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LONG-TERM PHOTOMETRIC AND SPECTRAL VARIATIONS OF DI CEPHEI

N.Z. Ismailov[1,2], K.N. Grankin[3], F.N. Efendieva[1]

[1] Shamakha Astrophysical Observatory, National Academy of Sciences of Azerbaijan, Shamakha, Azerbaijan, e-mail: Box1955n@yahoo.com

[2] Astrophysics Department of Baku State University, Baku, Azerbaijan

[3] Crimean Astrophysical Observatory, Nauchny, Ukraine

We have analyzed the photometric and spectral variations of the classical T Tauri star DI Cep for the last 50 years. Currently the star is at its faintest state and possesses an emission spectrum in the visual range. Synchronous spectroscopy and $UBVR$ photometry show that the higher the brightness, the stronger were the intensities of hydrogen Hα, Hβ emission lines and of FeII, HeI λ5876 Å emissions. For the first time, we detected, with a high probability, quasi-periodic variations of the star's brightness and of its spectrum with the period $P = 2020 \pm 200$ days.

1 INTRODUCTION

More than 60 years of photometric and spectroscopic observations of young T Tauri stars made it possible to collect a large amount of observations for individual members of this class. Nevertheless, many aspects of their observable physical characteristics still remain unexplained. Thus, it is necessary to undertake a detailed analysis of the available observations for individual stars to specify their common physical properties.

The question of long-term variability of young stars deserves special attention. Short-term brightness variations with an amplitude of $0\overset{\mathrm{m}}{.}1$–$0\overset{\mathrm{m}}{.}3$ per day or during an individual observing season are characteristic of many TTSs (T Tauri stars), while the character of long-term brightness and spectrum variations seems very individual for different stars. For example, some stars, observed for dozens of years, unexpectedly show a brightness rise and flare activity (for example, see Holtzmann et al., 1986), others reveal monotonous variations, with the light variability amplitude as large as $1^{\mathrm{m}}-3^{\mathrm{m}}$ (Herbst, 1986). A thorough analysis of all the aspects of long-term observations can help to reveal the reasons for such variations, to generalize them, and to get a better understanding of TTSs.

DI Cep belongs to classical T Tauri stars (CTTSs). The spectrum of the star in the optical range is characterized by strong emission lines of hydrogen (Balmer series), H and K CaII, as well as of FeII, FeI, etc. (Grinin et al., 1980; Krasnobabtsev, 1982; Gahm and Petrov, 1983; Ismailov, 1987; Hessman and Guenther, 1997). Bastian and Mundt (1979) found the star to show fast spectral and photometric variations within one hour. In the red part of the spectrum, the CaII $\lambda\lambda$8498, 8542 ÅÅ emission lines and a weak OI$\lambda\lambda$ 7773, 8446 ÅÅ emission are observed (Hamann and Persson, 1992). In the UV part of the spectrum, SiIV, CIV, HeII, [SiIII], [CIII] emission lines and the MgII λ2800 Å doublet were detected (Gómez de Castro and Fernández, 1996). During the recent years, regular spectroscopy of the star revealed a 9-day quasi-periodic variability of the spectrum and brightness (Ismailov, 2004). From numerous observations, significant fluctuations of emission-line intensities in the spectrum on time scales from several minutes to hours and days were found.

Photometric observations were regularly carried out in different observatories, they were published by Grinin et al. (1980), Kardopolov and Filip'ev (1985), Kolotilov et al. (2004) and included into the data base (Herbst and Shevchenko, 1999). During several rather short-term time intervals, photometric observations of the star were also performed by Keleman (1985) and by Ismailov (1988, 1997, and this paper). Accurate $UBVR$ photometry of DI Cep of the largest duration were carried out in Mt. Maidanak Observatory by the staff of the Variable Stars Department of the Astronomical Institute (Uzbekistan Academy of Sciences). On 17 observing seasons, they obtained 1200 $UBVR$ measurements of DI Cep (Grankin et al., 2007).

The purpose of our study is to analyze the results of long-term spectroscopy and photometry of DI Cep.

