

LETTER TO THE EDITOR

# Discovery of a magnetic field in the CoRoT hybrid B-type pulsator HD 43317<sup>★</sup>

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## ABSTRACT

**Context.** A promising way of testing the impact of a magnetic field on internal mixing (core overshooting, internal rotation) in main-sequence B-type stars is to perform asteroseismic studies of a sample of magnetic pulsators.

**Aims.** The CoRoT satellite revealed that the B3IV star HD 43317 is a hybrid SPB/ $\beta$  Cep-type pulsator that has a wealth of pulsational constraints on which one can perform a seismic modelling, in particular, probing the extent of its convective core and mixing processes. Moreover, indirect indicators of a magnetic field in the star were observed: rotational modulation due to chemical or temperature spots and X-ray emission. Our goal was to directly investigate the field in HD 43317 and, if it is magnetic, to characterise it.

**Methods.** We collected data with the Narval spectropolarimeter installed at T lescope Bernard Lyot (TBL, Pic du Midi, France) and applied the least-squares deconvolution technique to measure the circular polarisation of the light emitted from HD 43317. We modelled the longitudinal field measurements directly with a dipole.

**Results.** Zeeman signatures in the Stokes *V* profiles of HD 43317 are clearly detected and rotationally modulated, which proves that this star exhibits an oblique magnetic field. The modulation with the rotation period deduced from the CoRoT light curve is also confirmed, and we found a field strength at the poles of about 1 kG. Our result must be taken into account in future seismic modelling work of this star.

**Key words.** stars: magnetic field – stars: individual: HD 43317

## 1. Introduction

The study of the magnetic properties of pulsating B-type stars –  $\beta$  Cep and slowly pulsating B (SPB) stars – is particularly interesting because when it is combined with the study of their pulsational properties, it provides a unique way of probing the impact of magnetism on the physics of non-standard mixing processes inside these stars. Comparing the amount of mixing obtained by asteroseismic investigation for a sample of magnetic  $\beta$  Cep stars with that of a sample of non-magnetic objects would already allow us to corroborate or disprove that magnetic fields inhibit mixing in stellar interiors. Moreover, the surface field strength obtained from modelling the magnetic measurements is an additional constraint for a comparison with the internal field strength needed to inhibit mixing in the radiative zone, as obtained by different criteria (e.g., Mathis & Zahn 2005).

Up to now, asteroseismic modelling has been performed for two magnetic  $\beta$  Cep stars only:  $\beta$  Cephei itself (Shibahashi & Aerts 2000) and V2052 Oph (Briquet et al. 2012). For V1449 Aql, which was also modelled asteroseismically (Aerts et al. 2011), a magnetic field was detected by Hubrig et al. (2011), but Shultz et al. (2012) disputed the presence of this field. Magnetic fields have also been detected in a number of other  $\beta$  Cep and SPB stars (e.g., Donati et al. 2001;

Hubrig et al. 2006, 2009), but there is no seismic modelling available for them. Moreover, the approach presented in the previous paragraph has been accomplished only for V2052 Oph so far (Briquet et al. 2012; Neiner et al. 2012a). Asteroseismic investigations of this magnetic target, which has a polar field strength of about 400 G (Neiner et al. 2012a), showed that the stellar models that explained the observed pulsational behaviour needed no convective core overshooting (Briquet et al. 2012). This outcome is in contrast to other results of dedicated asteroseismic studies of non-magnetic  $\beta$  Cep stars (e.g., Briquet et al. 2007): it is usually found that convective core overshooting needs to be included in the stellar models (Aerts et al. 2010). The most plausible explanation is that the magnetic field inhibits non-standard mixing processes inside V2052 Oph. Indeed, the field strength observed in this star is higher than the critical field limit needed to inhibit mixing that was determined from theory (see Zahn 2011; Neiner et al. 2012a).

A recent study of the B3IV single star HD 43317 revealed it to be a promising target to explore the effects of magnetism on stellar interiors of main-sequence B-type stars in more detail. Indeed, an analysis of the CoRoT light curve of this star showed *p* and *g* pulsation modes of  $\beta$  Cep and SPB types, as well as two series of consecutive frequencies with an almost constant period spacing near 6300 seconds (Pápics et al. 2012, hereafter P12). Such an observation carries information on the extent of the convective region and mixing processes (Miglio et al. 2008), as applied to only one hybrid B-type pulsator so far (Degroote et al. 2010). Moreover, if the star is magnetic, the detected high-order

<sup>★</sup> Based on observations obtained using the Narval spectropolarimeter at the Observatoire du Pic du Midi (France), which is operated by the Institut National des Sciences de l'Univers (INSU).

