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MULTICOLOR PHOTOMETRY OF NOVA LACERTAE 1910 = DI Lac IN 1962-2002

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We present an analysis of the behavior of nova DI Lac 52 years after the outburst and over the next 40 years. Similar to a dwarf nova, DI Lac demonstrates flare activity with a characteristic time of 36 days and an amplitude of about $0^m.6$. *A flare profile is asymmetrical, the rise in brightness lasting about five days and the fading lasting about twenty days. Shorter flares sometimes occur between the main ones. The flares can be divided into three types in accordance with their behavior on magnitude–color diagrams. The ascending and descending branches of flares of the first type practically coincide on the diagrams, the second type describe counterclockwise loops, and the third type describe clockwise loops. The first and second types of flares can be explained within the framework of the theory of thermal instability as arising first in the outer and inner parts of the accretion disk, respectively. The nature of flares of the third type is still unclear.*

Key words: *(stars:) novae – stars: individual: DI Lac*

1. Introduction

The nova DI Lacertae was discovered by Espin [1] in 1910. At the maximum it reached $4^m.3$ in the B band [2]. The amplitude of its outburst was relatively low, about 11^m. But its orbital period, according to Ritter [3] and Goranskii et al. [4], on the contrary, lies in the "long-period" tail of the distribution of cataclysmic variables by orbital periods (about 0.5 days). After several decades the star became interesting to investigators in that it was found to have short-period brightenings, with a characteristic time of 40 days, resembling the flares of dwarf novae but with a smaller amplitude than for dwarf novae, about $0^m.5$. This discovery was made independently by Honeycutt et al. [5, 6] and Shugarov and Lipatov [7]. Similar activity is also known for a small number of other novae in the post-outburst stage. For example, GK Per flares up about once in $n\times400$ days [8], Q Cyg does so about every 60 days [9], V841 Oph every 35 days, and V446 Her every 22 days [5]. The cycle length can be fairly stable for some time and then be disrupted. Flares with far lower amplitudes may also be observed during these cycles.

Such behavior of "aged" novae is predicted by the scenario of the evolution of classical novae between outbursts, which occur once in 10^4-10^5 years [10-13]. Recall that the nova phenomenon occurs in a close binary system consisting

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of a white dwarf and a secondary component of a late spectral type that has filled its Roche lobe and is losing matter to the white dwarf. In accordance with the scenario, the white dwarf undergoes a thermonuclear explosion, after which its surface remains hot for another hundred years. The hot (100,000 K) white dwarf heats the side of the secondary component facing it, which helps to maintain an increased rate of mass loss. After the white dwarf cools and ceases to heat the secondary component, the latter contracts somewhat, retreats inside its Roche lobe, and the mass loss by it decreases considerably (if it does not cease altogether). In Livio's expression [11], the nova enters a so-called "dormant" state. This stage of evolution may last thousands of years. Then gravitational radiation and/or magnetic braking results in filling of its Roche lobe by the secondary component and an increase in the rate of mass loss. An accretion disk is formed around the white dwarf and, if the conditions for thermal instability are created in it (the temperature of the outer parts of the disk are lower than the hydrogen ionization temperature) [14], such a disk will flare up cyclically, i.e., flares of the dwarf nova type will be observed. Schreiber et al. have shown that two factors are decisive here: the temperature of the white dwarf and the rate of mass transfer [15].

So it will continue until the pressure and temperature in the outer parts of the white dwarf, formed from the accreted matter enriched in hydrogen, reach the critical values and the next thermonuclear explosion sets in.

Detailed and extended observations of various classical novae decades after the explosion should show how good this scenario is. Experience shows that the number of old classical novae that have entered the "dwarf nova stage" is very small, but even they have been insufficiently studied. Up to now only GK Per [16] and V446 Her [6] have been studied very well.

In this paper we present a multiyear photometric investigation of the behavior of DI Lac from 1962 to 2002. The purpose of this work is a detailed study of the star's flare activity over the 40-year interval and profiles of the flares and their development on magnitude–color diagrams.

2. Observations

In various years of the 40-year interval of observations, as the light-receiving apparatus has been developed, the photometry of DI Lac has been done by various methods: photographic, photoelectric, and using a CCD camera in the *UBVRI* color bands, which are close to the system of Johnson and Morgan.

