

4-1-2011

The 2001-2003 Low State of Nova Lacertae 1950 (DK LAC)

R. K. Honeycutt

S. Kafka

H. Jacobson

A. A. Henden

D. Hoffman

See next page for additional authors

Follow this and additional works at: https://orc.library.atu.edu/faculty_pub_phys

 Part of the [Physical Sciences and Mathematics Commons](#)

Recommended Citation

Honeycutt, R. K.; Kafka, S.; Jacobson, H.; Henden, A. A.; Hoffman, D.; Maxwell, T.; Robertson, J. W.; and Croxall, K., "The 2001-2003 Low State of Nova Lacertae 1950 (DK LAC)" (2011). *Faculty Publications - Physical Sciences*. 14.
https://orc.library.atu.edu/faculty_pub_phys/14

This Article is brought to you for free and open access by the Department of Physical Sciences at Online Research Commons @ ATU. It has been accepted for inclusion in Faculty Publications - Physical Sciences by an authorized administrator of Online Research Commons @ ATU. For more information, please contact cpark@atu.edu.

Authors

R. K. Honeycutt, S. Kafka, H. Jacobson, A. A. Henden, D. Hoffman, T. Maxwell, J. W. Robertson, and K. Croxall

THE 2001–2003 LOW STATE OF NOVA LACERTAE 1950 (DK LAC)

R. K. HONEYCUTT¹, S. KAFKA², H. JACOBSON^{1,5}, A. A. HENDEN³,
D. HOFFMAN^{1,6}, T. MAXWELL¹, J. W. ROBERTSON⁴, AND K. CROXALL^{1,7}

¹ Astronomy Department, Indiana University, Swain Hall West, Bloomington, IN 47405, USA; honey@astro.indiana.edu, jacob189@msu.edu, dhoffman@nmsu.edu, tmaxwell@astro.indiana.edu, kevin.croxall@utoledo.edu

² Department of Terrestrial Magnetism, Carnegie Institute of Washington, 5241 Broad Branch Rd. NW, Washington, DC 2001, USA; skafka@dtm.ciw.edu

³ American Association of Variable Star Observers, 49 Bay State Rd., Cambridge, MA 02138-1203, USA; arne@aavso.org

⁴ Arkansas Tech University, Department of Physical Sciences, 1701 N. Boulder, Russellville, AR 72801-2222, USA; Jeff.Robertson@atu.edu

Received 2010 November 4; accepted 2011 January 31; published 2011 March 7

ABSTRACT

We report on extensive photometry of DK Lac obtained during the interval 1990–2009, which includes a 2 mag low state during 2001–2003. Much of the photometry consists of exposures obtained with a typical spacing of several days, but also includes 26 sequences of continuous photometry each lasting 2–7 hr. We find no evidence for periodicities in our data. We do find that the random variations in the low state are approximately twice those in the high state, when expressed in magnitudes. The lack of orbital-timescale variations is attributed to the nearly face-on presentation of the disk. There is a 0.2 mag decline in the high-state brightness of the system over 19 years, which is consistent with the behavior of other old novae in the decades following outburst. High-state spectra are also presented and discussed. We find that the equivalent width of H α falls by about double from 1991 to 2008. The photometric properties are discussed in the context of the hibernation scenario for the behavior of novae between outbursts, in which we conclude that low states in old novae are probably unrelated to their possible entrance into hibernation.

Key words: novae, cataclysmic variables – stars: individual (DK Lac)

Online-only material: machine-readable and VO tables

1. INTRODUCTION

DK Lac was a moderately fast ($t_3 = 32$ day) nova in 1950, reaching $V = 6$ mag. The nova light curve developed small eruptions midway down the decline (e.g., Ribbe 1951), and the nebulae was spatially resolved (barely) by Cohen (1985) and by Slavin et al. (1995); otherwise DK Lac has rather undistinguished nova properties (Duerbeck 1981) and is not well studied in its post-nova stage. As far as we are aware there has not been an orbital period study (spectroscopic or photometric) for DK Lac.

Nova-like (NL) cataclysmic variables (CVs) sometimes fade by 1–4 mag, remaining low from months to years; these are known as VY Scl stars. The VY Scl phenomenon is thought to be due to a cessation or diminution of the mass transfer from the secondary star to the white dwarf, temporarily robbing the system of its accretion luminosity. In 2001 the autonomous 0.41 m telescope at Indiana University found that DK Lac had entered a low state (Henden et al. 2001), which lasted about 3 years. A preliminary report on this low state, based on partial data available at that time, appeared in Hoffman et al. (2003). This current paper reports on nearly 20 years of sampled DK Lac photometry surrounding this low state, plus continuous photometric sequences on numerous nights during both the low state and the subsequent return to the high state. We also report on spectra acquired during the high state. The DK Lac low state studied here is of interest because it is one of the

very few old nova to have displayed VY-Scl-like behavior. The character of the low state therefore bears on how novae behave between nova outbursts and whether they have long intervals of hibernation (Shara 1989) between nova eruptions, without accretion luminosity.

2. DATA ACQUISITION AND REDUCTION

2.1. Photometry

Our DK Lac photometry is of two types. First, we have long-term monitoring at a typical cadence of two to three observations per week, obtained mostly with the local Indiana automated photometric telescopes. This program, operating nearly continuously since 1990, is mostly used to monitor ~ 120 NL and old nova CVs for low states, both for what can be learned from the photometry itself (e.g., Honeycutt et al. 1994; Honeycutt & Kafka 2004; Kafka & Honeycutt 2005) and to trigger low-state spectrographic studies (e.g., Kafka et al. 2005a, 2006, 2008) as well as trigger more intensive low-state photometry (e.g., Kafka et al. 2005a, 2005b, 2007, 2008). To ensure good time coverage, the Indiana telescopes are fully automated for autonomous operation, including open-up/close-down decisions, dynamic scheduling, liquid nitrogen autofills, acquisition of daily bias and flats, and data reduction. No comprehensive description of these systems was ever published, but much of the technical details (Honeycutt et al. 1990, 1994a; Honeycutt 1992; Honeycutt & Turner 1992) as well as motivations and strategies (Honeycutt 1994; Honeycutt et al. 1994b, 1994; Robertson et al. 1995; Honeycutt & Kafka 2004; Kafka & Honeycutt 2005) are available.

The second variety of our DK Lac photometry consists of continuous monitoring in sequences lasting 2–7 hr each. These data were mostly acquired in attended mode using a variety

⁵ Current address: Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-4540, USA.

⁶ Current address: Astronomy Department, New Mexico State University, P.O. Box 30001, Las Cruces, NM 88030-8001, USA.

⁷ Current address: Department of Physics & Astronomy, University of Toledo, Toledo, OH 43606, USA.

