

MULTIYEAR PHOTOMETRY AND A SPECTROSCOPIC ORBITAL PERIOD SEARCH FOR THE VY SCULPTORIS TYPE CATAclySMIC VARIABLE V794 AQUILAE

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ABSTRACT

Continued photometry of the nova-like cataclysmic variable (CV) V794 Aql shows that the unusual repetitive, slow, deep declines that were reported earlier for 1990–1992 have persisted now for over 6 years. The slow declines and rapid rises are shown to have relatively consistent shapes. This continued behavior presents some potential problems for the model of Honeycutt, Cannizzo, & Robertson, in which the “sawtooth”-shaped light curve was considered to be an accretion disk instability initiated as \dot{M} dropped from the nova-like regime. Alternative mechanisms are briefly explored and are argued to also encounter difficulties in accounting for the light curve. A radial velocity study of V794 Aql yields a best period of 0.1533 days (3.68 hr). Periods of 0.1336 and 0.1787 days are considerably less likely but cannot be ruled out from the data at hand. These periods are in the expected range for VY Sculptoris type nova-like CVs.

Key words: novae, cataclysmic variables — stars: individual (V794 Aquilae)

1. INTRODUCTION

VY Sculptoris stars are cataclysmic variables (CVs) that exhibit pronounced high and low photometric states as the accretion rate, \dot{M} , from the donor star varies (Robinson et al. 1981; Shafter et al. 1985; Warner 1995). These \dot{M} -variations appear to be random in amplitude, shape, and recurrence interval. The random nature of the changes offers few clues from photometry alone as to the mechanism for the behavior. However, an exception is the VY Sculptoris star V794 Aql, which Honeycutt, Cannizzo, & Robertson (1994, hereafter HCR94) reported to have “sawtooth”-shaped transitions, in which the slow declines and fast rises were of relatively consistent shape during 1990–1992. Using Cannizzo’s models as a guide, HCR94 concluded that the systematic photometric changes were caused by the response of the accretion disk to the cessation of mass transfer from the secondary star. The “sawtooths” were taken to be accretion disk oscillations that arose as the temperature of the disk decayed into the instability regime following a sudden strong decrease in \dot{M} .

In respects other than the character of its long-term light curve, V794 Aql appears to have observational properties consistent with those of members of the nova-like VY Sculptoris class. The X-ray emission is consistent with a nonmagnetic or weakly magnetic CV (Eracleous, Halpern, & Patterson 1991; Verbunt et al. 1997; Greiner 1998), and there is no evidence in the X-ray periodogram for a rotating magnetic white dwarf (Eracleous, Patterson, & Halpern 1991). The *IUE* spectrum of V794 Aql (Szkody, Downes, & Mateo 1988; la Dous 1991), as well as optical spectra (Szkody et al. 1981; Honeycutt & Schlegel 1985), shows relatively strong emission lines of intermediate excitation, similar to those seen in other VY Sculptoris stars in both the low state and the high state.

In contrast to these undistinguished nova-like VY Sculptoris characteristics, the unusual long-term light curve is seen to persist. This paper increases the time base of

the V794 Aql photometry to 6.7 yr, revealing that the “sawtooths” have continued and permitting a more extensive characterization of the shapes. We also report spectroscopy of V794 Aql, allowing an investigation of the orbital period.

2. PHOTOMETRY

The data acquisition and data reduction are as described in HCR94. The zero point of the differential photometry was set using secondary standards from Henden & Honeycutt (1995). Figure 1 shows the complete light curve from 1990 November until 1997 September, totaling 501 points obtained on 414 separate nights.

