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CHARACTERISTICS OF HIGH-STATE/LOW-STATE TRANSITIONS IN VY SCULPTORIS STARS

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ABSTRACT

About 12 years of photometric monitoring of 65 nova-like cataclysmic variables (CVs) have allowed analysis of occasional VY Sculptoris type low states, which we define as a fading of more than 1.5 mag in less than 150 days. Detailed light curves of eight systems exhibiting these low states are presented and discussed. The data are sufficient to measure the speeds and the shapes of 29 transitions to and from the low state: both single-slope and dual-slope rises and falls are found, with the dual-sloped transitions always being faster when fainter. This behavior is consistent with the low states being due to a starspot on the secondary star, drifting under the inner Lagrangian point, if the two slopes are interpreted as being due to the passage of the umbral and penumbral portions of the starspot.

Key words: novae, cataclysmic variables

1. INTRODUCTION

Cataclysmic variables (CVs) are close binary systems consisting of a white dwarf primary that is accreting gas from a companion K–M dwarf that is filling its Roche lobe (Warner 1995; Hellier 2001). Most of the luminosity at visible wavelengths arises from the release of gravitational potential energy as the gas finds its way into the deep potential well of the white dwarf. CV subclasses are distinguished primarily by the different light curves resulting from the manner and geometry by which this energy is converted to radiation. In AM Herculis systems (polars) the gas is funneled to the white dwarf surface along the field lines of a strongly magnetized ($B \sim 10^7$ G) white dwarf. When the magnetic field is weaker, the white dwarf becomes encircled by an accretion disk, in which viscous forces convert the gravitational energy of the infalling gas into heat. Models of CV accretion disks show two stable states: a bright, hot, high-viscosity configuration with nearly steady state accretion through the disk, and a fainter, cool state in which gas from the secondary star accumulates in the outer disk because of low viscosity (Cannizzo 1993). This bistability is widely thought to be responsible for dwarf nova (DN) eruptions, in which the disk changes between the two states even in the presence of steady mass transfer ($\dot{M}$) from the secondary star. This thermal/viscous instability occurs only in a restricted range of disk temperatures (and hence in a restricted range of $\dot{M}$) over which partially ionized hydrogen controls the thermal disk structure. The regime of $\dot{M}$ occupied by the DN is illustrated by the dependence of $\dot{M}$ on the surface density or temperature of the disk. This is a multivalued S-curve that leads to a limit cycle when $\dot{M}$ is in the instability range below $\dot{M}_{crit}$ (Cannizzo 1993). Here $\dot{M}_{crit}$ is the rate of accretion associated with the local minimum of the S-curve appropriate to conditions in the outer disk and has a typical value of $\sim 10^{-9.5}\ M_\odot\ yr^{-1}$ for CVs. For $\dot{M} > \dot{M}_{crit}$, accretion takes place under steady state conditions, and the system appears as a nova-like (NL) CV, while systems having $\dot{M} < \dot{M}_{crit}$ appear as DN.

The VY Sculptoris subclass of NL CVs has pronounced low states in which the system fades by up to 5 mag at irregular intervals, which are considered to be due to the temporary cessation of mass transfer from the secondary star. Although low states occur in both disk and magnetic systems (Warner 1999), many authors restrict use of the term "VY Scl" to the disk systems. The most viable candidate mechanisms for VY Scl low states are the presence of a starspot or a starspot group on the secondary star, drifting underneath the inner Lagrangian point (Livio & Pringle 1994), or an irradiation feedback mechanism in which shadowing of the hot inner accretion disk by the fattened outer disk rim controls the mass loss from the secondary star (Wu et al. 1995). Hessman (2000) gives a short review of CV low states; a recent list of VY Scl stars can be found in Kato et al. (2002).

Low states appear to be a common property of accreting systems (including X-ray sources with neutron star or black hole primaries; Priedhorsky & Holt 1987), the evolution of which (and hence the identification of the ancestors and descendants) is controlled by the long-term $\dot{M}$. Until low states are understood, our snapshot knowledge of $\dot{M}$ may be easily misinterpreted. Using new data, this paper attempts to place observational constraints on the nature of VY Scl low states in NL CVs by examining the shapes of the transitions. A preliminary version of this work (Honeycutt & Kafka 2003) used shorter photometric time sequences and a somewhat different set of CVs but reached similar conclusions. Here, in § 2 we describe the data acquisition and reduction. Section 3 presents the light curves of the eight individual systems used, whereas the VY Scl transitions of the systems are analyzed and discussed in §§ 4 and 5. Section 6 summarizes our conclusions.

2. DATA ACQUISITION AND REDUCTIONS

Our data were acquired by RoboScope, a 0.41 m automated, unattended photometric telescope located in central Indiana that is devoted to long-term monitoring of accreting sources (Honeycutt et al. 1994a and references therein). Exposures have a typical duration of 4 minutes, providing a magnitude limit (for 0.15 mag accuracy) of $V = 17–18$, depending on lunar phase and sky transparency. Under good conditions the accuracy is less than 0.02 mag for $V \lesssim 16$.

The technique of incomplete ensemble photometry (Honeycutt 1992) is employed to form the differential light curve of each program star, with an arbitrary zero point. Secondary standards are then used to establish the proper zero point. Typically,

TABLE 1
ENSEMBLE REDUCTIONS

Star	Range	No. Exposures[a]	No. Comparisons[b]	No. Standards[c]	$\sigma_{\text{Zero point}}$ (mag)	Standards Reference
V794 Aql	1990 Nov–2003 Jul	1085	77	11	0.006	(1)
KR Aur	1990 Nov–2003 Apr	888	104	6	0.009	(1)
V533 Her	1990 Nov–2003 Jul	1257	64	9	0.008	(2)
MV Lyr	1990 Nov–2003 Jul	1233	128	11	0.007	(1)
LQ Peg	1993 Jul–2003 Jul	737	47	8	0.008	(2)
FY Per	1990 Nov–2003 Apr	1379	106	11	0.007	(1)
DW UMa	1990 Nov–2003 Dec	875	29	3	0.041	(1)
LN UMa	1993 Nov–2003 Jul	571	10	4	0.022	(2)

[a] Not including exposures used for upper limits.
[b] Number of comparison stars used in the photometry ensemble solution.
[c] Number of secondary standards used to determine the zero point.
REFERENCES.—(1) Henden & Honeycutt (1995); (2) Henden & Honeycutt (1997).

between 75 and 150 usable exposures are acquired each year for each of the ~125 program objects. The original target list included all the known (in 1989) old nova and NL CVs north of $\delta \sim -15^\circ$ that commonly appear brighter than the RoboScope magnitude limit. Anticipating that statistical analysis would be valuable after the program had run long enough to sample a variety of long-term behaviors, we have made an effort to preserve homogeneity of the target list and of the data reduction techniques. At the time the system was implemented, capabilities for storing large numbers of digital images were limited. For that reason, the original images have not been saved for most of the years of operation; instead, only the extracted instrumental magnitudes plus a characterization of each stellar profile have been retained. Therefore, unrecognized cosmic-ray events occasionally corrupt a light-curve point. This is more likely to affect the star aperture than the sky annulus in the reductions, since the sky is measured using a median estimator. Isolated deviations from a regular light-curve trend, especially single brightward deviations for faint stars, are therefore likely to be artifacts. Based on examination of repeated 4 minute dark exposures, it is estimated that a cosmic ray will affect about 1 in 500 magnitudes, typically producing a 0.8 mag brightward excursion at $V \sim 18$, 0.2 mag at $V \sim 16$, and 0.03 mag at $V \sim 14$.

The system was shut down during the interval of 1991 January 27–May 3 to diagnose a detector problem. This resulted in the eventual replacement of the original CCD, which took place during a second shutdown between 1991 December 27 and 1992 January 30. There is considerable variation in the average number of data points yr^{-1}, partly due to weather, but mostly due to variations in the resources available to operate the facility: although the observatory is fully automated, it still requires regular attention to maintain high efficiency. During intervals when the facility received regular funding, the "down" time is only 5%–10%; during intervals of reduced support, the "down" time sometimes degraded to 20%–40%, resulting in changes in the number of data points acquired yr^{-1}.

The light curves are all in the V bandpass. The transformation coefficients for the RoboScope filters are established by regular observations of standard star fields. Known $B-V$ colors of the secondary standards in the field of each CV are taken into account in deriving the zero point of the ensemble solution. However, the color of the CV is not measured. We assume that the $B-V$ of each CV is 0.0, which is an average value for NL CVs. Use of this constant $B-V$ for the variable introduces an estimated additional ~0.015 mag uncertainty into the zero point. About 65 old nova and NL CVs received between 5 and 13 yr of coverage during the interval 1990–2003. In this paper we discuss the light curves of eight systems in which we have seen at least one unambiguous low state.

Table 1 gives details of the data reductions for each of these eight stars, and the light curves of these 8 systems are given in Figures 1–8. An initial multiyear plot for each star shows the full light curve, which is followed by a series of paneled plots presenting each observing season on an expanded scale. The figure captions give details regarding these plots. These data will be archived with the AAVSO.

3. LIGHT CURVES OF INDIVIDUAL SYSTEMS

3.1. *V794 Aql*

This is a reasonably well-studied nova-like CV, with occasional deep low states and a likely orbital period of 3.68 hr (Honeycutt & Robertson 1998). The long-term light curve of the system is reviewed briefly in Honeycutt et al. (1994b) and in Honeycutt & Robertson (1998), in which the 1990–1997 RoboScope photometry of this system is also presented. The current paper adds the 1998–2003 data to these earlier studies.

The low-state transitions in V794 Aql usually display a pronounced asymmetry, having much more rapid rises than declines, which were interpreted as being the response of the accretion disk to a cessation of mass transfer from the secondary star (Honeycutt et al. 1994b). However, Honeycutt & Robertson (1998) reported that these transitions continued with a similar pattern for ~6 yr, casting doubt on whether a single, abrupt cessation of mass transfer from the mass-losing star is responsible for them.

In addition to the above, the system has shown a number of additional peculiar light-curve behaviors, some of which are discussed in Honeycutt & Robertson (1998). For example, in the top panel of Figure 1*c* a pair of nearly identically shaped outburst-like events are observed, which retain a rapid-rise/slow-decline pattern so prevalent in V794 Aql. After a low state in 1997 reaching $V \sim 17$, the system is seen to remain at $V \sim 14–15$ for the next six observing seasons. The light curve during 2001–2002 (see, for example, Fig. 1*d*) has quasi-periodic sinusoidal variations with a full amplitude of ~0.6 mag and a characteristic repetition interval of ~20–25 days, quite similar to the phenomenon of stunted outbursts.

