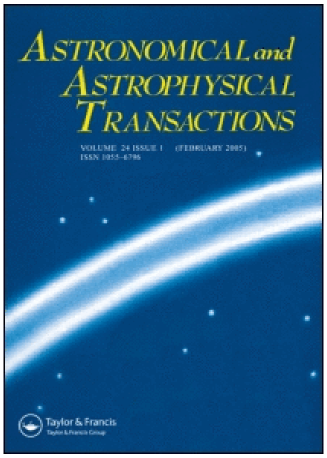

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PHOTOMETRIC VARIABILITY OF THE YOUNG STAR DI CEP

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We analyse our new and our previously published optical photometric data on DI Cep, a classical T Tau star. We study the variability of optical brightness with different temporal and amplitude characteristics. On a long-term scale, DI Cep shows 14–19 year cycles of variations with a magnitude of amplitude from 0.1 to 0.5 in different cycles. We also found a period of 9.185 days in the variations in the U-V colour. Probably, this period is connected with the rotation of a hot spot on DI Cep.

Keywords: Stars pre-main sequence; DI Cep; Optical variability

1 INTRODUCTION

DI Cep is a classical T Tau star of spectral type G8IV. Grinin *et al*. (1980) presented the results of extensive optical spectral, photometric and polarization observations during the joint programme on the investigations of young stars. Fernandez and Eiroa (1996) suggested a period of about 11 days from optical photometry. de Castro and Fernandez (1996) studied the ultraviolet (UV) spectrum of DI Cep, obtained with the International Ultraviolet Explorer. They also suggested that $P \approx 11$ days in the light curves of the UV continuum.

The purpose of our investigation was to study the optical variability of DI Cep from all the available photometric data including our new data.

2 PHOTOMETRIC OBSERVATIONS

Photometric observations of DI Cep were carried out at the 60 cm reflector of the Crimean laboratory of the Sternberg Astronomical Institute, with the photoelectric-pulse-counting photometer (Lyuty, 1971). The entrance diaphragm of 27″ was used in most cases. Altogether, 259 estimations of brightness were made in 184 nights in the periods 1980–1991 and 1996–2001.

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In addition, fast photometry in the *U* passband was carried out for several hours on three nights in September 1999 (895 exposures of 10 s).

The reference star c described by Rossiger (1984) was used. Observations of another reference star q (Gahm *et al.*, 1977) for 58 nights proved the constancy of star c. The accuracy of our photometry is of magnitude 0.01–0.02 in the *B* and *V* passbands, and 0.03 in the *U* passband. The results of our photometric observations of DI Cep are presented in Table I.

TABLE I *UBV* photometry of DI Cep (JD, Julian date).

JD24+	*V*	*B*	*U*	*JD24+*	*V*	*B*	*U*
44,538.187	11.44	12.34	–	46,682.363	11.35	12.15	11.76
44,539.190	11.48	12.39	12.27	46,685.481	11.38	12.21	11.97
44,541.195	11.49	12.37	12.32	46,703.391	11.44	12.24	12.03
45,327.153	11.56	12.52	12.58	46,769.229	11.41	12.27	12.18
45,328.151	11.61	12.61	12.69	47,000.506	11.42	12.28	12.04
45,552.473	11.57	12.47	12.47	47,003.494	11.47	12.28	12.11
45,562.530	11.52	12.40	12.26	47,004.471	11.44	12.28	11.99
45,566.500	11.51	12.41	12.32	47,013.391	11.45	12.35	12.03
45,567.521	11.47	12.32	12.16	47,032.411	11.55	12.40	12.60
45,579.488	11.49	12.38	12.23	47,033.410	11.53	12.42	12.38
45,581.427	11.58	12.49	12.43	47,034.407	11.47	12.34	12.13
45,582.496	11.48	12.34	12.16	47,036.302	11.48	12.36	12.14
45,608.475	11.51	12.39	12.38	47,043.421	11.44	12.30	12.00
45,615.464	11.47	12.39	12.28	47,057.322	11.49	12.40	12.26
45,617.400	11.44	12.31	12.12	47,124.200	11.48	12.38	12.32
45,619.410	11.52	12.41	12.32	47,127.170	11.49	12.33	12.15
45,622.340	11.53	12.39	12.34	47,183.269	11.54	12.41	12.26
45,624.253	11.53	12.34	12.43	47,184.262	11.46	12.24	12.06
45,634.251	11.56	12.44	12.31	47,185.222	11.40	12.33	12.22
45,642.353	11.60	12.51	12.43	47,360.413	11.53	12.43	12.45
45,657.255	11.50	–	–	47,417.427	11.52	12.42	12.44
45,659.260	11.55	12.50	12.56	47,418.386	11.44	12.27	12.11
45,750.285	11.57	12.51	12.54	47,419.381	11.46	12.31	12.09
45,913.445	11.49	12.39	12.24	47,477.372	11.55	12.47	12.54
45,918.425	11.48	12.45	12.40	47,855.228	11.36	12.24	12.16
45,942.455	11.50	12.44	12.47	47,918.178	11.44	12.32	12.29
46,035.253	11.50	12.41	12.50	48,089.359	11.30	12.14	12.04
46,344.286	11.56	12.43	12.34	48,095.475	11.30	12.18	12.10
46,388.237	11.52	12.41	12.41	48,104.478	11.33	12.20	12.01
46,400.254	11.51	12.40	12.36	48,111.495	11.36	12.24	12.15
46,406.208	11.54	12.43	12.55	48,113.503	11.35	12.20	12.10
46,467.185	11.38	12.21	12.07	48,114.342	11.36	12.24	12.15
46,618.471	11.29	12.02	11.55	48,115.466	11.35	12.25	12.19
46,619.465	11.44	12.26	11.98	48,150.430	11.30	12.15	11.95
46,625.437	11.46	12.35	12.21	48,158.438	11.29	12.13	11.96
46,643.500	11.36	12.14	11.84	48,159.473	11.26	12.09	11.85
46,644.513	11.43	12.23	12.02	48,164.280	11.25	12.08	11.87
46,671.427	11.39	12.21	11.94	48,169.363	11.24	12.08	11.86
46,677.473	11.47	12.37	12.27	48,172.392	11.49	–	–
46,679.411	11.45	12.32	12.20	48,173.383	11.36	12.18	11.96
48,196.204	11.33	12.14	12.04	50,365.4129	11.326	12.153	11.796