2 SPECTROSCOPY

Most of our spectroscopic observations were carried out in the Cassegrain focus of the echelle spectrometer at the 2-m telescope of the Shamakha Astrophysical Observatory using a 530×580-pixel CCD detector. The spectral resolution near the Hα line was 14000, with the average signal-to-noise ratio of 60. The spectral range covered was $4700-6700$ Å. Our observations were performed during the summer and autumn in 2004–2006.

A part of the CCD spectral data on hydrogen emission lines were obtained by Dr. J.F. Gameiro (Portugal) and kindly sent to us. Besides, in our analysis of the star's spectral variations, we use the spectroscopy from Grinin et al. (1980) and Ismailov (1987), where observations were made using photographic plates. These observations were obtained with rather similar characteristics of detectors and have virtually the same linear dispersion (100 Å per mm and 93 Å per mm at Hγ, respectively).

Uncertainties of radial-velocity measurements for CCD spectra did not exceed 2 km/s, and those of equivalent widths, about 3–4%. For spectrograms on photographic plates, the equivalent-width uncertainties amounted to 15%–20%.

We measured equivalent widths, line widths at half intensity (FWHM), displacements of individual components of the Hα and Hβ emissions as well as of the HeI λ5876 Å, NaI $\lambda\lambda$5889, 5896 ÅÅ (D2, D1), FeII lines. The lines of FeII, FeI, and HeI are observed as weak emissions. Equivalent widths of such lines are within $0.1-1.0$ Å, they vary synchronously with the hydrogen Hα and Hβ lines. The λ5876 Å line is frequently observed with two peaks and a central drop. Better-defined similar structures are observed also for the NaI D1, D2 lines (Fig. 1).

The two top panels of Fig. 2 display time variations of the equivalent widths of the hydrogen Hα and Hβ emission lines. The time range marked "1" on the first panel corresponds to the observations performed in June – December, 1975 (Grinin et al., 1980). The group of data points marked "2" are from observations by Ismailov (1987). These data cover the time interval of 1975–1987. No information on the Hα emission line is available in this case. The third time interval contains CCD observations by Gameiro acquired in 1988–1999 and the fourth interval, Ismailov's CCD observations made in 2004–2006. The last two intervals also have a comparable uncertainty of measured equivalent widths, at the level of 3–4%.

