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MAGNETO-ASTEROSEISMIC STUDY OF ι LIB

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Abstract. About 10 % of early-type stars host a large-scale magnetic field, which is expected to affect their physical conditions. However, only a limited amount of observations exist to corroborate the extent of the effects of the large-scale magnetic field. Therefore, we searched for magnetic pulsating early-type stars, as the stellar pulsations provide an exclusive observational window to the internal stellar properties. In this work, we have analysed the ESPaDOnS and Narval spectropolarimetry to characterize the large-scale magnetic field of ι Lib and derive the star's rotation period. In addition, we investigated the K2 light curve of ι Lib with the aim to detect possible pulsation mode frequencies. Two of the low-amplitude frequencies fall in the frequency domain of g modes. However, more observations are needed to confirm these to be actual g modes and whether they originate from the magnetic early-type star in the ι Lib binary system.

Keywords: stars: early-type - stars: magnetic field - stars: oscillations - stars: rotation

1 Introduction

We continue to identify and study magnetic pulsating early-type stars to observe how the presence of a stable large-scale magnetic field affects and alters the deep interior of these stars. In particular, the magnetic field is expected to cause a uniform rotation rate in the radiative layer (e.g., Ferraro 1937; Moss 1992; Spruit 1999; Mathis & Zahn 2005; Zahn 2011), which in turn reduces the amount of convective core overshooting compared to similar non-magnetic stars (Briquet et al. 2012; Buysschaert et al. 2018a).

Here, we investigate the primary B9IV Si component of ι Lib, which is part of a hierarchical binary system, for which the shortest orbital period is 23.42 years (Heintz 1982). This star has a peculiar chemical abundance (Renson & Manfroid 2009), characteristic for a magnetic early-type star. The presence of the large-scale magnetic field was confirmed by Buysschaert et al. (2018b), which also derived an effective temperature $T_{\rm eff} = 11900 \pm 200\,{\rm K}$, a surface gravity $\log g = 3.8 \pm 0.1\,{\rm dex}$, and a $v \sin i = 60 \pm 2\,{\rm km\,s^{-1}}$ for the star. In addition, Wraight et al. (2012) indicated that the STEREO photometry of this object shows three dominant periods, which could hint towards stellar pulsations. First, we characterize the large-scale magnetic field in more detail using additional Narval spectropolarimetric data. Next, we analyse the periodic variability in the K2 light curve.

2 Magnetometric analysis

In total, we collected 42 high-resolution and high-signal-to-noise observations in circular polarization mode with Narval mounted at the Télescope Bernard Lyot on Pic du Midi in France (Aurière 2003) and two with ESPaDOnS mounted at the Canada France Hawaii Telescope on Mauna Kea in Hawaii (Donati et al. 2006). Standard settings were employed, with bias, flat-field, and ThAr calibration images taken at both the beginning and end of each night. These data were reduced with the Libre-Esprit software (Donati et al. 1997) available

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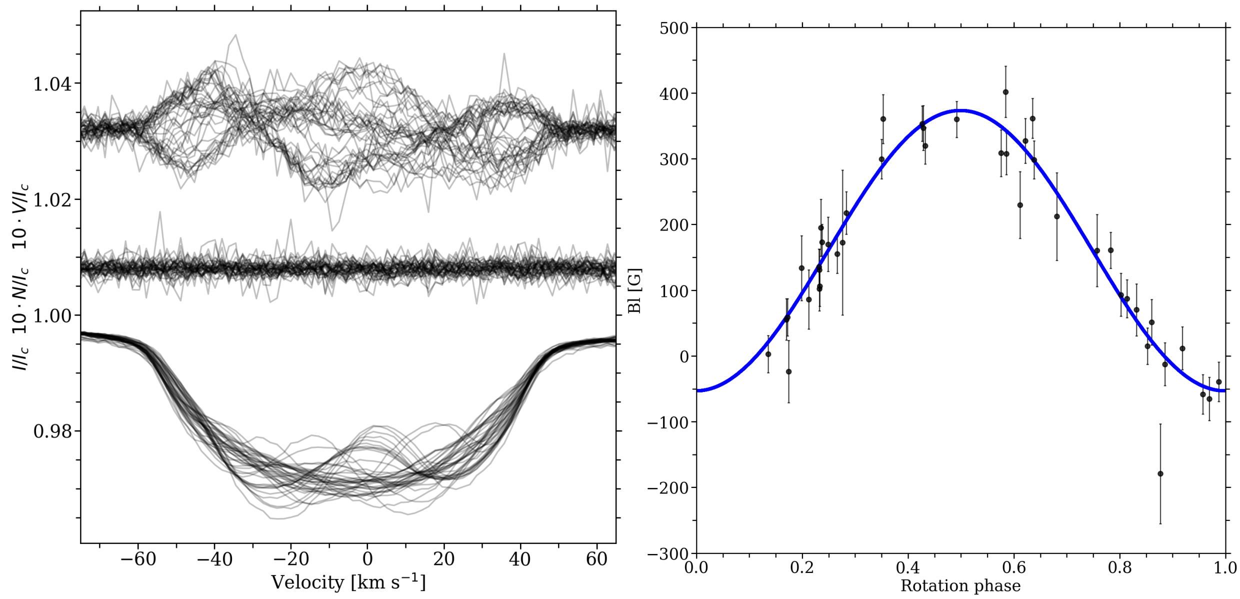