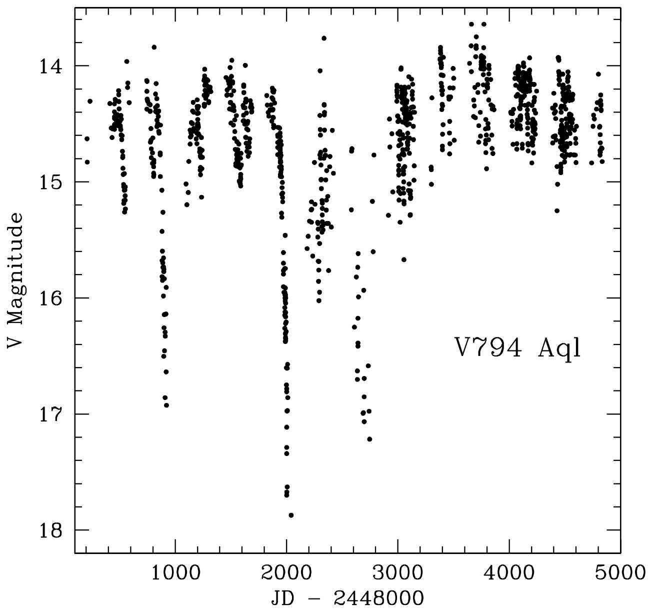

FIG. 1*a*

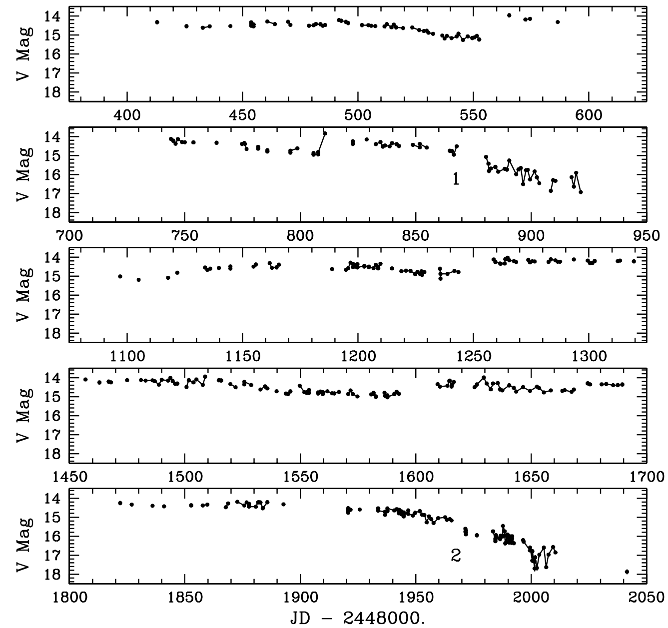

FIG. 1*b*

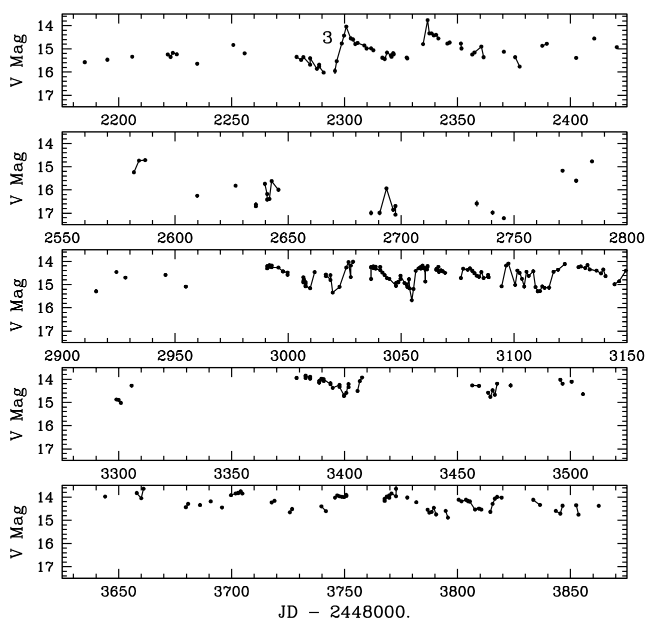

FIG. 1*c*

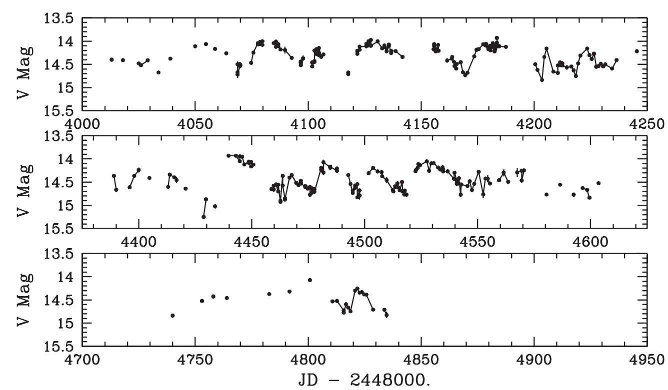

FIG. 1*d*

FIG. 1.—Approximately 12 yr of photometry of the VY Scl system V794 Aql. (*a*) Complete light curve, in which error bars are omitted for clarity. (*b–d*) Light curves on an expanded timescale. Each panel is an observing season contained in a single calendar year; these also include error bars, which are often too small to be seen. Data spaced less than 3.5 days apart are connected by straight lines. The transitions that have been measured are labeled with numbers that correspond to their numbering in the second column of Table 2.

Stunted outbursts are eruptions seen in ∼25% of the NL and old nova CVs, including several of the systems in this paper. They have characteristic durations of 5–20 days and amplitudes of 0.4–1.0 mag. Honeycutt (2001) has pointed out numerous similarities in the observational properties of stunted outbursts to those of conventional DN outbursts. These include similar distributions of the widths and spacings of the events and similarities in the degree of coherence and repeatability of the outburst spacings. DN outbursts are sometimes so closely spaced that they appear as a continuous sinelike variation, a behavior also found among stunted outbursts. In Z Cam stars, DN outbursts sometimes take the form of an outburst/dip pair, resembling a single isolated cycle of a sinelike variation that interrupts an otherwise steady light curve; this behavior is also found among the stunted outbursts. It appears that the only way in which the light curves of stunted outbursts in NL CVs differ from those of regular DN outbursts is that the amplitudes are 0.4–1.0 mag instead of 2–6 mag. This led Honeycutt (2001) to suggest that they are conventional accretion disk instabilities but seen against a steady background luminosity source (perhaps from nuclear burning on the white dwarf), which makes them appear attenuated.

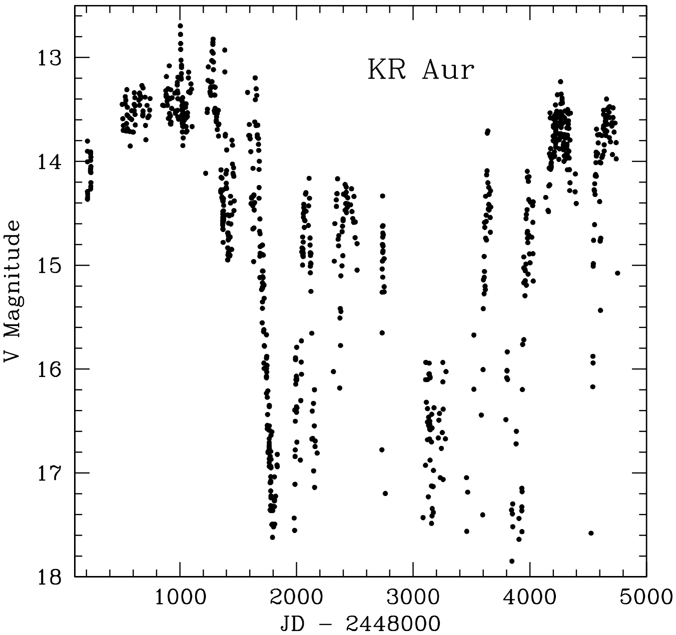

FIG. 2*a*

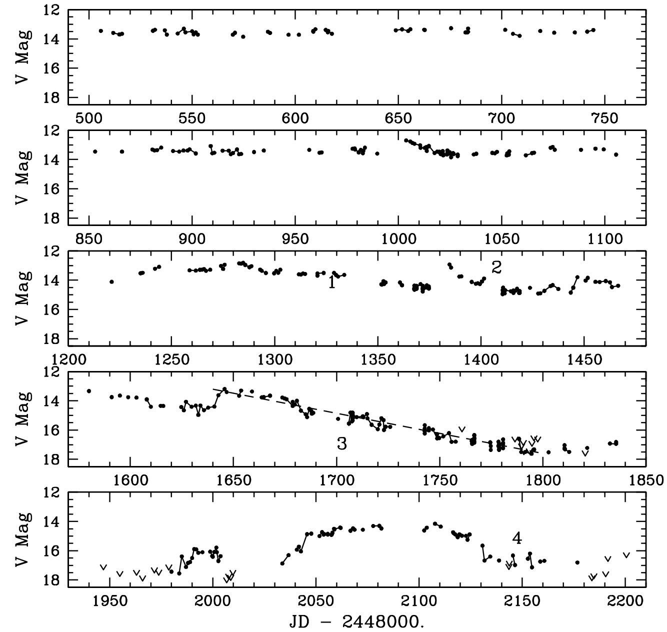

FIG. 2*b*

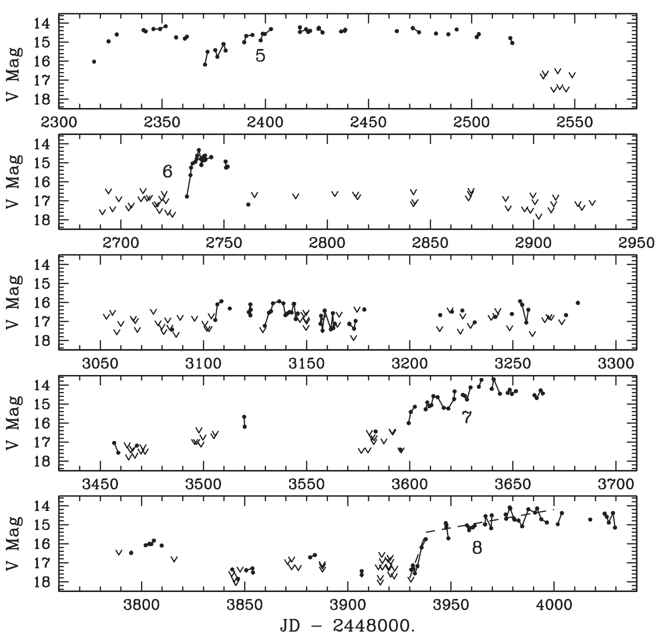

FIG. 2*c*

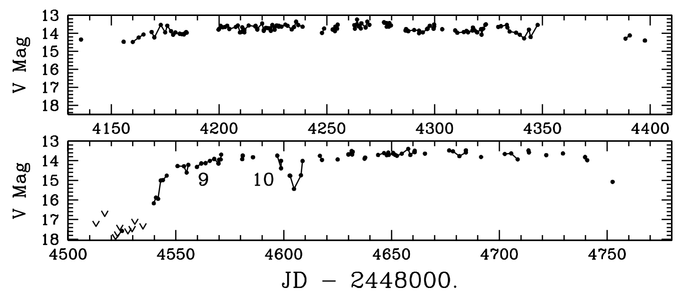

FIG. 2*d*

FIG. 2.—Same as Fig. 1, but for KR Aur. Each panel is an observing season that is part of two calendar years. Upper limits are given as carets. The dashed line in the fourth panel of (*b*) is an example of the fitting of a single straight line to transition 3. The dashed lines in the bottom panel of (*c*) are an example of the fitting of two straight lines to transition 8 (see text for details).