(*continued*)

TABLE I Continued.

JD24+	*V*	*B*	*U*	*JD24+*	*V*	*B*	*U*
48,217.229	11.27	12.08	11.82	50,366.4205	11.283	12.091	11.820
48,219.220	11.28	12.10	11.89	50,366.4275	11.292	12.101	11.871
48,229.419	11.34	12.20	12.13	50,372.3799	11.447	12.333	12.324
48,272.244	11.41	12.30	12.21	50,372.3876	11.437	12.340	12.299
48,276.180	11.32	12.15	11.91	50,372.3945	11.447	12.338	12.318
48,294.188	11.32	12.18	12.03	50,373.4660	11.405	12.250	12.033
48,410.410	11.27	12.10	11.74	50,373.4733	11.393	12.241	12.036
48,411.453	11.36	12.02	12.10	50,373.4806	11.389	12.244	12.042
48,510.475	11.27	12.10	11.86	50,393.2917	11.250	12.049	11.766
48,512.485	11.44	12.32	12.24	50,393.2983	11.254	12.053	11.724
48,542.215	11.36	12.19	12.14	50,395.2927	11.379	12.225	12.030
48,566.163	11.36	12.23	12.08	50,395.2993	11.365	12.217	12.024
50,269.4716	11.461	12.377	12.410	50,400.3808	11.361	12.210	11.970
50,269.4813	11.436	12.341	12.408	50,400.3874	11.360	12.219	12.007
50,272.4919	11.339	12.195	12.082	50,401.2332	11.420	12.286	12.190
50,273.4680	11.403	12.295	12.289	50,402.3957	11.302	12.130	11.798
50,273.4770	11.406	12.296	12.157	50,402.4013	11.305	12.120	11.784
50,273.4857	11.407	12.300	12.267	50,403.3068	11.413	12.272	12.219
50,275.4962	11.399	12.270	12.130	50,403.3138	11.410	12.272	12.188
50,279.4936	11.330	12.180	11.861	50,404.3894	11.385	12.227	11.977
50,293.4625	11.217	12.038	11.658	50,404.3974	11.386	12.232	11.980
50,324.3164	11.431	12.392	12.540	50,405.3168	11.409	12.265	12.132
50,324.3255	11.429	12.369	12.585	50,478.3253	11.384	12.197	11.969
50,324.3328	11.425	12.390	12.416	50,478.3329	11.376	12.195	11.973
50,325.3508	11.421	12.357	12.255	50,504.2003	11.308	12.112	11.865
50,325.3585	11.433	12.315	12.280	50,504.2083	11.326	12.137	11.844
50,326.3273	11.376	12.243	12.155	50,521.2167	11.384	12.244	12.161
50,326.3349	11.373	12.279	12.230	50,521.2264	11.393	12.279	12.267
50,344.4465	11.302	12.119	11.886	50,695.3232	11.347	12.162	12.000
50,344.4528	11.316	12.134	11.895	50,695.3298	11.354	12.160	12.010
50,361.3670	11.386	12.243	12.087	50,696.4784	11.355	12.306	12.154
50,361.3726	11.384	12.243	12.096	50,696.5031	11.414	12.293	12.300
50,362.3844	11.343	12.192	11.988	50,697.4149	12.296	12.096	11.975
50,362.3907	11.348	12.197	11.993	50,697.4212	11.296	12.100	11.978
50,363.4855	11.335	12.181	12.026	50,699.4757	11.373	12.187	11.934
50,363.4917	11.350	12.185	12.009	50,699.4823	11.359	12.184	11.935
50,364.3810	11.352	12.190	11.985	50,704.3631	11.400	12.263	12.235
50,364.3882	11.349	12.182	11.981	50,704.3693	11.385	12.266	12.235
50,365.4070	11.330	12.156	11.842	50,705.3034	11.330	12.200	12.136
50,705.3100	11.397	12.232	12.160	51,124.2544	11.469	12.353	12.436
50,745.5510	11.371	12.219	12.149	51,141.3246	11.390	12.242	12.089
50,745.5583	11.395	12.239	12.212	51,152.3040	11.423	12.249	12.125
50,748.4037	11.330	12.143	11.892	51,152.3099	11.424	12.283	12.207
50,748.4093	11.338	12.140	11.862	51,161.2856	11.441	12.329	12.372
50,753.5148	11.328	12.148	12.015	51,163.2015	11.329	12.117	11.799
50,753.5217	11.326	12.150	11.999	51,164.4278	11.361	12.159	12.050
50,755.3113	11.424	12.252	12.176	51,176.1860	11.432	12.292	12.251
50,755.3165	11.427	12.260	12.205	51,176.1919	11.423	12.252	12.157
50,758.3001	11.385	12.235	12.071	51,180.1796	11.448	12.292	12.268
50,758.3064	11.385	12.241	12.065	51,180.1862	11.436	12.276	12.282