Information on the observations is given in Table 1, in the first column of which we give the time interval of the observations, in the second we give the telescope, then the number *N* of measurements for the given method of image recording, the color system, and finally, the light receiver.

A finder chart of the vicinity indicating the comparison stars is given in the catalog of Cherepashchuk et al. [17]. The photographic measurements were made relative to the comparison stars "a," "b," "c," "d," "e," and "z" in the vicinity of DI Lac in a band close to the *B* band. Simultaneous photoelectric observations in the *UBV* bands were made relative

TABLE 1

Date	Telescope	*N*	Color system	Detector
1962-1991	40-cm astrograph	134	*Phg*	ORWO ZU-2
1991-1995	Zeiss-600, Crimea	all	*UBV*	Phe
	AZT-2, 70-cm, Moscow	343×3	*UBV*	Phe
2001-2002	Zeiss-600, Crimea	all	*BVRI*	ST-7 CCD
	K-380, Crimea	443	*BVRI*	ST-8 CCD

to star “H,” while *BVRI* CCD observations were made relative to star “a.”

The exposure time depended on the telescope and the image receiver. A typical exposure in photographic observations was 4 5 min, for photoelectric ones 2 3 min, and for CCD observations 1 3 min. The measurement accuracy for the photoelectric observations was determined from the photon statistics and was $0^m.01$-$0^m.03$ in the *B* and *V* bands and $0^m.05$ in the *U* band. The accuracy in recording photographic images and images obtained on the CCD was determined from the difference between the control star and the comparison star and was $0^m.15$-$0^m.20$ (photography) and $0^m.01$-$0^m.04$ (CCD). We note that in the photoelectric observations the $U-B$ and $B-V$ color indices were determined simultaneously, and the tie-in to the comparison star was made once every several dozen minutes. The color indices in the CCD observations were calculated in successive measurements of the star in the *BVRI* bands with a minimum time difference of no more than 5 min. The comparison star was recorded simultaneously with the variable, since it fell inside the field of view of both the ST7 CCD on the Zeiss-600 telescope, which is (5′×4′) and inside the field of view of the ST8 CCD on the K-380 telescope (10′×8′). In the present work we give values of $U-B$ and $B-V$ reduced to the Johnson system and relative (with an arbitrary zero point) values of $V-R$ and $V-I$.

3. Flare Activity

All three light receivers make it possible for us to trace the star’s long-term behavior, over a 40-year interval in the *B* spectral band and over a 10-year interval in the *V* band. Based on photographic measurements, the brightness of DI Lac in 1962-1991 fluctuates from 15^m to $14^m.3$, on the average. In Fig. 1 we give six light curves for several years of observations from 1983 to 1989. Since the star was not photographed continuously, it is difficult to follow the evolution of flare activity over this time interval. In 1987 no significant brightenings were noted at all, but it is very likely that they occurred just in the gaps in observations.

In Fig. 2 we give the densest photoelectric runs of observations of the star in the *UBV* bands for 1991-1992. The maximum (averaging over a night!) brightness in the *B* band reached $14^m.5$ while the minimum reached $15^m.1$, which are comparable to the data of the photographic measurements. The star’s average brightness in the *B* band based on CCD measurements a decade later fluctuates in exactly the same range. In Fig. 3 we show light curves in the *B* and *V* bands and in the *R* and *I* bands (on a relative scale).

Thus, 52 years after the nova’s outburst, for the next 40 years DI Lac exhibited brightenings in the *B* band with an amplitude of about $0^m.6$ in a virtually constant range of from $15^m.1$ to $14^m.5$.

Some of the densest runs of observations of those given in Figs. 1 3 clearly show that the brightenings of DI Lac do not have a random character but look like flares. Most of the observations, however, pertain to fragments of different flares. To determine the characteristic time of the flares we used the longest runs of data in the *B* band, obtained by the photographic and photoelectric methods, and for each of them we constructed a Fourier periodogram in the range of periods of from 17 to 50 days. The results are given in Fig. 4. The periodograms show a set of frequencies, separated both by the annual on-off period and by the nonuniform time distribution of the data. The peak with the maximum significance based on the photoelectric observations corresponds to 36.2 days, which also coincides with a peak on the periodogram for photographic data (marked by a dotted line). This same result is close to the characteristic flare time for DI Lac (40 days) obtained by Honeycutt et al. [5] from CCD measurements in 1993. In Fig. 5 we give convolutions with this observation period for the photographic and photoelectric observations. In calculating the phases we took the same initial epoch, JD 2447798.4. Despite the large scatter of the points, the convolutions show that the characteristic time of the flares is fairly stable over several decades. Because the flares occur just with a characteristic time rather than a strict period, however, the phase curve cannot objectively reflect the shape of a flare profile.