The panels in Figures 2 and 3 show expanded views of the photometry in Figure 1, each panel encompassing a separate observing season. The declines and rises labeled in Figures 2 and 3 are characterized with regard to mean magnitude and e -folding times, τ , in Table 1. For some of the declines the shape changes systematically (see also HCR94) as the system fades. Our designations for the declines incorporate a different letter for each decline along with a suffixed number for each part of the decline that has a significantly different slope. The sharp rises are generally designated by two letters incorporating the letter designations of the declines that fall immediately on either side of the rise. In the bottom panels of Figures 2 and 3, short vertical lines mark the dates during which spectrographic observations were obtained, as detailed in § 3.

V794 Aql appears to display three kinds of photometric behavior: The first is slower sawtooths having declines with $\tau \approx 50$ –100 days followed by rapid rises with $\tau \lesssim 10$ days, then immediately starting another decline. Typical recurrence intervals are 100–250 days. This is the dominant kind of light variation during 1991–1995, with only a few instances of contrary behavior. The second behavior is faster sawtooths having declines with $\tau \approx 30$ days followed by rapid rises with $\tau \leq 3$ days, and a typical recurrence interval of ~ 35 days. This is the dominant behavior during 1996 and during 1970–1972 (Meinunger 1979). In the third kind of photometric behavior, the magnitude often remains relatively constant near $V \sim 14.3$, interspersed with erratic

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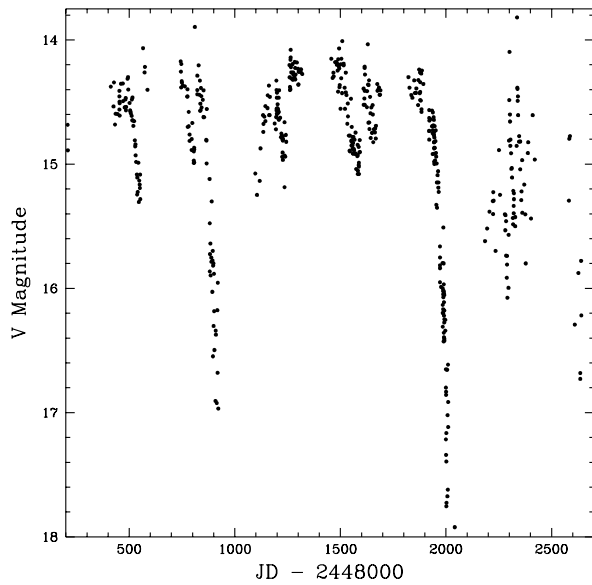


FIG. 1.—Light curve of V794 Aql for 6.7 yr, 1990 November to 1997 July. Error bars are omitted for clarity.

variations on many timescales from this level. This is apparently the behavior during much of the historical record 1932–1982 (reviewed in HCR94). However, the sampling is poor enough over much of this time that large intervals of both slower and faster sawtooths cannot be ruled out. This third, “nonsawtooth,” behavior is also present occasionally during 1990–1997; note the anomalous slow rise labeled “DE” in Figure 2 and the interval of constant light in the middle panel of Figure 3.

Figure 4 plots the e -folding time versus the mean magnitude for the transitions in Table 1, allowing an examination of the systematics of the sawtooths. Note first that the open circles (designating the declines in the first five panels of Figs. 2 and 3) follow a general pattern in which the system