(*continued*)

TABLE I Continued.

JD24+	*V*	*B*	*U*	*JD24+*	*V*	*B*	*U*
50,759.4807	11.403	12.262	12.187	51,199.1913	11.408	12.271	12.291
50,759.4869	11.421	12.261	12.186	51,227.2045	11.403	12.236	12.172
50,760.2220	11.341	12.171	12.011	51,227.2111	11.382	12.220	12.141
50,760.2272	11.354	12.188	12.029	51,420.4825	11.290	12.097	11.731
50,761.2959	11.289	12.109	11.872	51,420.4891	11.264	12.072	11.729
50,761.3015	11.280	12.111	11.873	51,432.4498	11.426	12.266	12.156
50,762.2223	11.333	12.179	11.979	51,432.4679	11.439	12.319	12.175
50,762.2289	11.324	12.179	11.967	51,432.4742	11.421	12.285	12.179
50,793.3239	11.361	12.155	11.916	51,433.3693	11.429	12.296	12.264
50,793.3309	11.324	12.184	11.892	51,433.4138	11.425	12.300	12.247
50,933.4764	11.381	12.172	11.979	51,434.4673	11.444	12.341	12.345
50,942.3999	11.310	12.135	11.976	51,438.4097	11.413	12.244	12.053
50,942.4069	11.329	12.095	12.007	51,438.4166	11.409	12.250	12.063
50,942.4138	11.338	12.158	11.998	51,438.4951	11.405	12.258	12.096
50,942.4204	11.321	12.147	11.979	51,439.4278	11.406	12.270	12.095
50,942.4270	11.365	12.146	11.912	51,445.3084	11.424	12.299	12.358
50,942.4340	11.339	12.154	11.878	51,445.3150	11.422	12.296	12.322
50,942.4409	11.336	12.191	11.930	51,485.2343	11.315	12.131	11.835
51,103.4547	11.353	12.158	11.997	51,488.2387	11.461	12.315	12.231
51,104.5121	11.495	12.373	12.405	51,488.2453	11.453	12.317	12.243
51,105.4476	11.485	12.367	12.389	51,491.3542	11.414	12.273	12.077
51,105.4545	11.483	12.375	12.384	51,491.3612	11.408	12.263	12.108
51,109.4088	11.433	12.271	12.159	51,492.2122	11.414	12.262	12.147
51,110.4730	11.451	12.323	12.279	51,492.2184	11.421	12.263	12.161
51,111.4743	11.433	12.339	12.439	51,492.2250	11.423	12.266	12.180
51,112.4052	11.451	12.347	12.440	51,492.2455	11.426	12.270	12.202
51,121.4124	11.382	12.256	12.097	51,492.2521	11.435	12.281	12.205
51,121.4193	11.405	12.217	11.990	51,499.2998	11.448	12.303	12.183
51,124.2481	11.460	12.364	12.431	51,502.2685	11.333	12.124	12.874
51,502.2747	11.318	12.117	11.877	51,831.4226	11.438	12.345	12.656
51,502.2813	11.329	12.115	11.873	51,832.2306	11.414	12.289	12.406
51,549.1907	11.397	12.225	11.988	51,842.2343	11.420	12.290	12.225
51,549.1977	11.413	12.219	12.058	51,842.2475	11.429	12.282	12.218
51,770.4853	11.358	12.229	12.185	51,842.2545	11.424	12.286	12.273
51,819.3219	11.353	12.186	11.994	51,843.3610	11.371	12.207	12.073
51,820.4705	11.339	12.160	11.991	51,927.1755	11.319	12.162	12.095
51,821.3205	11.411	12.276	12.215	52,201.3775	11.339	12.166	12.012
51,822.5125	11.439	12.310	12.342	52,201.3937	11.311	12.155	11.968
51,823.3476	11.447	12.308	12.162				