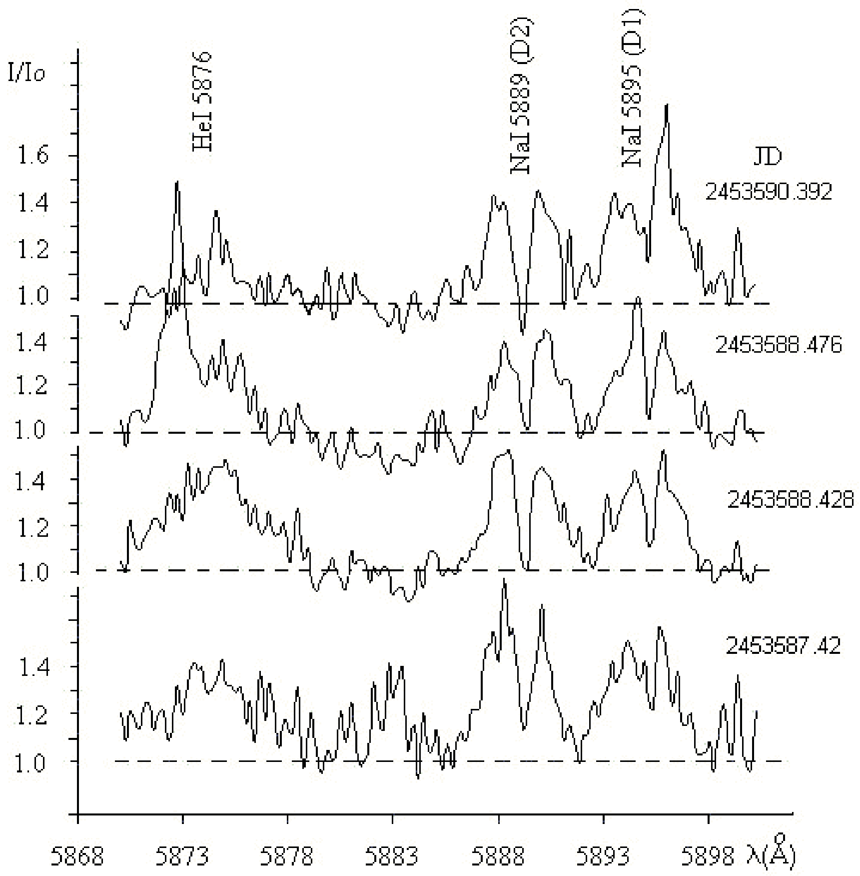

Figure 1. The region of the HeI λ5876 Å and NaI λ5889, 5896 ÅÅ (D2, D1) lines in the spectrum of DI Cep.

It appears from Fig. 2 that, while photographic observations show a relatively large scatter about the mean, the general tendency displayed by the curves is a monotone decrease of emission equivalent widths. Over 30 years of observations, the mean equivalent widths of the emission lines decreased more than twofold.

3 PHOTOMETRY

A historical light curve of the star was recently presented by Kolotilov et al. (2004). From this curve, it appears that, according to early photographic observations, the absolute minimum of the star's light, $m_{\rm pg} = 13\overset{\rm m}{.}6$, was observed in 1940. During the whole history of its observations, the star was again in a similar condition only in 1953 and 1983. The second deep photographic minimum was detected in 1953–1956. Photoelectric observations started in 1970s and revealed the first minimum in 1983–1984. The combined light curve in Kolotilov et al. (2004) gives a good general description of the brightness variations but is insufficiently complete after 1980.

In 2006, we obtained 13 new BV brightness estimates at Shamakha Observatory. For further analysis, we add all observations available in the literature and the data covering 17 years we obtained in Uzbekistan (Grankin et al., 2007). We have collected the total of 1960 V-band brightness estimates and plotted the combined photoelectric light curve. It is shown in the bottom panel of Fig. 2. It can be seen that a deep minimum occurred

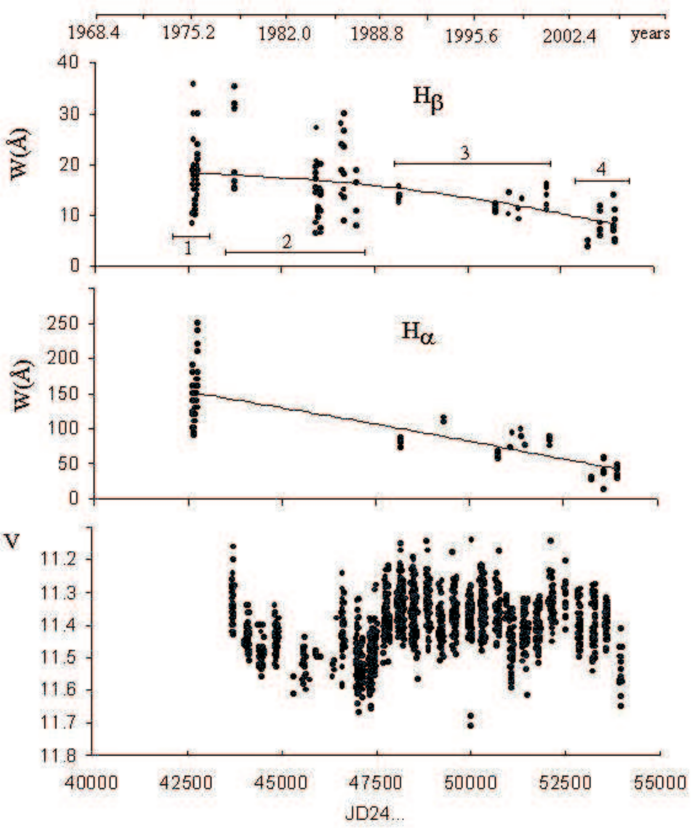

Figure 2. The time variability of Hα and Hβ emission equivalent widths and combined light of DI Cep for 30 years of observations. The marked intervals correspond to data from: 1 — Grinin et al. (1980), 2 — Ismailov (1987), 3 — Gameiro, 4 — our unpublished data obtained in 2006.

on JD 2447041 (1987), then the star's brightness increased rather quickly, reaching a maximum at JD 2448155 (1990), and then a slower decline started, which continues till now. There also happened a small fading on JD 2451087 (1998), and then the brightness was quickly restored.

