Magnetic field and radial velocities of the star Chi Draconis A

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ABSTRACT

We present high-resolution spectropolarimetric observations of the spectroscopic binary χ Dra. Spectral lines in the spectrum of the main component χ Dra A show variable Zeeman displacement, which confirms earlier suggestions about the presence of a weak magnetic field on the surface of this star. Within about 2 years of time base of our observations, the longitudinal component $B_l$ of the magnetic field exhibits variation from $-11.5 \pm 2.5$ G to $+11.1 \pm 2.1$ G with a period of about 23 days. Considering the rotational velocity of χ Dra A in the literature and that newly measured in this work, this variability may be explained by the stellar rotation under the assumption that the magnetic field is globally stable. Our new measurements of the radial velocities (RV) in high-resolution $I$-spectra of χ Dra A refined the orbital parameters and reveal persistent deviations of RVs from the orbital curve. We suspect that these deviations may be due to the influence of local magnetically generated spots, pulsations, or a Jupiter-size planet orbiting the system.

Key words: magnetic fields – stars: individual: χ Dra: binaries.

1 INTRODUCTION

The spectroscopic binary system χ Dra is a classic spectroscopic binary first discovered by [Campbell 1898]. Since 1987 [Tomkin et al. 1987; Schoeller et al. 1998] the system is also known as an interferometric binary. The angular separation between components is 0′′12, and the orbital period is 280.55 days [Tomkin et al. 1987; Schoeller et al. 1998]. The primary component χ Dra A is a F7V 4th magnitude star with a projected rotational velocity of $v \sin i = 2.5$ km s$^{-1}$ [Gray 1984a] and a radius of $1.2 R_\odot$ [Torres et al. 2010]. The secondary component is a convective K type star, two magnitudes fainter than the primary.

In a comparatively recent study by Monin et al. (2002), it was suggested that the main component, χ Dra A, has a weak longitudinal field of up to a few tens of Gauss. This suggestion, along with the binarity of χ Dra, makes this system an interesting laboratory to study the formation and evolution of magnetic stars within multiple stellar systems. Motivated by this idea, we conducted an extensive set of high-resolution spectropolarimetric observations of χ Dra with spectropolarimetric facilities of the Bohyunsan Optical Astronomical Observatory (BOAO) of the Korea Astronomy and Space Science Institute (KASI) in Republic of Korea. Another goal of this study was a high-precision search for the radial velocity (RV) variations of the system’s main component. Observations, data reduction, and measurements are described in the next section. Section 3 presents results of magnetic field and RV measurements. In Section 4, we discuss our findings.
2 Observations, Data Reduction and Measurements

Observations of χ Dra were carried out on 15 nights between 2006 and 2008. The BOES spectropolarimeter at the 1.8-m of the BOAO was used. The spectrograph and spectropolarimetric observational procedures are described by Kim et al. (2007). The instrument is a moderate-beam fiber-fed high-resolution spectrograph which incorporates 3 STU Polymicro fibers of 300, 200, and 80 µm core diameter (corresponding spectral resolutions are $\lambda/\Delta\lambda = 30,000, 45,000$, and 90,000, respectively). We used a 3800 – 10 000 Å working wavelength range and a spectropolarimetric mode provided with a spectral resolution of 60 000 by using two additional fiber-fed channels. An overview of observations is given in Table 1, where we list the date of observations, total number of exposures, typical exposure time for an individual frame, and sky conditions.

We identified several hundred lines in the spectrum of χ Dra within the range 3 800 – 10 000 Å from which we selected about 300 deepest ($r_c \geq 0.4$ where $r_c$ is the central depth of the line) single narrow and symmetric absorptions with non-zero Lande factors. By measuring Zeeman displacements individually in all these lines, weighting and averaging these measurements as described by Monin et al. (2002), we obtained the estimates and corresponding uncertainties of the star’s longitudinal magnetic field at paired exposures of different orientation of the quarter-wave plate following the scheme described in detail by Kim et al. (2007). Since the spin period of χ Dra A is much longer than several days, we integrated these individual estimates within a combined exposure for each observing nights. The duration of such exposure is equal to $N \times \text{Exp}$ (see Table 1) and ranges from a few tens of minutes to a few hours.