Table 1
Photometry Log

Seq.	UT	JD	Telescopes	Filters	Time (s)	No. of Exposures	Duration
	1990 Nov 12 to 2004 Dec 4	2448207 to 2453343	IU 0.41 m	V	240	739	14.1 yr
	2006 Aug 23 to 2009 May 21	2453947 to 2454972	IU 1.25 m	V,C	150	251	2.8 yr
01-1	2001 Dec 18	2452261	USNO/FS 1.0 m	V	120	54	3.4 hr
01-2	2001 Dec 20	2452263	USNO/FS 1.0 m	V	120	50	3.1 hr
02-1	2002 Jan 7	2452281	USNO/FS 1.0 m	V	120	60	2.7 hr
03-1	2003 Jun 29	2452819	WIYN 0.91 m	V	90–150	55	3.3 hr
03-2	2003 Jun 30	2452820	WIYN 0.91 m	V	120–240	63	4.6 hr
03-3	2003 Jul 2	2452822	WIYN 0.91 m	V	100–500	35	4.1 hr
03-4	2003 Jul 3	2452823	WIYN 0.91 m	V	100	87	4.2 hr
03-5	2003 Jul 10	2452830	WIYN 0.91 m	V	180	40	3.0 hr
03-6	2003 Jul 11	2452831	WIYN 0.91 m	V	180	33	3.4 hr
03-7	2003 Jul 16	2452836	WIYN 0.91 m	V	180	26	2.8 hr
04-1	2004 Jun 29	2453185	WIY 0.91 m	V	60	43	1.6 hr
04-2	2004 Jul 3	2453189	WIY 0.91 m	V	60	18	0.9 hr
04-3	2004 Jul 5	2453191	WIY 0.91 m	V	60	70	2.4 hr
06-1	2006 Sep 30	2454008	WIY 0.91 m	V	120	35	2.0 hr
06-2	2006 Oct 1	2454009	WIY 0.91 m	V	120–300	109	7.0 hr
06-3	2006 Sep 3	2454011	WIY 0.91 m	V	120–300	77	7.0 hr
06-4	2006 Oct 4	2454012	WIY 0.91 m	V	120–300	18	1.3 hr
06-5	2006 Oct 5	2454013	WIY 0.91 m	V	120–300	40	4.0 hr
07-1	2007 Aug 18	2454330	IU 1.25 m	V	180	70	4.6 hr
07-2	2007 Sep 4	2454347	IU 1.25 m	C	180	70	4.7 hr
07-3	2007 Sep 14	2454357	IU 1.25 m	C	180	68	4.6 hr
07-4	2007 Oct 7	2454380	IU 1.25 m	C	120	63	2.7 hr
07-5	2007 Oct 10	2454383	IU 1.25 m	C	120	65	3.9 hr
08-1	2008 Oct 3	2454742	IU 1.25 m	C	150	46	4.5 hr
08-2	2008 Oct 4	2454743	IU 1.25 m	C	150	20	2.4 hr
08-3	2008 Oct 5	2454744	IU 1.25 m	C	150	41	4.3 hr

of telescopes and observers. The motivation for the monitoring was twofold: (1) it was hoped that the orbital period might be revealed, and (2) the low-state photometric behavior of VY Scl stars on timescales of minutes to tens of minutes is not well defined, with several interesting effects to be explored. For example, in the low state of some CVs one sometimes sees 0.6 mag flares lasting 10–20 minutes, which have been attributed to either stellar flares on the M dwarf donor star or mass transfer bursts (e.g., Honeycutt & Kafka 2004, and references therein).

Table 1 is a log of the photometric observations. Column 1 is a sequence designation (provided only for continuous exposures on a given night). Column 2 gives the date (or the date range), while Column 3 provides similar information for the JD. Column 4 is the telescope, Column 5 is the filter, Column 6 is the exposure time in seconds, Column 7 is the number of useable exposures, and Column 8 is the duration of the data stream.

The long-term photometry was acquired and processed in two different Indiana University (IU) observing programs. The first program is an unattended, autonomous 0.41 m telescope in central Indiana, informally called RoboScope. This telescope collected V-band exposures of DK Lac for about 14 years, 1990–2004 (the first entry in Table 1). Flats and other detector calibration data were automatically acquired and applied after each exposure, followed by aperture photometry and field identification, all using custom software (Honeycutt & Turner 1992). Final photometric reductions were done using the incomplete ensemble technique contained in Astrovar, which is a custom package based on the technique described in Honeycutt (1992), but with the addition of a graphical user interface. The second program for the long-term photometry used an unattended, autonomous 1.25 m telescope at the same site as RoboScope (the

second entry in Table 2). DK Lac exposures were acquired by this telescope for nearly three years, 2006–2009. The real-time data reductions used for the RoboScope data were tightly integrated into our old VMS operating system, while the 1.25 m telescope is Linux based. The 1.25 m data were therefore reduced using a batch pipeline (not real time) consisting of IRAF⁸ routines for detector calibrations, followed by the application of SExtractor.⁹ The light curves were then generated using Astrovar. The IU 1.25 m exposures of DK Lac were acquired during commissioning of the instrumentation. The nightly dome flats gave poor results, and we did not have twilight flats on most nights. Therefore, we used median sky flats constructed from all the exposures in a given filter (typically 25–75) on a given (or adjacent) night. We had significant dark current from the thermoelectrically cooled CCD that was in service on the IU 1.25 m at this time, which somewhat degraded the signal to noise ratio (S/N). The errors for the 1.25 m DK Lac data are typically 0.025 mag, about $2\times$ the expected error if we had been able to use high S/N dome flats and if the dark current was negligible. The IU 1.25 m exposures of DK Lac began with the V filter, but later (after JD 2454330) switched to a Clear (C) filter. However, we have no secondary standards for the C filter so the V standards were used instead. This has little effect on the differential light curve, but does introduce some additional uncertainty into the zero point.

⁸ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

⁹ SExtractor is a source detection and photometry package described by Bertin & Arnouts (1996). It is available from <http://terapix.iap.fr/soft/sextractor/>.

Table 2
Magnitudes for DK Lac

JD	V	Error	Source
2448207.68948	16.943	0.034	RoboS
2448208.63269	16.841	0.031	RoboS
2448208.76882	16.862	0.044	RoboS
2448209.64547	16.938	0.031	RoboS
2448209.73172	16.923	0.040	RoboS
2448209.80370	16.899	0.048	RoboS
2448233.72259	17.054	0.063	RoboS
2448234.61401	16.919	0.044	RoboS
2448234.71393	16.872	0.052	RoboS
2448235.58032	16.907	0.039	RoboS
...
...
...
2454972.82035	17.130	0.029	IU 1.25 m

(This table is available in its entirety in a machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

The DK Lac exposures which consist of continuous (or nearly continuous) sequences on a given night (as opposed to the much more widely spaced automated long-term photometry) originated from three different observing programs. First, we have *V*-band sequences on three nights in 2001 from the 1.0 m telescope at the U. S. Naval Observatory, Flagstaff Station (USNO/FS; entries 01-1 to 02-1 in Table 1). These images were reduced using IRAF routines for both detector calibrations and aperture photometry. Next we have *V*-band sequences on 15 different nights 2001–2006 using the 0.91 m WIYN¹⁰ telescope at Kitt Peak (entries 03-1 to 06-5 in Table 1). Most of these images were reduced using IRAF for both detector calibrations and aperture photometry. However, a few sequences used Cmunwin,¹¹ a PC (Windows) based photometry package originally developed by Hroch (1998). These 0.91 m WIYN sequences were often (but not always) implemented as backup programs for use on non-photometric nights, and therefore sometimes have gaps due to passing clouds. Finally, we have sequences on eight nights 2007–2008 obtained with the IU 1.25 m telescope (entries 07-1 to 08-3 in Table 1), using the same reduction pipeline described earlier for the long-term photometry of DK Lac on this telescope.

We also have occasional DK Lac exposures (not parts of sequences) from the USNO/FS 1.0 m telescope, from the WIYN 0.91 m telescope, and from the Tenagra Observatory¹² 0.8 m telescope in southern Arizona; these occasional measures have been incorporated into our long-term light curve.

