

# HD 965: An extremely peculiar A star with an extremely long rotation period<sup>★</sup>

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## ABSTRACT

**Context.** One of the keys to understanding the origin of Ap stars and their significance in the general context of stellar astrophysics is by considering the most extreme properties displayed by some of them. For this reason, HD 965 is particularly interesting as it combines some of the most pronounced chemical peculiarities with one of the longest rotation periods known.

**Aims.** We characterise the variations of the magnetic field of the Ap star HD 965 and derive constraints about its structure.

**Methods.** We combined published measurements of the mean longitudinal field  $\langle B_z \rangle$  of HD 965 with new determinations of this field moment from circular spectropolarimetry obtained at the 6-m telescope BTA of the Special Astrophysical Observatory of the Russian Academy of Sciences. For the mean magnetic field modulus  $\langle B \rangle$ , literature data were complemented by the analysis of ESO archive spectra.

**Results.** We present the first determination of the rotation period of HD 965,  $P_{\text{rot}} = (16.5 \pm 0.5)$  yr. The star HD 965 is only the third Ap star with a period longer than ten years for which magnetic field measurements have been obtained over more than a full cycle. The variation curve of  $\langle B_z \rangle$  is well approximated by a cosine wave. Furthermore,  $\langle B \rangle$  does not show any significant variation. The observed behaviour of these field moments is well represented by a simple model consisting of the superposition of collinear dipole, quadrupole, and octupole. The distribution of neodymium over the surface of HD 965 is highly non-uniform. The element appears concentrated around the magnetic poles, especially the negative one.

**Conclusions.** The shape of the longitudinal magnetic variation curve of HD 965 indicates that its magnetic field is essentially symmetric about an axis passing through the centre of the star. Overall, HD 965 appears similar to the bulk of the long-period Ap stars, as far as its magnetic field is concerned.

**Key words.** stars: individual: HD 965 – stars: chemically peculiar – stars: rotation – stars: magnetic field

## 1. Introduction

[Svolopoulos \(1963\)](#) appears to have been the first to notice the peculiarity of the spectrum of HD 965 (= BD -0 21), which is a star of spectral type A8p SrEuCr according to [Renson & Manfroid \(2009\)](#). Very little attention was paid to this star until it was found to have resolved magnetically split lines ([Mathys et al. 1997](#)). The subsequent effort that was undertaken to study its magnetic field suggested the possible occurrence of the core-wing anomaly (CWA) in the hydrogen Balmer lines,

a suspicion that was soon confirmed by means of a dedicated observation ([Cowley et al. 2001](#)). This indicates that the structure of the atmosphere of HD 965 cannot be represented by a normal A-star model atmosphere. It has also been reported that the magnetic field of HD 965 decreases with increasing optical depth ([Nesvacil et al. 2004](#)), but more observations would be needed for full characterisation of its structure. More generally, the spectrum of HD 965 is extremely peculiar, bearing considerable resemblance to that of Przybylski's star (HD 101065), the Ap star with the most unusual spectrum ([Hubrig et al. 2002](#)). Similar to Przybylski's star, HD 965 shows in its spectrum spectral lines that have been tentatively attributed to promethium, an unstable element ([Cowley et al. 2004](#)).

The presence of the CWA in its spectrum motivated a photometric search for rapid oscillations in HD 965. Despite the high precision of the observations, no such oscillations were detected ([Kurtz et al. 2003](#)). A subsequent attempt using high-cadence high-resolution spectroscopy did not yield any detection either ([Elkin et al. 2005](#)).

Besides its extreme and intriguing spectral features, HD 965 also has the distinction of rotating very slowly. [Mathys \(2017\)](#) reports that its rotation period must exceed 13 yr. This puts it

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firmly among the group of Ap stars with rotation periods that are longer than one month. This group, which has progressively emerged in recent years, comprises several percent of the whole Ap star class. Studying it is essential in understanding the processes responsible for the differentiation of stellar rotation rates. This is discussed in more detail elsewhere (Mathys et al. 2019).

In this paper, we present new determinations of the mean longitudinal magnetic field  $\langle B_z \rangle$  and of the mean magnetic field modulus  $\langle B \rangle$  of HD 965. They are both based on new, dedicated observations and archive spectra. We used the complete set of existing  $\langle B_z \rangle$  measurements of the star to determine the value of its rotation period for the first time. The observational data and their analysis are presented in Sect. 2, and the determination of the stellar rotation period is described in Sect. 3. In Sect. 4, we derived constraints on the geometrical structure of the magnetic field. Finally, we discuss the implications of the obtained results for HD 965 itself, and how it fits within the general context of the slowly rotating Ap stars.