3.2. *KR Aur*

KR Aur is a relatively well-studied VY Scl system with an orbital period of 3.41 hr (Shafter 1983) and numerous recorded low states. Kato et al. (2002) provide references to published work on the long-term light curve, which shows occasional fadings lasting from months to years. This active, erratic nature of the long-term behavior is confirmed in the RoboScope light curve of Figure 2, in which occasional 0.5–1 mag outbursts and dips (Honeycutt et al. 1998) are also present. KR Aur often falls below the RoboScope faint magnitude limit, in which case an upper limit symbol is plotted.

3.3. *V533 Her (=N Her 1963)*

This system was a moderately well-observed fast nova reaching third magnitude in 1963 (Duerbeck 1987). Although V533 Her is not included in published lists of VY Scl stars, it displayed prominent low states in 1995 June and 1996 January (Figs. 3*a*–3*c*). As far as we are aware, it is one of only two old novae with reported VY Scl low states, the other being DK Lac (Henden et al. 2001). Spectroscopy by Thorstensen & Taylor (2000) revealed an orbital period of 3.53 hr and emission/absorption line behavior suggesting membership in the SW Sex grouping of nova-like CVs. SW Sex stars

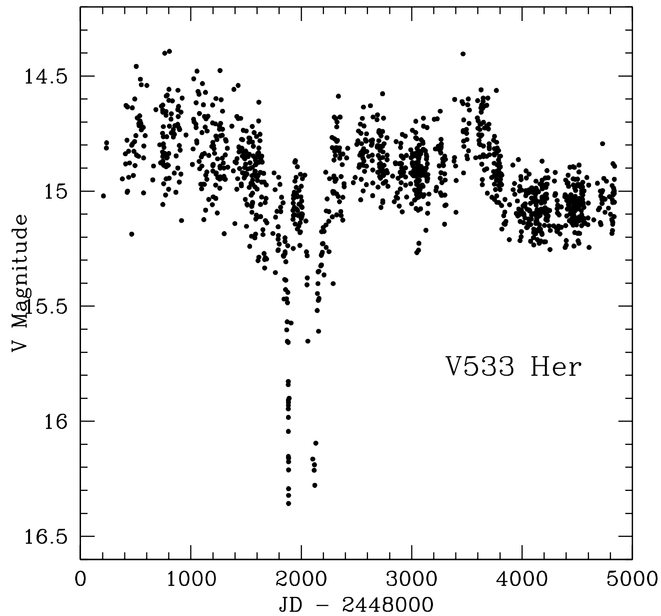

FIG. 3*a*

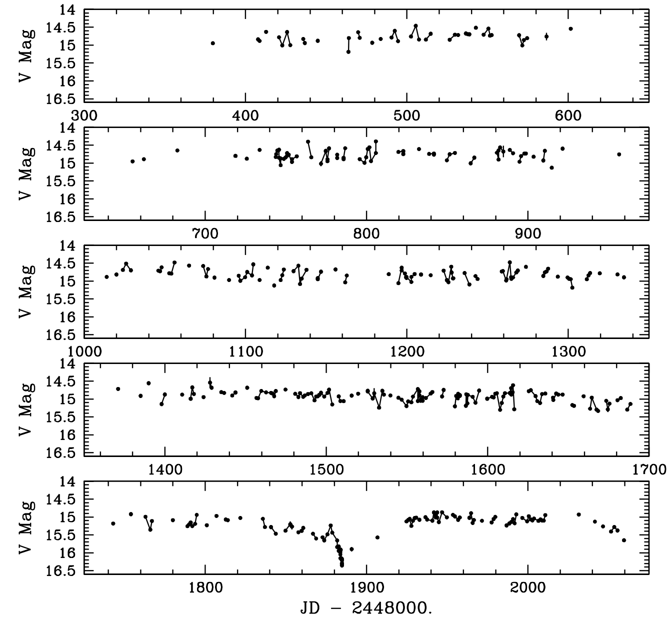

FIG. 3*b*

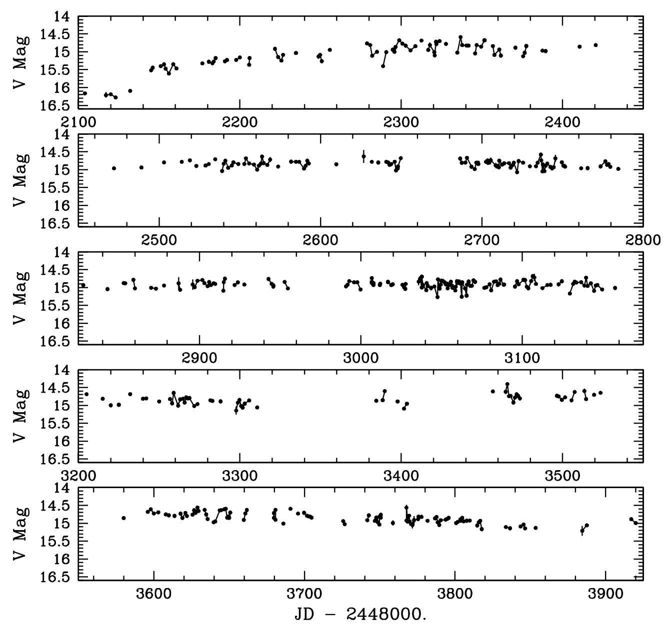

FIG. 3*c*

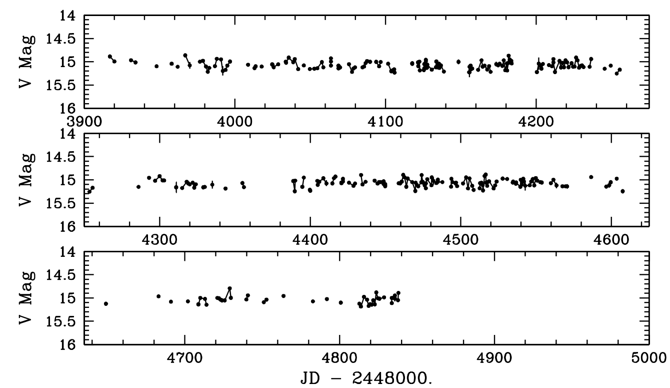

FIG. 3*d*

FIG. 3.—Same as Fig. 1, but for V533 Her. Each panel is an observing season contained in a single calendar year.

(Thorstensen et al. 1991; Murray & Chiang 1996) share common properties of single-peaked emission lines, absorption near orbital phase 0.5, and radial velocity phase lags of the emission lines relative to the white dwarf. Coherent photometric oscillations at 63.53 s, the signature of a rotating, magnetized white dwarf, have been reported (Patterson 1979), implying that V533 Her is an intermediate polar (DQ Her system); however, Robinson & Nather (1983) were not able to confirm this oscillation period. Recently Rodríguez-Gil & Martínez-Pais (2002) resurrected the IP classification for V533 Her, but with $P_{\rm spin} = 23.33$ min. V533 Her is therefore an old nova, a VY Scl star, a likely DQ Her system, and an SW Sex star, perhaps a record for club membership among the nova-like CVs.

We note that the night-to-night scatter in the light curve was $\sigma \sim 0.15$ mag when the system was at $V \sim 14.8$ during 1991–2000 (excluding 1995 and 1996 when the low states occurred). Interestingly, when V533 Her dropped to $V \sim 15.1$ in 2001–2003, the scatter decreased to $\sigma \sim 0.08$ mag. No coherent signal is apparent when the yearly photometry is folded on the orbital period. It therefore seems likely that the scatter is due to flickering and that the amplitude of the flickering in V533 Her is sensitively dependent on the photometric state of the system.

3.4. *MV Lyr*

This is one of the longest known and brightest VY Scl systems and has therefore received considerable attention.