The last reduction stage for all the DK Lac data used Astrovar, which provides photometric errors based on the repeatability of non-variable stars as a function of instrumental magnitude. These errors are for differential magnitudes with respect to the ensemble, which for DK Lac consisted of 86 nearby stars. All of the DK Lac photometry used the secondary standards found in Henden & Honeycutt (1997) to establish the zero point. The error in this zero point is typically ~ 0.015 mag. The RoboScope data and the USNO/FS data have been transformed

¹⁰ The WIYN Observatory is a joint facility of the University of Wisconsin–Madison, Indiana University, Yale University, and the National Optical Astronomy Observatory

¹¹ <http://integral.sci.muni.cz/>

¹² <http://www.tenagraobservatories.com/>

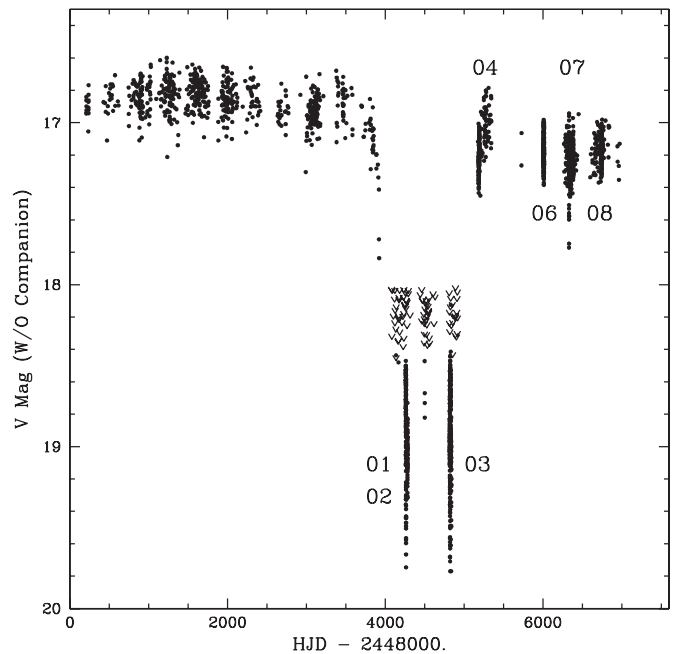


Figure 1. Full light curve of DK Lac from 1990 November 12 to 2009 May 21. The contribution of the companion star has been removed (see the text for details). Error bars have been omitted for clarity. The upper limit symbols during the 2001–2003 low state are from RoboS. The vertical clusters of unresolved points labeled 01 through 08 are continuous sequences of exposures, typically obtained on several successive or nearly successive nights. The sequence root number is the last two digits of the year. A serial number is appended to the sequence root to form the sequence number column in Table 1, and this notation is preserved for plots of the individual sequences (Figures 3 and 4).

to the standard *UBV* system using transformation coefficients evaluated from regular *B, V* observations of standard star fields. In applying this transformation we assumed a color for DK Lac of 0.0 because *B* measures were usually not available for DK Lac; this approximation will introduce some additional error into the zero point. Finally, no transformations were applied for the WIYN 0.91 m data or for the IU 1.25 m data (neither *V* nor *C*), resulting in additional zero-point error for that data. Overall we estimate that the zero-point error is $\lesssim 0.05$ mag for all the data and significantly less for most of the data.

DK Lac has a faint companion $\sim 5''$ east. On a low-state USNO/FS 1.0 m image acquired 2001 December 17 UT (JD = 2452260.70278) in good seeing, these two stars were measured separately using DAOPhot point-spread function (PSF) photometry in IRAF, with the following results: DK Lac $V = 19.36 \pm 0.03$, $B - V = -0.17 \pm 0.03$; Companion $V = 19.56 \pm 0.03$, $B - V = 1.40 \pm 0.09$. In combined light, the companion contributes $\sim 30\%$ – 50% of the *V*-band low-state light (depending on the variable low-state brightness of DK Lac) and $\sim 9\%$ of the high-state light. It was not practical to do PSF photometry on all our images because the two stars are not resolved in poor seeing nor when the system is in the high state. Therefore, we chose to use a numerical diaphragm for DK Lac that includes both stars and correct the resulting magnitude for the contribution of the companion. This means that our high-state magnitudes are ~ 0.10 mag fainter than the magnitudes which other observers might report for the same high-state epoch, if they are unaware of the contribution from the companion.

Figure 1 shows our full light curve (with 2304 points plus 92 limits), where we have plotted the magnitudes corrected

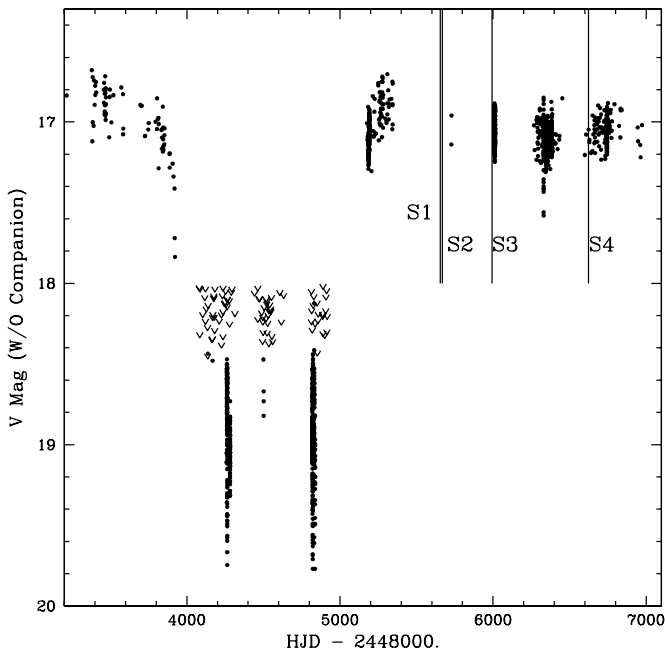


Figure 2. Latter portion of Figure 1 with the times of spectroscopic data marked. The labels for the times of spectral exposures correspond to Column 1 of Table 3.

for the light of the companion. The error bars (which are not shown in Figure 1, but which are present on subsequent light curve plots) are for differential magnitudes with respect to the ensemble. Table 2 lists all the magnitudes and errors (for the differential magnitudes). The complete version of Table 2 is available only in electronic form. The data will also be archived with the AAVSO.

In the low state, DK Lac is mostly just beyond the magnitude limit for RoboScope, resulting in numerous upper limits (which nevertheless help define the duration of the low state) in Figure 1. When a limit is obtained, this means that the combined light of DK Lac and the companion was not detected. Technically then, the limits are for a different circumstance than for the magnitudes, which are for DK Lac only, and the limits are actually fainter (by an unknown amount) than shown. Labels 01-08 in Figure 1 designate continuous sequences; see Table 1 and the caption to Figure 1 for further information.

It is seen in Figure 1 that DK Lac experienced a 2 mag deep low state beginning in 2001 January and ending sometime between 2003 July and 2004 June, for a duration of 2.5–3.4 years. There also appears to be an overall decline of ~ 0.2 mag in the high-state brightness over our 19 years of data.

2.2. Spectroscopy

Spectra of highly magnetic NL CVs (polars) in the low state typically have emission lines arising from the inner hemisphere of the donor star. These lines are not single peaked but have satellite components whose origin remains uncertain (Kafka et al. 2005a, 2005b, 2007, 2008). These satellites may arise from large-scale magnetic structures on the secondary star, or magnetic structures connecting the secondary star to the white dwarf. A central question is whether this behavior is induced by the strong magnetic field of the white dwarf or is a property of “hyperactivity” on the secondary star. It is therefore important to obtain low-state spectra of CVs which are disk systems (such as DK Lac) rather than polars, in order to help distinguish these two possibilities.

Table 3
Spectroscopy Log

Set	UT	JD	Telescopes	Time (s)	No. of Exposures
S1	2005 Oct 12	2453655	KPNO 2.1 m	600–900	2
S2	2005 Oct 26	2453669	WIYN 3.5 m	600	3
S3	2006 Sep 16	2453994	MMT 6.5 m	900	2
S4	2008 Jun 7	2454624	KPNO 2.1 m	900	4

Our attempts at low-state spectroscopy of DK Lac were unsuccessful because of system faintness. By the time we were able to obtain spectra using larger telescopes, DK Lac had returned to the high state. Figure 2 is an expanded portion of the DK Lac light curve in Figure 1, with the times of our spectra marked. Table 3 is a journal of our spectroscopic observations.