## 2. Observations and data analysis

### 2.1. Mean magnetic field modulus

The mean magnetic field modulus  $\langle B \rangle$  is the average over the visible stellar hemisphere of the modulus of the field vector; this average is weighted by the local emergent line intensity. All the mean field modulus values used in this analysis were determined from the measured wavelength separation of the two magnetically split components of the Fe II  $\lambda$  6149.2 diagnostic line. The following formula was applied to derive  $\langle B \rangle$ :

$$\lambda_r - \lambda_b = g \Delta\lambda_Z \langle B \rangle. \quad (1)$$

In this equation,  $\lambda_r$  and  $\lambda_b$  are the wavelengths of the red and blue split line components, respectively;  $g$  is the Landé factor of the split level of the transition ( $g = 2.70$ ; Sugar & Corliss 1985);  $\Delta\lambda_Z = k \lambda_0^2$  with  $k = 4.67 \cdot 10^{-13} \text{ \AA}^{-1} \text{ G}^{-1}$ ; and  $\lambda_0 = 6149.258 \text{ \AA}$  is the nominal wavelength of the considered transition.

The Fe II  $\lambda$  6149.2 line is strongly blended on the blue side with an unidentified rare earth line. This blend complicates the application of the above-described procedure. It is present at different degrees in a fraction of the Ap stars. As can be seen in Figs. 2–4 of Mathys et al. (1997), for example, HD 965 is one of the stars in which its impact is the most severe. Dealing with this blend as consistently as possible while measuring the separation of the split components of the Fe II  $\lambda$  6149.2 line in spectra of HD 965 obtained at different epochs is essential in achieving the best precision and uniformity in the derived values of  $\langle B \rangle$ . This precision and uniformity are required to ensure that the variations of  $\langle B \rangle$  along the stellar rotation cycle can be characterised correctly.

Obviously, we cannot be sure that the way in which we measured recent HARPS and UVES archive spectra is consistent with the way in which spectra obtained (mostly) with other instruments were measured in the past to derive the published values of  $\langle B \rangle$  (Mathys et al. 1997; Elkin et al. 2005; Mathys 2017). Accordingly, to ensure that the set of mean magnetic field modulus data under consideration is as uniform as possible, we remeasured all the spectra of the cited references and used them to derive updated  $\langle B \rangle$  values. Thus, the full set of observations that we analysed consists of:

- Nine spectra recorded with the Long Camera (LC) of the Coudé Echelle Spectrograph (CES) fed by the ESO Coudé Auxiliary Telescope (CAT), one of which had a somewhat lower resolution than the others due to a detector problem;

- One spectrum recorded with the Short Camera (SC) of the CES that was fed by the CAT;
- One spectrum recorded with the AURELIE spectrograph fed by the 1.52-m telescope of the Observatoire de Haute-Provence (OHP);
- Four spectra recorded with the Gecko spectrograph fed by the Canada-France-Hawaii Telescope (CFHT);
- Six spectra recorded with the Ultraviolet and Visible Echelle Spectrograph (UVES) fed by Unit Telescope 2 (UT2) of the ESO Very Large Telescope (VLT). One of them is the average of the 111 high-cadence spectra analysed by Elkin et al. (2005); the others were retrieved from the ESO Archive;
- 14 spectra recorded with the High Accuracy Radial velocity Planet Searcher (HARPS) fed by the ESO 3.6-m telescope, which were retrieved from the ESO Archive.

More details about the first four configurations of this list and the corresponding data reduction processes are provided by Mathys et al. (1997). See also Elkin et al. (2005) for information about the reduction of the respective observations. For the other UVES observations, and for the HARPS spectra, we used science grade pipeline processed data available from the ESO Archive. The only additional processing that we carried out was a continuum normalisation of the region ( $\sim 100 \text{ \AA}$  wide) surrounding the Fe II  $\lambda$  6149.2 diagnostic line.

In view of the challenge of achieving consistent measurements of the wavelength separation of the split components of the Fe II  $\lambda$  6149.2 line despite the heavy blending of its blue wing, we had to revise the estimate of the uncertainty affecting the derived  $\langle B \rangle$  values that had been adopted by Mathys et al. (1997) and by Mathys (2017). The latter, 30 G, is definitely too optimistic as it is of the same order as the estimated  $\langle B \rangle$  uncertainty for stars such as HD 50169, for which measuring the wavelength splitting of the Fe II  $\lambda$  6149.2 line is much more straightforward (Mathys et al. 2019). Taking this into account, and after comparing the results of measurements of a number of spectra repeated multiple times, we adopted 50 G as a revised, hopefully more realistic, estimate of the uncertainty affecting the determinations of the mean magnetic field modulus of HD 965.

The 35 values of the mean magnetic field modulus obtained in the above-described way are presented in Table 1. The columns give, in the following order: the heliocentric (or barycentric, for HARPS) Julian date of mid-exposure, the value  $\langle B \rangle$  of the mean magnetic field modulus, and the instrumental configuration with which the analysed spectrum was obtained.

### 2.2. Mean longitudinal magnetic field

The mean longitudinal magnetic field  $\langle B_z \rangle$  is the average over the visible hemisphere of the component of the magnetic vector along the line of sight, weighted by the local emergent line intensity. The following published measurements of this field moment were used in this study: seven measurements from Elkin et al. (2005); one measurement from Romanyuk et al. (2014); 18 measurements from Romanyuk et al. (2015); two measurements from Romanyuk et al. (2016); seven measurements from Mathys (2017); four measurements from Romanyuk et al. (2017); and four measurements from Romanyuk et al. (2018).