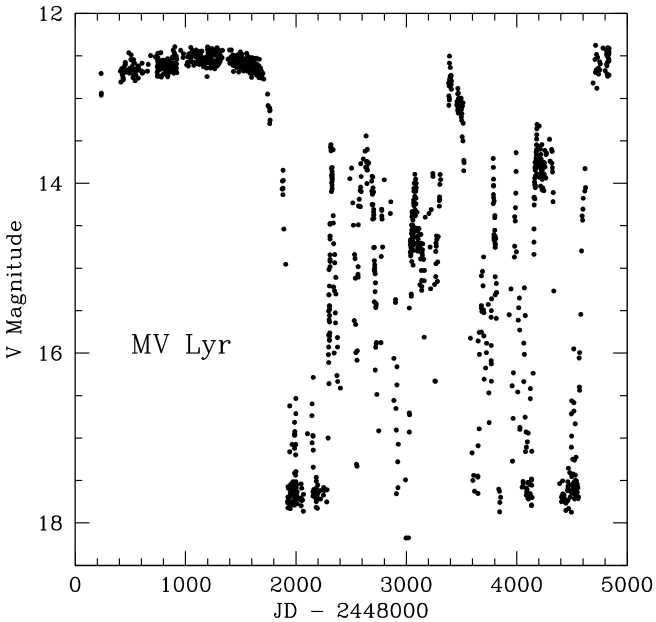

FIG. 4*a*

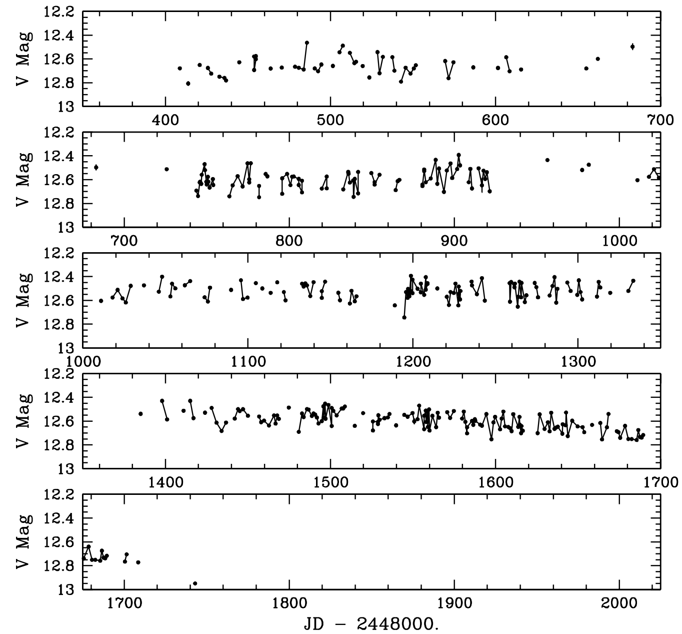

FIG. 4*b*

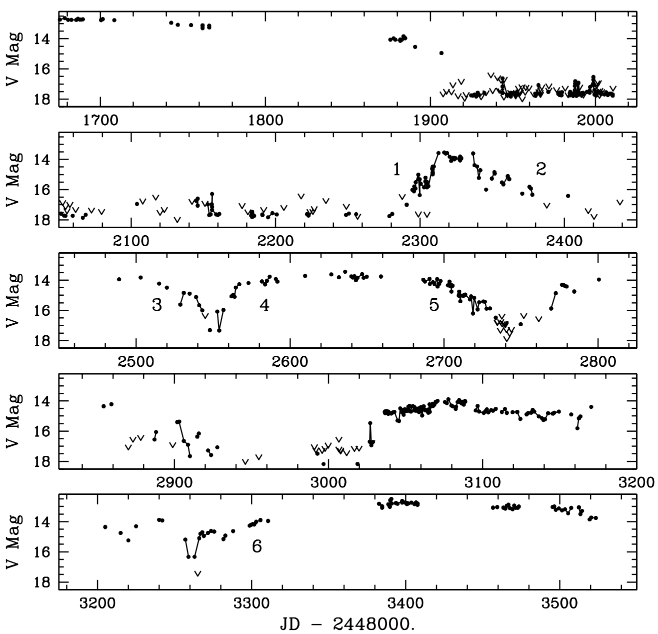

FIG. 4*c*

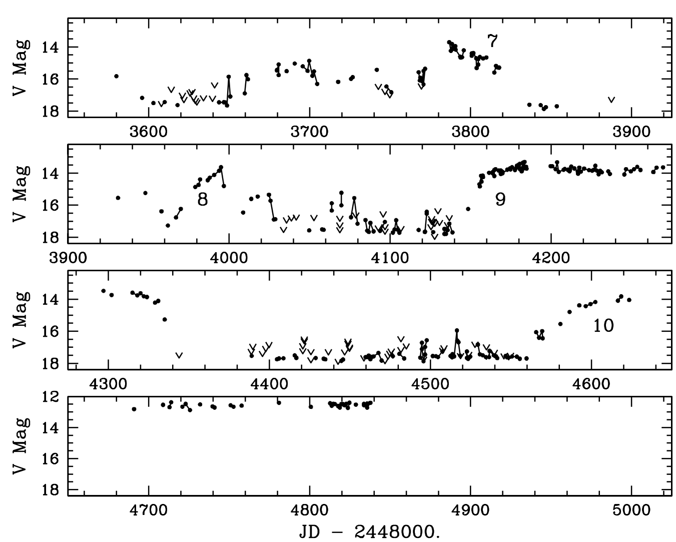

FIG. 4*d*

FIG. 4.—Same as Fig. 1, but for MV Lyr. Each panel is an observing season contained in a single calendar year. The bottom panel of (*b*) is repeated as the top panel of (*c*) with a different magnitude scale. Upper limits are given as carets.

The orbital period is 3.19 hr (Skillman et al. 1995), and the extensive photometric history is presented and/or discussed by, among others, Wenzel & Fuhrmann (1983), Rosino et al. (1993), Pavlenko & Shugarov (1998), Leach et al. (1999), and Katysheva et al. (2002). The AAVSO lightcurve shown in Hoard et al. (2004) is complementary to our light curve in that it has some data obtained at times not covered by RoboScope. In addition to the long-term behavior, these papers and others (e.g., Kraicheva et al. 1999) discuss suspected quasi-periodic variations over characteristic timescales ranging from minutes to hours, faster than the time resolution of our data.

The MV Lyr light curve of Figure 4 shows that the system remained in a relatively constant high state during 1991–1994 then entered an active phase in mid-1995, with numerous high-state/low-state transitions since then. Some of these low states were quite brief (e.g., Fig. 4*c*, *middle*) while others lasted more than a year (e.g., Fig. 4*b*, *top two panels*). During the extended low states in 1995–1996 (Fig. 4*c*) and 2001–2002 (Fig. 4*d*), rapid flares with amplitudes of about 1 mag are also visible. Flarelike activity on timescales of tens of minutes has been previously reported (e.g., Pavlenko & Shugarov 1998); examples of such brief excursions from the low state are displayed in the top two panels of Figure 4*c* and the middle

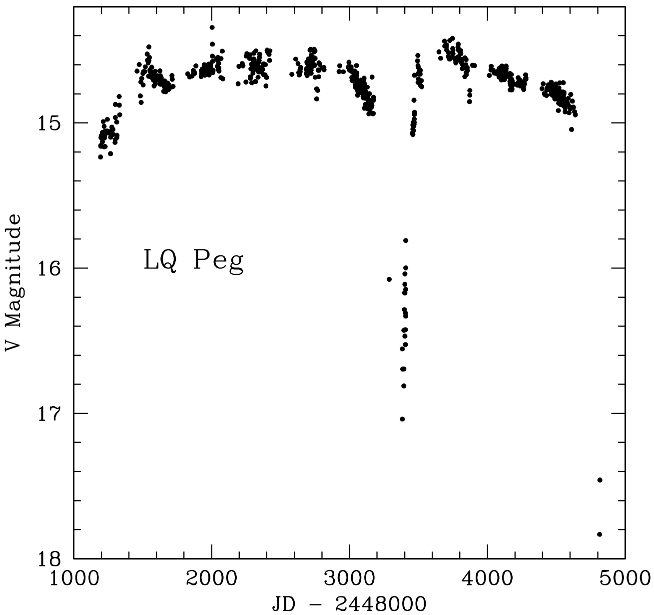

FIG. 5*a*

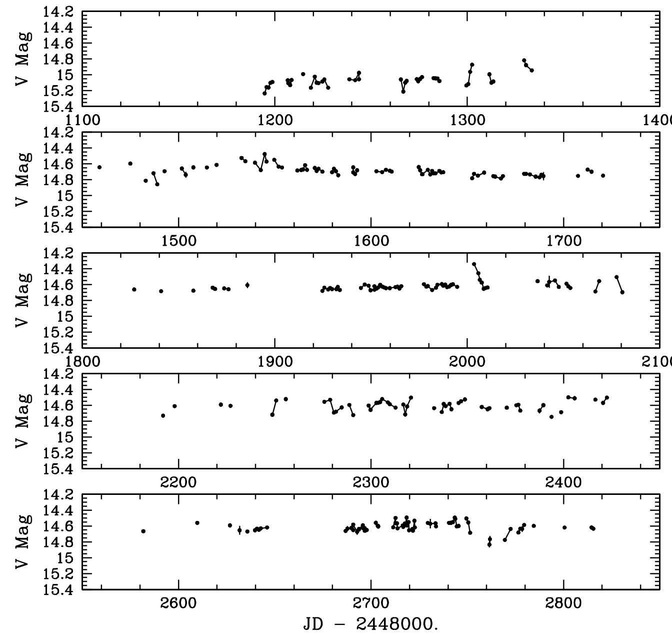

FIG. 5*b*

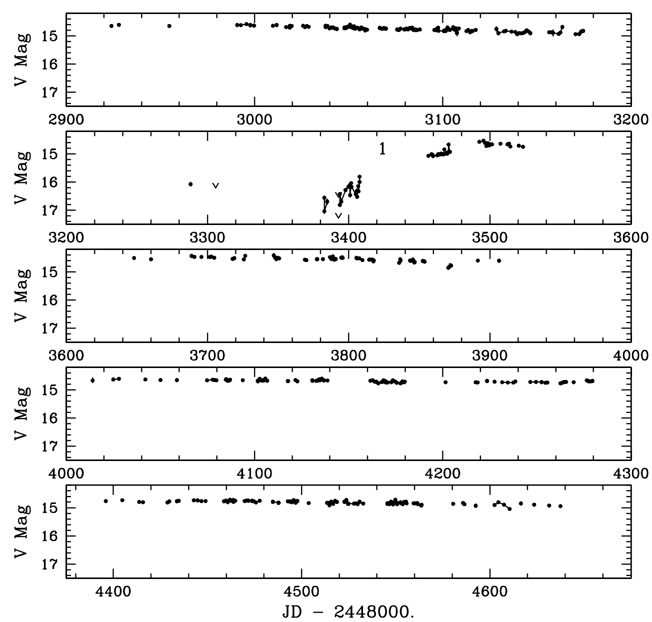

FIG. 5*c*

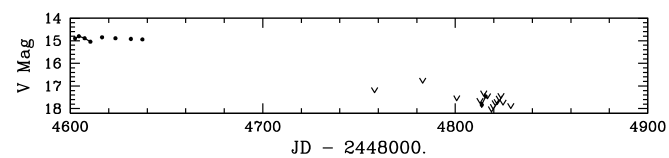

FIG. 5*d*

FIG. 5.—Same as Fig. 1, but for LQ Peg. Each panel is an observing season contained in a single calendar year.

two panels of Figure 4*d*. Those events occurring in low states after 1995–1996 are mostly sampled at 1–3 day intervals and remain unresolved. However, during the extended low state of 1995–1996, multiple observations per night were acquired, and the flares are often marginally resolved, with durations of 2–3 hr.

3.5. *LQ Peg (=PG 2133+115 = Peg 6)*

LQ Peg is a poorly studied nova-like CV with a possible 2.9 hr orbital period (Ringwald 1993). The system shows occasional low-amplitude outbursts (Fig. 5*b*, *middle*) and dips (Fig. 5*b*, *bottom*), in addition to fadings that occurred in 1969 (Sokolov et al. 1996) and in 1999 (Kato & Uemura 1999). The latter (1999 July–August) event was recorded by RoboScope and is shown in Figure 5*a* and in the second from top panel of Figure 5*c*. An additional pronounced low state in 2003 can be seen in the bottom panel of Figure 5*d*, but it is poorly sampled. Schmidtke et al. (2002) found that flickering in LQ Peg was considerably larger in the 1999 low state (0.09 mag) than when the system returned to its high state (0.02 mag), suggesting that accretion did not completely cease.