Spectral sets S1 and S4 were obtained using the GoldCam slit spectrograph on the KPNO¹³ 2.1 m telescope. Grating 35 was used in first order, providing coverage ~ 5000 – 8100 Å at ~ 3 Å resolution. Spectral set S2 was obtained using the MOS/Hydra multiple object spectrograph on the WIYN telescope. Grating 600 was used in first order, providing coverage ~ 5300 – 8200 Å. The “red” 2” fiber bundle was employed, yielding ~ 3 Å resolution; numerous other fibers were used for sky subtraction. Spectral set S3 used the 6.5 m MMT¹⁴ at Mt. Hopkins, Arizona. The Blue Channel slit spectrograph was employed with a 500 line/mm grating, providing coverage ~ 5000 – 8100 Å at a resolution of ~ 3.6 Å.

For all spectra our detector calibrations used standard IRAF procedures, and for spectral extractions and wavelength calibrations we used IRAF’s onedspec/twospec packages. No spectrophotometric calibrations were applied for any of the spectra, and the continua in the reduced spectra were normalized to unity. Also, no corrections were made for telluric spectral features in the near-IR. Each spectral sequence contained 2–4 exposures (see Table 2), which were combined after reductions.

3. ANALYSIS

3.1. Photometry

Figures 3 and 4 are representative plots of the light curves of the individual photometric sequences listed in Table 1. Figure 3 contains two nights of low-state data, demonstrating that some nights have little variation, while other have systematic 1 mag changes over several hours. Furthermore, the mean low-state magnitude can change by 0.5 mag between nights. Figure 4 is an example of a night of high-state photometry, where we see flickering-type behavior with little change in mean magnitude over 7 hr.

The location of the sequences in the long-term light curve is labeled in Figure 1. We discuss separately below the low-state and the high-state photometry.

3.1.1. The Low State

Livio & Pringle (1994) proposed that VY Scl low states are due to a large starspot drifting into the L1 region of the donor star.

¹³ Kitt Peak National Observatory is a division of the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

¹⁴ The MMT Observatory is a joint facility of the Smithsonian Institution and the University of Arizona.

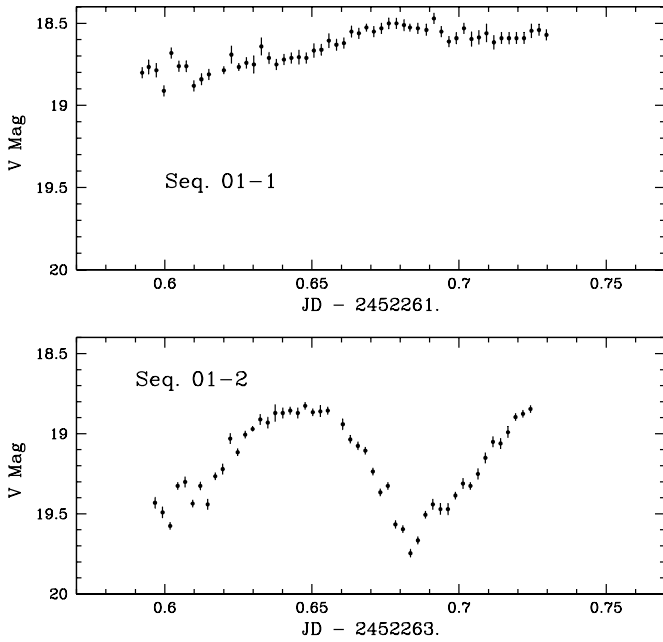


Figure 3. Examples of low-state photometric sequences. The sequence notation refers to labels in Figure 1 and Table 1. The V magnitudes have been corrected for the contribution of the close companion. This plot is for two sequences obtained 2001 December 18 (UT) and 2001 December 19 (UT). Error bars are plotted but are often too small to be seen.

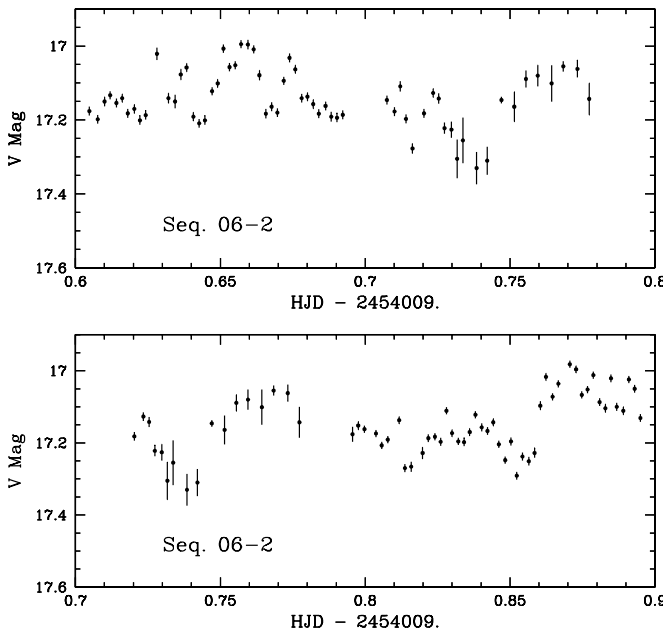


Figure 4. Example of a high-state photometric sequence. The sequence notation refers to labels in Figure 1 and Table 1. Note that the data in these two panels overlap somewhat. The V magnitudes have been corrected for the contribution of the close companion. This plot is for a sequence obtained 2006 October 01 (UT).

By analogy to sunspots (which are observed to have significantly lower gas densities than the surrounding photosphere) it was argued that a starspot at L1 will greatly lower \dot{M} , reducing the accretion luminosity and producing a VY Scl low state. VY Scl stars typically take a few tens of days to enter a low state. In the starspot hypothesis the ingress and egress timescales of low states are not well constrained because they depend on the poorly known drift rate of star spots on CV donor stars. Honeycutt & Kafka (2004) reported that the shapes of many VY Scl ingress

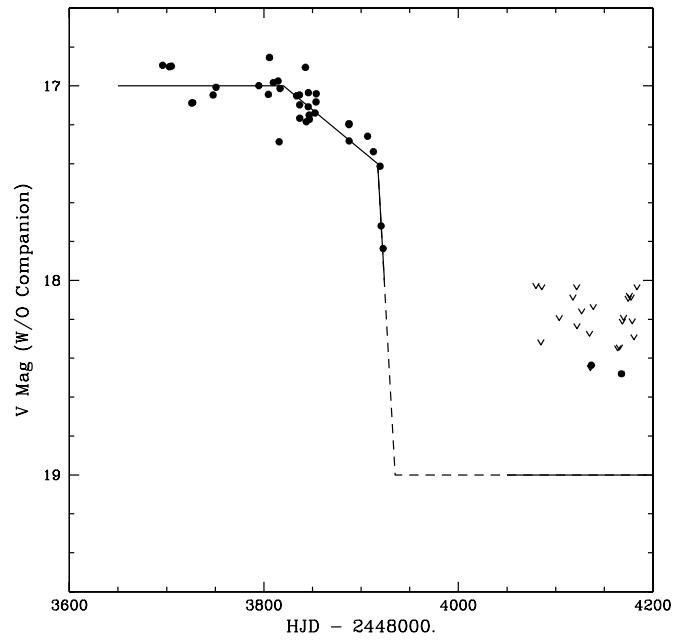


Figure 5. Expanded view of the portion of Figure 1 containing the ingress to the low state. The characterization of the shape of the ingress as two straight lines is adapted from the behavior of high-state/low-state transitions in numerous other VY Scl stars from Honeycutt & Kafka (2004). The level of the low state is fixed at $V = 19$ using data off the plot to the right (see Figure 1), where the low-state magnitude varies between 18.5 and 19.5. The occasional RoboScope detections in near 18.5 in the plot are presumably the peaks of this distribution of low-state magnitudes.

and egress events were dual sloped, always being faster when fainter. It was argued that this effect is consistent with the starspot scenario in a number of respects, if the two slopes are associated with the passage of the umbral and penumbral portions of the starspot drifting across L1.