All of these measurements were carried out through the analysis of medium spectral resolution observations of metal lines in circular polarisation. The data from Mathys (2017) are based on observations obtained with the CASPEC spectrograph mounted on the ESO 3.6 m telescope in the post-1995 configuration specified by Mathys & Hubrig (1997). All of the other listed studies

**Table 1.** Mean magnetic field modulus measurements.

JD	$\langle B_z \rangle$ (G)	Configuration
2449301.597	4320	ESO CAT + CES SC
2449534.896	4366	ESO CAT + CES LC
2449535.879	4306	ESO CAT + CES LC
2449881.918	4247	ESO CAT + CES LC
2449908.843	4263	ESO CAT + CES LC
2449947.836	4268	ESO CAT + CES LC (lower res.)
2450231.914	4199	ESO CAT + CES LC
2450296.576	4386	OHP 1.52 m + AURELIE
2450971.914	4256	ESO CAT + CES LC
2451042.807	4326	ESO CAT + CES LC
2451084.731	4192	ESO CAT + CES LC
2451740.105	4234	CFHT + Gecko
2451741.060	4264	CFHT + Gecko
2452190.627	4303	ESO VLT UT2 + UVES
2452420.063	4228	CFHT + Gecko
2452535.723	4352	ESO VLT UT2 + UVES
2452924.154	4293	ESO VLT UT2 + UVES
2453215.093	4287	CFHT + Gecko
2453334.505	4213	ESO 3.6 m + HARPS
2453581.741	4165	ESO 3.6 m + HARPS
2453582.764	4225	ESO 3.6 m + HARPS
2453583.867	4242	ESO 3.6 m + HARPS
2453661.702	4279	ESO VLT UT2 + UVES
2453711.565	4237	ESO 3.6 m + HARPS
2453712.595	4177	ESO 3.6 m + HARPS
2453713.585	4201	ESO 3.6 m + HARPS
2453714.583	4238	ESO 3.6 m + HARPS
2453715.568	4208	ESO 3.6 m + HARPS
2453716.567	4245	ESO 3.6 m + HARPS
2454336.860	4185	ESO 3.6 m + HARPS
2454338.796	4215	ESO 3.6 m + HARPS
2454406.585	4310	ESO VLT UT2 + UVES
2454442.613	4224	ESO 3.6 m + HARPS
2454443.560	4186	ESO 3.6 m + HARPS
2454469.580	4259	ESO VLT UT2 + UVES

were carried out with the instrumentation introduced in the next paragraph.

Here the measurements from the literature are complemented by additional  $\langle B_z \rangle$  determinations obtained from observations of the same type. That is, spectra of HD 965 recorded at  $R \approx 14\,500$  in both circular polarisations with the Main Stellar Spectrograph of the 6-m telescope BTA of the Special Astrophysical Observatory (SAO) on 21 nights ranging from September 2015 to January 2019. This is the same configuration as used by Romanyuk et al. (2014) and in the other works of the same group. The instrumental configuration and the data reduction procedure are as described in detail in this reference.

The mean longitudinal magnetic field was determined from the wavelength shifts of a sample of spectral lines between the two circular polarisations in each of these spectra, by application of the formula:

$$\lambda_R - \lambda_L = 2 \bar{g} \Delta \lambda_Z \langle B_z \rangle, \quad (2)$$

where  $\lambda_R$  (resp.  $\lambda_L$ ) is the wavelength of the centre of gravity of the line in right (resp. left) circular polarisation and  $\bar{g}$  is the effective Landé factor of the transition. The value of  $\langle B_z \rangle$  is determined through a least-squares fit of the measured values of

$\lambda_R - \lambda_L$  by a function of the form given above. The standard error  $\sigma_z$  that is derived from that least-squares analysis is used as an estimate of the uncertainty affecting the obtained value of  $\langle B_z \rangle$ . The implementation details have been described by Mathys (2017) for the analysis of the CASPEC observations, and by Romanyuk et al. (2014) and Romanyuk et al. (2015) for the SAO spectra. Whenever both the modernised Babcock method and the regression method were applied for determining  $\langle B_z \rangle$  from these spectra, the value yielded by the regression method was adopted. For HD 965, the differences between the mean longitudinal values derived through application of either method (Romanyuk et al. 2015) are insignificant.

The values of the mean longitudinal field obtained in the way described above are presented in Table 2. For the convenience of the reader, this table also includes the previously published measurements. In total, 65  $\langle B_z \rangle$  measurements are analysed in this study. The table columns give, in order, the heliocentric Julian date of mid-observation, the mean S/N of the recorded spectrum, the value  $\langle B_z \rangle$  of the mean longitudinal magnetic field and its uncertainty  $\sigma_z$ , and the source of the measurement.