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g-modes have the potential to probe its internal magnetic field, as suggested by the theoretical work of [Hasan et al. \(2005\)](#); but this has never been applied to a massive star.

In both the photometry and spectroscopy of P12, rotational modulation connected to chemical or temperature spots were observed, providing us with a precise value of the rotation period of the star ( $P_{\text{rot}} = 0.8969$  days), which rotates at 50% of its critical velocity. The clear signature of rotational modulation in the He lines, as shown and discussed in P12 (see their Fig. 7), is an indirect indicator of a magnetic field in HD 43317. Indeed, it is generally believed that magnetic fields are responsible for the formation of chemical spots at the surface of chemically peculiar Bp stars (e.g., [Michaud et al. 1981](#)). Moreover, X-ray emission for our object is reported in the ROSAT all-sky survey catalogue of optically bright OB-type stars with  $L_X \sim 8.3 \times 10^{30}$  erg s<sup>-1</sup> ([Berghoefer et al. 1996](#)). This may also point towards a magnetic field, because X-rays can be produced by shock waves in the stellar winds or by confinement of matter at the magnetic equator.

In this paper, we present the first direct detection of a magnetic field in HD 43317 by making use of the high-efficiency and high-resolution Narval spectropolarimeter installed at the *Télescope Bernard Lyot* (TBL) 2-m telescope (Pic du Midi, France).

## 2. Observations

Nineteen high-resolution ( $R = 65\,000$ ) spectropolarimetric Stokes  $V$  Narval observations of HD 43317 were collected in 2012 (see Table 1). The first four measurements (of  $4 \times 1000$  s each) were obtained to investigate the presence of a magnetic field. A Zeeman signature being detected, we continued our sequence of observations to sample other rotational phases, but changed our observing strategy to consider the fact that the star is pulsating and to increase the signal-to-noise ratio (S/N). The next 15 observations consisted of  $5 \times 3$  successive sequences (which were afterwards averaged) of  $4 \times 800$  s each. Each sequence was shorter than 1/20th of the pulsation period to avoid that the deformations of the intensity profile by pulsations during the measurement polluted the Stokes  $V$  signal. Because the main pulsation period detected in the spectroscopy of HD 43317 is 0.735 d (P12), the exposure time is expected not be longer than  $4 \times 800$  s at once.

The usual bias, flat-fields, and ThAr calibrations were obtained each night. The data reduction was performed using LIBRE-ESPRIT ([Donati et al. 1997](#)), the dedicated software available at TBL. The intensity spectra were then normalised to the continuum by fitting a cubic spline function. Stokes  $V$  spectra were derived by constructively combining the left- and right-hand circularly polarised light together from the four sub-exposures. The three measurements obtained successively each night were averaged so that we finally had nine magnetic measurements that covered different phases of rotation. They were normalised to the continuum intensity.

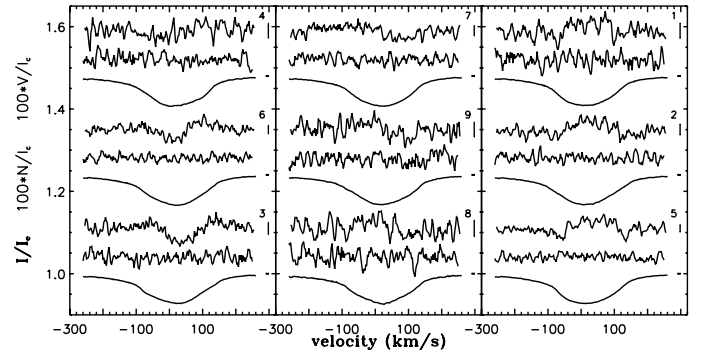
We adopted the ephemeris of HD 43317 from P12, that is, a rotation period  $P_{\text{rot}} = 0.8968634$  d and a reference date  $\text{HJD}_0 = 2\,455\,174.57665$ .

We applied the least-squares deconvolution (LSD) technique ([Donati et al. 1997](#)) to the photospheric spectral lines in each échelle spectrum ( $\lambda = [3750\text{--}10\,500]$  Å) to construct a single profile with an increased S/N (note that no additional normalisation was applied to the LSD profiles). In that way, the Zeeman signature induced by a magnetic field is clearly visible in the high S/N Stokes  $V$  profiles (Fig. 1), proving that HD 43317 is a