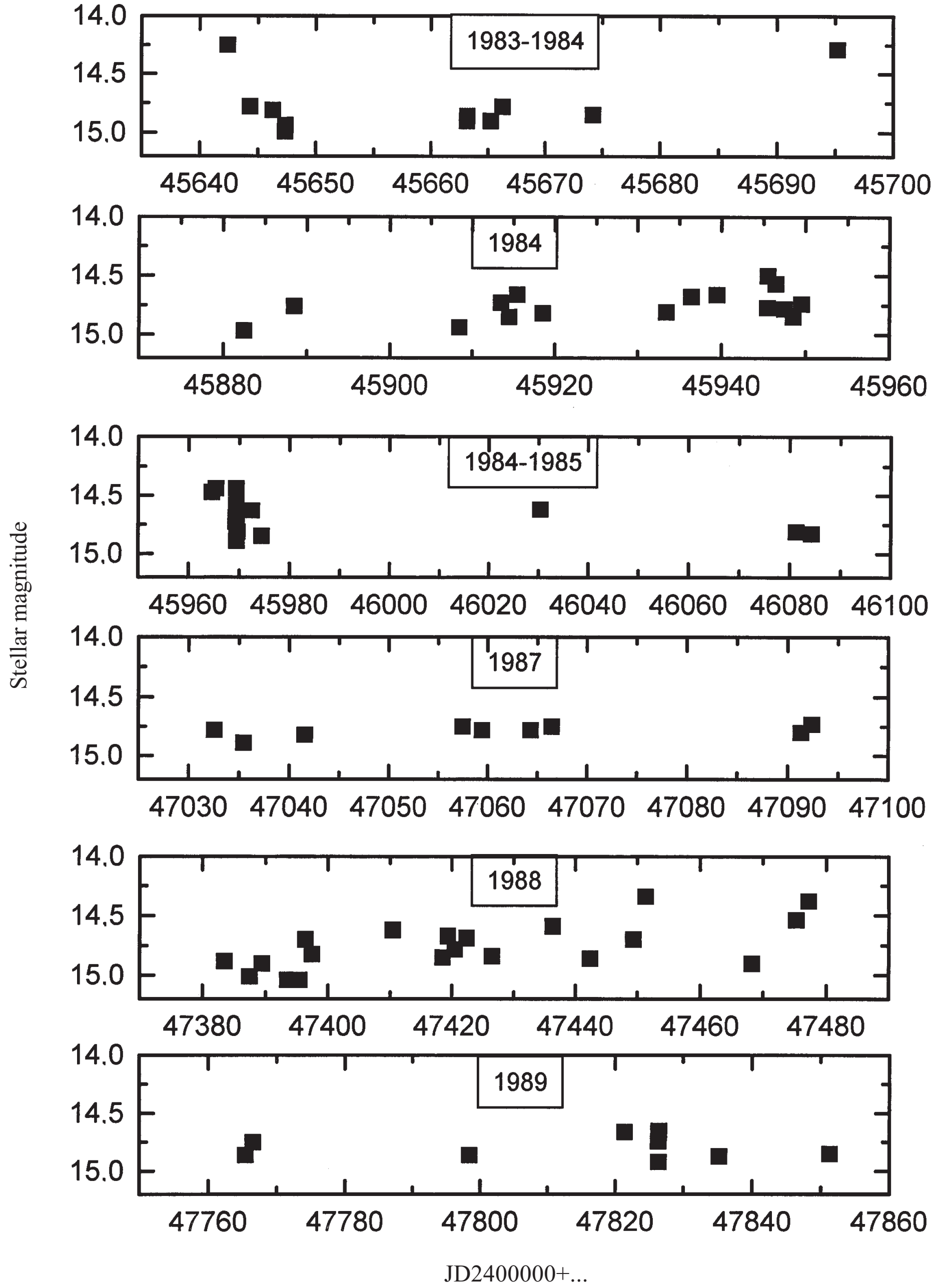

Fig. 1. Some light curves based on photographic measurements, reduced to the *B* band. Each point is the result of averaging several measurements during a night.