### 3. Variability and rotation period

To determine the rotation period of HD 965, we fitted the measurements of its mean longitudinal magnetic field by either a cosine wave, or the superposition of a cosine wave and of its first harmonic. We progressively varied the period of these waves, in order to find the value of the period that minimises the reduced  $\chi^2$  of the fit. These fits are weighted by the inverse of the square of the uncertainties of the individual measurements. Through this procedure, we concluded without ambiguity that the rotation period of the star must be of the order of 6000 d. The corresponding periodogram is shown in Fig. 1.

The time elapsed between the first determination of the mean longitudinal magnetic field of HD 965 by Mathys (2017) and our most recent spectropolarimetric observation of the star is 8596 d, or  $\sim 1.4$  rotation period. This provides a very sensitive approach to refine the determination of the period and to estimate its uncertainty. By plotting a phase diagram of the  $\langle B_z \rangle$  measurements for a series of tentative values of the period around the one suggested by the periodogram, one can visually identify the period value that minimises the phase shifts between field determinations from different rotation cycles, and constrain the range around that value for which those phase shifts remain reasonably small.

Systematic differences frequently occur between determinations of  $\langle B_z \rangle$  that are obtained with different instruments and by the application of different data analysis methods. The existence of such differences between the two sets of data that are combined here cannot be definitively ruled out. However, in general, previous studies indicate that for Ap stars with fairly sharp spectral lines, there are at most minor systematic differences between the longitudinal field values determined through the application of the metal line spectropolarimetric technique by Mathys and collaborators (from ESO CASPEC spectra), on the one hand, and by Romanyuk and collaborators (with the Main Stellar Spectrograph of the 6-m telescope BTA of the SAO), on the other. One can also note that as the spectral range spanned by the SAO spectra has increased over time (Romanyuk et al. 2015), different sets of lines have been measured at different epochs without introducing any obvious inconsistencies in the derived  $\langle B_z \rangle$  values.

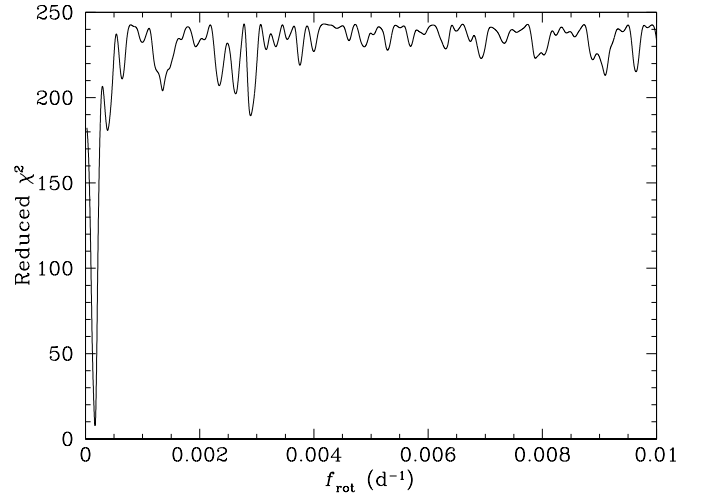
Assuming that the  $\langle B_z \rangle$  datasets that we combined here are indeed mutually consistent, we derived the following best value

**Table 2.** Mean longitudinal magnetic field measurements.

JD	$S/N$	$\langle B_z \rangle$ (G)	$\sigma_z$ (G)	Reference
2449916.907	140	-574	113	Mathys (2017)
2449974.744	110	-691	141	Mathys (2017)
2450039.588	120	-863	44	Mathys (2017)
2450294.905	120	-1063	125	Mathys (2017)
2450615.928	120	-1057	52	Mathys (2017)
2450629.884	125	-1159	142	Mathys (2017)
2450784.596	150	-1270	139	Mathys (2017)
2451806.479	100	-430	120	Elkin et al. (2005)
2452130.497	100	-360	70	Elkin et al. (2005)
2452153.356	40	-280	120	Elkin et al. (2005)
2452625.209	90	-160	80	Elkin et al. (2005)
2452626.232	90	-80	50	Elkin et al. (2005)
2452831.529	180	-30	80	Elkin et al. (2005)
2453273.296	190	320	50	Elkin et al. (2005)
2453362.231	300	360	30	Romanyuk et al. (2015)
2453666.290	330	330	40	Romanyuk et al. (2015)
2453667.270	250	470	40	Romanyuk et al. (2015)
2453718.245	450	420	30	Romanyuk et al. (2015)
2453953.425	350	600	40	Romanyuk et al. (2015)
2454015.236	350	420	50	Romanyuk et al. (2015)
2454402.285	300	530	50	Romanyuk et al. (2014)
2455017.511	250	150	40	Romanyuk et al. (2016)
2455075.438	300	240	50	Romanyuk et al. (2016)
2455431.458	250	-70	20	Romanyuk et al. (2017)
2455459.492	250	-240	50	Romanyuk et al. (2017)
2455461.462	300	-140	50	Romanyuk et al. (2017)
2455553.174	300	-340	20	Romanyuk et al. (2017)
2455555.139	200	-360	30	Romanyuk et al. (2017)
2455583.148	180	-359	26	Romanyuk et al. (2018)
2455842.411	250	-624	23	Romanyuk et al. (2018)
2455843.398	250	-643	23	Romanyuk et al. (2018)
2455871.176	150	-470	29	Romanyuk et al. (2018)
2455962.138	150	-590	30	Romanyuk et al. (2015)
2456174.540	200	-670	40	Romanyuk et al. (2015)
2456177.429	300	-800	50	Romanyuk et al. (2015)
2456234.208	110	-1030	30	Romanyuk et al. (2015)
2456500.509	160	-1190	20	Romanyuk et al. (2015)
2456589.383	160	-1250	20	Romanyuk et al. (2015)
2456640.125	150	-1130	50	Romanyuk et al. (2015)
2456940.302	150	-1170	30	Romanyuk et al. (2015)
2456967.292	150	-1130	60	Romanyuk et al. (2015)
2456995.144	200	-1360	50	Romanyuk et al. (2015)
2457169.525	150	-1340	30	Romanyuk et al. (2015)
2457246.465	200	-1200	20	Romanyuk et al. (2015)
2457288.469	200	-1170	20	This paper
2457352.232	150	-1110	40	This paper
2457355.195	200	-1120	20	This paper
2457592.479	120	-1090	40	This paper
2457740.260	100	-910	60	This paper
2457761.132	130	-960	30	This paper
2457762.156	120	-920	30	This paper
2457764.149	120	-1070	50	This paper
2457950.436	180	-990	30	This paper
2458006.458	110	-780	20	This paper
2458009.364	100	-820	30	This paper
2458061.227	130	-680	30	This paper
2458067.216	150	-780	30	This paper
2458116.161	140	-610	30	This paper
2458117.213	150	-690	30	This paper

