Long-Term Optical and X-Ray Observations of the Old Novae DI Lacertae and V841 Ophiuchi

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ABSTRACT. We present an analysis of ground-based optical photometry and spectroscopy and Rossi X-Ray Timing Explorer X-ray observations of the old novae DI Lacertae and V841 Ophiuchi. Our optical photometry data (obtained with the automated photometry telescope RoboScope) comprise an almost decade-long light curve for each star, while the contemporaneous spectroscopy and X-ray observations repeatedly sampled each nova during separate intervals of $\approx 45-55$ days in length. The long-term optical light curves of both novae reveal quasi-periodic variability on typical timescales of $30-50$ days with amplitudes of $\Delta V \sim 0.4-0.8$ mag. V841 Oph also displays a long-term, sinusoidal modulation of its optical light on a timescale of $3.5-5$ yr. The optical spectra of these novae display quite different characteristics from each other, with DI Lac showing narrow Balmer emission cores situated in broad absorption troughs while V841 Oph exhibits strong single-peaked Balmer, He I, and He II emission lines. We find little change between spectra obtained during different optical brightness states. The X-ray count rates for both novae were very low ($\approx 1.5$ counts s$^{-1}$), and there was no reliable correlation between X-ray and optical brightness. The combined X-ray spectrum of DI Lac is best fit by a bremsstrahlung emission model (with $kT \approx 4$ keV and $N_H < 1.8 \times 10^{22}$ cm$^{-2}$); the X-ray spectrum of V841 Oph is too weak to allow model fitting. We discuss the possible origin of variability in these old novae in terms of magnetic activity on the secondary star, dwarf nova type disk instabilities, and the "hibernation" scenario for cataclysmic variable stars.

1. INTRODUCTION

Cataclysmic variables (CVs) are semidetached interacting binary stars composed of a white dwarf (WD) primary star and a low-mass ($\lesssim 0.5$ $M_\odot$) main-sequence secondary star, with typical orbital periods of $\lesssim 1$ day. The Roche lobe filling secondary star loses mass through the inner Lagrangian point into an accretion disk formed around the WD (for nonmagnetic CVs). Classical novae are a subclass of CV in which a thermonuclear runaway is triggered in a reservoir of matter that has been gradually accreted onto the WD. The resultant outburst produces a peak brightness increase of $\approx 6-15$ mag and releases $10^{42}-10^{46}$ ergs (see review in Warner 1995, chap. 5).

The outbursts of novae are often well observed, and the long-term behavior of many dwarf novae and nova-like
CVs is monitored by the American Association of Variable Star Observers. However, there have been few programs for monitoring the variability of novae at quiescence. One such program, using an automated telescope called RoboScope (see § 2.1), has monitored 22 old novae and 42 nova-like CVs, most of them for over 9 years now. RoboScope has found several kinds of unusual photometric behavior. About one-third of the old novae have shown quasi-periodic variability for a year or two, interspersed with stable light curves. These variations do not appear stochastic as they repeat at similar periods when they reappear. Preliminary analysis of RoboScope light curves spanning several years for the old nova DI Lacertae suggested brightness oscillations on a timescale of $\approx 35$ days (Honeycutt, Robertson, & Turner 1995), while the old nova V841 Ophiuchi also displayed prominent variability (Honeycutt et al. 1994). In order to determine if these oscillations could be related to a disk instability mechanism (as operates in dwarf novae) or to mass transfer or magnetic effects on the secondary star, we attempted a detailed study of DI Lac and V841 Oph, which are among the most active and brightest of the systems showing the oscillations.

DI Lac (= Nova Lac 1910) was a moderately fast nova that reached a maximum brightness of $m_V(\text{max}) = 4.3$ mag during its outburst. V841 Oph (= Nova Oph 1848) was a slow nova that reached a similar brightness, $m_V(\text{max}) = 4.2$ mag (Kukarkin et al. 1971). The reddening for both objects has been measured from International Ultraviolet Explorer (IUE) ultraviolet and ground-based optical spectra. The range for DI Lac is $E(B-V) = 0.15-0.41$ (Bruch 1984; Cassatella & Gonzalez-Riestra 1990), while for V841 Oph it is $E(B-V) = 0.30-0.58$ (Bruch 1984; Cassatella & Gonzalez-Riestra 1990; Weight et al. 1994; Verbunt et al. 1997). Nova shells were not detected in H$\alpha$ for either CV (Cohen 1985). In X-rays, DI Lac was undetected in the ROSAT PSPC All Sky Survey, with a $2 \sigma$ upper limit of $0.013 \text{ counts s}^{-1}$ in the 11–201 channel (0.1–2.0 keV) energy range during 299 s total exposure time, while V841 Oph was a marginal detection with $0.017 \pm 0.007 \text{ counts s}^{-1}$ in the “hard” 0.9–2.0 keV ROSAT energy range ($0 \pm 0.025 \text{ counts s}^{-1}$ in the full ROSAT energy range) during 402 s total exposure time (Verbunt et al. 1997).

We report here on the results of ground-based optical photometry and spectroscopy and Rossi X-Ray Timing Explorer (RXTE) X-ray observations of DI Lac and V841 Oph. The optical photometry comprises an almost decade-long light curve for each star, while the contemporaneous spectroscopic and X-ray observation repeatedly sampled each nova during separate intervals of $\approx 45$–55 days in length.

### 2. Observations and Analysis

Our long-term optical photometry of DI Lac and V841 Oph was accomplished from 1990 to 1998, while the spectroscopic and X-ray observations took place in 1997. These observations are summarized in Tables 1 and 2 and are discussed in detail below.