3.6. *FY Per*

FY Per is also a poorly studied nova-like CV whose properties are reviewed briefly in Honeycutt (2001). Sazonov & Shugarov (1992) found a photometric period of about 1.5 hr, which has not been confirmed (Okazaki 1993; Zamanov & Zamanova 1994). It has been suggested that FY Per is not a CV

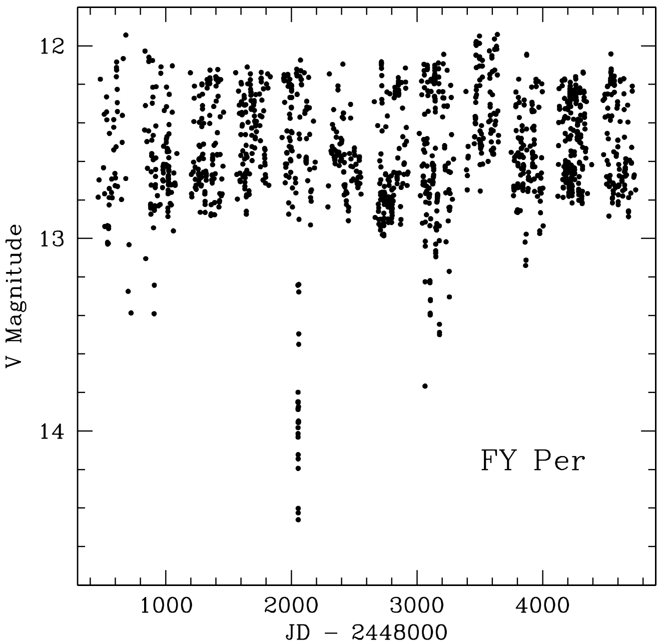

FIG. 6*a*

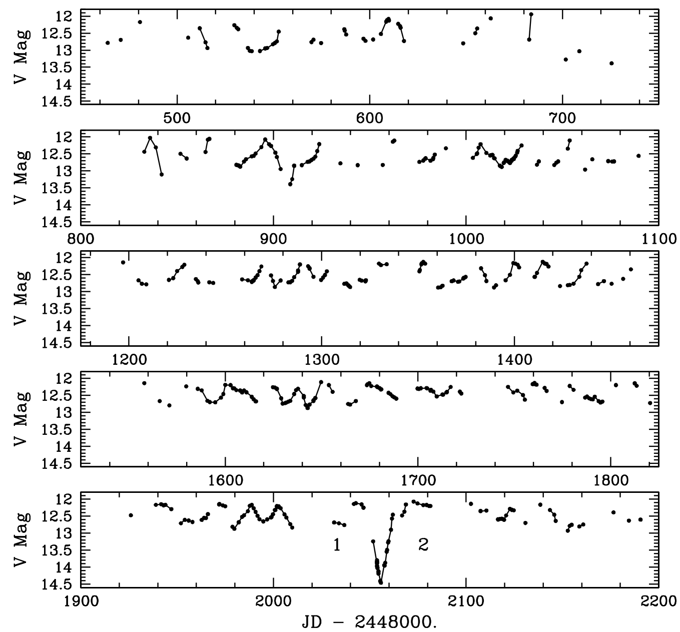

FIG. 6*b*

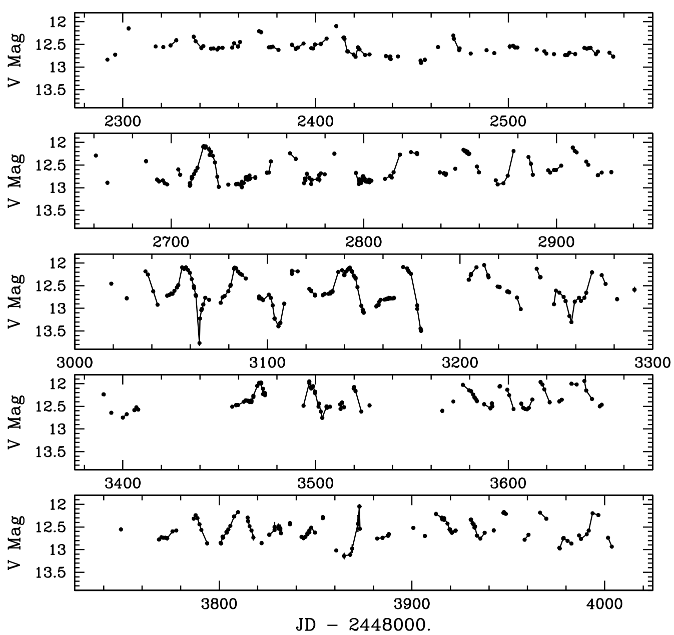

FIG. 6*c*

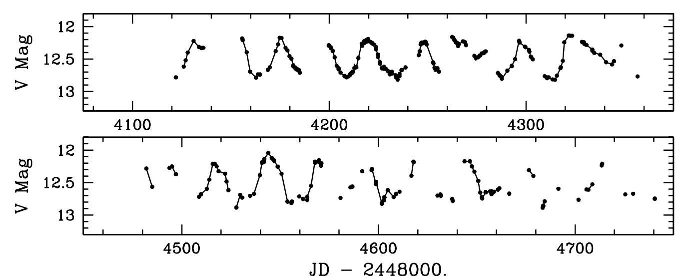

FIG. 6*d*

FIG. 6.—Same as Fig. 1, but for FY Per. Each panel is an observing season that is part of two calendar years.

(Okazaki 1993; Downes et al. 1995) since Hα is quite narrow; however, the occasionally published spectra of the system (Okazaki 1993; Downes et al. 1995; Honeycutt 2001) appear to be consistent with a high-inclination nova-like CV. Furthermore, FY Per had a VY Scl–type low state (Fig. 6*b*, *bottom*), and flickering has been reported (Richter 1964; Kozhevnikov et al. 2004), both properties associated with CVs. We therefore accept that FY Per is in fact a CV.

The long-term light curve of FY Per in Figure 6 is noteworthy for the common occurrence of 0.6 mag oscillations with a characteristic interval of 20–25 days, which are discussed in Honeycutt (2001); however, their origin remains uncertain. Honeycutt (2001) argues that properties in common between these low-amplitude stunted outbursts (prominent in the 2001–2003 data of Fig. 6*d*) and dwarf nova outbursts favor these events being due to an accretion disk instability of the type widely thought to be responsible for dwarf nova eruptions, as opposed to mass transfer events. There are also a number of occasions when FY Per dipped below the normal oscillation level for a few days, as seen in the second panel of Figure 6*b* and the middle and bottom panels of Figure 6*c*. This behavior is very similar to the occasional dips (Honeycutt et al. 1998) and outburst/dip pairs (Honeycutt 2001) that are part of the phenomenology of stunted outbursts.

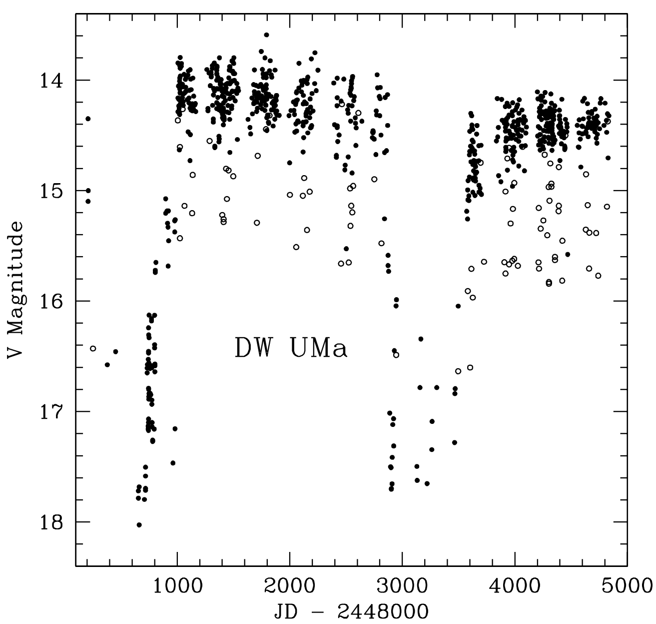

Fig. 7*a*

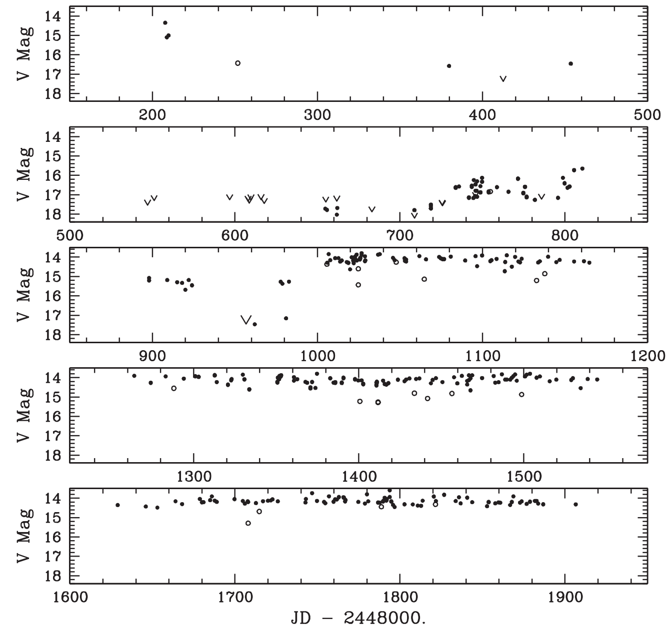

Fig. 7*b*

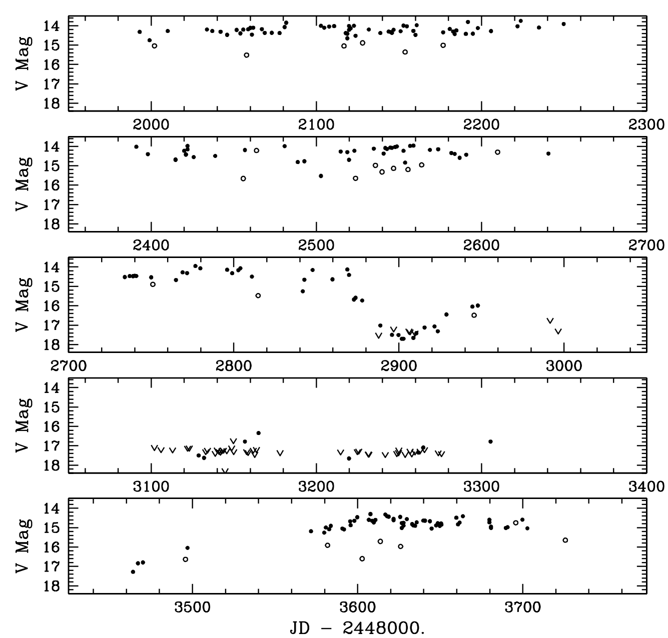

Fig. 7*c*

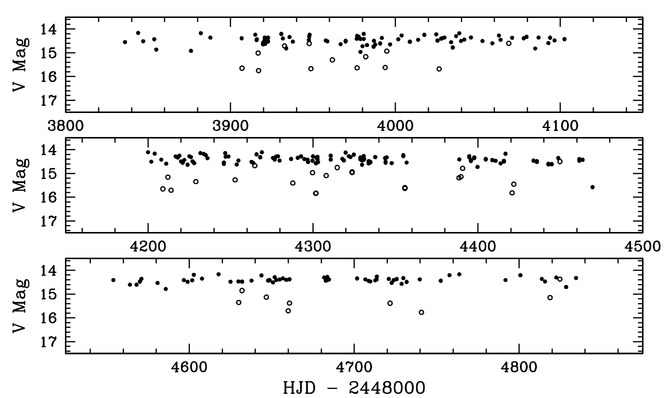

Fig. 7*d*

Fig. 7.—Same as Fig. 1, but for DW UMa. Each panel is an observing season that is part of two calendar years. Data in eclipse are coded as open circles.