**Table 2.** continued.

JD	$S/N$	$\langle B_z \rangle$ (G)	$\sigma_z$ (G)	Reference
2458126.137	150	-650	20	This paper
2458151.136	120	-740	20	This paper
2458447.277	150	-320	20	This paper
2458448.298	170	-340	30	This paper
2458449.162	100	-290	40	This paper
2458512.155	160	-260	40	This paper

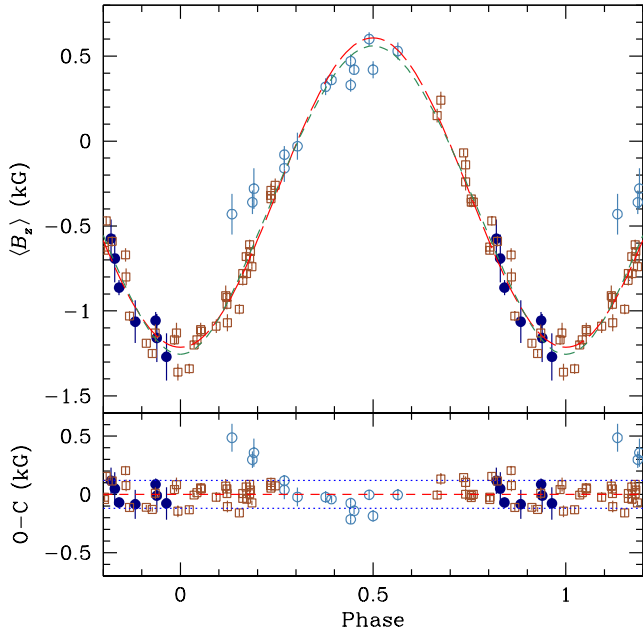
**Fig. 1.** Periodogram of the variations of the mean longitudinal magnetic field of HD 965. The ordinate is the reduced  $\chi^2$  of a fit of the  $\langle B_z \rangle$  measurements by a cosine wave, with the frequency given in abscissa.

of the rotation period of HD 965:

$$P_{\text{rot}} = (6030 \pm 200) \text{ d.} \quad (3)$$

The phase variation curve of the mean longitudinal magnetic field for this value of the period is shown in Fig. 2. It is important to note the consistent behaviour of the measurements of Mathys (2017) and of Romanyuk's group on the descending branch between phases 0.82 and 0.96. The apparent inconsistency of the first three measurements of Elkin et al. (2005) (open circles at phases 0.13–0.19) with the rest of the data likely reflects that some early SAO measurements are affected by stochastic errors greater than indicated by the formal uncertainties. These errors are related to instrumental shifts that could not always be fully corrected through the observation of null standards. In support of this interpretation of the observed inconsistency, we note that the increase in the length of the adopted period that would be required to make the three  $\langle B_z \rangle$  values under consideration consistent with the 2018–2019 SAO measurements would imply an irreconcilable discrepancy between the ESO and SAO data. Indeed, the former would still show a monotonic decrease at phases at which the latter have already started to increase from the negative  $\langle B_z \rangle$  extremum towards zero. There is no plausible way to account for such different behaviour by systematic effects between different instruments.