The spectral data show a many-year monotone decrease of mean emission equivalent widths (Fig. 2).

From available observations, we selected the nights when the star was simultaneously observed photometrically and spectroscopically. From a small amount of synchronous observations, we earlier demonstrated (Ismailov and Grankin, 2007) that that equivalent widths of emission lines in the spectrum of DI Cep were increasing during brightness increases. To check this conclusion on a large number of observations, we found, for different filters of the $UBVR$ system, from 6 to 17 nights of synchronous observations. Figure 3 presents a plot of the star's brightness versus equivalent width of hydrogen emission lines. It appears that an increase of the Hα and Hβ emission was always accompanied with a brightening of the star. In all cases, the correlation coefficient was $r \geq 70\%$.

The combined photoelectric light curve in Fig. 2 shows wave-like variations, with waves of 5–7-year duration, interrupted with rather deep fadings. Each compact group of points in the light curve of Fig. 2 consists of observations of one year. It can be seen that the total amplitude of V-band brightness variations is about $0\overset{\mathrm{m}}{.}6$, while the largest variation

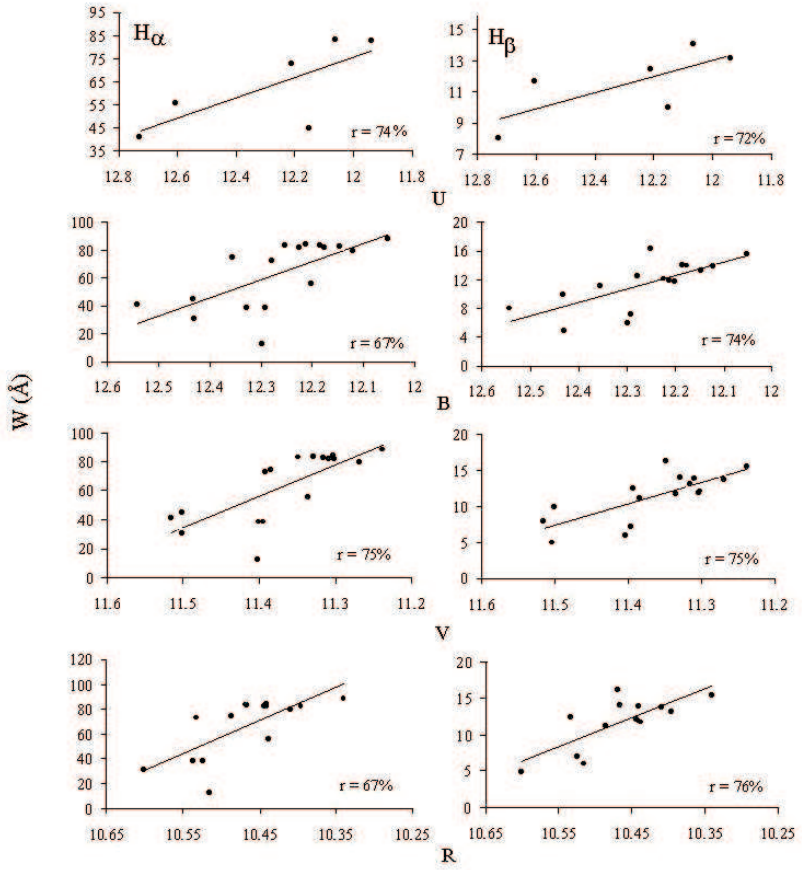

Figure 3. Equivalent widths of Hα and Hβ emission lines versus photoelectric $UBVR$ magnitudes. For each panel, the corresponding correlation coefficient is indicated.

amplitude within one year is $0\overset{\mathrm{m}}{.}3$. The photometric light curve, like in the case of the prototype, T Tau, corresponds to type IV of the classification by Ismailov (2004) — both the amplitude of yearly variations and the year-average brightness vary. Grankin et al. (2007) also note that the character of long-term variations is very similar for DI Cep and T Tau. We can suppose that two different mechanisms are simultaneously responsible for brightness variations of these stars. One of them, possibly related to local inhomogeneities of physical conditions on the stellar surface, probably causes the seasonal variability. A second mechanism operates at longer time scales.