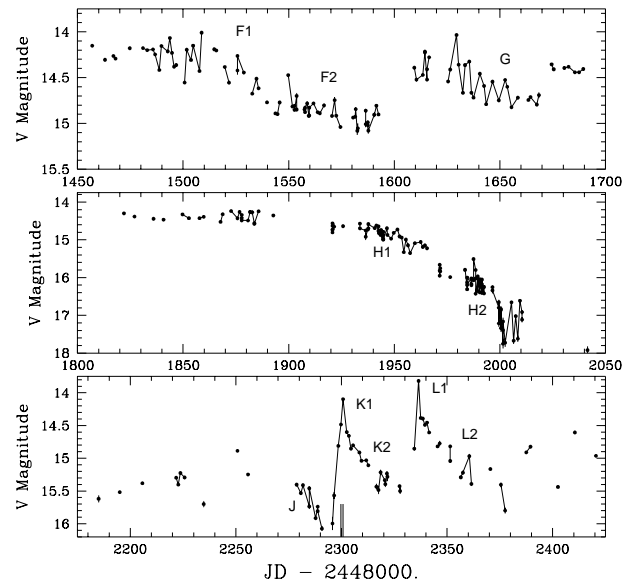


FIG. 3.—Same as Fig. 2, but for three observing seasons 1994–1996

first fades rapidly and then slows the rate of fading, finally fading more rapidly again if the fading continues beyond $V \approx 15$. Most of the declines begin in the range $14.4 \leq V \leq 15$, thereby omitting the initial fast decline that seems to occur only for $V \lesssim 14.4$. Note that the rises (triangles) all are quite fast, with $\tau \lesssim 20$ days (with the exception of anomalous rise DE). The distinction between the decline and rise time is quite extreme, especially when one recognizes that nearly all of the rises are unresolved and that the triangles in Figure 4 are nearly all upper limits. The only rise that is well resolved is rise JK, with $\tau = 2.3$ days. Finally, note that the filled circles and filled triangles (declines and rises in Fig. 3, bottom) are all systematically

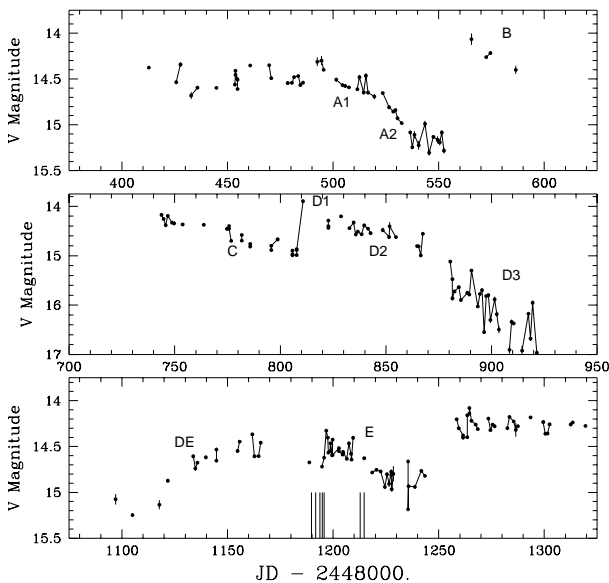


FIG. 2.—Expanded light curve of V794 Aql for three observing seasons, 1991–1993. Data points closer than 3 days are connected by lines. Error bars are plotted but are usually too small to be seen. The labels refer to the transition designations in Table 1, and the vertical lines mark the times spectra were acquired.

TABLE 1

TRANSITIONS IN V794 AQUILAE 1991–1996

Transition	Mean JD (2,448,000+)	Mean Magnitude	τ (days)
Decline A1	512	14.6	104
Decline A2	539	15.1	61
Rise AB	559	14.7	<13
Decline B	576	14.2	69
Decline C	776	14.6	102
Rise CD	810	14.4	<3
Decline D1	817	14.1	26
Decline D2	845	14.6	90
Decline D3	895	15.9	32
Rise DE	1128	14.8	82
Decline E	1222	14.7	81
Rise EE	1251	14.7	<22
Decline F1	1533	14.5	75
Decline F2	1572	14.8	272
Rise FG	1602	14.6	<28
Decline G	1639	14.6	122
Rise GG	1671	14.6	<14
Decline H1	1960	15.2	48
Decline H2	1998	16.7	14
Decline J	2288	15.7	19
Rise JK	2298	15.1	2.3
Decline K1	2301	14.4	5
Decline K2	2315	15.1	27
Rise KL	2332	14.7	<4
Decline L1	2338	14.1	2
Decline L2	2357	15.1	29