The application of the above-described period determination procedure is justified in detail by Mathys et al. (2019). It must be stressed that the accuracy of the period determination carried out in this manner only depends on the reproducibility of the variation curve from one cycle to the next and not on its exact shape. The adopted uncertainty of the derived period value is based on

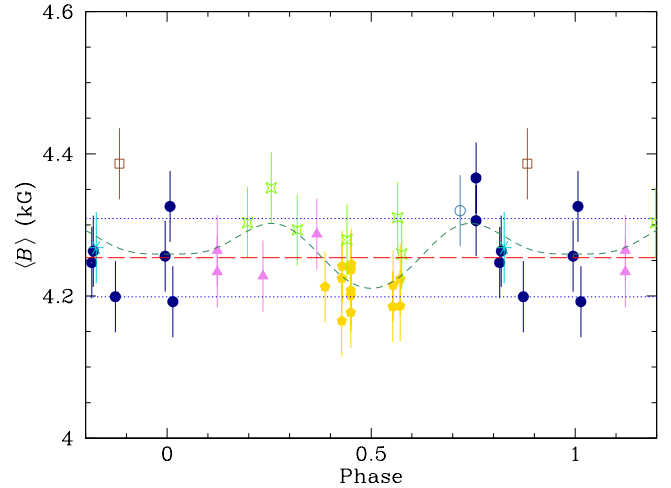


**Fig. 2.** *Upper panel:* mean longitudinal magnetic field of HD 965 against rotation phase. To distinguish measurements obtained at similar phases in different cycles, circles (blue) were used to identify observations acquired until 2008; squares (brown) correspond to spectra taken since 2009. Filled symbols are used for the measurements of Mathys (2017), and open symbols for all determinations based on SAO spectra. The long-dashed line (red) is the best fit of the observations by a cosine wave, see Eq. (4). The short-dashed line (dark green) corresponds to the superposition of low-order multipoles discussed in Sect. 4. *Lower panel:* differences O – C between individual  $\langle B_z \rangle$  measurements and best fit curve, against rotation phase. The dotted lines (blue) correspond to  $\pm 1$  rms deviation of the observational data about the fit (red dashed line). The symbols are the same as in the upper panel.

the assumption that any systematic offset between the mean longitudinal magnetic field measurements obtained with the two different telescope-instrument combinations that were used for this study does not significantly exceed the random errors affecting these measurements. For a more detailed discussion on this point, see Mathys et al. (2019).

The measurements of the mean magnetic field modulus  $\langle B \rangle$  are also plotted against the rotation phase, in Fig. 3. There is no apparent trend; the  $\langle B \rangle$  values do not show any dependencies on the observation phase. Furthermore, the scatter of these values is consistent with their estimated uncertainties: the average of our 34 measurements is  $\langle B \rangle_{\text{av}} = 4254$  G with a standard deviation of 55 G. This leads us to conclude that the mean field modulus of HD 965 is constant at the achieved precision level.

On the other hand, consideration of Fig. 3 suggests that the  $\langle B \rangle$  measurements obtained from HARPS spectra may be slightly, but systematically, shifted downwards, while those that were obtained from UVES spectra are shifted upwards, with respect to the values obtained with the CES and Gecko. This may be indicative of some amount of systematic error of instrumental origin. However, the magnitude of the observed offset, a few tens of G, is small. At most it is of the same order as the random measurement uncertainties, so one should be careful not to overinterpret it. It is also noteworthy that the highest  $\langle B \rangle$  value was obtained from the only AURELIE observation. This again may arise from an instrumental effect since AURELIE is known to definitely be subject to such effects (Mathys et al. 1997). However, no definitive conclusion can be drawn from solely



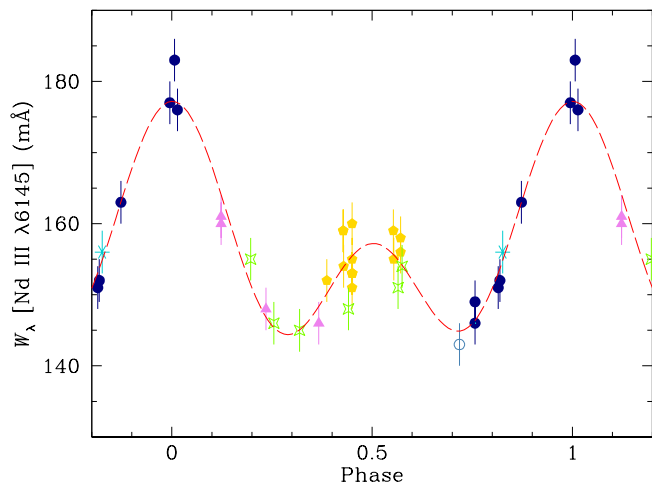
**Fig. 3.** Mean magnetic field modulus of HD 965 against rotation phase. The different symbols identify the instrumental configuration from which the  $\langle B \rangle$  value was obtained, as follows. Filled in circles (dark blue) correspond to CAT + CES LC; asterisk (turquoise) corresponds to CAT + CES LC, lower resolution; open circle (steel blue) corresponds to CAT + CES SC; open squares (brown) correspond to OHP 1.52 m + AURELIE; filled in triangles (violet) correspond to CFHT + Gecko (all previous symbols are identical to Mathys 2017); four-pointed open stars (light green) correspond to UT2 + UVES; and filled in pentagons (yellow) correspond to 3.6 m + HARPS. The short-dashed line (dark green) corresponds to the superposition of low-order multipoles as discussed in Sect. 4. The dotted lines (blue) correspond to  $\pm 1$  standard deviation of the individual measurements about their average value (red dashed line).