Figure 2 shows a few data points on the decline of DK Lac into the low state, especially the early stages. However, later portions of the decline have few points because RoboScope does not reliably reach fainter than $V \sim 18$. The recovery from the low state was almost totally missed. The low state had an amplitude of 2.0 mag and (taking into account the missing-data intervals) lasted between 2.5 and 3.4 years. Figure 5 shows an expanded portion of Figure 1 where we have characterized the decline as two straight lines by appealing to the behavior of better-sampled high-state/low-state transitions of VY Scl stars in Honeycutt & Kafka (2004). In that work it was found that, for $\sim 40\%$ of the observed transitions, a pronounced slope change occurred during the transition to and from the low state. That slope change was always in the sense that the transition was faster when fainter. The speed of the transitions was characterized by an e -folding time, τ . For 17 transitions having dual slopes in Honeycutt & Kafka (2004), it was found that τ_{faint} ranged from 3 to 40 days (with a mean of 15 days), while τ_{bright} ranged from 4 to 160 days (with a mean of 52 days). For the straight lines plotted in Figure 5, we have for DK Lac $\tau_{\text{faint}} = 12$ days and $\tau_{\text{bright}} = 175$ days, values within or near the range for other VY Scl stars.

The photometric sequences acquired during the low state fall naturally into two sets. Set 1 consists of three sequences obtained over a 21 night interval between 2001 December 18 and 2002 January 07 (Sequences 01-1 to 02-1 in Table 1), while Set 2 consists of seven sequences obtained 20 months later, over an 18 night interval in 2003 June/July (sequences

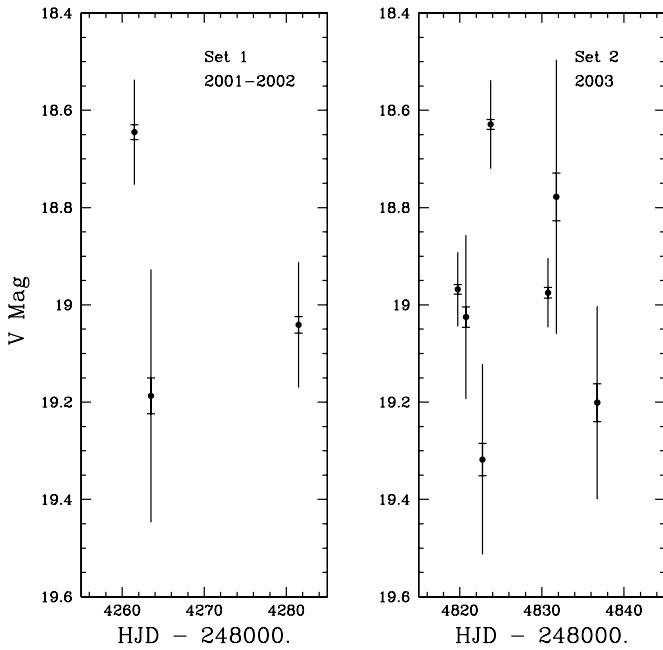


Figure 6. Mean magnitude of the low-state sequences for Set 1 (left) and for Set 2. Sets 1 and 2 each encompass ~ 3 weeks, separated by 1.5 years. The short error bars are for sdm and the longer ones for sds.

03-1 to 03-7). Figure 6 shows the mean magnitudes for the sequences from 2001 to 2002 (Set 1) alongside a similar plot for the sequences from 2003 (Set 2). There does not appear to be any systematic change in the mean low-state brightness over these intervals. The short error bars (with caps) are for the standard deviation of the mean (sdm), showing that night-to-night variations substantially exceed the sdm of the individual sequences. The long error bars (without caps) are for the standard deviation of a single observation (sds), which should be independent of the number of points in the sequence, measuring instead how “noisy” or “quiet” is each photometric sequence. There is no apparent systematic change in sds as the low state progresses, nor any correlation of sds with low-state mean magnitude. The mean value of sds for the 10 low-state sequences is 0.16 mag, and the mean low-state magnitude is 19.0.

Our data provide little leverage to characterize the low-state night-to-night variations. Therefore, we searched for periodicities in the expected orbital period range of 1–12 hr, using data which we pre-whitened by adjusting the level of each sequence to a common mean magnitude. Periodograms (not shown) were constructed for a variety of groupings of the low-state data. In these power spectra there are no isolated peaks that stand out well from the noise and the arising background. Instead we see that the major power is distributed primarily between 2 and 3 hr for the 2001–2002 data, but primarily between 3 and 5 hr for the 2003 data. We folded the data on the highest peaks, but the resulting light curves did not provide any additional insight into the nature of the variations. When we constructed new periodograms by randomizing the magnitudes, keeping the same JDs, it was concluded that the excess power at these characteristic frequencies is real, as is the change in the characteristic timescale.

3.1.2. The High State

Periodograms of the high-state photometry were examined using pre-whitened data and a variety of data groupings. For

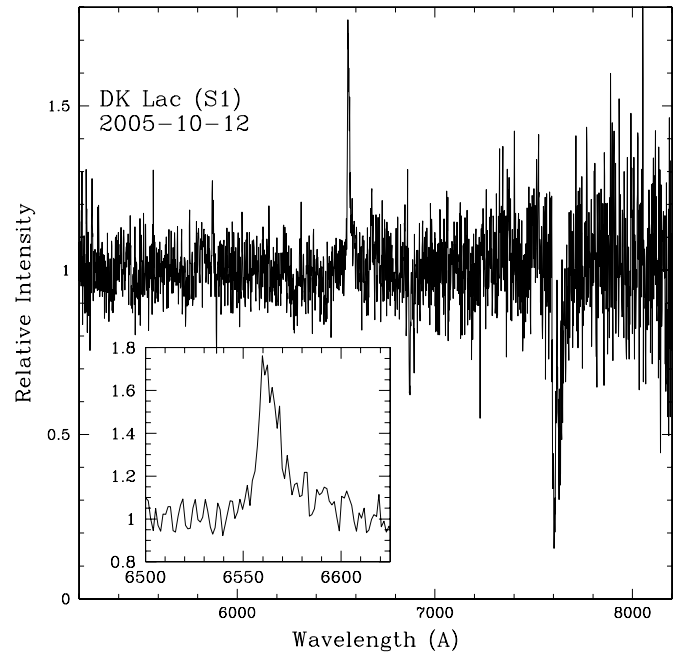


Figure 7. Average of two exposures of DK Lac obtained 2005 October 12 (UT) with the KPNO 2.1 m telescope (spectrum S1 as labeled in Figure 2 and Table 3). The continuum has been normalized to unity and the $H\alpha$ line profile is shown on an expanded scale. No corrections for atmospheric extinction have been applied; therefore the telluric absorption bands remain.