4 SEARCH FOR THE LONG-TERM PERIOD

To search for long-term cyclic variations, we applied the PERIOD software package for analysis of time series. This software package was developed under the Council for the Central Laboratory of the Research Councils in the framework of the StarLink project. We used two methods incorporated in the package, the Lomb–Scargle method and the χ^2 technique (Chisq). The Lomb–Scargle method (Lomb, 1976; Scargle, 1982) is a modification of the classical Fourier periodogram technique making it invariant for unevenly spaced times of observations. It is a very powerful method for unevenly spaced and noisy data. Later, the method was further modified by Horne and Baliunas (1986), and then Press and Rybicki (1989) proposed the algorithm used in the PERIOD package.

The χ^2 technique is a relatively simple method where input data are folded with a number of trial periods. For each trial period, the data are described with a sinusoid. The resulting χ^2 values are plotted as a function of trial frequencies, and minima in these diagrams are considered probable periods (Horne et al., 1986).

Both methods showed a significant peak at the frequency 0.000495 d^{-1}. This frequency corresponds to the period $P = 2020 \pm 200$ days.

We estimated the significance of the period by repeated modeling of white noise. This procedure is implemented in the SIG routine of the PERIOD package, which applies the so-called Fisher's method of randomization, or the Monte Carlo method (Nemec and Nemec, 1985). Randomization of time series and computation of periodograms in the SIG routine are repeated for hundreds of permutations. The period we obtained for DI Cep has a very high probability, in excess of 95%. Thus, we have reasons to believe that the period $P = 2020 \pm 200$ days is real.

Figure 4 presents the power spectrum and the spectral window obtained using the Lomb–Scargle for the interval of frequencies $0 - 0.006d^{-1}$. Phases correspond to the light elements:

$$\mathrm{Min}V = \mathrm{JD}2447041 + 2020^{\mathrm{d}} \cdot E.$$

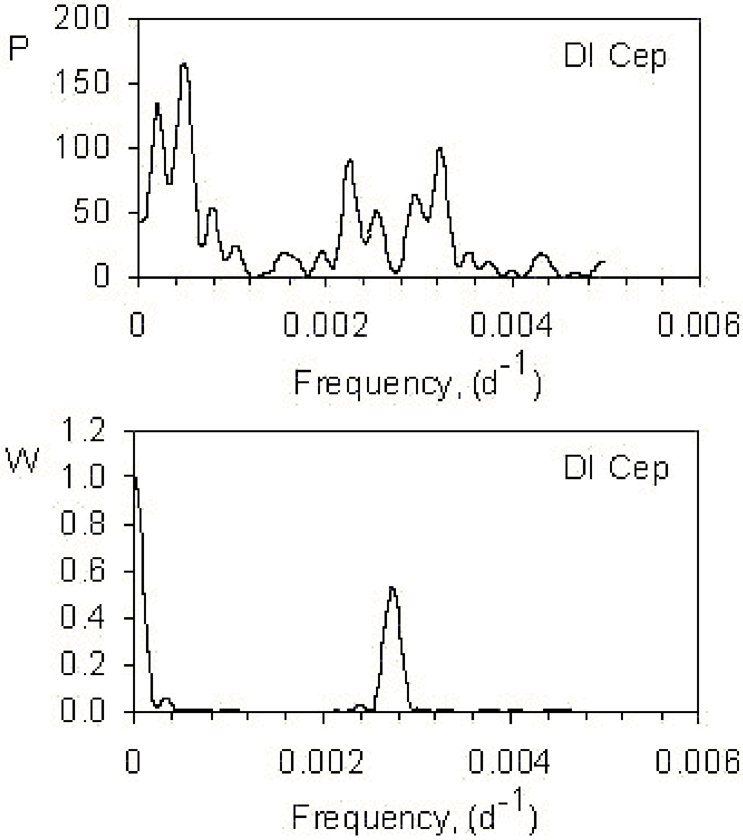

Figure 4. The power spectrum and spectral window from the Lomb–Scargle method.