considering a single measurement point. In any event, whether the instrumental effects discussed above are actually present or not, their magnitude is small enough so that the conclusion, that the mean magnetic field modulus of HD 965 does not show any significant variability, is not questioned.

One observable that shows prominent variability with the same period as  $\langle B_z \rangle$  is the intensity of the Nd III  $\lambda 6145$  line. While the high-resolution spectra from which we determined  $\langle B \rangle$  cover a variety of spectral ranges, some of them very narrow, the Nd III  $\lambda 6145$  line is present in all of them. The values of the equivalent width  $W_\lambda$  of this line that we measured from these high-resolution spectra are plotted against the rotation phase in Fig. 4<sup>1</sup>. They follow a very definite double-wave variation curve with a primary maximum close to the phase of the negative extremum of the mean longitudinal magnetic field, and with a secondary maximum near the phase of the positive extremum of  $\langle B_z \rangle$ . The observed variation of the equivalent width of the Nd III  $\lambda 6145$  line in HD 965 represents an independent confirmation of the rotation period of this star.

As noted by Mathys (2017), the equivalent widths of the Fe lines do not show any variability, so there is no indication of departures from uniformity in the distribution of this element over the stellar surface. The equivalent width and magnetic resolution of several of the Fe lines are of the same order as for the Nd III  $\lambda 6145$  line. This represents a strong indication that the observed variations of the equivalent width of the latter reflect the inhomogeneous distribution of Nd over the

<sup>1</sup> The equivalent width was not measured in the single AURELIE spectrum since experience indicates that equivalent width determinations with this instrument may be affected by significant errors, which are due to uncertainties in the contribution of the dark current of the detector in spectra of faint stars, such as HD 965 (e.g. Mathys et al. 1997).



**Fig. 4.** Equivalent width of the Nd III  $\lambda$  6145 line against rotation phase. The symbols have the same meaning as in Fig. 3. The long-dashed line (red) is the best fit of the measurements by a cosine wave and its first harmonic. It has been included to guide the eye despite its lack of physical meaning.

stellar surface rather than the occurrence of non-uniform magnetic desaturation.

#### 4. Magnetic field characterisation

The observed variations of the mean longitudinal magnetic field of HD 965 can be well represented by a cosine wave. The best least-squares fit solution for  $P_{\text{rot}} = 6030$  d is:

$$\begin{aligned} \langle B_z \rangle(\phi) = & (-306 \pm 14) \\ & + (911 \pm 21) \cos[2\pi[\phi - (0.501 \pm 0.003)]] \\ (\nu = 62, \chi^2/\nu = 7.9), \end{aligned} \quad (4)$$

where the field strength is expressed in Gauss,  $\phi = (\text{HJD} - \text{HJD}_0)/P_{\text{rot}} \pmod{1}$ , and the adopted value of  $\text{HJD}_0 = 2451000.0$  corresponds to a negative extremum of the mean longitudinal magnetic field, within the uncertainty of the phase;  $\nu$  is the number of degrees of freedom, and  $\chi^2/\nu$  is the reduced  $\chi^2$  of the fit. The fitted curve is shown in Fig. 2; the O – C differences between the individual measurements and this curve are also illustrated. The rather high value of  $\chi^2/\nu$  may indicate that the uncertainty of some of the measurements is slightly underestimated, that there are some small systematic differences between the measurements of the different groups, that the actual shape of the  $\langle B_z \rangle$  variation curve departs somewhat from a cosine wave, or some combination of these three effects. However, no mathematically significant contribution of the first harmonic was found. In particular, the  $\langle B_z \rangle$  variation curve appears to be very nearly mirror-symmetric about the phases of its extrema.

The reversal of the sign of the mean longitudinal field over the rotation cycle indicates that both magnetic poles of the star come alternatively into sight. The constancy of the mean magnetic field modulus in a star of which both magnetic poles come alternatively into sight is unique (see Fig. 9 of Mathys 2017). Combined with the large amplitude and the sign reversal of the mean longitudinal field, it sets a strong constraint on the geometrical structure of the magnetic field of HD 965.