In order to control the sign and zero level of the measured field, we used typical magnetic stars (HD 215441, HD 32633, and HD 40312) which have magnetic field of different strengths as well as zero-field stars (for details, see Kim et al. (2007)). To control our measurements, we used non-saturated telluric spectral lines and the star Procyon which has not demonstrated a magnetic field higher than one G (Kim et al. 2007) and has a spectral class very similar to χ Dra A.

Since individual RV estimates obtained for each short-time exposure have shown no remarkable features, we averaged all RV measurements within combined exposures in the same manner as magnetic field estimates.

3 Results

Results of our measurements for each observing date are presented in Table 2 where column (1) is the date of observations, column (2) is a Heliocentric Julian Date of mid-exposure, columns (3) and (4) display a nightly mean value of RV and its uncertainty $\sigma$, columns (5) and (6) give corresponding estimates of the longitudinal magnetic field $B_L$ and its uncertainty $\sigma$. Let us consider the results of Zeeman and RV measurements independently.

3.1 Magnetic field

As clearly seen from Table 2, ten out of fifteen estimates of the longitudinal field have a significance exceeding the $3\sigma$
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The found period is shown in Fig.1 (middle plot). The phase variation of the longitudinal field is symmetric with some deviations from the sinusoidal symmetry (for example two points between $\phi = 0$ and $\phi = 0.25$). If from minimum to maximum individual measurements of $B_l$ vary from $-11.5 \pm 2.5 \, G$ to $+11.1 \pm 2.1 \, G$, the sinusoidal fit of these data by the Marquard $\chi^2$ minimization method (Bevington 1969) gives the field variation from $-11.5 \pm 1.5 \, G$ to $+5.2 \pm 1.5 \, G$. This discrepancy suggests, that the field geometry is more complicated than a simple dipole. The moment of maximum of the mean longitudinal field can be calculated according to the following ephemeris: $T0 = 2454006.095 + 23.39(9) \, E$.

### 3.2 Radial velocities

Good quality of the RV data owing to the high mechanical stability of the BOES makes it possible to reanalyse RVs of $\chi$ Dra A with an accuracy higher than achieved in previous studies. To the best of our knowledge, the most complete set of RV data for the system was presented and analysed by Tomkin et al. (1987). Using several tens of individual RV measurements as well as speckle observations, these authors determined the RV orbit for $\chi$ Dra. In more recent studies by Schoeller et al. (1998) and Farrington et al. (2010), the orbit was further refined by interferometric method. Combining RV measurements published by Tomkin et al. (1987) with our new measurements described here, we get a modified orbital solution. The best-fit results are summarized in Table 3, which lists the projected velocity semi-amplitude of $\chi$ Dra A ($K$), the periastron angle ($W$), the epoch of periastron ($T_p$), the orbital period ($P$), the eccentricity ($e$), the offset RV ($V0$), and the linear slope $S$ of RV variation to remove the linear component of the variation.

![Graph](image_url)

**Figure 1.** Upper panel: power spectrum of the field variation. Middle panel: observed phase variation of the longitudinal field $B_l$ of the star $\chi$ Dra (filled circles) and the best sinusoidal fit to the data (a solid line). Lower panel: control results of “zero-field” measurements in the spectra of Procyon (filled triangles) and telluric lines in the spectra of $\chi$ Dra (open circles)
are not due to uncertainties in the orbital solution. For example, inspecting our RV estimates obtained within the longest two-week observing run (22 Jan. – 4 Feb. 2007) reveal an unexpectedly high scatter of the data (several times larger than observational uncertainties). Visual inspection of Fig. 2 hints a periodicity within days to tens of days in the deviations of observed RVs from the orbital curve. A similar picture can be seen in Fig. 2 from Tomkin et al. (1987). This suggests the presence of additional cause of RV variations in \( \chi \) Dra A. In order to examine this variability, we have analyzed the “O-C” residuals from the spectroscopic orbital solution obtained here for all available RV measurements.

