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Superhumps in Cataclysmic Binaries. IX. AL Comae Berenices

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ABSTRACT. We report photometry of the 1995 superoutburst of the dwarf nova AL Comae Berenices. The overall eruption light curve was striking, suggestive of two superoutbursts in rapid succession. During the first week of eruption, the light curve sported a period of 81.63±0.07 min. This signal declined quickly in amplitude, and was replaced by a stronger signal at 82.55±0.03 min. The latter bears all the earmarks of a "common superhump," a feature usually seen in SU UMa-type dwarf novae in superoutburst. This superhump endured at least 40 d, with no secular period change. We reexamined the quiescent light curves to search for a stable photometric signal which might signify the true binary period. We found a stable double-humped wave with a fundamental period of 81.6025±0.0001 min—the shortest period yet seen among dwarf novae, and probably very nearly the shortest period attainable by any binary star with a hydrogen-rich secondary. In orbital period and quiescent light curve, as well as in the eruption light curve, the star is a virtual twin of WZ Sge. There are also large-amplitude waves with a period in the range 83–90 min; these "quiescent superhumps" are rarely found in cataclysmic variables, and require an origin somewhat different from that of the common superhumps characteristic of SU UMa stars in eruption. We speculate that they arise from instability at the 2:1 orbital resonance in the accretion disk, and that the secondary has been whittled down to $<0.04\ M_\odot$.

1. INTRODUCTION

AL Comae Berenices ($\alpha_{2000}=12^h32^m25\overset{s}{.}6$, $\delta_{2000}=+14°20'57''$) is a dwarf nova which spends most of its life around 20th magnitude, with large and infrequent eruptions. Month-long eruptions to $V=13$ occurred in 1961 and 1975, and short eruptions (~2 days) occurred in 1965 and 1974. Bertola (1964) describes photometry and spectroscopy of the 1961 eruption; other accounts of the eruption history are given by Duerbeck (1987) and Howell et al. (1996). The dichotomy of eruption types (short versus long) is the defining credential of the SU UMa class of dwarf novae (reviewed by Warner 1985, 1995a), and the long recurrence period and high amplitude is the defining credential of the "WZ Sge" subclass (Bailey 1979; Downes and Margon 1981; O'Donoghue et al. 1991).

AL Com has also been studied at minimum light. The quiescent light curve contains signals with periods reported in the range 38–42 min and 84–90 min (Howell and Szkody 1988, 1991; Szkody et al. 1989; Abbott et al. 1992). The interpretation of these signals is still unclear, and is hampered by observational uncertainties about their *stability*. Mukai et al. (1990) presented spectroscopy at quiescence, showing the usual signature of low-$\dot{M}$ dwarf novae at quiescence: strong Balmer lines superposed on a cool continuum.

In 1995 April another superoutburst occurred. Three circumstances combined to make this the most thoroughly observed dwarf nova eruption in history:

(1) Despite the 20-yr wait from the previous eruption and the star's invisibility 99% of the time, visual observers caught the star right away as it steeply climbed to maximum (York 1995). We are still in awe of this observation!
(2) Variable-star alert networks had recently been established over e-mail by the American Association of Variable-Star Observers (AAVSO) and Kyoto University, enabling observers to exchange information rapidly and efficiently. This proved invaluable for quickly assessing the progress of the eruption, and for studying periodic waves in the light curve.
(3) The star erupted in the season when it was crossing the meridian around local midnight, enabling long nightly observations (~8 hr). This greatly eased problems with period finding, since it eliminated the ±1 c d^{-1} aliases which often plague this enterprise.

In this paper we report coverage of the eruption over a 50-day baseline, from maximum light through late decline. Most of the data consist of long nightly light curves, designed to study the periodic waves. For most of the eruption, these waves bear all the earmarks of "superhumps," a standard feature of SU UMa stars in superoutburst. The superhump phase drifts slightly but with no obvious signature of systematic period change. Guided by the periods present in superoutburst and in particular the elimination of 1 c d^{-1} aliases, we also reexamined the minimum-light photometry and found an underlying stable signal which must surely be the true orbital period of the binary. The star is a virtual twin of WZ Sge and thus is certainly a member of that subclass.

2. PHOTOMETRY IN SUPEROUTBURST

2.1 Data Acquisition

Most of the photometric data consist of differential magnitudes in unfiltered light, obtained with CCD cameras on the two telescopes of the Center for Backyard Astrophysics (CBA-East: Skillman and Patterson 1993; CBA-West: Harvey et al. 1995). CBA-West used as its primary comparison star the bright star 7′ W of AL Com; we estimate this star to have $V=10.39$. CBA-East used a star 4′ W of the variable—"Bertola's star," with $V=13.51$ (Bertola 1964). Some V-band photometry was also obtained with CCD photometers on the MDM 1.3-m telescope and the Dutch 0.9-m telescope at ESO. These observations used the two stars immediately NE of AL Com: the nearer one with $V=16.72$, and the farther one with $V=16.93$. The observing log, comprising 153 hr of photometry, is given in Table 1.