#### TABLE 1

| UT Date and Time* | HJD* | Observatory | Mode* | Exposure or GTI (s) | Comment |
|-------------------|------|-------------|-------|---------------------|---------|
| 1990 Nov 12 ............... | 2,448,207.7 | RoboScope | P | 240* | Starting date |
| 1997 Jul 25 10:43:44...... | 2,450,654.94822 | RXTE | X | 2528 | ID 20037-02-01-00 |
| 1997 Jul 27 09:01:47...... | 2,450,654.87744 | APO | S | 900 | |
| 1997 Jul 27 09:16:53...... | 2,450,654.88792 | APO | S | 737 | |
| 1997 Jul 30 04:16:00...... | 2,450,659.67921 | RXTE | X | 944 | |
| 1997 Aug 03 04:11:12 ...... | 2,450,663.68424 | RXTE | X | 1536 | ID 20037-02-03-00 |
| 1997 Aug 07 04:12:00 ...... | 2,450,667.67683 | RXTE | X | 1680 | ID 20037-02-04-00 |
| 1997 Aug 12 03:42:40 ...... | 2,450,672.65668 | RXTE | X | 592 | ID 20037-02-05-00 |
| 1997 Aug 17 03:42:18 ...... | 2,450,677.65666 | APO | S | 900 | |
| 1997 Aug 17 03:45:36 ...... | 2,450,677.65893 | RXTE | X | 1024 | ID 20037-02-06-00 |
| 1997 Aug 23 03:46:40 ...... | 2,450,683.65991 | RXTE | X | 832 | ID 20037-02-07-00 |
| 1997 Aug 27 03:46:56 ...... | 2,450,687.66024 | RXTE | X | 736 | ID 20037-02-08-00 |
| 1997 Sep 01 08:12:48 ...... | 2,450,692.84503 | RXTE | X | 1616 | ID 20037-02-09-00 |
| 1997 Sep 03 05:56:28 ...... | 2,450,694.74974 | WIYN | S | 900 | No flux calibration |
| 1997 Sep 04 03:33:17...... | 2,450,695.69269 | WIYN | S | 900 | No flux calibration |
| 1997 Sep 06 08:08:48 ...... | 2,450,697.84239 | RXTE | X | 1776 | ID 20037-02-10-00 |
| 1998 Nov 30 ................ | 2,451,147.6 | RoboScope | P | 240* | Ending date |

* At midpoint of exposure or Good Time Interval (GTI).

* P: ground-based photometry; S: ground-based spectroscopy; X: X-ray.

* One or two measurements per night.
**TABLE 2**

**LOG OF OBSERVATIONS FOR V841 OPH**

| UT Date and Time | HJD | Observatory | Mode | Exposure or GTI (s) | Comment |
|------------------|-----|-------------|------|--------------------|---------|
| 1991 May 31      | 2448407.7 | RoboScope | P    | 240^a              | Starting date |
| 1997 Apr 30      | 2450569.1797 | RXTE | X    | 1936               | ID 20037-01-01-00 |
| 1997 May 05      | 2450574.03997 | RXTE | X    | 1856               | ID 20037-01-02-00 |
| 1997 May 07      | 2450575.77120 | APO | S    | 600                |         |
| 1997 May 10      | 2450579.37966 | RXTE | X    | 1936               | ID 20037-01-03-00 |
| 1997 May 14      | 2450582.77618 | RXTE | X    | 1408               | ID 20037-01-04-00 |
| 1997 May 17      | 2450585.76552 | WIYN | S    | 4500               | Three combined spectra |
| 1997 May 20      | 2450587.83795 | RXTE | X    | 1792               | ID 20037-01-05-00 |
| 1997 May 26      | 2450594.75235 | RXTE | X    | 1872               | ID 20037-01-06-00 |
| 1997 May 27      | 2450595.76552 | APO | S    | 600                |         |
| 1997 May 30      | 2450598.71888 | RXTE | X    | 1648               | ID 20037-01-07-00 |
| 1997 Jun 04      | 2450604.46244 | RXTE | X    | 832                | ID 20037-01-08-00 |
| 1997 Jun 09      | 2450608.78613 | RXTE | X    | 2160               | ID 20037-01-09-00 |
| 1997 Jun 18      | 2450618.18935 | RXTE | X    | 1376               | ID 20037-01-11-00^d |
| 1998 Sep 04      | 2451060.5 | RoboScope | P    | 240^a              | Ending date |

^a At midpoint of exposure or Good Time Interval (GTI).  
^b P: ground-based photometry; S: ground-based spectroscopy; X: X-ray.  
^c One or two measurements per night.  
^d Our 10th RXTE observation of V841 Oph on 1997 Jun 14 UT (ID 20037-01-10-00) was unusable due to a software event that shut down all of the detectors during the slew to the target.

### 2.1. Optical Photometry

Our optical photometry data were acquired by RoboScope, a 41 cm telescope in Indiana equipped for automated differential CCD stellar photometry (Honeycutt & Turner 1992). All observatory operations (including data reductions) are accomplished as fully unattended and unsupervised tasks, which makes practical the acquisition of long homogeneous data streams. Typically, RoboScope obtains one or two 4 minute exposures per clear night for each of ~140 program stars. The data are reduced using the method of incomplete ensemble photometry (Honeycutt 1992). For DI Lac, 85 ensemble stars were used in 987 exposures over nine observing seasons from 1990 November to 1998 November. For V841 Oph, 24 ensemble stars were used in 611 exposures over eight observing seasons from 1991 May to 1998 September. The zero points of the differential light curves were established using secondary standard stars from Henden & Honeycutt (1995, 1997). Six such secondary standards were used for V841 Oph, while 13 were employed for DI Lac. Typical 1σ uncertainties in the calibrated magnitudes are on the order of 0.01–0.05 mag. Over the entire multiyear range of the RoboScope light curves, the mean magnitudes were $V \approx 14.55$ for DI Lac and $V \approx 13.6$ for V841 Oph, with full ranges of variability of $\Delta V \approx 0.9$ mag and $\Delta V \approx 1$ mag, respectively. The RoboScope light curves of DI Lac and V841 Oph are shown in Figures 1 and 2.