An isolated 2.3 mag deep low state occurred in 1995 November–December (Fig. 6*b*, *bottom*). Interestingly, most of the aforementioned dips, as well as the 1995 low state, seem to have occurred as a faintward extension of a "normal" ∼0.6 mag stunted outburst cycle of oscillation. That is, the system seemed to simply get fainter than expected (by a lot in the case of the 1995 November–December low state) as it approached the bottom of one of a series of continuous stunted outbursts. This impression is reinforced by the fact that these dips and low states have about the same timescales (rise/fall time, as well as duration) as the stunted outbursts in FY Per (with the exception of the dip near JD 2451065, which is sharper and more narrow). These similarities suggest that the 0.6 mag, 30 day oscillations in FY Per may be related to the low states in this system. In FY Per we have an example of a system displaying both stunted outbursts and a VY Scl–type low state. If both these effects are due to mass transfer modulations, then the time dependence of mass transfer has an unexpected complexity.

3.7. *DW UMa (=PG 1039+590)*

This is an eclipsing nova-like CV that is a founding member of the SW Sex class (Honeycutt et al. 1986; Szkody & Piché 1990; Thorstensen et al. 1991). The period is exceptionally well determined at ∼3.27 hr (e.g., Stanishev et al. 2004). Several studies of the eclipses have provided a relatively detailed picture of the accretion process: the disk becomes

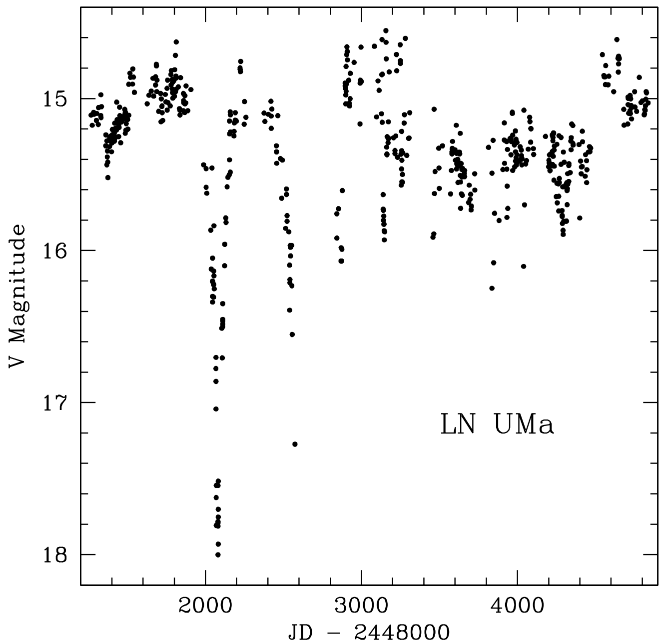

FIG. 8*a*

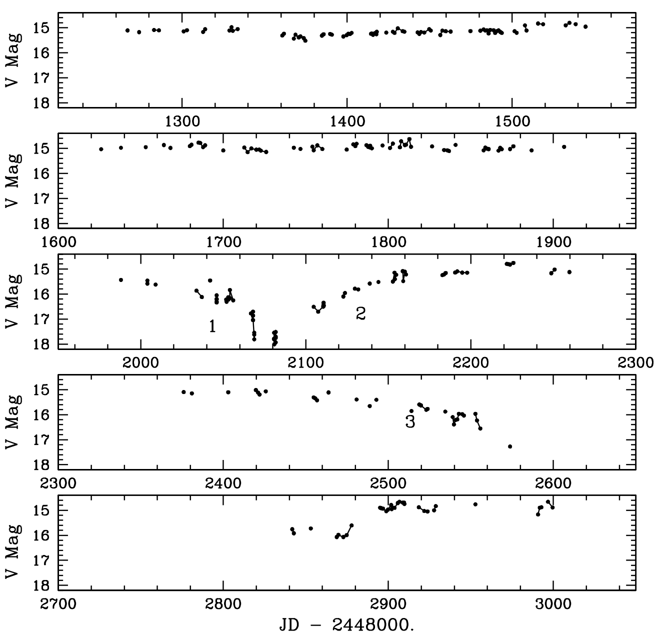

FIG. 8*b*

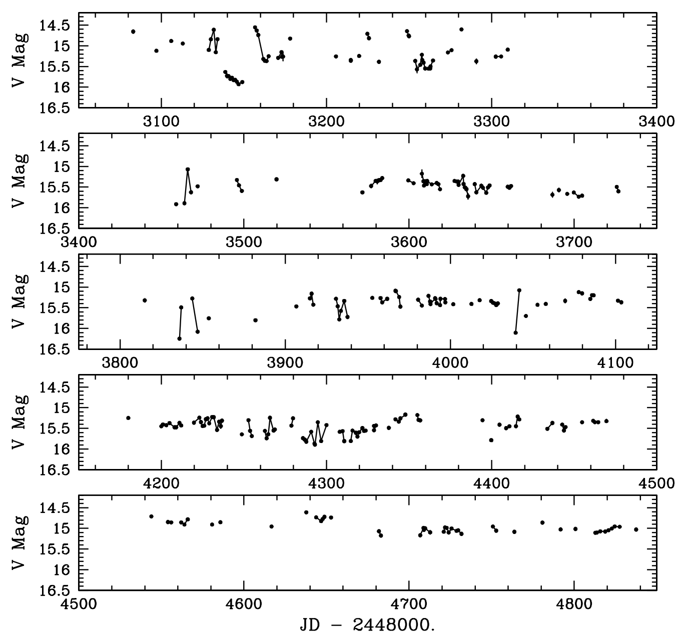

FIG. 8*c*

FIG. 8.—Same as Fig. 1, but for LN UMa. Each panel is an observing season that is part of two calendar years.

larger in the high state (Dhillon et al. 1994; Stanishev et al. 2004), with the hot spot disappearing when the system is brightest (Bíró 2000). Ultraviolet studies of the eclipses have concluded that the disk is geometrically flared, producing a self-occultation of the inner disk and the white dwarf (Knigge et al. 2000; Hoard et al. 2003). Analysis of the ultraviolet eclipses have also been used to constrain system parameters such as distance, masses, radii, and temperatures (Araujo-Betancor et al. 2003).

The 1990–1993 RoboScope light curve was discussed by Honeycutt et al. 1993); this current work extends the light curve to 2003. In Figure 7 the data obtained during eclipse are plotted as open circles. The low-state magnitude of DW UMa is near, and sometimes beyond, the RoboScope limit, leading to numerous upper limits. Nevertheless, these limits help define the widths and depths of the low states. Figure 7*a* clearly shows the 1990–1993 low state, followed by more than 5 yr of a rather uniform high state. In early 1998 March, DW UMa entered another extended low state, returning to the high state in 2000 February in which it has remained until 2003.

3.8. *LN UMa (=PG 1000+667 = UMA 7)*

Hillwig et al. (1998) reported two low states in the 1993–1997 RoboScope data on LN UMa and determined an orbital period of 3.47 hr. Since then, little else has been published on this system. The 1993–2003 light curve in Figure 8 shows the two low states prior to 1998, which are followed by rather erratic behavior in subsequent years.

4. PROPERTIES OF THE HIGH-LOW STATES

Following our discussion of individual light curves, we now turn to low-state properties in common to the group, focusing on the observational properties of the transitions. As an initial analysis tool, a single straight line was fitted to each adequately sampled transition (see the example in Fig. 2*b*). For comparison, this fitting was also done for the transitions in a few polars that have long-term coverage by RoboScope. It is clear that, as a group, the high-state/low-state transitions in polars are faster than in disk systems. In 23 resolved transitions seen in three polars, the average *e*-folding time,[1] τ, is 12 ± 3 (standard deviation of the mean) days, while for 29 resolved transitions in disk systems, the average is 16 ± 3 days. However, most of the transitions in the six polars in our sample are unresolved at our typical data spacing of 3 days, as opposed to the better sampled transitions in the disk systems. Therefore the difference in τ is actually greater than this comparison would suggest, an effect that may be due to the mitigating effect of the disk in responding slowly to changes in the mass transfer rate from the secondary star. As pointed out by Warner (1999), a number of DN also have light curves that resemble those of VY Scl stars, but with smaller amplitudes, a result confirmed by the long-term light curves of some DNs on the RoboScope program. An analysis of the light curves of the RoboScope polars and the DNs will be the subject of future papers.

Because of the difficulty of distinguishing lower amplitude transitions from general stochastic variations, we have adopted a fairly strict criterion for the VY Scl events we analyze, namely, that the transition must be completed in less than 150 days and must have an amplitude greater than 1.5 mag. This lower limit to the amplitude was adopted to avoid confusion with stunted outbursts, because when stunted outburst/dip pairs occur, the full amplitude can approach 1.5 mag (Honeycutt 2001). The upper limit on the duration of the transition is needed to minimize confusion with slow stochastic changes. However, using these criteria, VY Scl events are relatively rare. RoboScope monitored 18 NL CVs for an average of 5.2 yr, plus 47 NLs for an average of 12.1 yr each, yet only eight8 systems (12%) displayed clear VY Scl transitions that fit our criteria. During the years of RoboScope monitoring, the fraction of time these eight systems spent in a low state ranged from less than 1% (FY Per) to $\sim$50% (KR Aur), with an average of $\sim$14%. If one considers all 65 NL monitored by RoboScope, most of which have not shown low states by our definition, then the average NL CV spends $\sim$2% of the time in a low state.

We restrict our further analysis to a subset of the transitions, labeled in Figures 1–8, for which our sampling is good enough to discern the speed, amplitude, and shape of the change in optical state. There is an unavoidable bias in this sample toward longer τ transitions because faster transitions are more likely to be poorly sampled; additional, more poorly sampled transitions and low states can be seen in the photometry but are not included in our analysis. Examples of transitions that do not satisfy our criteria can be seen in V533 Her (Fig. 3), which has transitions near JDs 2,449,880 and 2,450,110 with amplitudes less than 1.5 mag, and in DW UMa (Fig. 7), which has transitions near JDs 2,448,980 and 2,450,880 with large amplitudes that are not well sampled. Nevertheless, we have 29 transitions in six systems (see Table 2) to work with.