4. Flare Profile

To solve this problem we attempted to construct a "composite profile" of a flare from those observed in the most detail, by matching them along the time axis for best agreement. Composite profiles obtained in the *V* and *R* bands are shown in Fig. 6. It appears that the flare profile in both bands is asymmetrical on the average: the abrupt brightness increase lasts about five days and the fading lasts about twenty days. We can assume that the main flare is preceded by a shorter one lasting no more than ten days. Unfortunately, the available data are insufficient to describe it in detail. It is seen from the figure, however, that it decays fairly quickly, lasting only a few days, after which the main flare

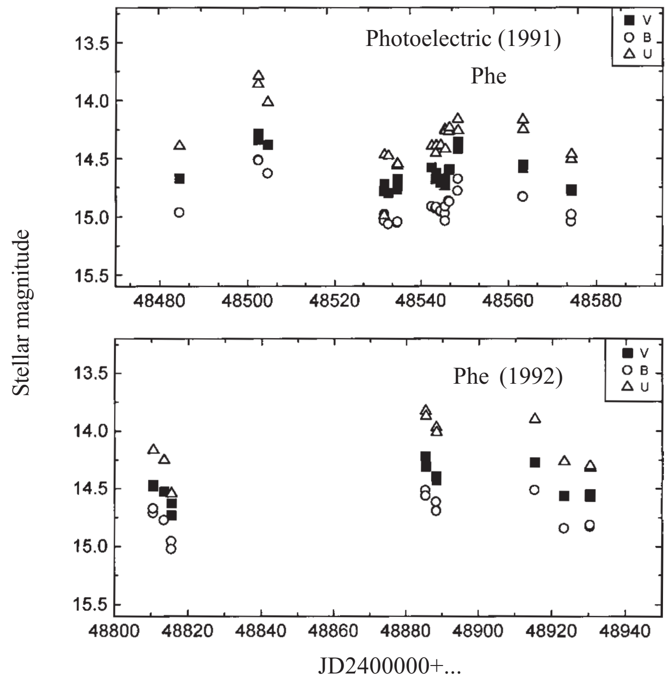

Fig. 2. Some light curves based on photoelectric observations in the *UBV* bands. Brightness estimates averaged over a night are given.

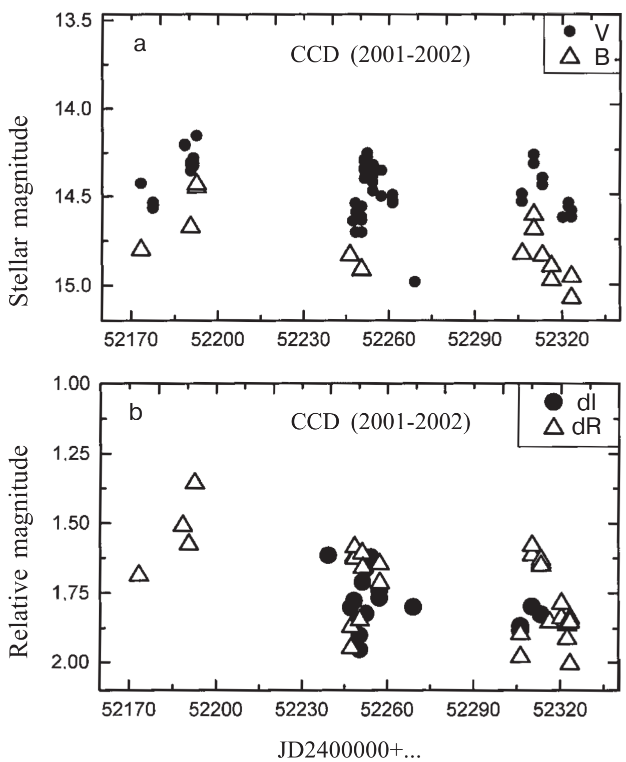

Fig. 3. Light curves based on CCD observations in the *BVRI* bands. The data in *B* and *V* are reduced to the system of Johnson and Morgan, while those in *R* and *I* are in relative stellar magnitudes.