In addition to our photometric observation, we use in this paper a large number of observations collected by other observers. 545 observations were taken from the database compiled by Herbst *et al.* (1994) and from publications by Fernandez (1995), Gahm *et al.* (1977, 1993), Grinin *et al.* (1980), Gullbring and Gahm (1996), Ismailov (1988), Kardapolov and Filip'ev (1985) and Kelemen (1985). 655 photographic observations were taken from Kholopov (1953) and Rossiger (1984). S. Yu. Shugarov kindly provided us with 25 estimations of brightness from the collection of the photographic plates of Moscow State University (Table II).

Therefore, this research is based on the maximal number of observations of DI Cep available at the moment. This includes 814 photoelectric observations (mostly *U*, *B* and *V* magnitudes,

TABLE II Photographic magnitudes of DI Cep in the period when no other photometric data are available.

JD24+	m_{pg}	*JD24+*	m_{pg}
34,223.441	12.30	34,678.265	12.55
34,224.370	12.30	34,681.241	12.24
34,229.393	12.33	34,681.292	12.21
34,239.408	12.37	35,343.476	12.43
34,250.376	12.43	35,347.482	12.53
34,329.184	12.70	35,362.429	12.73
34,329.249	12.50	35,363.469	12.55
34,330.211	12.40	35,365.444	12.28
34,331.244	12.50	35,366.468	12.51
34,477.464	12.37	35,394.395	12.36
34,608.375	12.36	35,724.362	12.20
34,610.438	12.37	36,084.493	12.02
34,628.377	12.27		

but sometimes only B and V or only V) and 691 photographic observations m_{pg}. The m_{pg} magnitudes are close to the B magnitudes; therefore we used them altogether for analysis of the long-term variations. The photoelectric observations cover the time interval 1974–2001, and the photographic observations expand this interval back to 1895.

In this paper we analyse the photometric variability of DI Cep on three different time scales: firstly, long-term variations on a time scale from 1 month to 10,000 days; secondly, variations on a time scale from 1 day to 1 month; thirdly, fast variations on a time scale from seconds to hours.

3 THE HISTORICAL LIGHT CURVE

The full light curve, composed of 1501 observations, is shown in Figure 1. In this format, not all the individual points can be resolved. In the period 1974–1983, when both B and m_{pg} magnitudes were measured, the photographic and the photoelectric light curves fit reasonably

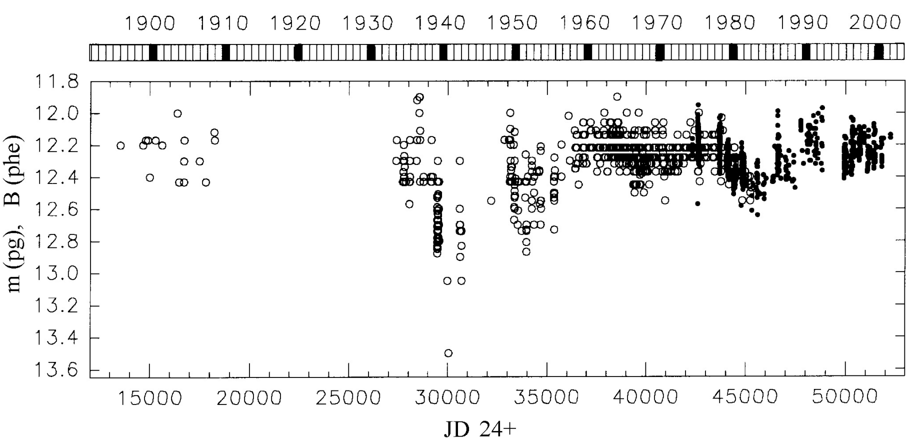

FIGURE 1 Historical light curve of DI Cep: ○, photographic m_{pg} magnitudes; ●, photoelectric B magnitudes.

well. In the seasons with a large number of observations, the fast variations smear the light curve in a broad strip. Nevertheless, the slow variations in brightness on a time scale of 5000–7000 days can be easily seen. It can be described as wave-like fadings of brightness of different durations and amplitudes, measured from the maximal level of magnitude about $B = 12$. There is no secular change in the maximal level of brightness; at the end of the nineteenth century it was about the same as during the twentieth century and at the beginning of the twenty first century.