With only limited excursions to anomalously fainter

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**FIG. 1.—**Optical ($V$) light curve of DI Lac from RoboScope. The top panel shows the entire light curve, while the bottom panel shows the region around the RXTE observations. The midpoint time of the RXTE observations is marked with an arrow. The horizontal bars above the data in the top panel show the eight observing seasons (the short initial observing season around HJD 2,448,200 is not marked), while the bar below the data shows the range of HJD displayed in the bottom panel.
magnitudes, the typical minimum magnitude of \( \approx 14.7 \) for DI Lac has a sharp boundary at any given epoch. However, the minimum brightness displays a slight, apparently linear, trend toward increasing brightness over the 8 years of RoboScope observation. If we ignore for the moment the small number of data points that fall below the well-defined low brightness limit seen in the top panel of Figure 1, then the typical minimum brightness of DI Lac changes from \( V \approx 14.75 \) mag at the beginning of the RoboScope coverage to \( V \approx 14.67 \) mag at the end. This corresponds to a mean increase of the minimum brightness by \( \Delta V \approx -0.01 \) mag yr\(^{-1}\). The maximum brightness of DI Lac is much less uniform, and it is difficult to determine if the maximum brightness behaves in the same manner as the minimum brightness. A linear fit to the complete DI Lac light curve (with each data point weighted by the inverse square of its \( 1 \sigma \) uncertainty) gives the rate of change of the mean magnitude as less than \( +0.001 \) mag yr\(^{-1}\); that is, the mean brightness of DI Lac is essentially constant. However, if we exclude the two excursions to fainter magnitudes at HJD 2,450,600 and HJD 2,451,000 (as well as the excursion to brighter magnitudes at HJD 2,450,300), then the slope of the linear fit changes to \( \Delta V = -0.004 \) mag yr\(^{-1}\), that is, a trend toward increasing mean brightness.

The faint magnitude excursions in the light curve of DI Lac are very similar to the “dips” seen by Honeycutt, Robertson, & Turner (1998a) in long-term RoboScope light curves of five old novae and nova-like CVs. In the latter systems, the dips were found to often be paired with a preceding or following outburst, although the dips also sometimes occurred as isolated events. Honeycutt et al. (1998a) do not find a clear mechanism (e.g., disk instabilities, truncated disks, mass transfer modulation) that is responsible for the dips, but conclude that the overall photometric behavior (dips and outbursts) of the novae and nova-like CVs that they studied is likely to be governed either by a combination of disk and mass transfer events or by mass transfer events alone.

In contrast to the linear trend in the minimum brightness of DI Lac, the minimum brightness of V841 Oph appears to follow an almost sinusoidal trend that completes approximately 1.5–2 cycles during the 7.5 year RoboScope coverage. As seen in the top panel of Figure 2, the minimum brightness of V841 Oph varies from \( V \approx 14.5 \) mag to \( V \approx 13.8 \) mag. The maximum brightness of V841 Oph, which ranges from \( V \approx 13.1 \) mag to \( V \approx 13.4 \) mag, displays the same behavior; that is, when the minimum brightness at a given epoch is at its faint (bright) level, the maximum brightness is also at its faint (bright) level. We note that the magnitude range spanned by the minimum brightness in V841 Oph is about twice as large as that spanned by the maximum brightness. Although a linear fit to this overall trend is perhaps not the optimum choice, the corresponding rate of mean magnitude change is \( \Delta V = +0.010 \) mag yr\(^{-1}\). It is possible (but not required by the data!) that the apparently linear trend in the light curve of DI Lac may also be a sinusoid, but with a much longer cycle length than in V841 Oph.

We searched for periodicities in the range 10–100 days in the RoboScope light-curve data in two ways: by applying the phase dispersion minimization (PDM) algorithm (Stellingwerf 1978), as well as performing an independent power spectrum analysis using the CLEAN algorithm (Roberts, Lehar, & Dreher 1987). We performed the period search on both the entire data set for each CV, as well as on the data subsets from individual observing seasons (indicated in Figs. 1 and 2). The most prominent period detected in each data set is listed in Table 3 (in several cases, most notably for the combined data sets for each nova, two

![Fig. 2.—As in Fig. 1, but for V841 Oph](image)

**Table 3**

| PERIODS IN OPTICAL LIGHT CURVES |
|---------------------------------|
| **PERIOD (days)**               |
| **OBSERVING SEASON**            | **DI Lac** | **V841 Oph** |
| 1 .................................. | 40         | 35           |
| 2 .................................. | 29         | 36           |
| 3 .................................. | 39         | 69           |
| 4 .................................. | 31         | 40           |
| 5 .................................. | 38         | 42           |
| 6 .................................. | 75, 40     | 49           |
| 7 .................................. | 80, 28     | 54           |
| 8 .................................. | 31, 21     | 48           |
| Combined ....................... | 43, 37     | 49, 36       |
significant periods are listed). In general, the two period search methods gave equivalent results to within better than 1–4 days. All of the detected timescales appear to correspond to quasi-periodic behavior rather than truly periodic variability such as that resulting from, for example, an eclipsing orbit. The timescales have significant “flexibility” (on the order of 1–5 days for periods ∼50 days, 5–20 days for periods ∼50 days) over the multiyear length of the light curves (as shown by substantially broadened dips and peaks in the PDM and CLEAN analyses, respectively). Phase-binned light curves of both CVs folded on the shorter period found for each combined data set are shown in Figure 3. We note that the true amplitude of variation in a given cycle or observing season will be larger than the 0.1–0.2 mag suggested by Figure 3, in which data from many cycles with slightly different amplitudes and periods have been averaged together. Inspection of Figures 1 and 2 shows amplitudes of 0.4–0.8 mag for the full range of variability within each observing season. The long-term sinusoidal trend in the light curve of V841 Oph is also well fit by a periodicity in the range 1800–1900 days or, with slightly less agreement, 1250–1300 days. (We note that these two period ranges are approximately related by the ratio 3:2, so we are likely seeing an aliasing effect due to the fact that only 1.5–2 cycles of these long periods are contained in the light curves.)