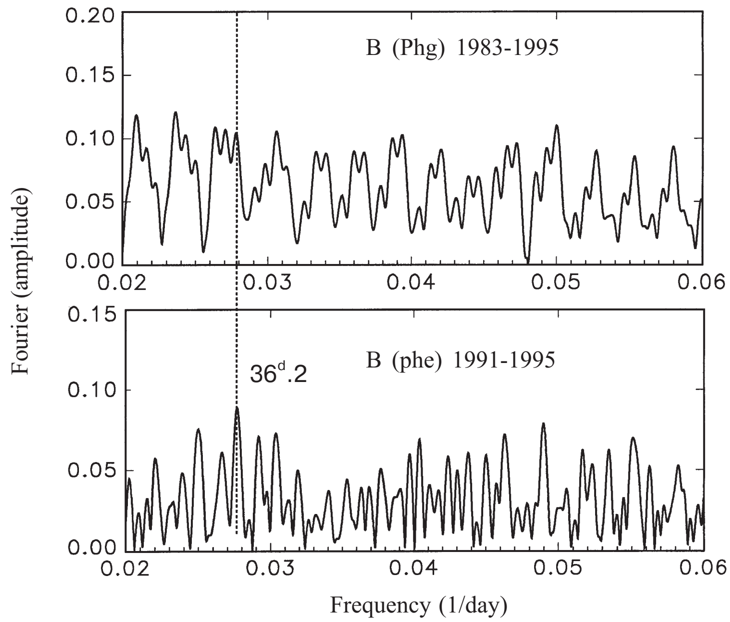

Fig. 4. Periodograms constructed by the Fourier method for photographic (top) and photoelectric (bottom) observations in an interval of from 17 to 50 days.

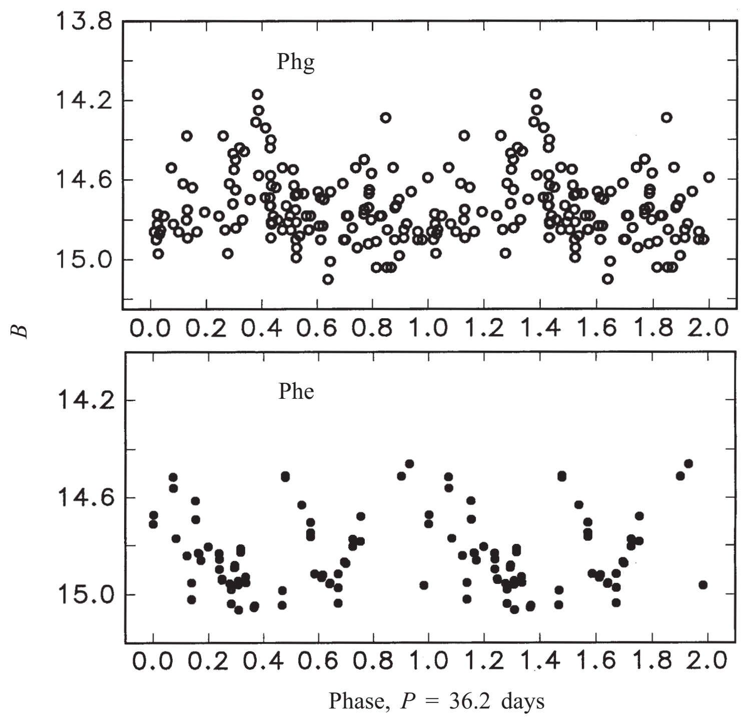

Fig. 5. Convolutions of data of photographic measurements (top) and photoelectric ones (bottom) with a characteristic flare time of 36.2 days.