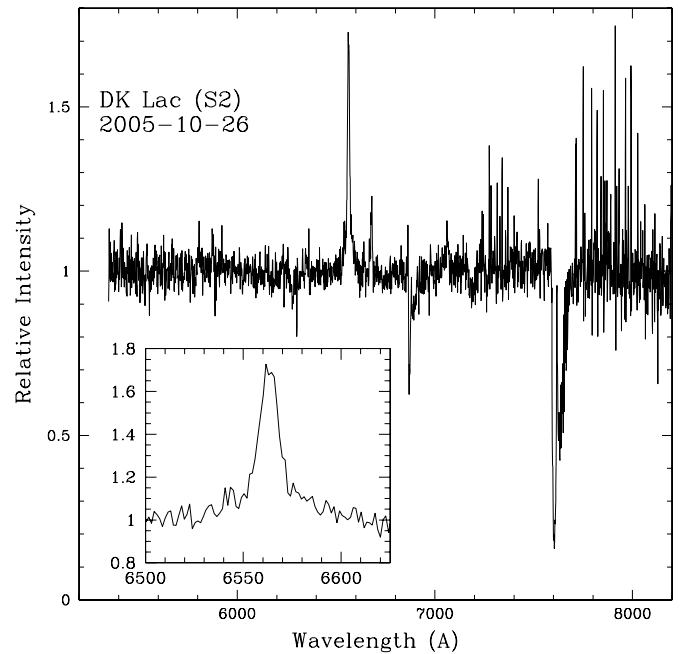


Figure 8. Like Figure 7 except average of three high-state exposures of DK Lac 2005 October 26 (UT) with the WIYN 3.5 m telescope (spectrum S2 as labeled in Figure 2 and Table 3).

the continuous sequences we find broad power from 2 to 3.5 hr, with somewhat isolated peaks at 0.11162(5) and 0.08431(3) day for some data groupings. The light curves folded on these two periods have sinusoidal amplitudes of ~ 0.03 mag with superimposed scatter of ~ 0.2 mag. It seems likely that all these “periods” are spurious, but we mention them for completeness.

The IU 0.41 m data of 1990–2002 consist of single exposures acquired at typical intervals of a few days. This cadence could hardly be more different than that for the sequenced photometry, which typically consists of 20–80 exposures over a few hr of a

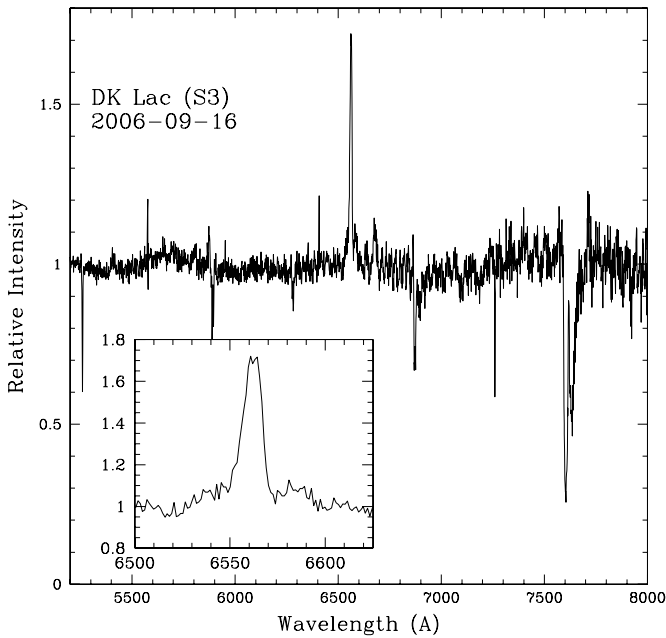


Figure 9. Like Figure 7 except average of two high-state exposures of DK Lac 2006 September 16 (UT) with the MMT telescope (spectrum S3 as labeled in Figure 2 and Table 3).

given night (see Table 1). The nights containing sequences are typical of conventionally scheduled observing runs, consisting of widely separated sets of several adjacent or nearly adjacent nights. The combination of these two cadences would seem to be ideal for establishing any reliable periodicities or quasi-periodicities, especially since the errors for the sequences and for the sampled photometry are similar. However, there are no significant peaks in common between the periodograms of the sequenced photometry and the sampled photometry, suggesting that no stable periodicities are present in the high-state data. Even the concentrated power between 2 and 3.5 hr seen in the periodograms of the sequence photometry is largely missing in the periodogram of the sampled photometry.

With regard to the $B - V$ color of DK Lac in the high state, Szkody (1994) reported 0.08 and Ringwald et al. (1996) gave 0.1. Ringwald et al. also provide $E_{B-V} = 0.45$, which implies an intrinsic color corresponding to a blackbody with $T \gtrsim 50,000^\circ$.

As for the DK Lac high-state spectra, Figures 7–10 show the combined spectra for sets S1–S4. The best S/N is found in S3 (Figure 9), although it has some residual near-IR fringing longward of $H\alpha$. In S3 we see in emission $H\alpha$, He I 5876, and He I 6676. He I 6676 is also visible in S2 (Figure 8) and S4 (Figure 10). The NaD doublet is in absorption with a total equivalent width of 1.8 Å.

4. DISCUSSION

Distance, extinction, and M_V are not well known for DK Lac. Duerbeck (1981), using a calibration of light curve decay time with luminosity (along with an adopted extinction of 1.2 mag), estimates a distance of 1500 ± 200 pc, while Slavin et al. (1995) used the method of nebular expansion parallax to derive 3900 ± 500 pc. In our spectrum S3 the equivalent width (EW) of Na D1 is 0.83 Å. Using the calibration found in Munari & Zwitter (1997) we find $A_V = 1\text{--}3$ mag. This wide range is due to saturation effects along with uncertainties introduced by unresolved multiple line components. Using the nebular expansion parallax distance and adopting $A_V = 1.2 \pm 0.2$, we

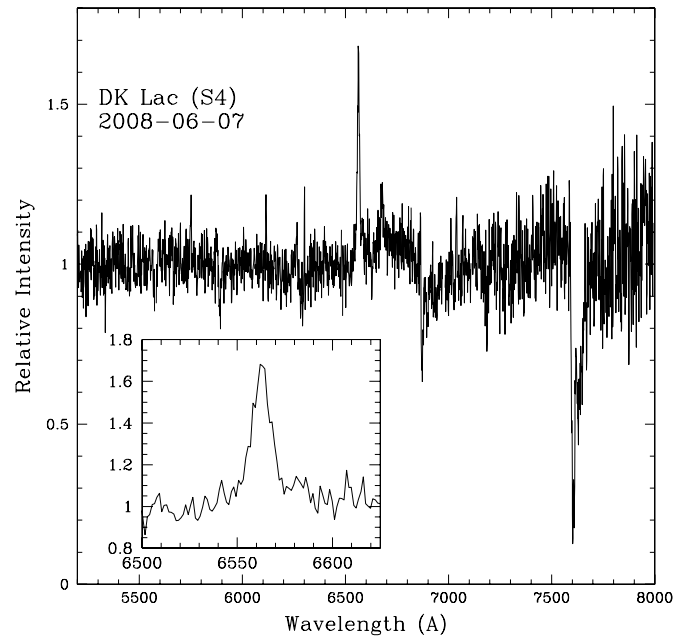


Figure 10. Like Figure 7 except average of four high-state exposures of DK Lac 2008 June 07 (UT) with the KPNO 2.1 m telescope (spectrum S4 as labeled in Figure 2 and Table 3).

find $M_{V,\max} = -9.1 \pm 0.4$ and $M_V = 2.9 \pm 0.4$ 59 years after the outburst, in 2009. These M_V values are consistent with results for other novae at maximum and for old novae decades after the nova (Warner 1995).