2.2. Optical Spectroscopy

We obtained optical spectra of both CVs using the Double Imaging Spectrograph on the Apache Point Observatory (APO) 3.5 m telescope (Gillespie, Loewenstein, & York 1995) during University of Washington share time. Spectra of DI Lac were obtained in 1997 July and August; spectra of V841 Oph were obtained in 1997 May. The APO spectra have a resolution of ∼2 Å and cover simultaneous wavelength ranges of ∼4200–5000 Å and ∼5800–6800 Å. The raw spectrum images were reduced in the standard fashion using IRAF. The instrumental response was removed via spectra of standard stars (Massey et al. 1988) obtained on the same nights; however, slit losses due to guiding errors rendered the absolute flux calibration unreliable. Consequently, we have normalized the spectra to a constant continuum level of 1.0.

A representative spectrum of DI Lac is shown in Figure 4. Note the prominent Balmer absorption troughs containing narrow, central emission cores. Our other two APO spectra of DI Lac (not shown) are essentially identical to this one, with the exception that the Balmer emission cores in the August spectrum are somewhat stronger (relative to He ii) than in the July spectra. The He i λ4471 feature (see inset) is present with the same profile shape in all three of our spectra. It is suggestive of the absorption trough with central emission as seen in the Balmer lines. The feature

Fig. 4.—Representative optical spectrum of DI Lac from APO on 1997 July 25 09:01:47 UT (HJD 2,450,654.87744). The spectrum has been normalized to a continuum level of 1.0. The wavelengths of prominent line transitions are marked. The box inset in the left panel shows an expanded view of the region from 4390 to 4520 Å. The two features highlighted by dark underlines are marked (from left to right) “?” and “He1” in the full spectrum plot.

2 Also see http://www.apo.nmsu.edu/.
Flux-calibrated optical spectra of both DI Lac and V841 Oph are shown in Williams (1983), with resolutions of 5.1 and 6.7 Å, respectively, and in Ringwald, Naylor, & Mukai (1996), with resolution of 15–20 Å for both. Williams (1983) obtained his spectra in 1981, while Ringwald et al. (1996) obtained theirs in 1990. In both papers, the spectra of both novae show steep blue continua; the observed continuum of DI Lac is bluer than that of V841 Oph (but different reddening values could eliminate or reverse this characteristic). Ringwald et al. (1996) fit a power law of the form $F_\lambda \propto \lambda^{-a}$ to the continuum regions 5600–6500 Å and 6650–8000 Å in their spectra. These fits yielded indices of $a = 1.81(2)$—dereddened to $a_0 = 3.10(3)$ using $E(B-V) = 0.41$—for DI Lac and $a = 1.45(1)$—dereddened to $a_0 = 2.79(1)$ using $E(B-V) = 0.58$—for V841 Oph. Castellana et al. (1989) performed this power-law fit to the wavelength region 1200–3200 Å in IUE UV spectra of DI Lac and V841 Oph. Using reddenings at the low ends of the ranges given in § 1, $E(B-V) = 0.15$ for DI Lac and $E(B-V) = 0.30$ for V841 Oph, they calculated dereddened slopes of $a_0 = 1.5$ and $a_0 = 2.0$, respectively. Comparison with the slope expected for the continuum flux distribution of a steady state accretion disk composed of parcels radiating as blackbodies, $a = 2.3$ (Pringle 1981), suggests that the true reddening values for DI Lac and V841 Oph are near the middle of the ranges given in § 1.

In 1936, both of these novae were observed spectroscopically by Humason (1938), who noted their strong blue continua, but also noted the absence of any lines, emission or absorption. Since that time, the available published spectra of DI Lac and V841 Oph in Greenstein (1960), Williams (1983), and Ringwald et al. (1996) are consistent with our current spectra (see spectroscopic histories summarized in Ringwald et al. 1996), with the exception that Williams (1983) did not report the detection of any He II $\lambda4686$ emission in either star.

### 2.3. X-Ray Observations

DI Lac and V841 Oph were each observed 10 times during 1997 July–September and 1997 April–June, respectively, with the Proportional Counter Array (PCA; Jahoda et al. 1996) on the RXTE satellite (e.g., Bradt, Rothschild, & Swank 1993). The PCA consists of five xenon-methane proportional counters effective over the range 2–60 keV (with 18% energy resolution at 6 keV). Each RXTE visit constituted a Good Time Interval on-source lasting $\approx 1000$–2500 s. We extracted the net average X-ray count rate from each visit and the X-ray spectrum from the 10 combined visits to each star using the FTOOLS/LHEASOFT (v5.0) software package. We utilized the faint source

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3 See http://www.noao.edu/wiyn/.

4 Also see http://heasarc.gsfc.nasa.gov/docs/xte/.
The X-ray light curves constructed from the mean count rates at each visit for DI Lac and V841 Oph are shown in Figures 6 and 7, respectively, along with the corresponding sections of their RoboScope $V$ band light curves. The light-curve counts were summed in the energy range 0–15 keV. Inspection of the X-ray spectra (see below) revealed an essentially zero count rate dominated by noise at energies higher than 15 keV. The mean X-ray count rates averaged over all 10 visits to each target are 1.30 $\pm$ 0.32 counts s$^{-1}$ for DI Lac and 0.56 $\pm$ 0.73 counts s$^{-1}$ for V841 Oph. Considering these very low count rates, it is not clear whether or not the variability seen in the X-ray light curves is real.

Additional analysis and model-fitting (DI Lac only) of the X-ray spectra of these novae was performed using the routine XSPEC (v11). Although we extracted the full range of available energy channels in the X-ray spectra, only the range 0–15 keV was used for fitting the models to the DI Lac data. The X-ray spectra for DI Lac and V841 Oph are shown in Figures 8 and 9. The X-ray spectrum of V841 Oph is shown on the same scale as that of DI Lac; the former is clearly much weaker than the latter. We attempted to extract a better spectrum of V841 Oph by using only the data from the four visits with the largest count rates (visits 3, 5, 9, and 11; see Table 2). Unfortunately, this spectrum was virtually identical to the total combined spectrum (i.e.,

Fig. 6.—The optical ($V$) light curve of DI Lac from RoboScope (small circles, left axis scale) with the mean RXTE count rate (0–15 keV) at each of the 10 epochs of observation (large circles connected by a dotted line, right axis scale). One $\sigma$ error bars are shown on all of the points; the arrows mark the times when optical spectra were obtained. The lowered arrows mark the WIYN spectra; the others are from APO.