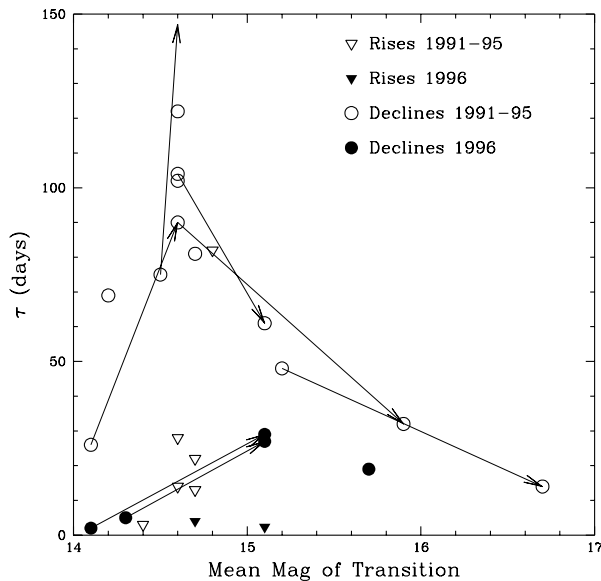


FIG. 4.—Characterization of the transitions listed in Table 1, showing the dependence of the speed of the transitions on mean magnitude, on direction of the transition, and on epoch. The data points connected by lines belong to the same transition in the order indicated by the arrows. Decline F2 in Table 1 is above the plot boundary in τ .

low compared with the open circles and open triangles. This means that during 1996 the transitions changed character, acquiring sharper transition times for both declines and rises. This was accompanied by a shortening of the interval between transitions, from ≥ 100 days (maximum power at ~ 220 days, strongly aliased by yearly gaps) to ~ 35 days. Comparing the filled circles with the filled triangles, we see that the pattern of the rises being faster than the declines was retained when the changes in τ and recurrence interval changed.

3. SPECTROSCOPY

Optical spectra of V794 Aql were obtained during a 3 week interval in 1993 and during a two-night interval in 1996. During the KPNO 2.1 m telescope queue experiment, four “blue” exposures were obtained on three different nights during the interval 1993 July 21–25. The GoldCam spectrograph was used with a 600 line mm^{-1} grating, yielding $\sim 3 \text{ \AA}$ resolution. The region covered was $\sim 3900\text{--}6600 \text{ \AA}$, and the exposure times were 1200 s. The top spectrum in Figure 5 shows one of these “blue” spectra. Also during the 2.1 m queue experiment, four “red” exposures were obtained on four different nights during the interval 1993 July 23 to August 15. The GoldCam spectrograph was used with a $1200 \text{ line mm}^{-1}$ grating, yielding $\sim 1.5 \text{ \AA}$ resolution. The region covered was $\sim 5900\text{--}6900 \text{ \AA}$, and the exposure times were 2400 s. The middle spectrum in Figure 5 shows one of these “red” spectra. Using the WIYN² 3.5 m telescope, a total of 24 spectra were obtained on two successive nights in 1996 August. The WIYN multiple-object spectrograph was used with a 600 line mm^{-1} grating and red fibers, yielding $\sim 3 \text{ \AA}$ resolution. The exposure times were 300 s.

² The WIYN Observatory is a joint facility of the University of Wisconsin–Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories.