The extinction is unlikely to be much higher than our adopted value because then the intrinsic color becomes too blue for a blackbody, requiring the assumption of strong emission lines or other non-thermal contributions to the $B - V$ color. Interestingly, the color of DK Lac assumed an even bluer value of -0.17 in the low state. This result is difficult to understand. Most CVs become redder in the optical when accretion luminosity falls, as the cool secondary star begins to dominate. Perhaps the secondary star in DK Lac is of particularly low luminosity and/or the accretion luminosity did not disappear completely. This blue color in the low state is based on only a single measurement, but nevertheless appears secure (see Section 2.1).

The inclination of the system can be estimated using the calibrations found in Warner (1986). Using the correlation of $H\alpha$ EW with orbital inclination, we find that $i = 0^\circ\text{--}50^\circ$ for DK Lac. The correlation of M_V with disk inclination is more confining, yielding $i = 0^\circ\text{--}25^\circ$. It seems clear that the disk of DK Lac is presented nearly face-on. This may account for the lack of any orbital signature in the photometry reported in this paper. The effect of various kinds of non-axisymmetric accretion structure(s) on the light curve is minimized when the portions of the disk seen by the observer are always in view, as is the case at low orbital inclination.

In fact both the high-state and the low-state photometry appear random in nature, though perhaps with preferred timescales. For the sampled high-state photometry obtained prior to the low state, pre-whitened by observing season, the rms scatter is 0.094 mag. For the sequenced high-state photometry after the low state, pre-whitened by sequence, the rms scatter is 0.085 mag. Let us take 0.09 mag rms as the characteristic scatter (flickering), during the high state, to be compared to 0.16 mag rms in the low state.

VY Scl stars do not often stay in the low state long enough to characterize their low-state variations, but when they do (e.g.,

MV Lyr in Honeycutt & Kafka 2004) the light curve seems flat to within ~ 0.15 mag, with brief 0.5 mag flares superimposed. This behavior is similar to that seen in polars, where the low states are more frequent (see low-state light curves of AM Her, ST LMi, and AR UMa in Kafka & Honeycutt 2005). Schmidtke et al. (2002) report on sequenced photometry obtained as LQ Peg recovered from a low state, finding 0.09 mag variations, with no coherent signal between 1 and 6 hr; these sequences were obtained roughly midway up the recovery to the high state. Schmidtke et al. (2002) found that as LQ Peg brightened from 15.8 to 14.5 the flickering decreased from 0.09 to 0.02 mag. This is in the same sense as the change we find in DK Lac. However, as DK Lac brightened from 19.0 to 17.0, the amount of flickering declined from 0.16 to 0.09 mag, a less extreme change than seen in LQ Peg. Schmidke et al. also found that the flickering was a constant fraction of the intensity as the system recovered from the low state. That is clearly not the case in DK Lac, in which the high-state rms variation expressed in intensity units is 3–4 times the low-state rms variation in intensity units.

The hibernation scenario for cyclic nova episodes (see Shara 1989 for a review) holds that at some point after the nova outburst accretion drops to a near zero, a state known as hibernation; the system is thought to remain in hibernation for most of the interval between nova outbursts. Advantages of hibernation include reducing the mean accretion rate to levels needed to allow the next thermonuclear runaway and providing consistency between nova rates and cataloged CVs because of the inconspicuous nature of hibernating systems. The scenario has received criticisms (e.g., Naylor et al. 1992) but remains a topic of considerable interest (e.g., Martin & Tout 2005). The fact that post-nova systems fade by 1–2 mag per century following the nova (Vogt 1990; Duerbeck 1992) is consistent with the hibernation scenario, but it may also be the case that the onset of low states marks the transition into hibernation.

At least one other old novae has had a low state subsequent to the nova outburst. V533 Her (Nova Her 1963) experienced two prominent low states in 1995 June and 1996 January, each lasting 2–3 months, with depths of 1.5 mag (Honeycutt & Kafka 2004). These V533 Her low states were too brief for in-depth study. The DK Lac and V533 Her low states occurred 51 years and 32 years, respectively, after the nova. Neither system was monitored regularly prior to 1990, so other low states might have been missed. Honeycutt & Kafka found that in 12 years of monitoring 65 old novae and NL CVs, $\sim 15\%$ showed at least one low state exceeding 1.5 mag. Statistics for the old novae portion of the sample are not as good as desired, but there is nevertheless no evidence that the rate of low states in old novae (2 of ~ 24) is any different from that for NLs, at least when the old novae are examined 30–60 years after the nova. One might expect that if low states mark the manner in which old novae approach hibernation, then low states would be more frequent and/or more prolonged as the old novae became NLs. Our tentative conclusion is that low states are unrelated to hibernation, as supported by the fact that the low state in Figure 1 seems to be photometrically independent of the slow high-state decline, appearing to simply be superimposed on the light curve as an independent phenomenon. This is consistent with low states being due to a short-term effect rather than part of an evolutionary progression, the migration of starspots under the inner Lagrangian point (Livio & Pringle 1994) being a well-regarded mechanism.

Ignoring the low-state interruption, the brightness of DK Lac is seen in Figure 1 to decline rather smoothly by 0.2 mag over

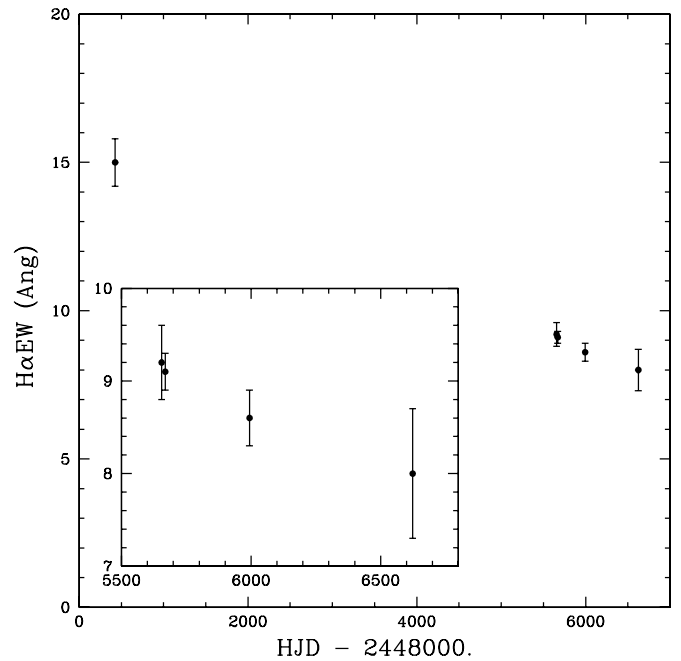


Figure 11. Equivalent width of $H\alpha$ in DK Lac as a function of JD, 1991–2008. The inset shows the most recent data points at sufficient scale to separate a closely spaced pair.

19 years. Activity cycles on the secondary stars of CVs have long been suspected to modulate the mass transfer rate and hence change the brightness of CVs on timescales of decades (e.g., Warner 1988; Bianchini 1990; Richman et al. 1994; Ak et al. 2001). However, we do not think that this effect is responsible for the 0.2 mag decline, for two reasons. First, there is no inflection in the decline as might be expected for cyclic behavior shorter than three decades. Second, the decline rate is consistent with the rate found for other old novae many decades after outburst. For nine old novae Duerbeck (1992) finds a mean rate of decline 50 years after outburst of 10 ± 3 mmag per year. This is attributed to the slow decline of irradiation-induced mass transfer and is concluded to be consistent with the hibernation hypothesis. The rate in DK Lac is 10.5 mmag per year, fully consistent with the behavior of other post-novae.