Fig. 1. Left: Overlayed LSD Stokes profiles for ι Lib. The top profiles are the LSD Stokes V profiles, the middle profiles are the diagnostic null profiles, and the bottom profiles are the LSD Stokes I profiles. These profiles are offset for increased visibility. **Right:** Longitudinal field measurements (in black) phase-folded with the rotation period ($P_{\rm rot} = 1.5570\,$d and T_0(HJD) $= 2457800.1864$). The sinusoidal model for a pure dipolar magnetic field is indicated by the blue solid line.

at the telescopes. We normalized the data per spectral order with the interactive spline fitting tool Spent (Martin et al. 2018).

Following the analysis of Buysschaert et al. (2018b), we used the same vald3 (Ryabchikova et al. 2015) line mask to create average line profiles for each observation using a Least-Squares Deconvolution technique (LSD, Donati et al. 1997). This line mask includes all sufficiently strong metal lines and Helium lines that are not blended with hydrogen lines, telluric lines, or DIBs. The computed LSD Stokes profiles are shown in the left panel of Fig. 1 and indicate both a variable Zeeman signature in the LSD Stokes V profiles and line profile variability in the LSD intensity profiles. The diagnostic null profiles indicate that no strong variability or any substantial instrumental effects were present during each spectropolarimetric sequence.

Further, we measure the longitudinal magnetic field for each LSD Stokes profile (Rees & Semel 1979). Using a Markov Chain Monte Carlo (MCMC) approach (Foreman-Mackey et al. 2013), we analyse the periodic variability of the longitudinal magnetic field measurements of ι Lib which is caused by rotational modulation. This analysis indicates a rotation period $P_{\rm rot} = 1.5570(3)\,$d for a sinusoidal model with $B_0 = 160.4 \pm 5.3\,$G and $B_1 = 213.2 \pm 8.2\,$G adequately describes the periodic variability. Thus, the large-scale magnetic field of ι Lib has a dominant dipolar configuration. We show the phase-folded longitudinal magnetic field measurements and the sinusoidal model in the right panel of Fig. 1. The derived rotation period is half of the value reported by Wraight et al. (2012).

Using an estimated radius of $3 - 4\,{\rm R}_\odot$ (see e.g., Fig. 1 of Pápics et al. 2017), appropriate for the star's $T_{\rm eff}$ and $\log g$, its $v \sin i$ and $P_{\rm rot}$ we obtain an equatorial velocity $v_{\rm eq} = 98 - 130\,{\rm km\,s^{-1}}$ and an inclination angle $i = 28 - 38\,^\circ$. This leads to an estimated obliquity angle $\beta = 60 - 69\,^\circ$ between the rotation and magnetic axes (Shore 1987) and a strength of the dipolar magnetic field $B_d = 1420 - 1750\,$G (Schwarzschild 1950).

3 Asteroseismic analysis

The K2 mission (Howell et al. 2014) observed ι Lib during Campaign 15. We constructed a light curve using the halophot (White et al. 2017) software to select a halo-aperture. This light curve is subsequently corrected for instrumental variability with the k2sc (Aigrain et al. 2015, 2016, 2017) Gaussian Process-based systematics correction code. Next, parts at the beginning and at the end of the light curve are discarded, because substantial decreases in flux are present and it is unclear whether these have an instrumental origin. A long-term trend in