There are four waves of brightness on the historical light curve. The first, with the largest amplitude, took place in JD 2,428,000–2,433,000, with the deepest minimum of magnitude $m_{pg} = 13.5$ at 2,430,026. The second wave of somewhat lower amplitude can be seen around JD 2,435,000. The third wave, around JD 2,440,000, had lower amplitude and shorter duration. The fourth wave, within JD 2,443,000–2,449,000, has been already observed photoelectrically. It is well covered by 814 observations for more than 20 years. Therefore, we may conclude that DI Cep shows 14–19 year cycles of brightness variations, with an amplitude of magnitude from 0.1 to 0.5 in different cycles.

4 SEARCH FOR ROTATIONAL MODULATION IN BRIGHTNESS AND COLOURS

Krasnobabtsev (1982) reported a probable rotational period of 16 days, as derived from spectral variations. However, Gahm *et al.* (1993) cou1d not find the period from their photometric monitoring programme in 1982–1983 and 1989. Later, de Castro and Fernandez (1996) reported a probable rotational period of 11 days and suggested the presence of a hot spot on DI Cep.

In our photometric data set, the largest amplitude is in the U passband. The relative range of variabilities in different passbands can be characterized by the magnitudes of the standard deviations (SDs) from the mean level: $\mathrm{SD}(U) = 0.206$; $\mathrm{SD}(B) = 0.110$; $\mathrm{SD}(V) = 0.084$; $\mathrm{SD}(U - B) = 0.127$; $\mathrm{SD}(B - V) = 0.050$. In principle, the variability can be caused by a circumstellar extinction, or by cool spots, or by hot spots. The ratio of amplitudes can be used to distinguish between these possibilities (Herbst *et al.*, 1994). From our data, the amplitude ratio $\mathrm{SD}(U - B)/\mathrm{SD}(B - V) = 2.54$ indicates that the hot spot hypothesis is the most plausible.

A hot spot on a T Tau star exists for not longer than a few rotations of the star (Vrba *et al.*, 1993); therefore we start with the search for rotational modulation in different seasons, using the most densely and evenly covered time intervals. In some seasons, small groups of points, which deviate in time from the main group, were excluded from analysis. The groups of data selected for the analysis are presented in Figure 2 and labelled with numbers from 1 to 16. There are in total 720 photoelectric observations in the selected groups.

The typical time interval between the individual observations is 1–3 days, and the typical length of one season of observations is 100–200 days. In the search for the periodicity we used the methods described by Lafler and Kinman (1965), Deeming (1975) and Stellingwerf (1978). Periodograms were calculated individually for each season of observations. For a few seasons, the periodograms show the probable periods, for example 9.5 days in group 1, 9.2 days in group 12, 4.5 days in group 13, 6.2 days in group 14, and 5.3 and 9.2 days in group 15. When the whole data set is used, no significant periodicity is seen in the variations in the U, B, and V magnitudes.

In a recent study of the photometric periodicity in RW Aur A, Petrov *et al.* (2001) found a significant period in the $U - V$ and $B - V$ colours, although the U, B and V magnitudes did not show any periodicity. We also searched for periodicity in the colours of DI Cep and found a period close to 9.2 days in the variations in the $U - V$ colour. The period is seen in the whole data set (673 observations in $U - V$), and in some of the individual groups of data (groups