Over roughly the same interval in which the continuum of DK Lac declines by 0.2 mag, the EW of $H\alpha$ declines by $\sim 2\times$. Because the continuum is falling at the same time, this weakening of $H\alpha$ is actually even more pronounced. In Figure 11, we plot the EW of $H\alpha$ versus JD, where we have added a 1991 data point from Ringwald et al. (1996). The suggestion of a linear decline in $H\alpha$ EW over 16 years is intriguing, but needs confirmation. The initial fall in \dot{M} (and therefore in system brightness) following the nova eruption is thought to be due to declining irradiation of the donor star as the white dwarf cools following the nova eruption (Duerbeck 1992, and references therein). The hibernation scenario (Shara 1989) holds that \dot{M} continues to fall even further, taking the system through the dwarf nova (DN) regime and finally into a detached binary state with little or no accretion luminosity. In general, the EW of DN emission lines is greater than that of emission lines in old novae, opposite to the trend in Figure 11. Therefore, we suggest that the emission lines in DK Lac arise mostly from the illuminated secondary star rather than from the accretion disk. The breadth of the emission lines in DK Lac are small ($\text{FWHM}_{H\alpha} = 12 \text{ \AA}$, $\text{FWHM}_{H\epsilon} = 8 \text{ \AA}$) compared to most old nova. While much of the narrowness can be attributed to the

low-system inclination, it is also consistent with the emission arising from the irradiated inner hemisphere of the secondary star.

5. SUMMARY

Long-term photometry of Nova Lac 1950 (DK Lac) from 1991 to 2008 shows a 2 mag deep VY-Scl-type low state beginning 2001 January and lasting for between 2.5 and 3.4 years. The shape of the ingress into the low state is similar to that of other VY Scl stars, having a more rapid fall as the ingress proceeds. There is also an overall decline of 0.2 mag in the high-state brightness over our 19 years of data, consistent with the fading rate of other old novae when measured several decades after the nova eruption.

Our photometry also includes 26 continuous sequences each lasting 2–7 hr. We searched unsuccessfully for photometric periodicities in the range of 1–12 hr (the range of expected orbital periods) using both the long-term and the sequenced data, and both the high- and low-state data. The lack of orbital-timescales variations is attributed to the nearly face-on presentation of the disk. High-state spectra are also presented and discussed. We find that the equivalent width of H α falls by approximately double from 1991 to 2008.

The fact that this low state occurred in an old novae suggests that it might be connected to the entrance of DK Lac into hibernation. However, no distinction is found between the low states of old nova and those of NL CVs (which were presumably unrecorded novae hundreds of years ago). Instead we conclude that low states are unrelated to the possible entrance of a system into hibernation.

Constantine Deliyannis, Caty Pilachowski, and their students had programs on the WIYN 0.91 m that required photometric weather. When the weather was mostly clear but non-photometric, DK Lac frequently became the backup target.

Some the initial work on this project was done by Doug Hoffman as a Research Experience for Undergraduates (REU) student at Indiana University, supported by the National Science Foundation.

REFERENCES

- Ak, T., Ozkan, T., & Mattei, J. A. 2001, *A&A*, **369**, 882
 Bertin, E., & Arnouts, S. 1996, *A&AS*, **117**, 393
 Bianchini, A. 1990, *AJ*, **99**, 1941
 Cohen, J. G. 1985, *ApJ*, **292**, 90
 Duerbeck, H. W. 1981, *PASP*, **93**, 165
 Duerbeck, H. W. 1992, *MNRAS*, **258**, 629
 Henden, A. A., Freeland, E., & Honeycutt, R. K. 2001, *IAU Circ.*, **7777**
 Henden, A. A., & Honeycutt, R. K. 1997, *PASP*, **109**, 441
 Hoffman, D., Honeycutt, R. K., Kafka, S., & Henden, A. A. 2003, *BAAS*, **35**, 1338
 Honeycutt, R. K. 1992, *PASP*, **104**, 435
 Honeycutt, R. K. 1994, in *ASP Conf. Ser. 55, Astronomy from the Earth and the Moon*, ed. D. M. Pyper & R. J. Angione (San Francisco, CA: ASP), **103**
 Honeycutt, R. K., Adams, B. R., Swearingen, D. J., & Kopp, W. R. 1994a, *PASP*, **106**, 670
 Honeycutt, R. K., Cannizzo, J., & Robertson, J. W. 1994, *ApJ*, **425**, 835
 Honeycutt, R. K., & Kafka, S. 2004, *AJ*, **128**, 1279
 Honeycutt, R. K., Robertson, J. W., Turner, G. W., & Vesper, D. N. 1994b, in *ASP Conf. Ser. 56, Interacting Binary Stars*, ed. A. W. Shafter (San Francisco, CA: ASP), **277**
 Honeycutt, R. K., & Turner, G. W. 1992, in *ASP Conf. Ser. 34, Robotic Telescopes in the 1990s*, ed. A. V. Filippenko (San Francisco, CA: ASP), **77**
 Honeycutt, R. K., Vesper, D. N., White, J. C., Turner, G. W., & Adams, B. R. 1990, in *CCDs in Astronomy. II. New Methods and Applications of CCD Technology*, ed. A. G. D. Philip, D. S. Hayes, & S. J. Adelman (Schenectady, NY: L. Davis Press), **177**
 Hroch, F. 1998, in *Proc. 29th Conf. on Variable Star Research, Computer Programs for CCD Photometry*, ed. J. Dusek & M. Zejda (Brno: Masaryk Univ.), **30**
 Kafka, S., & Honeycutt, R. K. 2005, *AJ*, **130**, 742
 Kafka, S., Honeycutt, R. K., & Howell, S. B. 2006, *AJ*, **131**, 2673
 Kafka, S., Honeycutt, R. K., Howell, S. B., & Harrison, T. E. 2005a, *AJ*, **130**, 2852
 Kafka, S., Howell, S. B., Honeycutt, R. K., & Robertson, J. W. 2007, *AJ*, **133**, 1645
 Kafka, S., Ribeiro, T., Baptista, R., Honeycutt, R. K., & Robertson, J. W. 2008, *ApJ*, **688**, 1302
 Kafka, S., Robertson, J. W., Honeycutt, R. K., & Howell, S. B. 2005b, *AJ*, **129**, 2411
 Livio, M., & Pringle, J. E. 1994, *ApJ*, **427**, 956
 Martin, R. G., & Tout, C. A. 2005, *MNRAS*, **358**, 1036
 Munari, U., & Zwitter, T. 1997, *A&A*, **318**, 269
 Naylor, T., Charles, P. A., Mukai, K., & Evans, A. 1992, *MNRAS*, **258**, 449
 Ribbe, J. 1951, *PASP*, **63**, 39
 Richman, H. R., Applegate, J. H., & Patterson, J. 1994, *PASP*, **106**, 1075
 Ringwald, F. A., Naylor, T., & Mukai, K. 1996, *MNRAS*, **281**, 192
 Robertson, J. W., Honeycutt, R. K., & Turner, G. W. 1995, *PASP*, **107**, 443
 Schmidtke, P. C., Ciudin, G. A., Indlekofer, U. R., Johnson, D. R., Fried, R. E., & Honeycutt, R. K. 2002, in *ASP Conf. Ser. 261, The Physics of Cataclysmic Variables and Related Objects*, ed. B. T. Gansicke et al. (San Francisco, CA: ASP), **539**
 Shara, M. M. 1989, *PASP*, **101**, 5
 Slavin, A. J., O'Brien, T. J., & Dunlop, J. S. 1995, *MNRAS*, **276**, 353
 Szkody, P. 1994, *AJ*, **108**, 639
 Vogt, N. 1990, *ApJ*, **356**, 609
 Warner, B. 1986, *MNRAS*, **222**, 11
 Warner, B. 1988, *Nature*, **226**, 129
 Warner, B. 1995, *Cataclysmic Variable Stars*, CAS 28 (Cambridge: Cambridge Univ. Press)