In contrast with other extremely slowly rotating Ap stars that were recently studied, such as HD 18078 (Mathys et al. 2016) or HD 50169 (Mathys et al. 2019), neither the mean

longitudinal magnetic field nor the mean magnetic field modulus of HD 965 show any hint that the geometrical structure of the large-scale magnetic field shows any significant deviation from axisymmetry. Accordingly, a simple axisymmetric model, such as the superposition of collinear dipole, quadrupole, and octupole (Landstreet & Mathys 2000), may in principle be adequate to represent this structure. We computed such a model by using a Python programme that is based on J. D. Landstreet's FLDCURV code (e.g., Wade et al. 2006) and solves a non-linear least-squares minimisation problem, fitting both the  $\langle B_z \rangle$  and  $\langle B \rangle$  variation curves simultaneously. The best parameter values are  $i = 75.4^\circ \pm 0.8^\circ$ ,  $\beta = 37.2^\circ \pm 1.1^\circ$ ,  $B_{\text{dipole}} = (-5653 \pm 119)$  G,  $B_{\text{quadrupole}} = (-281 \pm 171)$  G, and  $B_{\text{octupole}} = (2872 \pm 377)$  G. As usual, the angles  $i$  (inclination of the rotation axis on the line of sight) and  $\beta$  (angle between the rotation and magnetic axes) can be interchanged with no changes in the predicted variation curves. These curves are shown as dark green, short-dashed lines in Figs. 2 and 3. It is interesting to note the similarity of the model curve to the cosine best fit curve for the mean longitudinal magnetic field and that the amplitude of the model curve for the mean magnetic field modulus is lower than the standard deviation of the individual measurements of this field moment about their mean. The quadrupolar component of the model is almost negligible. The two main components, a dipole and an octupole with opposite orientations, give a good approximation of a field that appears essentially dipolar in  $\langle B_z \rangle$  but that must have a nearly constant modulus to be consistent with the  $\langle B \rangle$  measurements. However, while the adopted model provides a satisfactory representation of the observed variations, one cannot be sure that it is physically meaningful. Therefore, the uncertainties given for the model parameters are only formal.

#### 5. Discussion

With a rotation period of 6030 d, or 16.5 yr, HD 965 is only the third Ap star with a rotation period longer than 10 yr for which the value of this period has been determined exactly and well sampled magnetic variation curves have been obtained. Despite the extreme character of HD 965 in several respects (see Sect. 1), its magnetic field does not appear extraordinary in any way. Its most remarkable property is the lack of significant variability of  $\langle B \rangle$  within the excellent precision of the measurements of this field moment (within 50 G). While large values of the ratio  $q$  between the extrema of the mean magnetic field modulus are more frequently observed in slowly rotating Ap stars than in those that rotate faster (see Fig. 5 of Mathys 2017), this ratio is small in some of the long-period stars. HD 965 is becoming the longest-period star known to have  $q \sim 1$ . This does not make it exceptional, as only two of the Ap stars whose periods are exactly known rotate more slowly than HD 965. Once longer periods are determined for more stars, some of them will likely show low amplitude variability of  $\langle B \rangle$ .

The combination of  $q \approx 1.0$  with a value  $r = -0.50$  of the ratio of the smaller (in absolute value) to the larger (in absolute value) extremum of  $\langle B_z \rangle$  is somewhat more remarkable since large relative amplitudes of the mean magnetic field modulus tend to be found in stars for which both poles come alternately into view (see Fig. 9 of Mathys 2017). However, this should not be regarded as a major anomaly; other stars in which both magnetic poles are seen show  $\langle B \rangle$  variations of low relative amplitude.

The nearly constant value of the mean magnetic field modulus of HD 965, which averages at  $\langle B \rangle_{\text{av}} = 4254$  G, is well below the value of 7.5 kG that seems to represent an upper limit to the

field strength for those Ap stars with rotation periods longer than 150 d (Mathys et al. 1997; Mathys 2017). With a value of 0.18, the ratio of the rms longitudinal magnetic field (Bohlender et al. 1993),  $\langle B_z \rangle_{\text{rms}} = 776 \text{ G}$ , to  $\langle B \rangle_{\text{av}}$ , is also well within the typical range (see Fig. 8 of Mathys 2017).

Even though the modulus of the magnetic field vector must be mostly constant over the surface of HD 965, the distribution of the abundances of at least some elements (in particular, Nd) is markedly inhomogeneous. This suggests, perhaps not surprisingly, that the local orientation of the magnetic field must be more of a determining factor than its strength in the formation of chemical spots on the surfaces of Ap stars.

Elkin et al. (2005) suggested that the null results of the two attempts that were made to detect pulsations in HD 965 could possibly be attributed to the mostly equator-on aspect of the star at the epochs when the observations were performed. The phases of these observations can now be determined as follows: 0.249 for the photometric study of Kurtz et al. (2003), and 0.319 for the high-resolution spectroscopic recordings of Elkin et al. (2005). Consideration of Fig. 2 confirms that both observations primarily sampled the part of the stellar surface close to the magnetic equator. Accordingly, detecting non-radial pulsations in HD 965 may merit another attempt at a rotation phase close to a magnetic extremum, when one of the magnetic poles, around which the pulsation amplitude is expected to be the highest, is at maximum visibility. The next opportunity will arise close to the forthcoming positive extremum of the mean longitudinal magnetic field, in the second half of 2022.

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