The durations, amplitudes, and shapes of these 29 transitions were measured to search for correlations that might provide clues to the nature of the VY Scl phenomenon, with the results given in Table 2. The magnitude reference levels for the amplitudes were set by visual inspection, as either the magnitude at which the brightness was constant, or the magnitude at which the transition began or ended by a reversal of the slope of the light curve. There is no apparent pattern to the distributions of durations and amplitudes. Figure 9 is a histogram of the transition speeds, demonstrating the wide range of *e*-folding times. Earlier work on V794 Aql (Honeycutt et al. 1994b) concluded that the transitions were mostly faster in going from faint to bright than from bright to faint in that system. In our larger sample (with V794 Aql excluded), $\langle \tau_{\rm rise} \rangle = 22.9 \pm 4.3$ days and $\langle \tau_{\rm fall} \rangle = 30.8 \pm 7.3$. This is in the same sense as the V794 Aql result but is not very statistically significant.

Honeycutt et al. (1994b) also concluded that the V794 Aql low states often had systematic changes in slope, becoming steeper when fainter. That effect is also present in this larger data set, even when V794 Aql is excluded. We have attempted to quantify this by fitting two straight lines to each transition (see example in Fig. 2*c*); the numerical results of these dual-slope fits are given in Table 3 and are discussed shortly. Column (3) of Table 3 gives the JD that separates the data points used for the two slopes, was chosen visually, and does not necessarily coincide with the intersection of the two lines. For these dual-slope fits we list in Table 3 the *e*-folding time for the bright portion of the transition, $\tau_{\rm bright}$, as well as for the faint portion of the transition, $\tau_{\rm faint}$.

In Figure 10 we plot $\log(\tau_{\rm bright}/\tau_{\rm faint})$ versus the improvement in the fit when two slopes are used instead of one, using the rms scatter about the lines as a measure of the goodness of the fit. In the fits in which there is little improvement by going to two lines (that is, small values of rms1/rms2), the two slopes for the dual-slope fits scatter sensibly about the horizontal dashed line, representing equal slopes for the bright and faint portions. However, as the dual-slope fit becomes more justified by a significant improvement in the fit (that is, large values of rms1/rms2), there is a systematic trend in the sense that the faint portions are faster than the bright ones, by a factor up to $\sim$10. (The transitions in V533 Her also have this character [see Fig. 3], but their amplitudes are too small to have been included in our analysis sample.) Note in Figure 10 that more than half of the transitions are fitted just as well (to within the errors) by a single slope. The critical point is that, among the transitions that do change slope, the faint part is faster, without exception. It is suggestive that in Figure 10 the declining transitions may be more often single-sloped, compared to the rising transitions, although more data are needed to secure this conclusion.

5. DISCUSSION

In considering mechanisms that might be responsible for VY Scl low states, let us begin with several unconventional views. Verbunt (1997) argues that VY Scl low states may be a variant of the DN phenomenon. This suggestion derived from an analysis of the period distribution of CVs of various types,

[1] The *e*-folding time $= (\log_{10}e/0.4)/(\Delta m/\Delta t) = 1.086/(\Delta m/\Delta t)$.

TABLE 2
VY Scl Transitions Measured

Star	Transition	JD Start	JD End	Duration (days)	Start Mag	End Mag	Amplitude (mag)[a]	No. Points[b]	τ (days)
V794 Aql	1	808–811	922–1096	>113	13.8	16.6	2.8	47	42.7
	2	1938–1940	2041–2184	>102	14.6	17.2	2.6	81	31.1
	3	2291–2296	2301–2303	9	16.0	14.0	−2.0	5	2.9
KR Aur	1	1278–1282	1375–1384	100	12.8	14.5	1.7	60	63.1
	2	1373–1384	1418–1423	42	12.9	14.8	1.9	25	23.1
	3	1642–1645	1795–1802	155	13.2	17.4	4.2	101	39.0
	4	2103–2107	2146–2152	44	14.1	16.7	2.6	19	14.9
	5	2361–2370	2402–2404	38	16.2	14.3	−1.9	13	24.3
	6	2727–2731	2737–2738	10	16.8	14.3	−2.5	8	3.0
	7	3593–3594	3634–3639	43	17.4	13.7	−3.7	20	19.7
	8	3929–3930	3978–3979	49	17.4	14.1	−3.3	24	18.8
	9	4536–4539	4569–4570	32	16.2	13.9	−2.5	20	19.6
	10	4586–4597	4605–4609	25	13.7	15.4	1.7	6	5.8
MV Lyr	1	2281–2291	2313–2317	29	17.6	13.6	−4.0	32	10.9
	2	2313–2317	2378–2403	76	13.5	16.3	2.8	36	24.7
	3	2503–2515	2548–2553	42	13.8	17.3	3.5	10	17.6
	4	2553–2554	2592–2610	48	17.3	14.1	−3.2	14	18.2
	5	2659–2687	2734–2750	69	14.0	16.5	2.5	36	21.6
	6	3259–3263	>3311		16.3	14.0	−2.3	18	37.6
	7	3772–3787	3818–3837	48	13.7	15.3	1.6	26	24.3
	8	3958–3962	3995–3997	36	17.3	13.6	−3.7	11	10.0
	9	4139–4149	4185–4200	49	17.7	13.7	−4.0	39	19.8
	10	4560–4566	>4624		17.7	14.1	−3.6	14	21.1
LQ Peg...........................	1	<3383	3472–3493		16.9	14.9	−2.0	38	51.8
FY Per............................	1	2047–2052	2055–2056	8	12.3	14.5	2.2	17	3.6
	2	2055–2056	2062–2067	8	14.5	12.5	−2.0	11	3.3
LN UMa.........................	1	1907–1988	2081–2082	134	15.4	17.8	2.4	34	35.9
	2	2081–2082	2198–2221	128	17.8	15.2	−2.6	30	59.0
	3	2426–2455	>2574	134	15.3	17.3	2.0	24	94.4

[a] Negative amplitude corresponds to an increase in brightness.
[b] Number of data points used in fitting a straight line to the transition to obtain the *e*-folding time in the last column.

in which it was concluded that the distributions of DN and NL above the period gap are different if VY Scl stars are included with the NL but are the same if the VY Scl stars are grouped with the DN. (Note, however, that Hellier & Naylor 1998 have argued against Verbunt's suggestion based on revised statistics on the CV period distributions and on the large disparity between the light curves of DN and VY Scl stars; see also Kolb et al. 1998.) In FY Per and V794 Aql there are similarities in the properties of the stunted outbursts (which are likely a variant of DN outbursts) and the low state(s), which suggest a possible underlying commonality for the two phenomena. In FY Per the single observed low state has about the same width as the stunted outbursts in that system and about the same rise/fall times. This low state has the appearance of simply being a much deeper stunted outburst cycle in a continuing sequence of stunted outbursts. In V794 Aql both the low states and the stunted outbursts have, on average, faster rises than declines. Indeed, several of the eight low-state systems discussed in this paper have small outbursts that fall within the range of stunted outbursts with regard to their amplitude and width (see § 3). Nevertheless, that leaves many of our program stars with VY Scl low states and no observed stunted outbursts.

A second unconventional view is that NL CVs may manage to burn their accreted hydrogen as it arrives on the white dwarf surface. This is discussed by Honeycutt (2001): a possible way to produce stunted outbursts in NL systems would be to have disk instability events of conventional amplitude appear

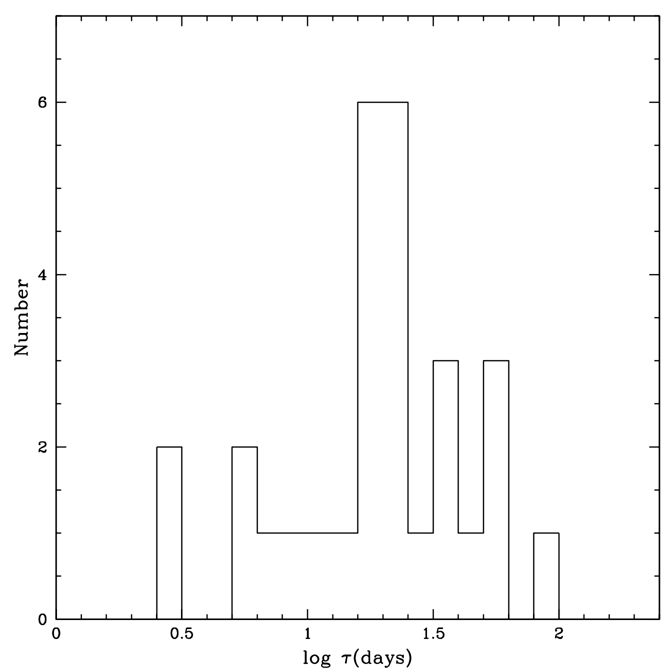

Fig. 9.—Histogram of $\log_{10}$ of the *e*-folding time, τ, for the transitions between high and low states; τ is derived from a single straight-line fit to the full mag vs. time transition. We see a wide range of speeds, with a peak near 20 days.

TABLE 3

Dual-Slope Fits to Transitions

Star (1)	Transition[a] (2)	JD Divide[b] (3)	rms1 (mag)[c] (4)	No. $\text{Points}_{\text{faint}}$[d] (5)	τ_{faint} (d)[e] (6)	No. $\text{Points}_{\text{bright}}$[f] (7)	τ_{bright} (days)[g] (8)	rms2 (mag)[h] (9)
V794 Aql	1	870	0.284	26	39.8	21	92.2	0.239
	2	1972	0.289	45	25.3	36	35.7	0.280
	3		0.038					
KR Aur	1	1340	0.131	36	73.9	24	74.2	0.127
	2	1400	0.219	17	28.1	8	12.7	0.179
	3	1730	0.252	55	40.3	46	34.5	0.244
	4	2125	0.281	6	30.6	13	20.1	0.221
	5	2385	0.210	6	17.5	7	32.9	0.201
	6	2734	0.236	3	1.6	5	4.8	0.110
	7	3604	0.434	4	3.2	16	27.8	0.250
	8	3952	0.464	11	8.6	13	25.2	0.298
	9	4547	0.338	6	4.2	14	45.3	0.161
	10		0.164					
MV Lyr	1	2300	0.388	10	7.2	22	6.2	0.311
	2	2350	0.314	10	24.7	26	19.6	0.300
	3	2532	0.483	5	5.7	5	20.8	0.259
	4	2570	0.557	7	5.0	7	88.2	0.197
	5	2715	0.274	11	22.2	25	25.6	0.266
	6	3282	0.332	9	27.5	9	29.0	0.324
	7	3800	0.241	14	23.5	12	13.4	0.230
	8	3981	0.250	5	7.7	6	18.2	0.108
	9	4159	0.466	8	5.8	31	56.4	0.149
	10	4587	0.444	7	12.2	7	71.2	0.246
LQ Peg	1	3425	0.159	19	39.8	19	85.3	0.152
FY Per	1	2054	0.047	10	4.2	7	3.7	0.031
	2	2059	0.046	6	3.6	5	3.2	0.038
LN UMa	1	2046	0.415	24	20.4	10	92.8	0.261
	2	2127	0.251	11	30.5	19	131.5	0.123
	3	2527	0.237	12	37.4	12	161.8	0.176