Fig. 7.—As in Fig. 6, but for V841 Oph

Fig. 8.—Top panel shows the combined X-ray spectrum of DI Lac (crosses) with the best-fitting bremsstrahlung model modified by photoelectric (H column) absorption (solid line). Bottom panel shows the residuals to the model fit.

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5 See http://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook_book.html.
by a multiplicative component representing photoelectric plasma, and (3) bremsstrahlung. Each model was modified spectrum: (1) blackbody, (2) Raymond-Smith thermal plasma models. In all models, is a normalization constant. Close to 1.0 indicates a good fit.

For DI Lac, we fit three simple models to the X-ray spectrum of DI Lac shown in Fig. 8.

As the X-ray spectrum of DI Lac shown in Fig. 8.

For DI Lac, we fit three simple models to the X-ray spectrum: (1) blackbody, (2) Raymond-Smith thermal plasma, and (3) bremsstrahlung. Each model was modified by a multiplicative component representing photoelectric (H column) absorption. More complex models were not warranted owing to the small number of counts per energy channel in the data. In all cases, the data were weighted using the XSPEC-recommended scheme appropriate for small count numbers, \( W_i = 1 + (N_i + 0.75)^{0.5} \) (Gehrels 1986). The results of these model fits are summarized in the first three rows of Table 4. All of the models produce nearly indistinguishable fits to the observed spectrum. The bremsstrahlung model is formally the best fitting (with lowest reduced \( \chi^2 \) and highest null hypothesis probability) and is plotted over the observed spectrum in Figure 8.

All of the models were only able to constrain the hydrogen column density to an upper limit; the values of \( N_H \) quoted in the first three rows of Table 4 are the upper ends of the one-parameter 90% confidence intervals. We used the relation

\[
N_H = E(B - V) \times 5.8 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}
\]

(Bohlin, Savage, & Drake 1978) to estimate values of \( N_H \) spanning the reddening range given in § 1. We then refit the models to the X-ray spectrum of DI Lac with only two free parameters: temperature and normalization. The results are listed in the bottom six rows of Table 4. While slightly different from those obtained from the original model fits, they are completely consistent with them. The bremsstrahlung model yields a slightly lower nominal temperature of \( kT \approx 4.1-4.2 \text{ keV} \) (vs. \( kT = 4.5 \text{ keV} \) when \( N_H \) is a free

### Table 4

| MODEL               | REDUCED \( \chi^2 \) | \( P_0 \) | H COLUMN DENSITY \( (N_H) \) \( \times 10^{22} \text{ cm}^{-2} \) | 2-15 keV MODEL FLUX \( \times 10^{34} \text{ ergs s}^{-1} \text{ cm}^{-2} \) | \( kT \) (keV) | \( C_{\text{norm}} \) |
|---------------------|---------------------|----------|-------------------------------------------------|--------------------------------|----------------|-----------------|
| Blackbody           | 0.705               | 0.937    | \( \leq 1.2 \)                                  | \( 2.2 \times 10^{-12} \)    | 1.1 \( ^{+0.3}_{-0.2} \) | \( 3.0^{+0.5}_{-0.4} \times 10^{-5} \) |
| Raymond-Smith       | 0.617               | 0.982    | \( \leq 3.3 \)                                  | \( 2.6 \times 10^{-12} \)    | 3.2 \( ^{+0.3}_{-0.2} \) | \( 3.4^{+0.5}_{-0.4} \times 10^{-3} \) |
| Bremsstrahlung      | 0.484               | 0.999    | \( \leq 1.8 \)                                  | \( 2.7 \times 10^{-12} \)    | 4.5 \( ^{+0.3}_{-0.2} \) | \( 1.1^{+0.5}_{-0.4} \times 10^{-3} \) |

H Column Density Fixed from \( E(B - V) = 0.15 \)

| MODEL               | REDUCED \( \chi^2 \) | \( P_0 \) | H COLUMN DENSITY \( (N_H) \) \( \times 10^{22} \text{ cm}^{-2} \) | 2-15 keV MODEL FLUX \( \times 10^{34} \text{ ergs s}^{-1} \text{ cm}^{-2} \) | \( kT \) (keV) | \( C_{\text{norm}} \) |
|---------------------|---------------------|----------|-------------------------------------------------|--------------------------------|----------------|-----------------|
| Blackbody           | 0.683               | 0.954    | 0.09                                            | \( 2.2 \times 10^{-12} \)    | 1.1 \( ^{+0.1}_{-0.1} \) | \( 3.1^{+0.4}_{-0.3} \times 10^{-5} \) |
| Raymond-Smith       | 0.604               | 0.986    | 0.09                                            | \( 2.7 \times 10^{-12} \)    | 2.9 \( ^{+0.3}_{-0.2} \) | \( 3.7 \times 10^{-3} \) |
| Bremsstrahlung      | 0.471               | 0.999    | 0.09                                            | \( 2.7 \times 10^{-12} \)    | 4.2 \( ^{+0.3}_{-0.2} \) | \( 1.2^{+0.5}_{-0.4} \times 10^{-3} \) |