The Lomb-Scargle power spectrum (Lomb 1976; Scargle 1982) of these “O-C” residuals is presented in Fig. 3. A considerable peak at \( \sim 12 \) days was found to suggest the presence of a periodical signal. Unfortunately, due to the strong inhomogeneity of the data, the very long time base of observations (tens of years), and insufficient amount of data limit ourselves to the illustration of the periodogram only; we are presently unable to clearly identify the true periodicity in the residual RVs of \( \chi \) Dra A. Additional high-precision spectral observations are needed for more reliable conclusions.

4 DISCUSSION

We obtained high-resolution spectropolarimetric observations of the star \( \chi \) Dra A. Analysis of these new and previously published data revealed the presence of variable longitudinal magnetic field. Within the 2-years time base of our observations the field varied from \(-11.5 \pm 1.5 \) G to \(+5.2 \pm 1.5 \) G with the period \( P = 23.39(9) \) days.

As discussed by Tomkin et al. (1987) and Torres et al. (2010), the star \( \chi \) Dra A is a low mass, low metallicity old star. As such, the origin of the field on \( \chi \) Dra A should be typical for low mass stars of spectral classes from late F to cooler classes (Reiners 2012). For these stars, as it is for the Sun, magnetic fields are concentrated mainly into locally generated, dynamically unstable strong-magnetic tubes seen as dark spots on stellar surfaces. These spots monotonously migrate with different velocities, giving additional contribution to the field variation in addition to rotation. The found period \( P = 23.39 \) days is in principle consistent with typical rotation periods of low mass stars with masses comparable to \( \chi \) Dra A, although it may be a bit longer than expected based on our measured longitudinal magnetic field strengths (Marsden et al. 2014). From this point of view it is important to establish whether the star’s rotation period is indeed around 23 days.

In order to clarify the situation with rotation we have analysed Doppler widths of spectral lines in the spectrum of \( \chi \) Dra A. To measure the projected rotational velocity \( v \sin i \), we have chosen several single lines with small Lande factors. By modeling profiles of these lines using the ATLAS/WIDTHS atmosphere model programs (Kurucz 1993), we derived \( v \sin i \leq 3 \) km/sec, which is consistent with the estimate \( v \sin i = 2.5 \) km/sec by Gray (1984). Surprisingly, \( v \sin i = 2.5 \) km/sec with the orbital inclination of about 75° (Tomkin et al. 1987) and the stellar radius of 1.2 \( R_\odot \) (Torres et al. 2010) yields the rotation period of 23.5 days, almost the same as the found period of \( P = 23.39 \) days.

Thus, we suspect that the found 23.39 days period is mainly due to the rotation of the star. This result, if confirmed, may also imply the existence of a long-living (more than several years) global poloidal magnetic field. In contrast to the solar-type stars’ unstable magnetic fields, stable poloidal (say dipolar) morphology of the field suggests that we may be seeing a special case of fossil or generated magnetic field, originated and evolving within the frame of the binary system. However, this interesting possibility is based on our currently limited observational data, and we don’t exclude the possibility that this variation could have more complicated origin and may not be regular. The detailed interpretation of the nature of the magnetic field in \( \chi \) Dra A requires further accumulation of observational data on longer time base. In this paper we restrict ourself with presentation of new observational data confirming the presence of magnetized field structures on the surface of \( \chi \) Dra A.
Lastly, measured RVs of χ Dra A exhibit systematic deviations from the orbital curve. Despite the fact that the measurements presented in this paper demonstrate improved agreement with the orbital solution, the deviation still exists. No explanation of this phenomenon has been found so far. It may result from additional line displacement due to magnetic nature of the star. For example, the presence of magnetic field with inhomogeneous distribution over the stellar surface (in particular, magnetically-induced spots) may simply distort integral symmetry of spectral lines. Rotational modulation of such line profiles can, in turn, cause “artificial” RV variations. However, the period found through the analysis of RV residuals is not consistent with the rotation period estimated by means of spectropolarimetric methods. Our data cannot exclude the existence of a hot Jupiter mass orbiting χ Dra A with a short period. Following this idea and taking into account that the system is seen almost edge-on, it seems reasonable to monitor χ Dra A photometrically in order to search for deep, 1 – 2%, transit. New high-precision, high-resolution spectral observations of the star χ Dra A are also necessary to answer this particularly important question.