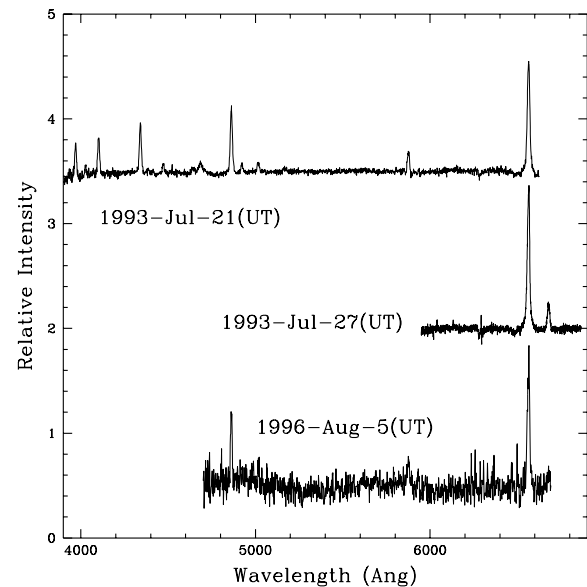


FIG. 5.—Representative spectra of V794 Aql from three different data sets. *Top*, from a set of $\sim 3 \text{ \AA}$ resolution data obtained in 1993 July; *middle*, from a set of $\sim 1.5 \text{ \AA}$ resolution data obtained in 1993 July/August; *bottom*, from a set of $\sim 3 \text{ \AA}$ resolution data obtained in 1996 August.

For all three sets of spectra, IRAF routines were used to fit a single Gaussian to the single-peaked $H\alpha$ emission line, with a typical error of $10\text{--}15 \text{ km s}^{-1}$. Table 2 gives the measured heliocentric velocities. Period searches revealed that the 1996 WIYN data alone provided useful periodogram peaks but that inclusion of velocities from 1993 KPNO spectra did not improve the period, instead making the period determination worse. A possible reason is that the

TABLE 2
V794 AQUILAE $H\alpha$ RADIAL
VELOCITIES

HJD	v_r (km s^{-1})
2,450,299.7197.....	−34
2,450,299.7319.....	49
2,450,299.7579.....	−49
2,450,299.7710.....	−12
2,450,300.6741.....	−75
2,450,300.6898.....	−33
2,450,300.6965.....	−21
2,450,300.7031.....	30
2,450,300.7165.....	54
2,450,300.7247.....	16
2,450,300.7331.....	22
2,450,300.7415.....	64
2,450,300.7499.....	54
2,450,300.7583.....	41
2,450,300.7678.....	−1
2,450,300.7764.....	−31
2,450,300.7853.....	−41
2,450,300.7937.....	−56
2,450,300.8021.....	−71
2,450,300.8105.....	−65
2,450,300.8189.....	−69
2,450,300.8282.....	−40
2,450,300.8366.....	−36
2,450,300.8450.....	−34
2,450,300.8534.....	−27
2,450,300.8618.....	20
2,450,300.8715.....	26
2,450,300.8805.....	35
2,450,300.8896.....	32

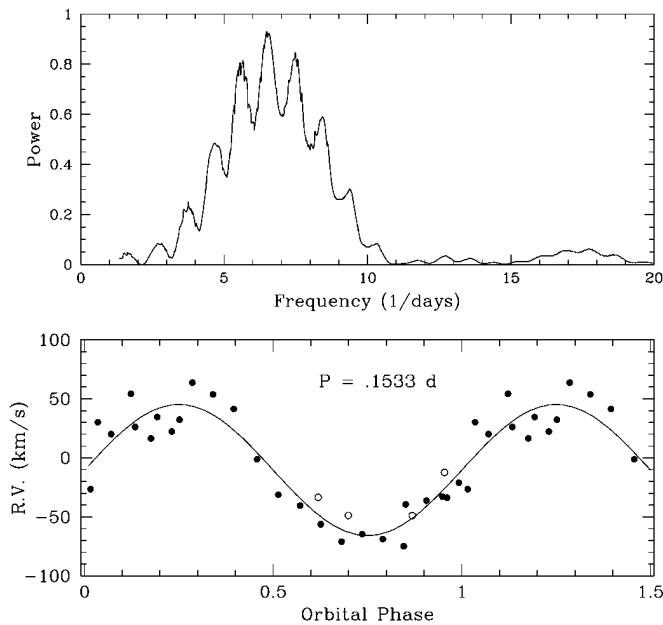


FIG. 6.—*Top*: Periodogram of the radial velocities in Table 2, with peaks near 3.2, 3.7, and 4.2 hr. *Bottom*: Results (see Table 3) of fitting a sine curve in the vicinity of the central peak. Open circles are data acquired 1996 August 4 (UT); filled circles were acquired the following night.