H Column Density Fixed from \( E(B - V) = 0.41 \)

| MODEL               | REDUCED \( \chi^2 \) | \( P_0 \) | H COLUMN DENSITY \( (N_H) \) \( \times 10^{22} \text{ cm}^{-2} \) | 2-15 keV MODEL FLUX \( \times 10^{34} \text{ ergs s}^{-1} \text{ cm}^{-2} \) | \( kT \) (keV) | \( C_{\text{norm}} \) |
|---------------------|---------------------|----------|-------------------------------------------------|--------------------------------|----------------|-----------------|
| Blackbody           | 0.689               | 0.951    | 0.24                                            | \( 2.3 \times 10^{-12} \)    | 1.1 \( ^{+0.1}_{-0.1} \) | \( 3.3^{+0.4}_{-0.3} \times 10^{-5} \) |
| Raymond-Smith       | 0.606               | 0.986    | 0.24                                            | \( 2.7 \times 10^{-12} \)    | 2.9 \( ^{+0.3}_{-0.2} \) | \( 3.8 \times 10^{-3} \) |
| Bremsstrahlung      | 0.475               | 0.999    | 0.24                                            | \( 2.7 \times 10^{-12} \)    | 4.1 \( ^{+0.4}_{-0.3} \) | \( 1.2^{+0.5}_{-0.4} \times 10^{-3} \) |

a There are 48 dof for fixed \( N_H \) models.
b Null hypothesis probability: the probability of obtaining a value of \( \chi^2 \) greater than or equal to the observed \( \chi^2 \) if the model is correct. A value close to 1.0 indicates a good fit.
c Quoted uncertainties are one-parameter 90% confidence intervals. \( T \) is the plasma temperature for the bremsstrahlung and Raymond-Smith plasma models. In all models, \( C_{\text{norm}} \) is a normalization constant.
d Additional model parameters of redshift and abundances were fixed at 0.0 and the values from Feldman 1992, respectively.

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parameter) and is still the best-fitting model for both values of $N_H$.

We note that the uncertainties quoted in Table 4 for $kT$ and $C_{\text{norm}}$ are one-parameter 90% confidence intervals; the interdependent parameter uncertainties will be slightly different. For example, for the bremsstrahlung model (with free $N_H$), the XSPEC routine *steppar* gives a two-parameter 90% confidence interval of

$$kT = 4.5^{+1.3}_{-1.2} \text{ keV}$$

for $kT$ with respect to $N_H$ and

$$kT = 4.5^{+1.8}_{-1.7} \text{ keV}$$

for $kT$ with respect to $C_{\text{norm}}$.

The X-ray count rates were too low to reliably fit spectrum models to any of the 10 individual RXTE visits to DI Lac. We constructed "low"- and "high"-state X-ray spectra by combining the data from visits with the lowest mean count rates (1, 2, 3, 4, 7) and from visits with the highest mean count rates (5, 6, 9) to see if there were any differences between the low and high X-ray brightness states. Other than a $\approx 1$ count s$^{-1}$ keV$^{-1}$ increase at the peak energy of the high-state spectrum, the two spectra are essentially indistinguishable from each other (and from the combined spectrum from all 10 visits). We conclude from this either that the spectral energy distribution of the X-ray-emitting source in DI Lac does not change as the overall brightness of the X-ray source changes or that the variability seen in the X-ray light curve of DI Lac is not real (i.e., it is a side effect of the very low count rates).

### 3. Discussion

#### 3.1. Optical Photometric Variability

Inspection of the RoboScope light curves of DI Lac and V841 Oph reveals variability on three distinct timescales. First, in the range 10–100 days, quasi-periods with typical lengths of $\approx 30–50$ days are present in each of these CVs. Yet, the presence (or lack) of periodic and/or quasi-periodic variability on timescales up to a few hundred days in V841 Oph has been contested in the literature. (To the best of our knowledge, no extensive database of photometric observations of DI Lac has been published prior to this work.) Using 420 archival visual observations of V841 Oph spanning 28 yr, Della Valle & Rosino (1987) quote an average period of 51.5 days with individual cycles ranging from 45 to 57 days. Shara, Potter, & Shara (1989) observed V841 Oph once per night for 31 nights during a 45 night interval in 1986 using a CCD camera + B filter and found a period of $\approx 40$ days. All of these values are comparable to the $\approx 35–50$ days we found for our complete RoboScope light curve of V841 Oph, as well as to the range of periods found for individual observing seasons in the RoboScope data (see Table 3). On the other hand, Duerbeck (1992) notes the presence of considerable variability in archival light curves of V841 Oph (including some of the same data used by Della Valle & Rosino 1987) but finds no evidence for periodicities up to 200 days.

It is quite interesting that the variability timescales in these two novae are similar to those that characterize dwarf nova outbursts (Warner 1995, chap. 3). Old novae are not assumed to have mass transfer rates, $\dot{M}$, above the threshold level ($\dot{M}_{\text{crit}}$) at which the accretion disk thermal instability mechanism operates in dwarf novae to produce their outbursts (Osaki 1996). However, the hibernation theory of cyclic evolution between CV variability types (Shara 1989, and references therein), predicts that when $\dot{M}$ eventually decreases back into the instability regime some decades after the nova outburst, then dwarf nova outbursts should resume. Both GK Persei (= Nova Per 1901; Bianchini et al. 1986) and V446 Herculis (= Nova Her 1960; Honeycutt et al. 1998b) have displayed dwarf nova eruptions in their postnova stages, and similar behavior has been suggested for a number of other old novae, commencing $\approx 50–200$ yr after their outbursts (Livio 1989; Warner 1995, chap. 4). The amplitudes of variability displayed by DI Lac and V841 Oph (see Figs. 1 and 2) are smaller than those typically observed for dwarf novae ($\Delta V \approx 2–4$ mag), but we cannot rule out the possibility of a disk instability mechanism being in operation—after all, it has been 90 years since the nova outburst of DI Lac and over 150 years since that of V841 Oph. Further, the classic thermal instability mechanism is not well explored for high-$\dot{M}$ disks, and other disk instabilities might operate as well (e.g., Whitehurst 1988; Mineshige 1993; Godon 1998).