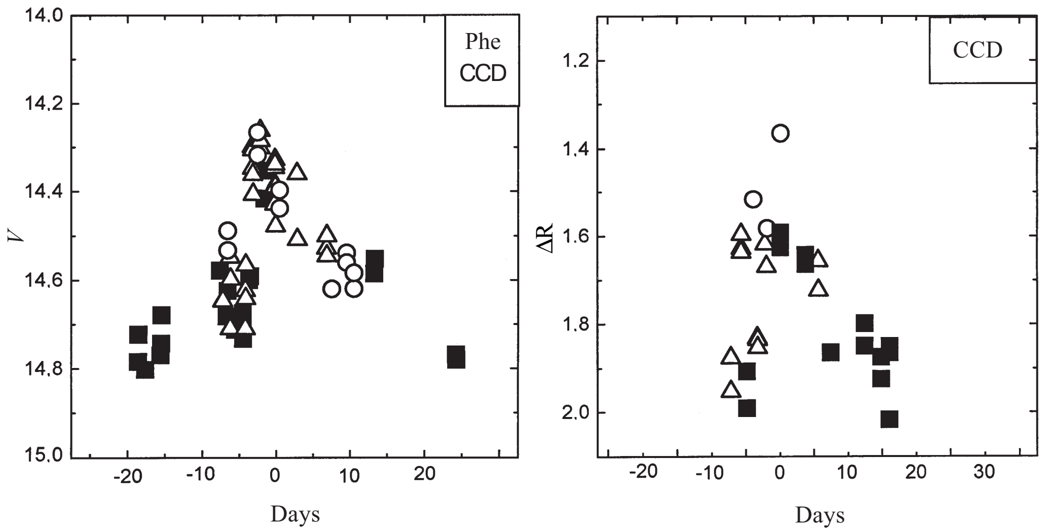

Fig. 6. Composite profiles obtained by matching individual flares. Left: in the *V* band based on photoelectric measurements (filled squares) and CCD measurements (open circles and triangles, denoting two different flares). Right: in the *R* band based on CCD measurements. Different flares are also given by different symbols. Time in days before and after the flare maximum is laid out along the horizontal axis. A time close to the flare maximum is taken as zero.

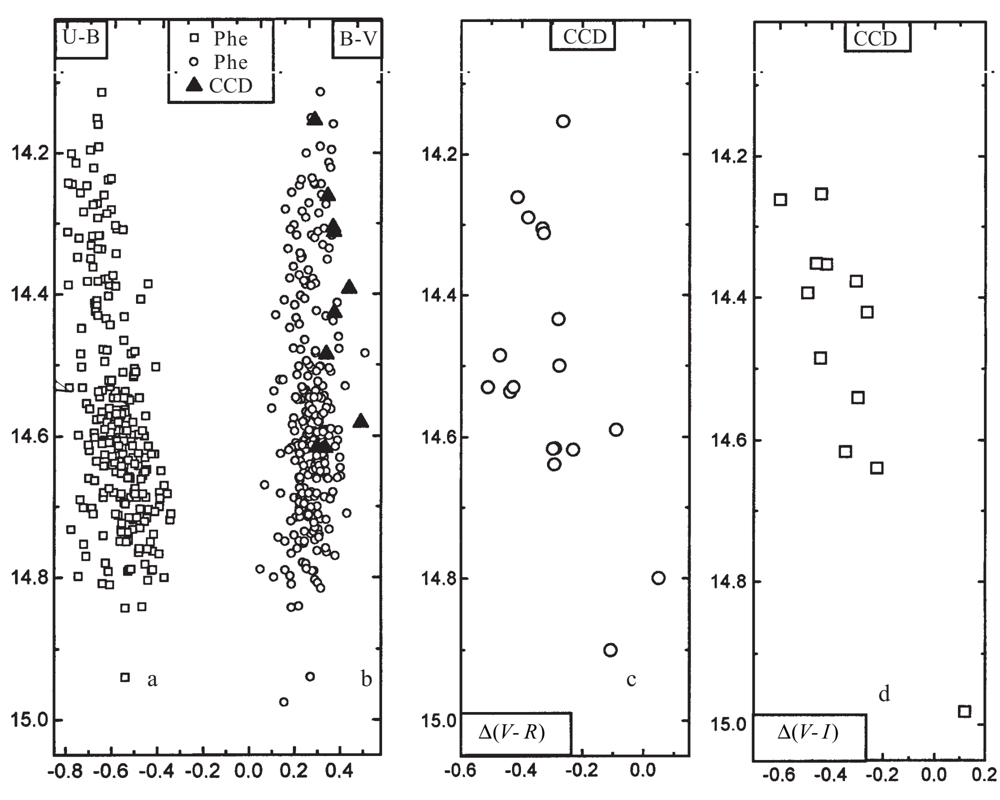

Fig. 7. Variation of the color indices $U-B$ (a), $B-V$ (b), $V-R$ (c), and $V-I$ (d) with brightness variation in the *V* band based on photoelectric and CCD measurements.

