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Linear Polarization of HD 37776

Yakunin I. A., Chountonov G. A., Semenko E. A., Romanyuk I. I.

Special Astrophysical Observatory, Nizhny Arkhyz, Russia

Abstract. The first observations of linear polarization in the lines of a unique He–rich star HD 37776 with a complex structure of magnetic field were carried out with the 6–m BTA telescope of the SAO RAS using the Main Stellar Spectrograph. The data analysis reveals an almost zero signal of the Stokes Q and U parameters in 4 different phases. We hence need to reconsider the model of magnetic field of this star.

Key words: stars: magnetic fields – stars: individual (HD 37776) – stars: polarization

1 Introduction

He–rich star HD 37776 is famous for its extremely strong magnetic field with a complex structure. Despite of numerous attempts, so far there is no satisfactory model of magnetic field which would explain all the observational data.

HD 37776 is the central star in the emission nebula IC 432 which belongs to the O–association I Ori. It has a parallactic distance of about 500 pc and the age of 3.5 Myr.

A two–dimensional classification performed by Crawford (1958) showed that the object has a spectral class B2V. McNamara & Larssson (1962) determined $v \sin i = 145$ km/s. Later, after discovering strong line broadening due to the magnetic field, the value of $v \sin i$ was decreased to 80 km/s (i. e., Romanyuk et al., 1995).

Nissen (1976) found HD 37776 to be a helium–strong star, the photoelectric observations of He I 4026 Å performed by Pedersen & Thomsen (1977) allow to determine the period of 1.5385 days. Later Adelman (1997) using the *ubvy* system improved the period of photometric variation to $P = 1.5385675 \pm 0.000005$ days. Pedersen (1979) showed that both helium and photometric variations have the same period. Walborn (1982) has presented the data that suggest that Si III lines vary in antiphase with He I lines, and Thompson & Landstreet (1985) showed that the longitudinal magnetic field B_e changes with the same period. Matching of photometric, spectral and magnetic periods definitely indicates that this is the real rotational period of the star.

Recently, Mikulasek (2008) has found the rotational braking of HD 37776 — it has lengthened by 17.7 s over the past 31 years. Effective temperature was determined by many authors, the discrepancy is very small. Average $T_e = 23000$ K is given by Glagolevskij (1994).

The strong magnetic field of a non–dipolar structure was found in the atmosphere of the star. This fact is considered in the next chapter.

2 Magnetic Field Measurements

Magnetic field was detected first time by Borra & Landstreet (1979) from the measurements of circular polarization in Hβ wings using the Balmer magnetometer. However, the obtained magnetic curve of B_e had an anomalously large scattering. Landstreet and his group continued observations on the magnetometer and obtained a large data set. After reducing it they published a new magnetic curve (Thompson & Landstreet, 1985), which has revealed a double wave with the extrema at -2 kG and $+2$ kG. They concluded that the topology of magnetic field differs from a dipole configuration.

Bohlender & Landstreet (1989) obtained the spectral observations on the Reticon without the Zeeman analyzer and found that the Si III lines vary at different rotation phases. After modelling the magnetic curve based on magnetic field measurements with the Balmer–line magnetometer and unpolarized spectra with a high S/N ratio Bohlender (Bohlender, 1994) offered a complex multipole magnetic field model (dipole + quadrupole + octupole) which predicts the value of surface magnetic field up to 60 kG, which significantly exceeds values of magnetic fields of all the discovered Main Sequence stars. In particular, a model published by Bohlender is a coaxial dipole, quadrupole and octupole with polar values of the field $+3.4$ kG (dipole), -59 kG (quadrupole), $+44$ kG (octupole). It is very close to the previously published model (Bohlender & Landstreet, 1989).

As the magnitude of surface field predicted by model is very high, at the same time the extrema of longitudinal magnetic field reach only 2 kG, it becomes clear that highly precision spectropolarimetric observations are necessary to check how well the obtained model describes the real magnetic field of HD 37776 with direct methods.

Spectropolarimetric observations were carried out at the 6–m telescope of SAO RAN. During 10 years (1995 – 2005) Romanyuk, Elkin and Kudryavtsev obtained more than 50 circular polarized spectra of HD 37776. A detailed description of the observed data is published in several papers, (e. g., Romanyuk et al., 1998).

A double–waved magnetic curve (Romanyuk et al., 1998) confirmed the fact that the equivalent widths of He lines have their minima at phase 0.2 and maxima at phase 0.7 – 0.8. The equivalent widths of He and Si lines vary in antiphase, the maximal width of Si III lines is reached at phase 0.8. The surface field at the corresponding phases is about 20 kG and 60 kG, if we take into account only the magnetic broadening mechanism. The longitudinal magnetic fiend measurement confirmed an assumption about its complex structure. For example, the measurement obtained from the cores of He lines shows a large value of B_e, while the measurements obtained from the centers of gravity (the Babcock method) are revealing a weak field. The magnitude of the Stokes V reaches 5% and changes in a complex way, which indicates the fact that the star has a strong and complex field.