[a] This transition numbering corresponds to the labels in Figs. 1–8. (V794 Aql transition 3 and KR Aur transition 10 had too few points for a dual-slope fit.)
[b] Data at JDs either side of this dividing line are fitted with separate straight lines.
[c] The rms scatter about the single straight line fit of Table 2.
[d] Number of data points fitted for the faint portion of the transition.
[e] The *e*-folding time in days for faint portion.
[f] Number of data points fitted for the bright portion of the transition.
[g] The *e*-folding time in days for bright portion.
[h] The rms scatter about the dual-slope fit.

attenuated (or stunted) by a strong relatively steady background luminosity from nuclear burning. This idea is mostly suggested by the fact that ~3 mag is not only the average amount by which NL are brighter than DN (Warner 1995) but is also the amount of background attenuation needed to make a conventional DN outburst appear stunted. If nuclear burning were to provide most of NL luminosity, then turning off the burning by temporarily exhausting the fuel supply would produce a conspicuous VY Scl low state. This scenario has the potential to explain otherwise puzzling observational properties of NL, such as why DN outbursts are not seen during VY Scl low states and why VY Scl low states occur infrequently, if at all, in DN. Under this hypothesis, the VY Scl low-state phenomenon is divorced from the $\dot{M}$ that is expected to control the appearance of both normal DN outbursts and stunted outbursts. Therefore, a disk that is stable against DN outbursts prior to a VY Scl low state can remain stable against DN outbursts in the low state. The temperature of the boundary layer at the inner edge of the disk is not hot enough for nuclear burning. On the other hand, conditions at the base of a magnetic funnel may approach the required temperatures, suggesting that VY Scl stars may all be intermediate polars, an idea explored by Hameury & Lasota (2002), based on the absence of outbursts in VY Scl low states. It appears to be difficult to test the hypothesis of nuclear burning in VY Scl stars at present, but for completeness we include the temporary cessation of nuclear burning on the white dwarf as a possible mechanism for low states. A third suggestion for the production of optical low (and X-ray high) states was made for supersoft X-ray sources, such as RX J0513.9−6951 (Hachisu & Kato 2003). However, that mechanism ("accretion wind evolution") requires mass rates $\dot{M} > 10^{-6}\ M_{\odot}$, far in excess of those observed in VY Scl systems.

The broadly accepted view is that VY Scl low states are due to a strong reduction or cessation of mass transfer from the secondary star, which is the model discussed in the remainder of this paper. However, it should be noted that some CV properties appear to present difficulties for this picture. King & Cannizzo (1998) discuss the fact that dwarf novae do not have obvious VY Scl–like low states as expected. Following Livio & Pringle (1994), they argued that starspots produce low states, and they suggest that DN have much less conspicuous low states than do NLs because starspots are more prevalent for systems in the period range 3–4 hr in which NLs are most

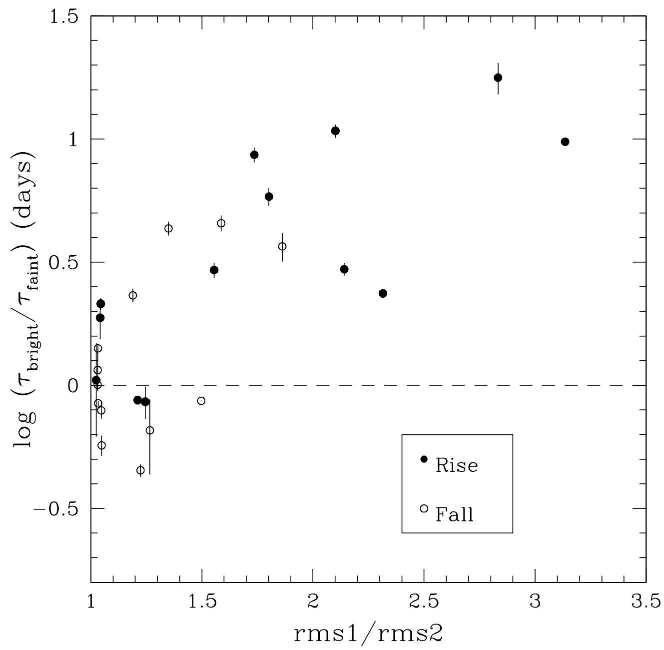

FIG. 10.—Ratio of the *e*-folding times for the bright and faint portions of dual-slope transitions vs. the ratio of the rms scatter about the single-slope fit (rms1) to that of the dual-slope fit (rms2). The horizontal axis therefore measures the improvement in the fit resulting from using two lines instead of one. The horizontal dashed line divides transitions that occur faster when fainter (*above the dashed line*) from those that are faster when brighter (*below the dashed line*). The error bars are the formal errors propagated to $\log(\tau_{\rm bright}/\tau_{\rm faint})$ from the errors on the straight-line fits to the transitions. The symmetrical scatter about the dashed line for points having rms1/rms2 $\lesssim$ 1.35 is taken to be observational scatter. For the transitions having rms1/rms2 $>$ 1.35, the faint portions seem to be, almost without exception, faster than the bright portions.

common. In addition, Leach et al. (1999) point out that VY Scl stars do not display the expected DN outbursts upon arriving in the low state. Even though mass transfer may have ceased, a series of DN outbursts is expected to occur within the low state because only a small fraction of the disk mass is accreted onto the white dwarf during a DN outburst. The disk remains subject to the thermal/viscous instability as it must drain its remaining gas onto the white dwarf through a series of DN eruptions, an effect demonstrated in Cannizzo's models (Honeycutt et al. 1994b) as well as those in King & Cannizzo (1998) and Leach et al. (1999). While these latter authors, as well as Hameury & Lasota (2002), offer possible explanations for these variances between predictions and observations of VY Scl low states (explanations mostly relating to truncated disks), one should nevertheless keep these difficulties in mind when making the common assumption that the low states are simply due to reductions in $\dot{M}$.

It appears difficult to attribute the dual-slope rises reported here to effects arising in the accretion disk. Rebuilding the disk from an extended low state is expected to initially take place on the slow viscous timescale of the low-state disk, eventually switching to a faster rise as the disk goes into DN outburst on the faster thermal timescale. This picture is opposite to the observed sense of the dual-slope rises, which are faster when the system is fainter. Therefore, we turn to the mass transfer process itself as the possible mechanism for shaping the dual-slope transitions. Two models for this modulation of $\dot{M}$ are most widely discussed. Wu et al. (1995) proposed a changing $\dot{M}$ caused by irradiation of the secondary star by the white dwarf and inner accretion disk. Periodic shielding of this radiation by the outer accretion disk can result in a feedback mechanism in which alternating high and low states are produced. Alternatively, Livio & Pringle (1994) explored the idea that a starspot near the L1 point can decrease $\dot{M}$ and produce a VY Scl low state. In this case, the magnetic pressure acts to decrease the gas pressure in the vicinity of the spot.

The shapes of the transitions reported here support the model of Livio & Pringle (1994) if the dual slopes are interpreted as the effects of the starspot umbra and penumbra on $\dot{M}$. If the diameter of the central umbra is ~35% that of the surrounding penumbra region (a typical situation for a sunspot), then a random set of crossing chords of L1 across the spot would result in ~65% of the encounters crossing only the penumbra, which we associate with a single-slope transition. This is consistent with our statistical results in which ~40% of the resolved transitions have dual slopes, which we associate with chords crossing both the penumbral and umbral regions. In this scenario the penumbra-only crossings will have systematically shorter chords. This predicts that the low-state durations should be longer for dual-slope transitions crossing near the center of the spot. Using the durations in Table 2, we find that $\langle D\rangle = 66 \pm 12$ for 15 single-slope transitions and $\langle D\rangle = 57 \pm 12$ for the average of 10 dual-slope transitions, where D is the measured duration in days. This sense is consistent with our expectations, but the errors overlap considerably. An additional prediction is that, in most cases, a dual-slope decline should be paired with a dual-slope rise and a single-slope decline paired with a single-slope rise. This test requires that the transitions not only are close enough to ensure that they are paired but also that both transitions must be resolved. In our sample, the only transitions that meet these criteria are a pair of likely single-sloped transitions in FY Per (Fig. 6*c*, *middle*) and a pair of dual-slope transitions in LN UMa (Fig. 8*b*, *bottom*; see Honeycutt & Kafka 2003 for a detailed fit). Although the sample is quite small, the data are in fact consistent with this prediction.

A possible difficulty with this picture is the fact that transitions in polars are faster than those in disk systems. One might interpret this to mean that the slower speeds (and hence the shapes) of the transitions in disk systems are due to the response of the disk, which contradicts our earlier conclusion that the shapes of the transitions in disk systems are caused by changes in $\dot{M}$. Holding to the latter appears to require that the speed and shape of transitions in polars (which are almost all fast and single sloped) results from $\dot{M}$ being modulated by starspots of a different character than those in disk systems or even by a mechanism other than starspots. This may not be unreasonable, considering that starspots are a magnetic phenomenon on the secondary star and that the effect of the strong magnetic field of the white dwarf on the secondary star is uncertain. We note that Hessman et al. (2000), by assuming that the low states in the polar AM Her are due to starspots on the secondary star, concluded that the spottedness at the L1 is unusual, consisting of a large number of possibly overlapping starspots.

We cannot rule out the possibility that more than a single mechanism produces VY Scl low states. The systems studied here appear to be rather distinctive in their patterns: some are rich in strong, long-lasting low states, others have only one or two narrow events, whereas some appear to be abundant in slow transitions. One must also keep in mind that $\frac{2}{3}$ of the transitions analyzed in this paper belong to only two systems, KR Aur and MV Lyr. It will be necessary to substantially increase monitoring programs like RoboScope's to address this bias.

6. CONCLUSIONS

We have presented an analysis of low states in the light curves of VY Scl CVs. We find that low states deeper than 1.5 mag are relatively rare among nova-like CVs: in our sample of 65 NLs, only ∼15% exhibit such a behavior.

The transitions to and from the low state are found to have some systematic patterns. The average *e*-folding time is ∼20 days, which varies widely in different systems. Most of these transitions are adequately fit by a single straight line to the magnitude light curve. For about 40% of them, two straight lines are a much better fit because of the dual-slope nature of the transition. In those cases the fainter portion is always faster (i.e., smaller *e*-folding time); this is true for transitions both to and from the low state.

This property of the shapes of the transitions is consistent with the low states being due to a starspot drifting underneath the L1 point on the secondary star if the steep portion of the transition is associated with the umbral portion of the spot and the less steep portion with the penumbra. Additional statistical properties of the transitions are found to be consistent with this picture, such as paired single-slope and paired dual-slope transitions.

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