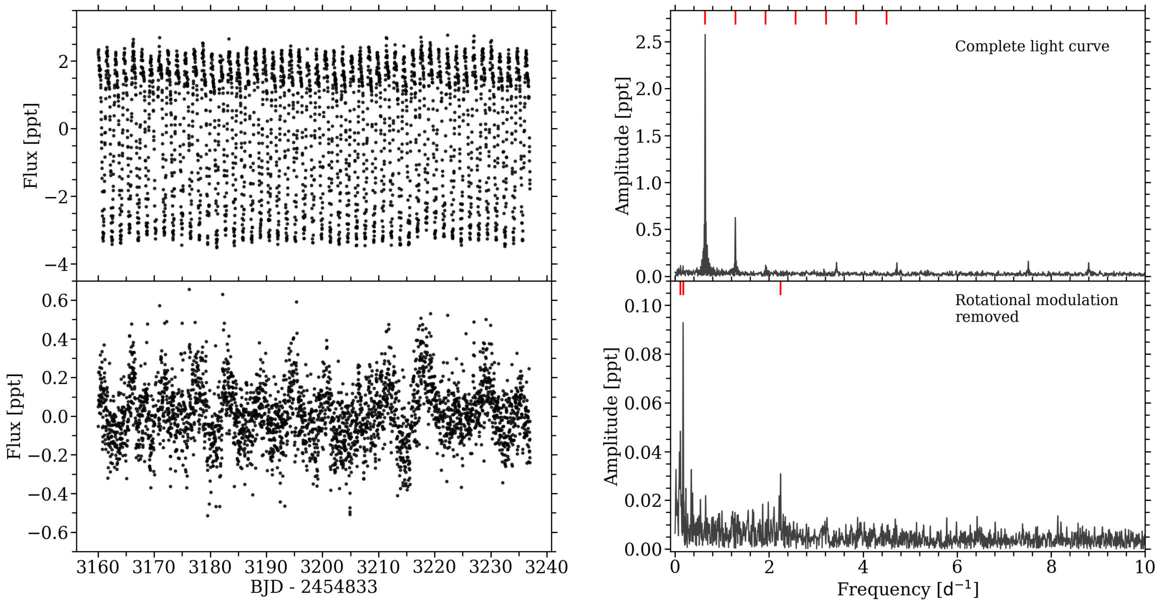

Fig. 2. Top: K2 light curve of ι Lib (*left*) and its periodogram (*right*), where the dominant periodic variability is due to rotational modulation. The employed harmonics of the rotation frequency are marked by the red ticks in the periodogram. **Bottom:** Residual K2 light curve (*left*), where the rotational modulation is removed, and its periodogram (*right*). The recovered significant frequencies are marked by the red ticks in the periodogram.

Table 1. Results from the iterative prewhitening of the residual K2 light curve. We report the frequency, amplitude and S/N of the recovered significant periodic variability. Uncertainties on the frequency and amplitude are formal errors of a non-linear least-squares fit Montgomery & O'Donoghue (1999), while the frequency resolution amounts to $f_{\rm res} = 0.013\,{\rm d}^{-1}$.

ID	Frequency [d^{-1}]	Amplitude [ppt]	S/N
f_1	0.1158(6)	0.043(4)	4.16
f_2	0.1738(3)	0.091(4)	7.64
f_3	2.2471(8)	0.031(4)	4.15

the light curve is accounted for with a linear polynomial. The reduced and corrected light curve is shown in the top left panel of Fig. 2.

The dominant photometric variability is caused by rotational modulation (see top right panel of Fig. 2) and confirms the rotation period from the magnetometric analysis. We describe this periodic variability with the method of Buysschaert et al. (2018b) using a sum of sinusoids whose frequencies are integer multiples from $f_{\rm rot}$ up to $7f_{\rm rot}$. The latter frequency is the last significant harmonic of the rotation frequency found in the periodogram. With the rotational modulation removed, we improve the description of the long-term trend in the light curve by means of a lowest filter. This residual light curve is shown in the bottom left panel of Fig. 2.

We employ a standard iterative prewhitening scheme to deduce whether this light curve still contains any significant periodic variability. The significance of frequency peaks is computed with the signal-to-noise ratio (S/N) criterion (Breger 2000) with a frequency window of $1\,{\rm d}^{-1}$ centered at the frequency under investigation. Frequency peaks are considered significant when they have a S/N ≥ 4. In total, we obtain three more significant frequencies (see Table 1), of which f_2 agrees with a literature value derived by Wraight et al. (2012). No significant periodic variability is retrieved with a frequency above $10\,{\rm d}^{-1}$, in agreement with instability computations of non-magnetic stars (Pamyatnykh 1999).

4 Conclusions

We analysed the Narval, ESPaDOnS and K2 data to initiate a magneto-asteroseismic study of the magnetic component of ι Lib. We measured a dipolar magnetic field with $B_p \sim 1.5$ kG and $\beta \sim 65°$. These characteristics are typical for that of a large-scale magnetic field of early-type stars. The derived rotation period of 1.5570 d was recovered during both the analysis of the longitudinal magnetic field measurements and the K2 photometry. The residual K2 light curve showed three significant frequencies, of which two fall in the frequency domain where g modes are expected to occur for early-type main-sequence stars. Further observations are needed to corroborate which component in the ι Lib system produces this variability and whether or not they are g modes of consecutive radial order, as in slowly pulsating B stars (e.g., Pápics et al. 2017). Only in this way can the modes be identified and forward asteroseismic modelling be done as in Pápics et al. (2017).

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