The previously described observational data has been used by Khokhlova et al. (2000) for building the model of the field and the He and Si surface distribution maps using the Doppler–Zeeman mapping. The model was built as a superposition of the central coaxial dipole and a quadrupole with the dominating quadrupole component. The maximal surface magnetic field is 60 kG. It was shown that He concentrates in the regions of maximal radial field, while the maximum concentration of O, Al, Si and Fe coincide with the regions of maximum tangential field. However, the model of Khokhlova et al. was not be able to describe the hydrogen curve of the longitudinal field of Bohlender and Landstreet.

It is obvious that for the construction of a satisfactory model of this unique star new data is necessary. We assume that a full analysis of the Stokes vector, i. e. measuring all 4 Stokes parameters in spectral lines is needed. As all the previous data showed a big value of Stokes V, there were all reasons to suppose that the Stokes Q and U which describe linear polarization will also be high (it is reasonable to consider that if the longitudinal component is high, the transverse component will be high too).

2.1 Observations of 4 Stokes Parameters

For the first time on 6–m telescope 4 Stokes parameters for HD 37776 were obtained by Romanyuk et al. (1992) in a wide spectral band ($\lambda = 4580 - 4810$ Å) using the BTA spectropolarimeter. Observations were carried out in 7 phases of the period of rotation. It was shown that the broadband

Table 1: Spectral data

HJD 2450000+	Phase	S/N
5224.29204	0.93	$\approx$480
5224.31426	0.94	$\approx$360
5224.38231	0.98	$\approx$200
5252.28641	0.12	$\approx$360
5252.30100	0.13	$\approx$360
5253.24605	0.74	$\approx$430
5253.26411	0.75	$\approx$420
5254.23694	0.39	$\approx$520
5254.25846	0.40	$\approx$520

circular polarization in the continuum of HD 37776 is undetectable (the Stokes V is less than 0.01%). At the same time, the stellar radiation was linearly polarized, the same linear polarization was detected in all phases ($p = 0.44\%$, $\theta = 38^\circ$). A constant linear polarization indicates its circumstellar or interstellar nature and has no relation to the star. For the investigation of linear polarization due to the Zeeman effect one needs to observe the Stokes Q and U in the lines profiles of high–resolution spectra.

In order to detect linear polarization in the spectral lines of HD 37776 in winter 2009 – 2010, the observations at the 6–m telescope with the circular and linear polarization analyzer mounted on the Main Stellar Spectrograph were carried out. A detailed description of the above analyzer is laid out in (Chountonov, 2004).

For the measurement of linear polarization, the half–wave plate was placed before the slit and the analyzer was mounted in one of the Nasmyth foci of the telescope. This detection method is complicated by the fact that reflection of light from the diagonal mirror brings an instrumental linear polarization. The second difficulty is linked with the field rotation in the Nasmyth foci of the telescope, which leads to the rotation of the polarization plane, and hence to the change of the Stokes Q and U. A possible solution of this problem is to use the rotating half–wave plate to track the field rotation. The half–wave plate needs to rotate opposite to the field of rotation with half velocity of the field rotation rate. Hence, the plane of polarization will be constant. In the case of bright stars, the duration of exposition is short and the field rotation does not bring a significant error in the measurement of the Stokes parameters.

To correctly restore all the Stokes parameters and therefore the plane and angle of polarization, two expositions with different analyzer angles are required. In case of a rotating half–wave plate, the restoration of the Stokes Q and U can be done after two consecutive expositions with the angles of rotation of 0° (the polarization axis of the plate coincides with the slit position), and 22.5°. Therefore, the paper is not about the Q and U parameters, but only on the conditional linear polarization, not tied to celestial coordinates.

The spectral region of 4460 – 4600 Å has been chosen for observations. This interval contains He I 4471 Å, Mg II 4481 Å lines and a Si III triplet at 4452 Å, 4567 Å, 4574 Å with different Lande factors. The information on the obtained spectral data is presented in Table 1.

The cubic ephemerides from Mikulasek (2008) was used to determine the rotation phase. We used the `zeeman` context, written for the ESO MIDAS system by Kudryavtsev (2000) for data reduction.