1993 data were acquired over a 26 day interval while the 1996 data are from two successive nights. Perhaps the spectrum changes significantly on timescales of weeks but is relatively stable over days. Another possible reason is that the WIYN fiber-fed spectrograph has superior wavelength stability. This result remains rather mysterious in view of the higher signal-to-noise ratio in the KPNO spectra and somewhat better spectral resolution. In any case, we will confine our radial velocity study to the WIYN data.

The top panel of Figure 6 is a modified Scargle periodogram (Horne & Baliunas 1986) of the WIYN velocities in Table 2. Based on a single 5 hr sequence of spectra, Shafter (1983) reported a preliminary orbital period of 0.23: days for V794 Aql, with $K = 100: \text{km s}^{-1}$. Shafter's preliminary period appears to be unlikely in view of this periodogram. The WIYN radial velocity data of Table 2 were fitted with a sine curve of the form

$$v_r = \gamma + K \sin [2\pi(t - T_0)/P],$$

with starting values of the period near each of the three central peaks in the periodogram. Table 3 gives parameters of these three fits. The bottom panel of Figure 6 shows the data folded on the favored period, along with the fitted curve.

4. DISCUSSION

The sawtooths that appeared in the 1990–1992 light curve of V794 Aql were modeled in HCR94 as disk insta-

bilities (i.e., dwarf nova outbursts) initiated as \dot{M} from the secondary star fell to zero from an initial high value characteristic of a nova-like CV. Such outbursts can occur for a while even with $\dot{M} = 0$, because only a small fraction of the disk gas is accreted onto the white dwarf during each outburst. However, the model outbursts do decline in amplitude as the disk is gradually depleted. The input parameters for these models were appropriate for a system just above the period gap, an assumption justified by the period study just described. The sawtooth shapes were best reproduced with $\alpha_{\text{cold}} \simeq 0.005$ and $\alpha_{\text{hot}} \simeq 0.005\text{--}0.01$. These values are smaller than generally inferred from the modeling of dwarf nova outbursts, and $\alpha_{\text{hot}}/\alpha_{\text{cold}}$ is also smaller.

An alternative scenario assumes that the sawtooths are mirroring \dot{M} -variations from the secondary star while the disk remains in the high state. In HCR94 it was found that $\alpha_{\text{hot}} > 0.1$ is required in order for the disk to react as fast as the rapid rises of the sawtooths. This explanation was not favored in HCR94, because it appears to be difficult for the disk to remain in the high state in the presence of an observed 3 mag decline, a situation made more difficult by a 4 mag decline seen in these later data.

The disk instability model of HCR94 would appear to require some modification to survive confrontation with the more extensive data in this paper. The slow sawtooths persisted for at least 5 years, 1991–1995, with no systematic diminution in amplitude. If dwarf nova outbursts are to remain a viable explanation for the sawtooths, then \dot{M} must be maintained within the instability regime for some time, meaning that V794 Aql is a true dwarf nova, not a nova-like CV. If a true dwarf nova, then what are we to make of the occasional intervals of steady brightness during 1991–1995 and in the historical photographic record? Z Camelopardalis stars are dwarf novae that sometimes stop outbursting as \dot{M} drifts above \dot{M}_{crit} and the disk becomes stable against dwarf nova outbursts. As a result, the average brightness over the outbursting intervals in Z Cam stars is fainter than during the standstills (Honeycutt et al. 1998), as is the case in V794 Aql. However, in most Z Cam stars the standstill brightness is only just above \dot{M}_{crit} , and the rapid outbursts oscillate both above and below the standstill brightness. In V794 Aql, the sawtooths are consistently much fainter than the occasional intervals of steady brightness, which all seem to occur near $V \simeq 14.2\text{--}14.5$, near the bright level of the sawtooths. In the historical record of Meinunger (1979), the declines during 1970–1972 appear to drop from a constant level near $M_{\text{pg}} \sim 15$. If V794 Aql is a Z Cam star, then it is certainly an unusual one.