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References

Bevington P.R., 1969, Data reduction and error analysis for the physical sciences, McGraw-Hill, New York
Campbell, W. W. 1898, ApJ, 8, 292
Farrington, C. D.; ten Brummelaar, T. A.; Mason, B. D.; Hartkopf, W. I.; McAlister, H. A.; Raghavan, D.; Turner, N. H.; Sturmann, L.; Sturmann, J.; Ridgway, S. T. 2010, AJ, 139, 2308F
Gray, D.F. 1984a, ApJ, 277, 640
Gray, D.F. 1984b, ApJ, 281, 719
Kang, Dong-Ii; Park, H.-S.; Han, Inwoo; Valyavin, G.; Lee, B.-C.; Kim, K.-M. 2005, Publication of the Korean Astronomical Society, 20, 97
Kang, Dong-Ii; Park, Hong-Suh; Han, In-Woo; Valyavin, G.; Lee, Byeong-Cheol; Kim, Kang-Min 2006, Publications of the Korean Astronomical Society, 21, 101
Kim, Kang-Min; Han, Inwoo; Valyavin, Gennady G.; Plachinda, Sergei; Jang, Jeong Gyun; Jang, Be-Ho; Seong, Hyeon Cheol; Lee, Byeong-Cheol; Kang, Dong-II; Park, Byeong-Gon; Yoon, Tae Seog; Vogt, Steven S. 2007, PASP, 119, 1052
Kupka F., Piskunov N.E., Ryabchikova T.A., Stempels H.C., & Weiss W.W. 1999, A&AS, 138, 119
Kurucz, R., ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid. CD-ROM No. 13 (Smithsonian Astrophys. Obs., Cambridge, 1993).
Lafler, J., & Kimman, T. D., 1965, ApJS, 11, 216
Lomb, N. R. 1976, ApSS, 39, 447
Marsden, S. C., Petit, P., Jeffers, S. V., Morin, J., Fares, R., Reiners, A. et al. 2014, MNRAS, 444, 3517
Monin, D., Fabrika, S., Valyavin, G. 2002, A&A, 396, 131
Piskunov N.E., Kupka F., Ryabchikova T.A., Weiss W.W., & Jeffery C.S. 1995, A&AS, 112, 525
Ramírez, I., Allende Prieto, C., Lambert, D. L. 2013, ApJ, 764, 78R
Reiners, Ansgar 2012, Living Reviews in Solar Physics, 9, 73
Ryabchikova T.A., Piskunov N.E., Stempels H.C., Kupka F., & Weiss W.W. 1999, in the 6th International Colloquium on Atomic Spectra and Oscillator Strengths, Victoria BC, Canada, 1998, Physica Scripta, T83, 162
Scargle, J. D. 1982, ApJ, 263, 835
Schoeller, M., Balega, I. I., Balega, Y. Y., et al. 1998, Astron. Lett., 24, 337
Stibbs, D. W. N. 1950, MNRAS, 110, 395S
Tomkin, J., McAlister, H. A., Hartkopf, W. I., & Fekel, F. C. 1987, AJ, 93, 1236
Torres, G., Andersen, J., Giménez, A. 2010, The Astronomy and Astrophysics Review, 18, 67

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