The amplitudes of the $\approx 30–50$ day oscillations in DI Lac and V841 Oph are similar to those of the spaced stunted outbursts seen in some nova-like CVs (Honeycutt et al. 1998a). One of the suggestions for stunted outbursts made in Honeycutt et al. (1998a) is that they are dwarf nova eruptions seen against a background of brighter light in the system. If that suggestion is correct, then the oscillations reported here (as well as similar 25 days oscillations reported for RW Tri; Honeycutt et al. 1994) may be examples of dwarf nova type outburst behavior at relatively short recurrence times, $T_o \lesssim 50$ days ($T_o$ is typically $\approx 10$ days to hundreds of days—even tens of years in extreme cases—for dwarf novae; Warner 1995, chap. 3). Among the true dwarf novae, the Z Camelopardalis stars have outburst recurrence
times of $\approx 10$–$30$ days, somewhat shorter than the timescales for the oscillations observed in these novae. The Z Cam stars are thought to have high mass transfer rates (near $M_{\text{crit}}$). This suggests that if the oscillations observed in novae are analogous to dwarf nova outbursts, then they may be linked to the presence of relatively high mass transfer rates that are, nonetheless, smaller than both $M_{\text{crit}}$ and $M$ in the Z Cam stars.

Second, V841 Oph displays a distinct sinusoidal variation with a best period of 1800–1900 days (4.9–5.2 yr) or a slightly less preferred period of 1250–1300 days (3.4–3.6 yr). DI Lac does not appear to display similar sinusoidal variability, unless it occurs with a much longer period than in V841 Oph. Bianchini (1990) reports a long-term period in V841 Oph of 3.4 yr with mean amplitude of $\pm 0.3$ mag, which was determined from 420 visual observations spanning 30 yr (essentially the same early to mid-20th century data utilized by Duerbeck 1992; see below). Richman, Applegate, & Patterson (1994) reanalyzed the light curves presented by Bianchini (1990) and consider the case for a multiyear periodicity in V841 Oph to be very weak. However, with our RoboScope light curve, sinusoidal variability on comparable multiyear timescales has now been observed in two separate data sets for V841 Oph spanning almost 80 years of observation. While this still does not provide firm evidence of strictly periodic behavior, it certainly points to the presence of a mechanism operating in this CV that modulates its brightness on a characteristic timescale of several years.

Photometric variability in old novae on timescales of several years has generally been attributed to solar-type magnetic cycles on the secondary star that might be able to control the rate of mass loss through the inner Lagrangian point (Bianchini 1990; Applegate 1992). Although Richman et al. (1994) find that no CV studied to date displays strictly periodic behavior over multiyear intervals, they also note that the observed amplitudes ($\sim 0.2$ mag) and “apparent” timescales of variability of 5–$40$ yr are “plausible consequences from solar-type magnetic cycles.” We note that the shorter timescale ($\sim 30$–$50$ day) variability discussed above might also be linked to modulation of $M$ due to secondary star magnetic activity. If solar-type magnetic cycles can affect $M$ on timescales of years, then starspots induced by the magnetic cycle that migrate under the L1 point might also affect $M$ on shorter timescales, in a manner suggested by Livio & Pringle (1994) to explain the very low brightness states seen in some CVs.

Third, the mean magnitudes of both CVs are changing slowly, at rates measured in a few millimagnitudes (mmag) per year. The mean brightness of DI Lac is increasing by $\approx 4$ mmag yr$^{-1}$ since 1990. Duerbeck (1992) analyzed a large set of visual, photoelectric, and CCD observations of post-novae available in the literature (see references in Duerbeck 1992). These data cover a large part of the 20th century, from the 1920s through the 1980s. Duerbeck (1992) summarizes the long-term behavior of DI Lac as exhibiting a steady decline of $13 \pm 1$ mmag yr$^{-1}$ in visual observations obtained between 1921 and 1952. Sparse photoelectric and CCD data from 1953 to 1981 suggest a possible small brightness increase, which is supported by our recent RoboScope observations. For V841 Oph, visual observations from 1919–1952 and 1978–1991 yield a brightness decline of $7 \pm 1$ mmag yr$^{-1}$, while “no definitive brightness decline” (Duerbeck 1992) was found in photoelectric data from 1954 to 1988. Our post-1991 observations of V841 Oph suggest a trend toward decreasing mean brightness comparable to that noted by Duerbeck (1992) in the archival visual observations, although the obvious sinusoidal variation that dominates our light curve at long timescales makes this conclusion somewhat suspect.

In the “classical” hibernation scenario (Shara 1989), novae stay bright for $\approx 50$–$300$ yr following outburst, gradually declining in brightness during this time to a hibernating state characterized by low brightness ($M \approx 10$ or fainter) and low mass accretion rate ($\dot{M} \leq 10^{-12} M_{\odot}$ yr$^{-1}$). However, the photometric record of DI Lac from the 1920s (a decade after its outburst) to the 1990s does not show a simple decline in brightness. Instead, the brightness of DI Lac decreased for about four decades after outburst, but then apparently leveled off for several decades. In the last decade (covered in our RoboScope light curve), the brightness of DI Lac has been increasing. It is possible that we are seeing the influence of a mechanism (such as magnetic activity of the secondary star—see above—and/or accretion-induced irradiation of the secondary star) that modulates $M$ (and, hence, the brightness) in DI Lac over a long-term cycle (with period on the order of many decades) that obscures the general decline predicted by the hibernation scenario.

### 3.2. Optical Spectrum Variability

The optical spectra of DI Lac and V841 Oph are quite different, and this can possibly be ascribed to their difference in postoutburst ages. The spectrum of V841 Oph is similar to those of nova-like CVs (e.g., Warner 1995, chap. 4)—this suggests that V841 Oph still has a high accretion rate, even $\approx 150$ yr after outburst. The narrow emission components in DI Lac are suggestive of emission originating from the irradiated inner face of the secondary star, while the absorption troughs imply the presence of optically thick material in the system. The latter feature could be material ejected during the outburst of this younger post-nova; the lack of any detected Hz emission shell (Cohen 1985) does not preclude the existence of denser, nonemitting circumstellar material. The former feature offers a possible explanation for the gradual brightness increase seen in our RoboScope light curve of DI Lac (discussed in § 3.1) if the secondary star is being slowly heated via irradiation and is,
in turn, increasing the rate of mass transfer through the L1 point.