**Table 1.** Journal of Narval/TBL observations and magnetic field measurements of HD 43317.

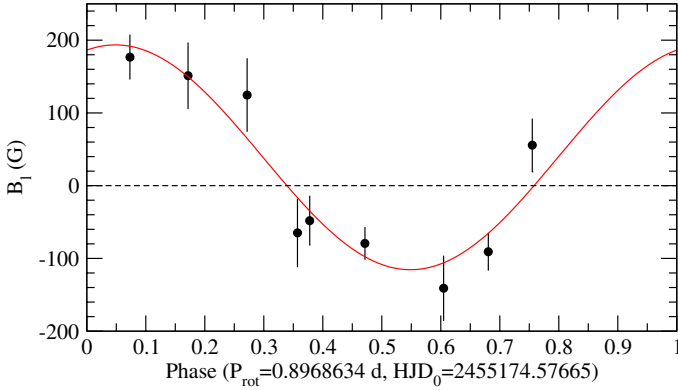
Nr.	Mid-HJD -2456000	$T_{\text{exp}}$ s	Phase	$B_l$ G	S/N
1	185.66197	$4 \times 1000$	0.35710	$-64.9 \pm 47.1$	3860
2	203.61791	$4 \times 1000$	0.37792	$-48.1 \pm 34.3$	5299
3	206.64675	$4 \times 1000$	0.75506	$55.6 \pm 36.7$	4901
4	214.58370	$4 \times 1000$	0.60474	$-141.1 \pm 44.9$	3971
5	230.60774	$3 \times (4 \times 800)$	0.47150	$-79.3 \pm 22.4$	7962
6	232.58893	$3 \times (4 \times 800)$	0.68052	$-90.8 \pm 25.9$	6862
7	244.60017	$3 \times (4 \times 800)$	0.07301	$176.8 \pm 30.9$	5756
8	245.67528	$3 \times (4 \times 800)$	0.27176	$124.6 \pm 50.6$	3595
9	254.55404	$3 \times (4 \times 800)$	0.17155	$151.1 \pm 45.8$	3939

**Notes.** Column 1 indicates the number of the magnetic measurement. Column 2 gives the heliocentric Julian date (HJD) at the middle of the observations, and Col. 3 gives the total exposure time in seconds. Column 4 provides the rotational phase using  $P_{\text{rot}} = 0.8968634$  d and the reference date  $\text{HJD}_0 = 2\,455\,174.57665$ . The longitudinal magnetic field value  $B_l$  in Gauss extracted from LSD profiles is given in Col. 5, and the S/N per 2.6 km s<sup>-1</sup> pixels in the LSD Stokes  $V$  profile is indicated in Col. 6.



**Fig. 1.** LSD Stokes  $V$  (top),  $N$  (middle), and  $I$  (bottom) profiles for the nine rotational phases. The number of the magnetic measurement, as listed in Table 1, is indicated on the right of each profile. Typical error bars are shown next to each  $I$  and  $V$  profile.

magnetic object. To diagnose possible spurious polarisation signatures, the null profiles  $N$  were also computed by destructively combining the four sub-exposures. The flatness of these profiles (Fig. 1) indicates that none of our measurements has been polluted by stellar pulsations, observing conditions, or instrumental effects, even those with slightly longer individual exposure times. To compute the LSD profiles, we made use of a mask created from the Kurucz atomic database and ATLAS 9 atmospheric models of solar abundance ([Kurucz 1993](#)), for  $T_{\text{eff}} = 17\,000$  K and  $\log g = 4.0$  (following P12), with intrinsic line depths higher than 0.1. This mask contains 199 photospheric He and metal lines of various chemical elements, together with their wavelength, depth, and Landé factor. The depths were modified so that they correspond to those of the observed spectral lines, with an interactive graphical user interface (GUI) program, written in IDL, that was kindly put at our disposal by Grunhut. The adjustment was straightforward for unblended individual lines. The relative depths of the blended lines in the original mask were kept fixed and the entire line blend depth was adjusted to the spectrum. Lines whose Landé factor is unknown or that did not appear in the spectrum were excluded. The average S/N is 5100 per 2.6 km s<sup>-1</sup> pixels in the LSD Stokes  $V$  profiles.



**Fig. 2.** Longitudinal magnetic field curve of HD 43317, folded in phase with the rotation period  $P_{\text{rot}} = 0.8968634$  d and a reference date  $\text{HJD}_0 = 2455174.57665$  from P12. A sinusoidal (dipole) fit is plotted in red.

### 3. Magnetic field

#### 3.1. Longitudinal magnetic field

We used the LSD Stokes  $I$  and  $V$  profiles to compute the line-of-sight component of the magnetic field integrated over the visible stellar surface, that is, the longitudinal magnetic field in Gauss, given for instance by Eq. (1) of Wade et al. (2000). In this equation we used  $\lambda = 501$  nm and  $g = 1.20$ . The integration limits were chosen to be high enough to cover the line width but also small enough to avoid artificially increased error bars due to noisy continuum. A range of  $123 \text{ km s}^{-1}$  around the line centre was adopted.