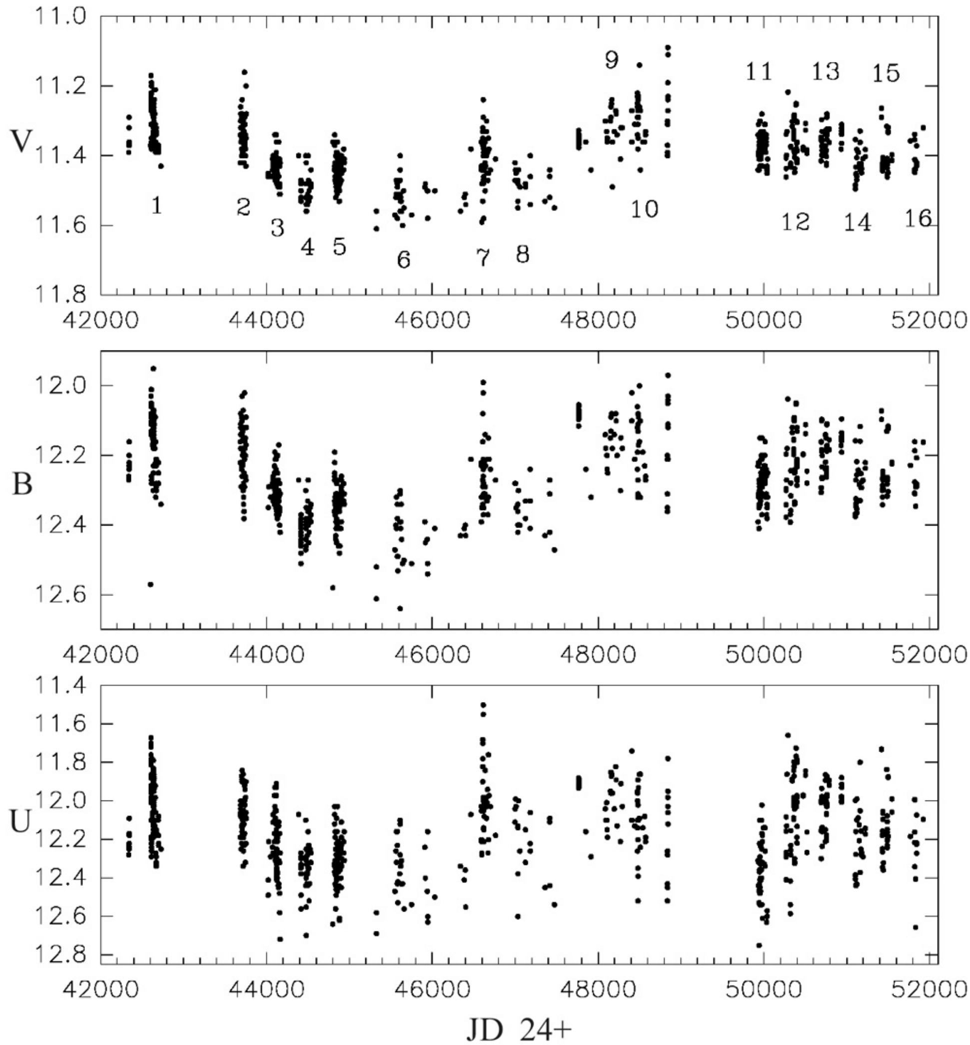

FIGURE 2 All the available photoelectric observations of DI Cep. The numbers indicate groups (seasons) of observations used for the frequency analysis (see text).

1, 3, 4, 11, 12 and 15). When the long-time-scale wave-like variations are removed, the result is about the same; therefore in the subsequent analysis we use the observed $U - V$ colours. Although the period is present in the whole set of data, not all the seasons contribute to the periodicity. For example, group 7, which contains 38 observations covering 110 days, does not reveal any period at all.

Figure 3 shows the periodogram for all the observed $U - V$ colours, for the range of frequencies 0.020–0.500 cycles day (periods from 50 to 2 days). The strongest peak corresponding to the period $P = 9.1849 \pm 0.0030$ days is labelled. The peak shows two close aliases on each side, caused by the annually spaced observational seasons. The next strong peak is at $2P$, and another group of peaks is around 30–35 days, which may be caused by the monthly spaced groups of data within a season.

The statistical significance of the main peak at $P = 9.1849$ days was estimated using Fisher's method of randomization (Nemec and Nemec, 1985). For the observed $U - V$ colours, the moments of observations were shuffled randomly, and a search for periodicity was made.