The Si III lines of opposite linear polarization and corresponding signal in different phases are demonstrated in Fig. 1. There is no significant signal of linear polarization in lines of HD 37776

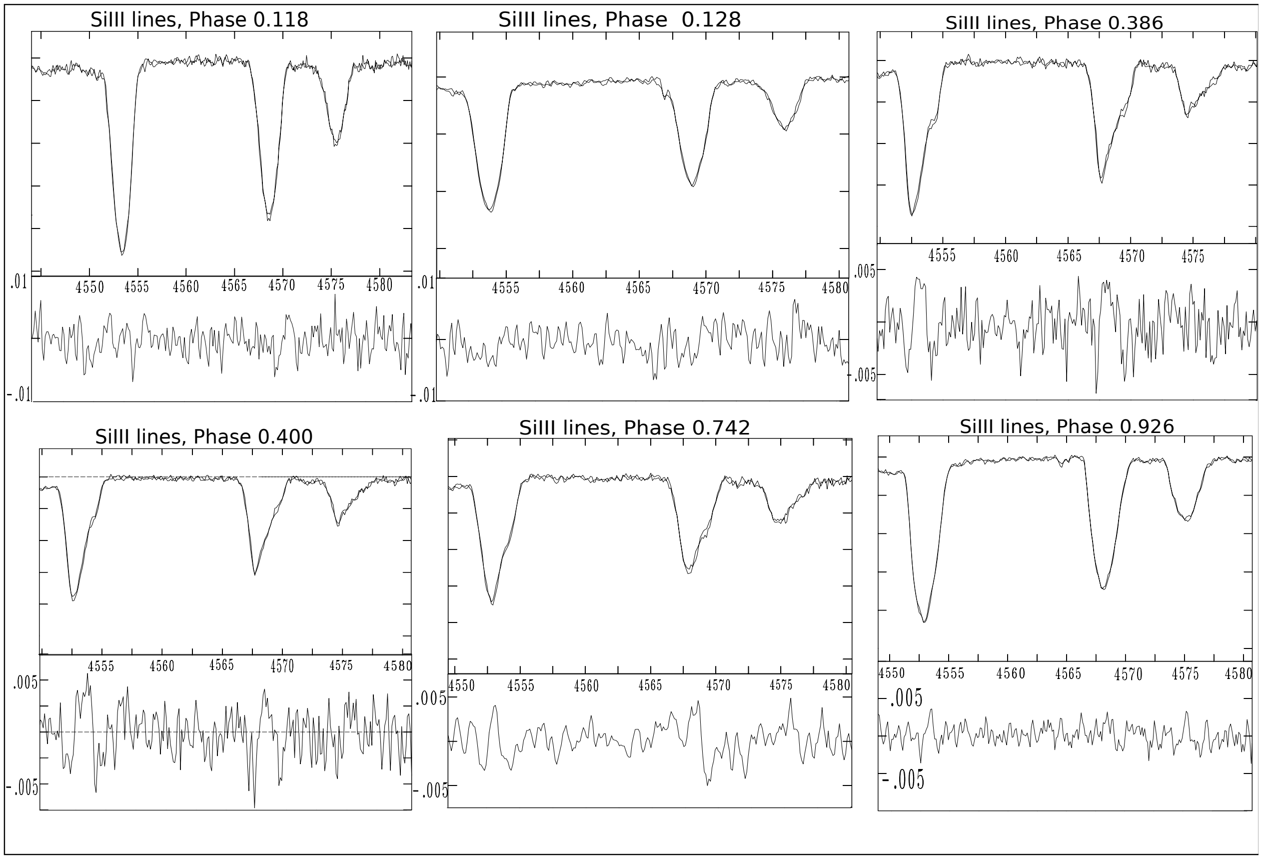

Figure 1: Overlapping spectra of opposite polarization and the signal of linear polarization in different phases.

neither in phase with a strong circular polarization signal, nor with the weak one. Some Si III lines show a weak signal (about 0.5%) at phases when the longitudinal magnetic field is about zero.

3 Discussion

Contrary to the expectations we did not manage to detect any significant linear polarization in the spectra of HD 37776. The S/N ratio of our data is larger than 200, what means that we did not detect the linear polarization signal at the level of 0.5% at the observed phases, while the circular polarization reaches 5%. It appears that the linear polarization level in the lines of HD 37776 is at least one order of magnitude smaller than circular, and a re–examination of the existing magnetic field model is hence required.

At the moment of presentation of this paper at the conference, we received a private communication that G. Wade and O. Kochukhov have carried out the observations of the Stokes Q and U parameters in the lines with high spectral resolution. A very weak signal was detected in the cores of the strongest lines. In the other lines there was no result. We therefore obtained an independent confirmation of our data.

At the time of preparation of this paper to print Kochukhov et al. (2011) has published the paper confirming our results. In this paper they built a new, very complex field model of HD 37776. The surface field does not exceed 30 kG, but the topology is very sophisticated with the dominating non–axisymmetric component, and represents by far the most complex magnetic field configuration found among the early–type stars. In this paper they used a magnetic curve by Thompson & Landstreet and a circularly–polarized spectra obtained with the 6–m telescope (Romanyuk et al., 1998). The INVERS10 code (Piskunov & Kochukhov, 2002) was used for the reconstruction of the magnetic field model.

We can expect that using the new data of linear polarization will allow to construct a new more realistic magnetic field model of this unique star.

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