It might also be difficult to reconcile the two different kinds of sawtooths, slow and fast, with an accretion disk instability. Although some dwarf novae do change their outburst shapes and spacing with time, the kind of rather discontinuous cycling between two quite different kinds of outbursting behavior in V794 Aql would be unusual among dwarf novae if V794 Aql were to be included in this group-

TABLE 3
PARAMETERS OF FITS TO V794 AQUILAE RADIAL VELOCITIES

γ (km s^{-1})	K (km s^{-1})	T_0 (days)	P (days)	σ (km s^{-1})
-11.2 ± 1.9	51.2 ± 2.6	$2,450,299.238 \pm 0.004$	0.1366 ± 0.0004	20
-10.3 ± 1.9	55.5 ± 2.7	$2,450,299.165 \pm 0.005$	0.1533 ± 0.0005	15
-8.5 ± 1.9	52.8 ± 2.7	$2,450,299.255 \pm 0.006$	0.1787 ± 0.0008	20

ing. All these difficulties point toward more serious consideration of an \dot{M} -modulation as the sawtooth mechanism, or a combination of \dot{M} -bursts and accretion disk instabilities. For an \dot{M} -burst alone, the problem remains that the high-state disk required for the observed fast rises would be expected to decay to the low state for the observed 3–4 mag drops. For a combination of \dot{M} -bursts and disk instabilities, it is pointed out in HCR94 that the disk cannot follow the fast rises unless the conjectured \dot{M} -bursts were unrealistically pretimed to coincide with a heating front in the disk.

Further clues regarding the viability of a thermal disk instability as the sawtooth mechanism are available from the character of the spectrum. At minimum light, dwarf novae typically have an emission-line spectrum from the optically thin portions of the accretion disk. At maximum most dwarf novae have an absorption-line spectrum, as the optically thick portions of the disk dominates (Warner 1995). This is especially true in low-inclination systems, a category to which V794 Aql likely belongs because of the absence of an eclipse. The emission-line spectra in Figure 5, all obtained at or near maximum brightness in V794 Aql, do not support the idea that V794 is undergoing a dwarf nova outburst at maximum. The character of all of our 1993 and 1996 spectra is identical, to within their errors, with regard to the equivalent widths of the emission lines, and these spectra are also consistent with the emission-line spectrum of V794 Aql shown by Szkody et al. (1981), again obtained near maximum light.

Although V794 Aql has many of the properties of a

typical disk VY Sculptoris star, there is no direct evidence yet that a disk exists in this system. If the kinds of interpretation difficulties summarized above persist after further efforts, then perhaps a broader range of possibilities should be considered. Speculatively, these might include cyclical burning of accreted hydrogen on the white dwarf (Iben 1982; Patterson et al. 1998; Steiner & Diaz 1998), or a cyclical \dot{M} -modulation onto a diskless system. In either case, a source of visual light at maximum sufficient to dominate the light of the secondary star is required, since there is no evidence in the spectrum of a red dwarf. Among the approximately 65 nova-like and old nova systems being monitored by Indiana University's robotic telescope RoboScope, several have occasional sawtooth variations with shapes and timescales similar to the ones in V794 Aql, but only V794 Aql has such large-amplitude sawtooths and is so consistently repeatable. The phenomenon is therefore rare but probably not unique to V794 Aql. This fact, plus the fact that V794 Aql appears to be distinguishable from other nova-like VY Sculptoris stars only by the unusual long-term light curve, would appear to argue that a rare and/or exotic explanation should not be required.

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