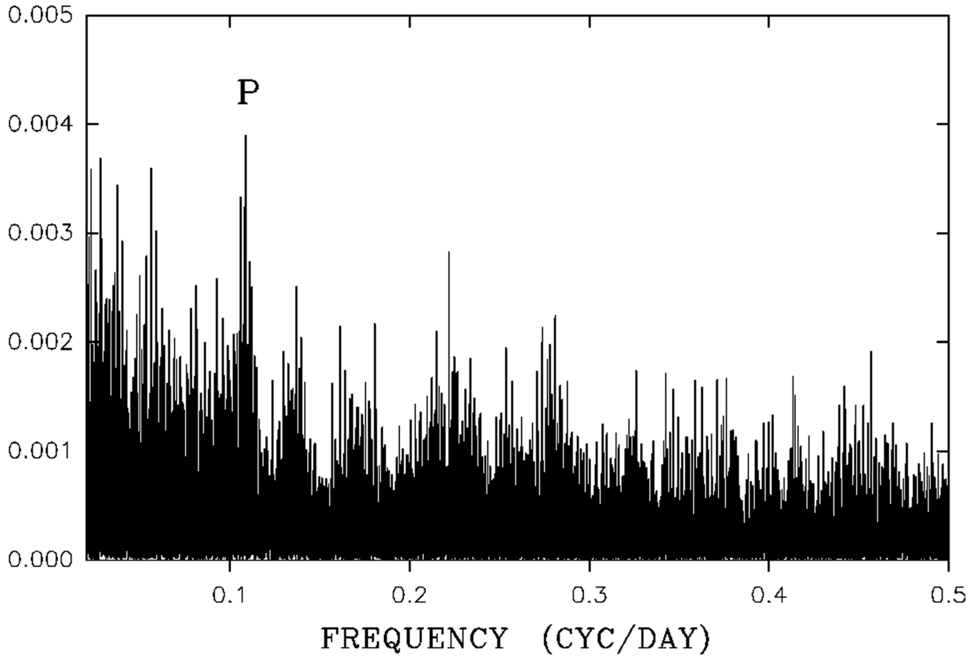

FIGURE 3 Periodogram for the whole set of the photoelectric observations for the $U - V$ colour. The square of the semi-amplitude of the harmonic signal is given along the Y axis. The peak labelled P corresponds to a period of 9.2 days.

Such a procedure was repeated many times in order to see how often peaks stronger than the peak observed at $1/P$ can appear at any frequency within a certain interval of frequencies. In our test, 2300 repetitions were made for an interval 1.2–50 days (16,000 discrete frequencies). As a result, four peaks stronger than the observed peak were found within the full interval of frequencies. We may conclude that the false alarm probability for the period P is about 0.2%.

In Figure 4, all the observed $U - V$ colours are convolved with the period P. The phase diagram can be approximated by a sinusoid with a semi-amplitude of magnitude 0.063. When the mean level of the colour within each season is subtracted from the observed colours, the semi-amplitude is of magnitude 0.11. The same convolutions for several individual groups of data are shown in Figure 5.

Hence, we conclude that the period $P = 9.185$ days was persistent over a long time interval (30 years) and might be relevant to the rotation of the star. However, some of the seasons do not

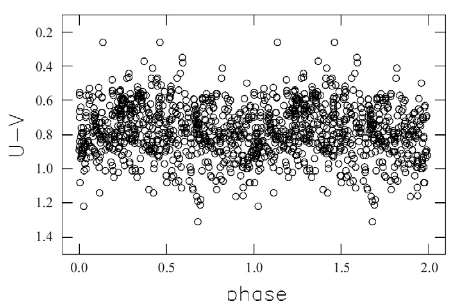

FIGURE 4 Phase diagram for the $U - V$ colour, convolved with $P = 9.1849$ days.

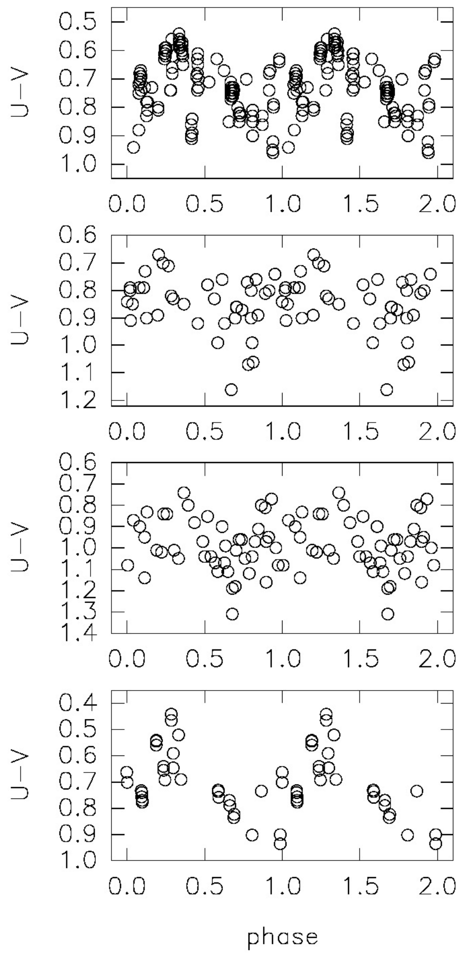

FIGURE 5 Phase diagrams for the $U - V$ colour, convolved with $P = 9.1849$ days for different groups of data. The diagrams from upper to lower are for groups 1, 4, 11 and 15 respectively.

reveal the periodicity, although the range of variabilities was large. Probably, flaring activity dominated in those seasons, thus hiding the less evident effect of a hot spot.

5 ON THE RAPID VARIABILITY OF DI CEP

Considerable brightness variations in DI Cep on the time scale of a day were noticed long ago. From the photographic plates, Kholopov (1953) found a change of 0.5 in the magnitude of the brightness of the star during 1 day. Later, from photoelectric *UBV* photometry, the brightness variations on a short time scale were reported, for example by Grinin *et al.* (1980) and Fernandez and Eiroa (1995). The variations were larger in the *U* passband and progressively smaller in the *B* and *V* passbands. The same kind of variability is also seen from our data (*e.g.* in JD 2,447,032–2,447,036 and JD 2,450,400–2,450,405).