immediately begins. On the composite profile (*V*) this looks like a brief brightness decrease on the ascending branch, and this point can easily be overlooked by observers, while the flare profile is interpreted to be symmetrical and sinusoidal (as was noted by Honeycutt et al.). On the other hand, it is possible that the main profile itself has an inconstant shape, and a preflare does not always accompany it. It seems possible to us to resolve this problem only by efforts at prolonged multilongitude monitoring.

5. Color Measurements

In Fig. 7 we give the variation of the $U - B$, $B - V$, $V - R$, and $V - I$ color indices with brightness variation in the *V* band. We used all the available data obtained with the electrophotometer and CCD to obtain the dependences. It is seen that DI Lac is bluer at a flare maximum and redder at a minimum, on the whole, although this occurs differently in different color bands. With a decrease in brightness the $U - B$ color index decreases from $-0^m.7$ to $-0^m.5$, on the average, and the scatter of the points increases from $0^m.2$ to $0^m.4$. The The $B - V$ color index based on photoelectric data hardly varies as a flare fades, lying within the band of $0^m.15$-$0^m.4$. The data obtained with the CCD agree with the photoelectric data only partially: they show a slight reddening from $0^m.25$ (at a flare maximum) to $0^m.45$ (half fading) and then variation in the range from $0^m.3$ to $0^m.5$. The relative value of the $V - R$ color index shows a large scatter during almost the entire development of a flare, varying by about $0^m.5$, but at a minimum the star is also redder here. The $V - I$ color index behaves similarly, and its reddening during fading is even more clearly expressed than for $V - R$.

The bands of scatter on the diagrams may be due to the fact that the color indices for the ascending and descending branches of flares do not coincide. For a detailed investigation of this effect, from all the data we chose only the densest runs of photoelectric and CCD observations, which best describe flares, and examined their behavior on magnitude–color index diagrams in chronological order. The proved to be three such flares: the first was observed photoelectrically in 1991 between JD 2448530 and JD 2448575 and the second and third using the CCD in 2001 (JD 2452243-2452270) and in 2002 (JD 2452305-2452325), respectively. The behavior of the first event, which includes a preflare and the main flare, is shown on V, $U - B$ and V, $B - V$ diagrams (Fig. 8, a, b). It is seen that the preflare (points 1 6) describes a counterclockwise loop on both diagrams: the star enters the flare redder and returns bluer. In both cases the "width" of the flare, i.e., the range of variation of the color index, does not exceed $0^m.1$. The main flare virtually does not describe a loop on either diagram. It is curious that another main flare, observed 11 years later using the CCD, describes a clockwise loop in the V, $B - V$ coordinates (points 1 4 in Fig. 8c) with a width of $0^m.15$. This flare also develops clockwise on the V, $V - R$ diagram (points 1 6 in Fig. 8d), where $V - R$ varies within $0^m.2$. The 2001 flare was best represented on the V, $V - I$ diagram (see Fig. 8e). It also describes a clockwise loop (point "3" drops out of the general trend, however, with a change in $V - I$ by $0^m.5$).

Is it possible to explain such unusual behavior of a flare by any instrumental effect, such as the Forbes effect (DI Lac was observed in 2002 with low air masses)? Evidently not. The comparison star "a" used in the CCD observations has a color index $B - V = 0^m.75$ according to the SIMBAD data base, where it is designated as "HH95 DI Lac-12." Thus, it is not such a red nova that with low air masses the Forbes effect would be comparable to the observed width of the loop. Moreover, another "reverse" loop was obtained under the conditions of the 2001 observations of DI Lac with a minimum air mass.

