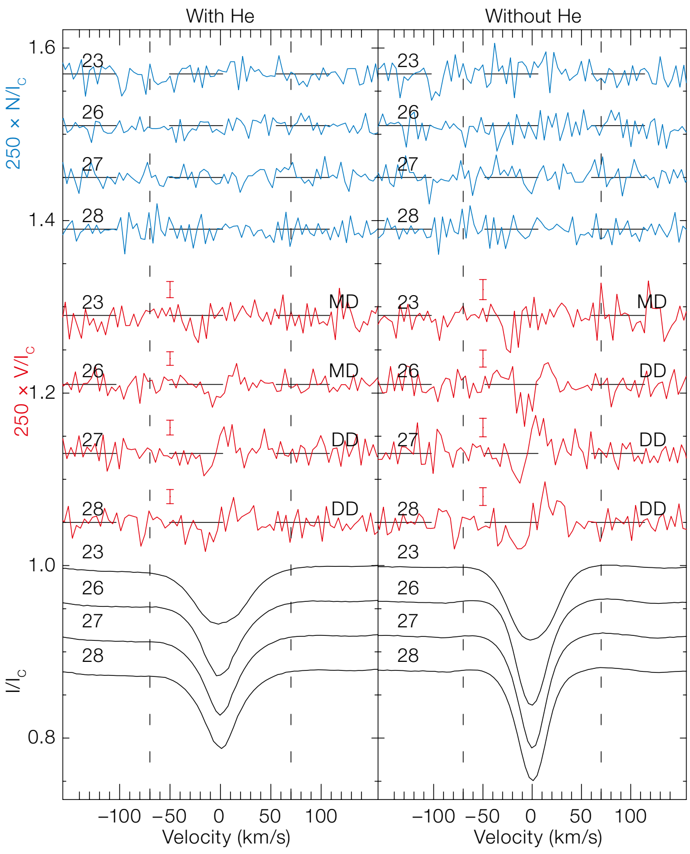
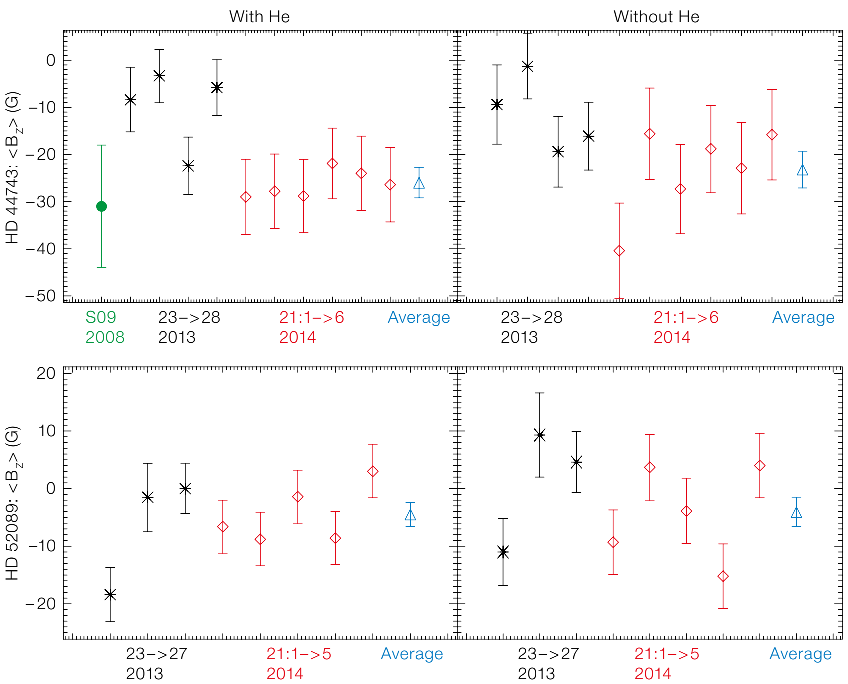


Figure 3. (Left) Stokes I (black), Stokes V (red), and diagnostic null N (blue) profiles of β CMa obtained through least squares deconvolution (LSD) techniques with HARPSpol during the period 23–28 December 2013. The left and right panels show the profiles obtained using a line mask with and without He lines, respectively. MD and DD correspond to a marginal and a definitive detection, respectively (from Fossati et al., 2014).