Figure 5 presents the phase diagrams for V magnitudes (bottom) and equivalent widths of the Hα and Hβ emission (top), plotted for the above elements. Only the CCD observations of equivalent widths obtained by Gameiro and Ismailov are shown. These observations have a good accuracy and were made more frequently, which is important for searches of a long-term period.

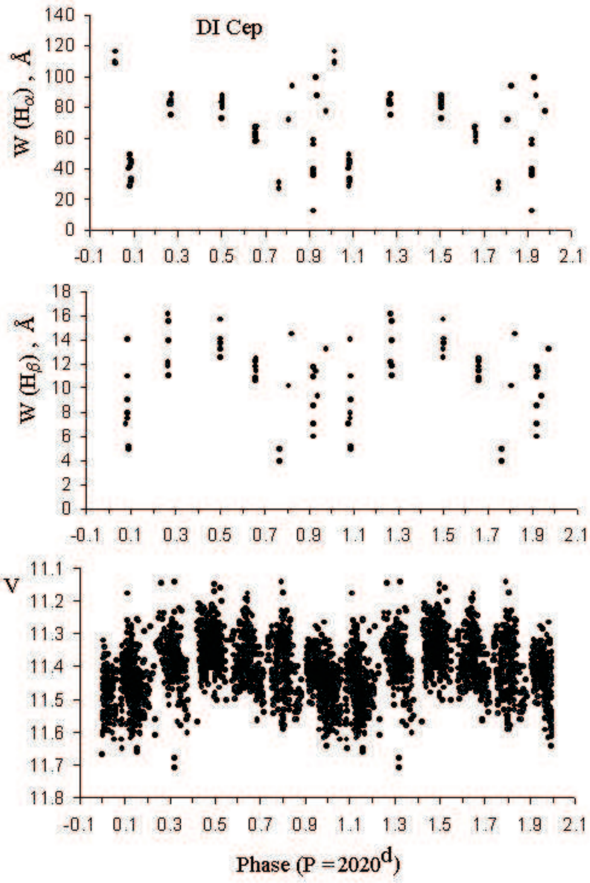

Figure 5. The phase diagrams for V magnitudes (bottom) and equivalent widths of the Hα and Hβ emissions (top), folded with the 2020-day period.

It appears from Fig. 5 that the variations of brightness and of the emission spectrum are correlated.

CONCLUSIONS

Our many-year observations of the CTTS DI Cep show that the star's visual brightness correlates with equivalent widths of emission lines. The variations of the mean brightness and spectrum are probably related to the same activity mechanism.

Photometric observations within a year do not reveal V-band brightness changes in excess of $0\overset{m}{.}3$, and the total amplitude of brightness variations during 30 years is $0\overset{m}{.}6$. The mean equivalent widths of emission lines decreased more than twofold in 35 years. These amplitudes correspond to maximal changes of flux with respect to its value at minimum by a factor of 1.32 and 1.74, respectively. Brightness variations within $0\overset{m}{.}3$ during individual observing seasons are quite characteristic of many T Tauri stars (see, for example, Petrov et al., 1999). It is possible to explain such variability range within several days by spotted structure causing modulations of brightness and spectrum due to axial rotation. Variations of brightness and spectrum with the period $9\overset{d}{.}24$ were found for DI Cep by Ismailov (2004) and by Kolotilov et al. (2004).

Long-term variations of the mean brightness have a completely different character, they cannot be explained in the model of spotted surface. The reasons for such long-term periodic variations can be (1) the existence of an invisible companion of the star, like a protostar or massive protoplanets, or (2) a long-term cyclic activity on the surface, similar to the 11-year cycle of the solar activity. In our opinion, the first option is more probable, taking into account that many T Tauri stars, including T Tau itself, have infrared components (Dyck et al., 1982; Koresko, 2000). It is interesting that a long period quite close to that of DI Cep was recently found for T Tau (Ismailov and Samus, 2003; Mel'nikov and Grankin, 2005). Gameiro et al. (2006), Ismailov and Grankin (2007) suspected variability of the center-of-mass radial velocity of DI Cep, also favoring binarity of DI Cep.