6. Discussion

An analysis of multiyear observations of DI Lac revealed its following properties:

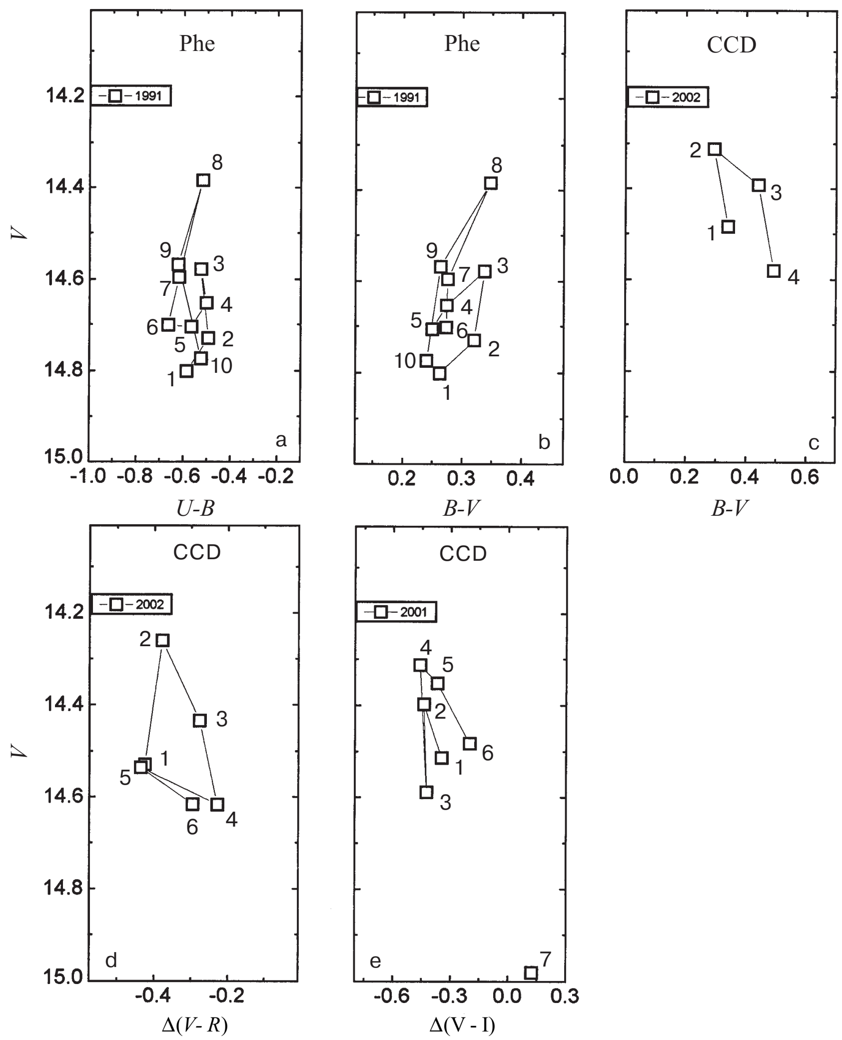

Fig. 8. Behavior of DI Lac flares on “magnitude–color” diagrams. The development of the flares is numbered in chronological order, “1” usually being close to the start of the ascending branch of the flare.

1. During the last several decades the star has flared up with a characteristic time of 36 days and an amplitude of about $0^m.6$. The average profile of a flare in the *V* and *R* bands is asymmetrical: the rise in brightness lasts about five days while the fading is four times longer. This flare seems to be preceded by a smaller flare lasting about 10 days. In this DI Lac differs from GK Per and V446 Her, the flares of which have symmetrical profiles.

2. The star becomes bluer with increasing brightness in almost all the spectral bands. This effect is best expressed in the $V - I$ band and least expressed (if not absent entirely) in the $B - V$ band.

3. The behavior of DI Lac on “magnitude–color” diagrams differs from flare to flare. It can be divided into three types. In this first case (this pertains mainly to the 1991 flare) its ascending and descending branches coincide, in another (the preflare) they do not coincide but form a loop developing counterclockwise, i.e., the star emerges from the flare bluer, and in the third case (the main flares of 2001 and 2002) the loop goes clockwise, i.e., the star emerges from the flare redder.

The first two cases actually recall the properties of flares of dwarf novae for different directions of development of thermal instability in the accretion disk: from the outer layers to the inner ones (preflare) and from the inner ones outward (main flare). Such behavior was obtained in Smak’s model calculations [18] and confirmed by observations of several dwarf novae (such as VW Hyi [19], SS Cyg [20], AH Her [21]), and V1504 Cyg [22]). The behavior of the third type of flares still requires an explanation.

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