The values for the longitudinal magnetic field are reported in Table 1. They vary between about  $-140$  and  $180$  G. The error bars are typically  $\sim 35$  G. A phase diagram of the longitudinal field folded with the rotation period is shown in Fig. 2.

From a dipolar fit of the  $B_l$  measurements, we derived  $B_{l,\text{max}} = 193 \pm 30$  G,  $B_{l,\text{min}} = -115 \pm 30$  G, and the phase difference  $\Delta\Phi = 0.58 \pm 0.02$  between two successive crossings of the  $B_l$  fit at 0. The dipole fit has a reduced  $\chi^2$  value of 1.3. From Eqs. (18) and (19) of Shore (1987), for instance, we then derived the obliquity angle  $\beta \in [70, 86]$  deg, assuming the inclination angle  $i \in [20, 50]$  deg as deduced for the star by P12, but considering the errors on the  $T_{\text{eff}}$  and  $\log g$  values.

With these values of  $i$  and  $\beta$ , we also deduced the polar field strength  $B_{\text{pol}} \in [650, 1750]$  G from Eq. (5) of Borra & Landstreet (1979).

#### 3.2. Magnetic confinement and magnetosphere

We checked whether the magnetic field we discovered in HD 43317 is sufficient to confine the stellar wind. We used the magnetic confinement parameter,  $\eta_*$ , defined by ud-Doula & Owocki (2002), which depends on the stellar equatorial magnetic field strength, radius, and wind momentum. When  $\eta_* > 1$ , wind material can be channelled along the field lines and be confined into a circumstellar magnetosphere.

To be conservative, we used the lower value of the polar field strength of  $B_{\text{pol}} = 650$  G discovered in this work and an upper value of the mass loss of  $\dot{M} = 10^{-9} M_{\odot} \text{ yr}^{-1}$  according to Fig. 4 of Petit et al. (2013) for a B3IV star. We measured the terminal wind velocity  $v_{\infty} \sim 150 \text{ km s}^{-1}$  from the Si IV 1394+1403 Å and Al III 1855+1863 Å lines available in the SWP IUE archival spectrum. Finally, we used  $i \in [20, 50]$  deg as derived above. We imposed that  $P_{\text{rot}} \sim 0.89$  d. We found that  $\eta_* = 3400$

for  $i = 50$  deg and  $\eta_* = 14500$  for  $i = 20$  deg. In addition, we obtained that the Alfvén radius is  $R_A = 7.6 R_*$  for  $i = 50$  deg and  $R_A = 11 R_*$  for  $i = 20$  deg, and the corotating Kepler radius is  $R_K = 2.6 R_*$  for  $i = 50$  deg and  $R_K = 1.2 R_*$  for  $i = 20$  deg, respectively. Therefore, wind material is confined by the magnetic field ( $\eta_* > 1$ ) and  $R_A > R_K$ , that is, the magnetosphere is supported by the centrifugal force. See ud-Doula et al. (2008), Petit et al. (2012) and Neiner et al. (2012b) for more details on magnetospheres.

We did not detect emission in the  $H\alpha$  line of HD 43317. This means that the emission measure in the centrifugally supported magnetosphere is too low, probably because the wind is weak and rather slow. Nevertheless, we recall that HD 43317 is detected as an X-ray source in the ROSAT catalogue (Berghoefer et al. 1996) with  $\log(L_X/L_{\text{bol}}) = -5.94$  and an estimated X-ray temperature of 0.49 keV. X-ray emission could be produced in the magnetic equator where wind particles from the two magnetic hemispheres collide.

### 4. Conclusions

Thanks to photometric data of unprecedented precision assembled by the CoRoT satellite complemented by ground-based spectroscopy (P12) and spectropolarimetry (presented in this paper), HD 43317 was discovered to be a single magnetic B-type hybrid pulsator with much observational information that can be used to constrain its interior properties and to study the effect of magnetism in the mixing processes that act inside the star. In future work on HD 43317, the magnetic field must be taken into account, for example to compute the oscillation periods that need to be compared with the two almost constant period spacings of high-order gravity modes observed in the star (Salmon et al., in prep.).

HD 43317 is also an interesting target in which to study physical mechanisms that take place at its stellar surface, such as the interplay between radiatively driven diffusion and magnetic field, which is expected to be responsible for the surface abundance inhomogeneities. To this end, additional spectropolarimetric data that cover the rotation cycle are required so that a Zeeman-Doppler imaging of the stellar surface can be performed, which will provide a detailed characterisation of the magnetic configuration as well as abundance mapping of the stellar surface.

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