The rapid variability during a night may be relevant to the accretion processes; in the case of non-stationary magnetic accretion, rapid variability may be seen at the phase when the hot accretion spot is towards the observer (Smith *et al.*, 1996); that is at the higher brightness of the star. de Castro and Fernandez (1996) have interpreted observations of DI Cep in terms of the magnetic accretion model with a hot spot. Very few special monitoring programmes of DI Cep have been earned out so far. Grinin *et al.* (1980) performed photometric monitoring of the star for several nights, 4–5 h every night. No considerable rapid variations were found, but in one night a flare in the U passband of magnitude 0.4 in 10 min was recorded.

In three nights of our observations the star was monitored in the U passband for a few hours with a time resolution of 10 s (Fig. 6). The star varied slowly within $U = 12.10–12.45$ from night to night, but no fast variations were detected at any level of brightness. However, the duration of our monitoring was not long enough to conclude that the fast variations were absent in that period.

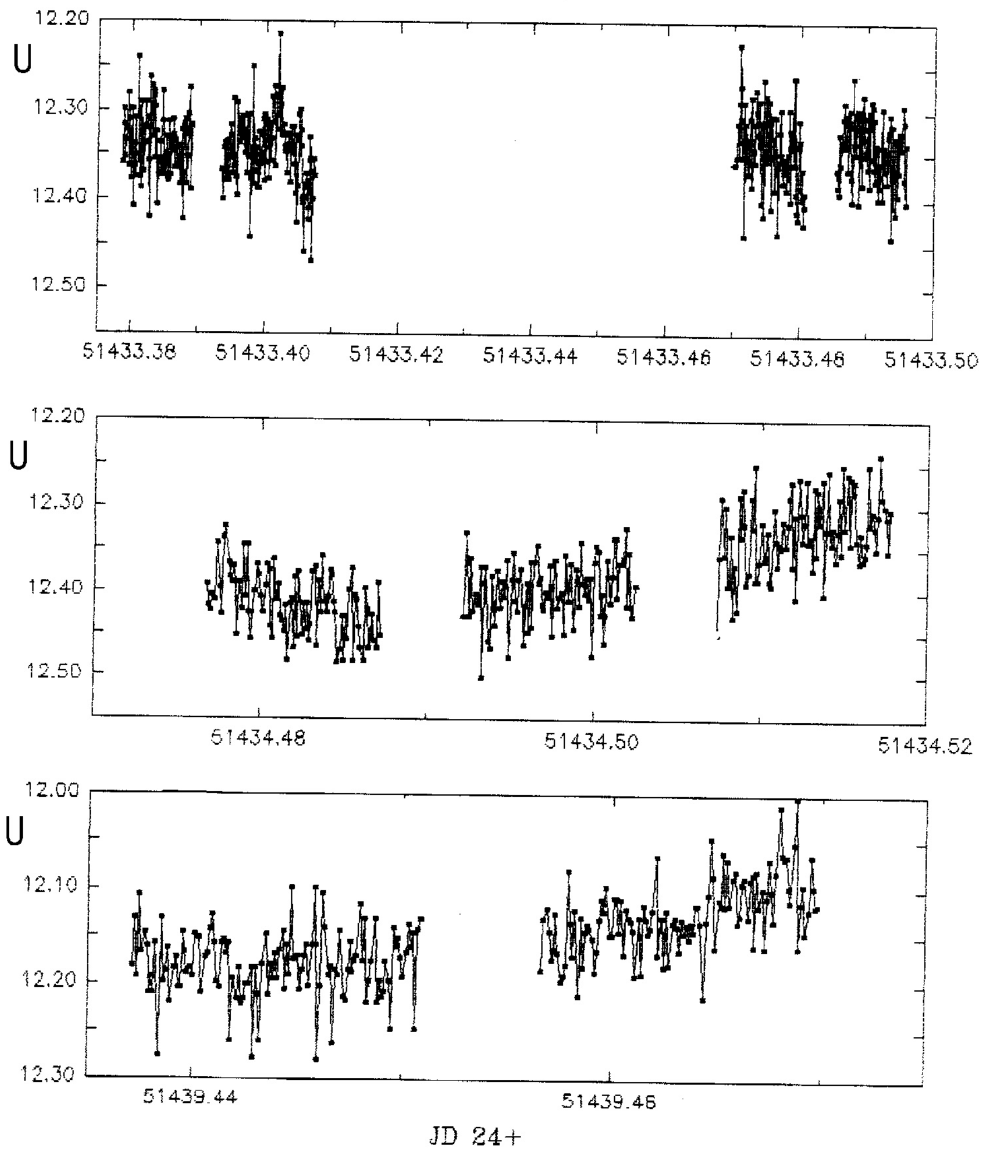

FIGURE 6 Photometric monitoring of DI Cep for three nights with a time resolution of 10 s.

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