Ismailov and Grankin (2007) present observational evidence for magnetosphere accretion model of DI Cep. If such a reliable mass source as a stellar companion is present in the system, with an extended gas and dust disk, then many difficulties connected with magnetic fields in accretion-disk models are removed. Note that many TTSs do not show strong magnetic fields, while the accretion disk theory demands the presence of a magnetic field at the level of 1 kGs or more (Johns-Krull et al., 1999). It is possible that many CTTSs have a structure similar to DI Cep.

Let us summarize the main conclusions of this study.

1. The level of activity revealed by the emission spectrum depends on brightness of DI Cep: the brighter the star, the larger are equivalent widths of emission lines.

2. Currently the star is at the lowest activity level of the spectrum and near its absolute brightness minimum. 30 years of spectroscopy and photometry testify to slow fading of the star since 1990 till present.

3. Possible quasi-cyclic brightness variations with a period of 2020 days are observed, indicating the existence of a companion near the young star DI Cep.

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References:

Bastian, U., Mundt, R., 1979, *Astron. & Astrophys.*, **78**, 181

Dyck, H.M., Simon, T., Zuckerman, B., 1982, *Astrophys. J.*, **255**, L103

Gahm, G.P., Petrov, P.P., 1983, *Activity in Red-Dwarf Stars*, J. Reidel Publ. Comp., p. 497

Gameiro, J.F., Folha, D.F.M., Petrov, P.P., 2006, *Astron. & Astrophys.*, **445**, 323

Gómez de Castro, A.I., Fernández, M., 1996, *MNRAS*, **283**, 55

Grankin, K.N., Melnikov, S.Yu., Bouvier, J., et al., 2007, *Astron. & Astrophys.*, **461**, 183

Grinin, V.P., Efimov, J.S., Krasnobabtsev, V.I., et al., 1980, *Peremennye Zvezdy*, **21**, 247

Hamann, F., Persson, S.E., 1992, *Astrophys. J. Suppl.*, **82**, 247

Herbst, W., 1986, *Publ. Astron. Soc. Pacific*, **98**, 1088

Hessman, F.V., Guenther, E.W., 1997, *Astron. & Astrophys.*, **321**, 497

Holtzman, J.A., Herbst, W., Booth, J., 1986, *Astron. J.*, **92**, 1387

Horne, J.H., Baliunas, S.L., 1986, *Astrophys. J.*, **302**, 757

Horne, K., Wade, R.A., Szkody, P., 1986, *MNRAS*, **219**, 791
Ismailov, N.Z., 1987, *Peremennye Zvezdy*, **22**, 489
Ismailov, N.Z., 1988, *Peremennye Zvezdy*, **22**, 892
Ismailov, N.Z., 1997, *IBVS*, No. 4470
Ismailov, N.Z., 2004, *Astron. Reports*, **48**, 393
Ismailov, N.Z., 2005, *Astron. Reports*, **49**, 309
Ismailov, N.Z., Grankin, K.N., 2007, *Astron. Letters*, **33**, 113
Ismailov, N.Z., Samus, N.N., 2003, *IBVS*, No. 5382
Johns-Krull, C.M., Valenti, J.A., Koresko, C., 1999, *Astrophys. J.*, **516**, 900
Kardopolov, V.I., Filip'ev, G.K., 1985, *Peremennye Zvezdy*, **22**, 103
Keleman, J., 1985, *IBVS*, No. 2744
Kolotilov E.A., Metlov V.G., Metlova N.V., Petrov P.P., 2004, *Astron. & Astrophys. Transact.*, **23**, 185
Koresko, C.D., 2000, *Astrophys. J.*, **531**, L147
Krasnobabtsev, V.I., 1982, *Bull. Crimean Astrophys. Observ.*, **65**, 91
Lomb, N.R., 1976, *Astrophys. & Space Sci.*, **39**, 447
Mel'nikov, S.Yu., Grankin, K.N., 2005, *Astron. Letters*, **31**, 109
Nemec, A.F.L., Nemec, J.M., 1985, *Astron. J.*, **90**, 2317
Petrov, P.P., Zajtseva, G.V., Efimov, Yu.S., et al., 1999, *Astron. & Astrophys.*, **341**, 553
Press, W.H., Rybicki, G.B., 1989, *Astrophys. J.*, **338**, 277
Scargle, J.D., 1982, *Astrophys.J.*, **263**, 835