Figure 4. (Below) Time series of the longitudinal field measurements of β CMa (upper panels) and ε CMa (lower panels). The black crosses correspond to the observations carried out on four different nights in December 2013, while the red rhombs show the values obtained from consecutive observations on 21 April 2014 (the blue triangle is the average value obtained on that night). The green circle indicates the ESPaDOnS measurement of β CMa carried out in 2008 by Silvester et al. (2009). From Fossati et al. (2014).



are necessary to confirm the lack of spectral peculiarities and, if so, to understand the distinct behaviour with respect to other strongly magnetised O stars. A parallel investigation of the magnetic variability also needs to be undertaken.

The occurrence of weak fields in OB stars

One of the most intriguing properties of magnetic stars of intermediate mass is the bimodal distribution of fields that are either strong (above 300 Gauss) or extremely weak (< 1 Gauss). The lack of objects with ordered fields of intermediate strength appears not to be an observational bias and therefore to reveal a real dichotomy (e.g., Lignières et al., 2014). Investigating the origin of this "magnetic desert" may prove essential in our quest to understand the origin and evolution of fields in stars that cannot support a dynamo acting in the deep, outer convective envelope.

To examine whether such a magnetic desert also exists for more massive stars (above ~ 8 $M_{\odot}$), we have obtained very high-quality spectropolarimetric observations with HARPSpol of two very bright (V ~ 1.5–2.0 mag) early B-type stars (β CMa and ε CMa). By pushing the signal-to-noise ratio to the limit (up to ~ 700 for the unpolarised Stokes I spectrum) during a run that took place in December 2013, we repeatedly managed to detect a weak Zeeman signature across the line profiles (see Figure 3). Subsequent observations carried out in April 2014 have confirmed the detection. This result is particularly interesting in the case of β CMa, which is a very well-known pulsating star of the β Cephei type, since our identification of the pulsation modes allows us to precisely constrain some important parameters, such as the inclination of the rotation axis with respect to the plane of the sky. It should be noted that the field measurements are not appreciably affected by pulsations.

As discussed by Fossati et al. (2014), the most interesting outcome of the measurements is that the fields appear to be roughly constant and relatively weak in both cases. The longitudinal components are at most 30 Gauss in modulus (Figure 4), which translates into a polar strength of ~ 150 Gauss assuming a dipolar geometry. Although all the available measurements of β CMa in the literature are entirely consistent with a field of that magnitude, it should be pointed out that there is some indication for a stronger field in ε CMa from FORS1 observations carried out back in 2007 (Hubrig et al., 2009b; Bagnulo et al., 2012). Despite the fact that the case for a weak field is much stronger in β CMa, we will continue to discuss both stars in the following.

Confidently detecting fields of tens of Gauss or less in fainter targets is very challenging, even with modern instrumentation. If our upcoming observations confirm the weakness of the fields in β CMa and ε CMa, then the question arises whether these two bright stars only represent the tip of the iceberg. Is there a large population of stars with weaker fields or that are even truly non-magnetic (see Neiner et al., 2014)? A clear answer to these questions may not be possible until similar detection thresholds can be routinely achieved for fainter stars. However, it seems conceivable that weak fields are considerably more widespread in massive stars than the currently available data would suggest.

It is important to note that the Zeeman signatures observed in β CMa and ε CMa are typical of stars hosting a stable, large-scale field. It is therefore likely that the field is not dynamo-supported. In this picture, the fields in β CMa and ε CMa are not continuously sustained and are prone to decay on evolutionary timescales. Indeed both stars are close to the terminal age main sequence. It is possible that their advanced evolutionary stage is at the origin of their weak fields (see Landstreet et al. [2008] in the case of the Ap/Bp stars). The possibly different field strength distribution of intermediate- and high-mass stars thus raises the issue of a mass-dependent time-scale for the field decay.

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Links

[1] BOB public web page: http://www.astro.uni-bonn.de/BOB/

Y. Beletsky (LCO)/ESO

Sunset image of La Silla taken in May 2013 when the three planets Jupiter (upper), Venus (lower left) and Mercury (lower right) were visible in near alignment — an example of a syzygy. See Picture of the Week dated 3 June 2013 for more information.