Although the RoboScope coverage is incomplete, we infer from the adjacent data that DI Lac was faint during our July spectra and bright during our August spectrum (see Fig. 6). As mentioned in § 2.2, the only difference between our July and August spectra is that the emission cores were somewhat stronger in August (bright state) than July (faint state). This is consistent with the hypothesis that these narrow emission features originate on the irradiated face of the secondary star if we make the logical assumption that the irradiation increases when DI Lac is bright. It does not, however, illuminate the exact mechanism producing the irradiation (i.e., whether the “excess” flux in the high state originates near the disk center—presumably due to a disk instability producing increased accretion onto the WD—or in the outer disk—presumably due to an increase in mass transfer through the L1 point). If we assume that the spectrum shown in Figure 4 (from July 27 09:01:47 UT) was obtained at an arbitrary orbital phase of 0.0, then the August 17 spectrum was obtained at a relative orbital phase of 0.9 (using $P_{\text{orb}} = 0.543773$ day; Ritter & Kolb 1998). Thus, these two spectra were obtained at similar orbital phases, and we do not expect the difference in the narrow emission component strength to be only due to system orientation.

The RoboScope coverage of V841 Oph during our spectroscopic (and X-ray) observations is more sparse than for DI Lac, but we can infer that the CV was returning to the faint state during our May 7 spectrum, was in its faint state during our May 14 and 17 spectra, and was likely near the bright state during our May 27 spectrum (see Fig. 7). The two elevated brightness points at HJD 2,450,610 and HJD 2,450,625 suggest that V841 Oph may have returned to a bright state sometime between the low states bracketing HJD 2,450,590 and HJD 2,450,630. If this is the case, then the somewhat stronger Hz emission of the May 7 and May 27 spectra (see Fig. 5) may be linked to the bright state of the CV. As with DI Lac, we calculated relative orbital phases for each of these spectra (using $P_{\text{orb}} = 0.60423$ day; Ritter & Kolb 1998), and obtained $\phi = 0.0, 0.6, 0.75, 0.1$ for May 7, 14, 17, 27, respectively. Unfortunately, this casts some doubt on the link between Hz emission strength and brightness state, since both of the bright state spectra (phases 0.0, 0.1) were obtained at different orbital phases than the faint state spectra (phases 0.6, 0.75). So, we cannot rule out the influence of system orientation effects in these spectra.

### 3.3. X-Ray Variability

Unfortunately, because of the weak X-ray emission from these CVs, little can be firmly stated about their X-ray variability. The count rates during visits 5 and 6 to DI Lac, which took place when we infer from the RoboScope light curve that the CV was in a bright state, are slightly elevated compared to the preceding visits. However, visit 7 also occurred during this optical bright state and does not show an elevated count rate. The mean X-ray count rate during each visit to V841 Oph also does not display any strong correlation with the corresponding optical state. The lack of large changes in X-ray flux or spectrum during the optical variations (as usually evident in dwarf novae; e.g., Szkody et al. 1999) argues against a disk instability scenario. Alternatively, this could indicate that the optical brightness is determined by activity in the outer disk only and, therefore, is not reflected in the X-ray behavior; however, the X-ray count rates are too low (and their corresponding error bars too large) to make any firm conclusions.

### 4. CONCLUSIONS

Our long-term optical light curves of the novae DI Lac and V841 Oph obtained with RoboScope reveal quasi-periodic variability with a characteristic timescale of $\sim 30–50$ days in both CVs. In addition, the light curve of V841 Oph displays evidence for sinusoidal variability with a period of 3.5–5 yr. The latter cannot be said to be strictly periodic since our data set covers only $\approx 1.5$ cycles; however, when this detection is added to past reports of multiyear periodicities in V841 Oph that have been reported in the literature, a strong case can be made for the presence of repeating multiyear variability with a preferred timescale in this CV. The most likely origin of such behavior is a solar-type magnetic cycle of the secondary star that modulates the rate of mass transfer through the L1 point. If this is the case, then the shorter $\sim 30–50$ days quasi-periodic variability in this system might also be related to the magnetic activity on the secondary star, for example, due to starspots that migrate under the L1 point and temporarily throttle mass transfer. DI Lac does not show evidence for cyclic multiyear variability, unless it occurs with a much longer period than the length of our RoboScope coverage ($\gtrsim 10$ yr). This casts some doubt on the origin of the $\sim 30–50$ day quasi-periodic variability as a facet of the secondary star’s magnetic activity, since both V841 Oph and DI Lac show the $\sim 30–50$ day quasi-periodic behavior, but only V841 Oph displays evidence for a multiyear solar-type magnetic cycle on the secondary star. On the other hand, the $\sim 30–50$ day timescale is very reminiscent of that expected for dwarf nova type behavior (although the amplitude of variability in these novae is smaller than in typical dwarf nova outbursts). This raises the possibility that this variability is caused by a disk instability (either the thermal disk instability that leads to dwarf nova outbursts operating at a low level or some other form of disk instability).

The X-ray spectrum of DI Lac is fit almost equally well by the three models we tried: a simple blackbody, a
Raymond-Smith thermal plasma, and bremsstrahlung emission. More complicated models (e.g., involving multiple components, lines, etc.) are unwarranted owing to the low X-ray flux. In addition to being the most physically plausible X-ray emission mechanism in a (nonmagnetic) CV, the bremsstrahlung model is formally the best fitting. Our X-ray spectrum model fit parameters ($kT_D \sim 4$ keV) are consistent with those obtained from ROSAT X-ray spectra of a sample of 37 disk-accreting CVs (Richman 1996). Unfortunately, the X-ray count rates in both of these systems were too low for any conclusions to be made about their time-resolved X-ray behavior. X-ray observations sample the innermost disk region, and we would expect to see different time-resolved behavior as the novae go into their optically bright state if the transition is triggered by a disk instability versus a change in $M$ from the secondary star. Additional time-resolved X-ray observations using the more sensitive Chandra and/or XMM X-ray satellites may be necessary to illuminate the inner workings of these old novae.

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