TABLE 1
Log of Photometry

(1995) UT Date	(2,449,000+) JD start-end	Telescope	(hr) Duration	Points	$\langle V \rangle$
06 April	813.64038-.92146	1	6.75	252	12.38
07 April	814.61666-.90861	1	7.01	270	12.56
09 April	816.73933-.93332	1	4.66	168	12.85
10 April	817.68801-.96703	1	6.70	235	12.96
11 April	818.63234-.96330	1	7.94	279	13.11
14 April	821.68318-.73110	2	1.15	86	13.53
16 April	823.57518-.76478	2	4.55	536	13.66
18 April	(825.67124-.95817)	3	6.89	59	13.61
20 April	(827.87197-.95417)	3	1.97	31	13.86
21 April	828.61947-.93694	1	7.62	165	14.00
22 April	829.58040-.77415	2	4.65	545	14.08
23 April	830.62041-.93119	1	7.46	199	14.16
24 April	831.62660-.91731	1	6.98	204	14.26
25 April	832.62417-.92008	1	7.10	206	14.34
26 April	833.67952-.75384	2	1.78	108	- -
26 April	833.63827-.92099	1	6.78	190	14.42
27 April	834.55452-.64412	2	2.15	127	14.55
27 April	834.66303-.84205	1	4.30	112	14.46
29 April	836.58577-.67259	2	2.08	122	14.75
29 April	836.66148-.89268	1	5.55	169	14.67
01 May	838.63023-.84371	1	5.12	149	15.67
04 May	841.66139-.73403	1	1.74	49	15.27
10 May	847.71177-.83399	1	2.93	93	15.10
11 May	848.73168-.82746	1	2.30	69	14.97
13 May	850.77356-.85832	1	2.03	68	15.14
14 May	851.71789-.86708	1	3.58	113	15.28
18 May	855.65288-.85408	1	4.83	147	16.01
20 May	857.52137-.68355	4	3.89	38	17.52
21 May	858.47539-.68188	4	4.96	52	18.43
22 May	859.47268-.68068	4	4.99	49	18.86
23 May	860.46128-.68048	4	5.26	55	18.88
24 May	861.48461-.66740	4	4.39	46	18.87
25 May	862.48004-.67886	4	4.77	50	18.93

Telescope code:
1 = CBA-West (35 cm, clear) 2 = CBA-East (66 cm, clear)
3 = MDM (1.3 m, V) 4 = ESO (1.5 m, V)

2.2 The Eruption Light Curve

The eruption light curve in V light is shown in Fig. 1. Most of the points plotted are nightly averages of our time series, with two points plotted per night when a significant secular trend was present. We also include average V magnitudes from the Ouda Research Station photometry. For the unfiltered photometry in our data, we chose to set the V magnitude (difficult to calibrate because it is unfiltered) by using contemporaneous Ouda photometry. The average scatter in this conversion was only 0.02 mag, compared to an estimated systematic uncertainty of ~0.07 mag from our own cruder attempt at calibration. Presumably this worked so well because both time series (CBA and Ouda) were densely sampled and because the star's variability is broadband and smooth.

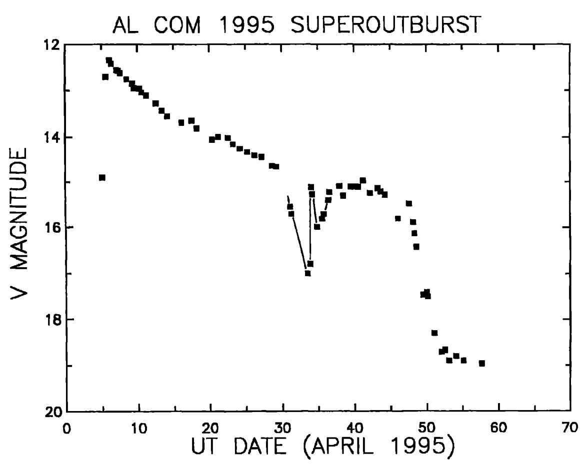

FIG. 1—Eruption light curve of AL Com in 1995. Maximum light occurred on April 6, JD 2449813. Most points are nightly averages from our data, with 2 points per night shown when the star showed a secular trend through the night. A few points come from the Ouda station photometry, and from reported visual observations. Most errors are smaller than the symbol size. A few points near the dip are connected by lines, to indicate the trends in this important interval.

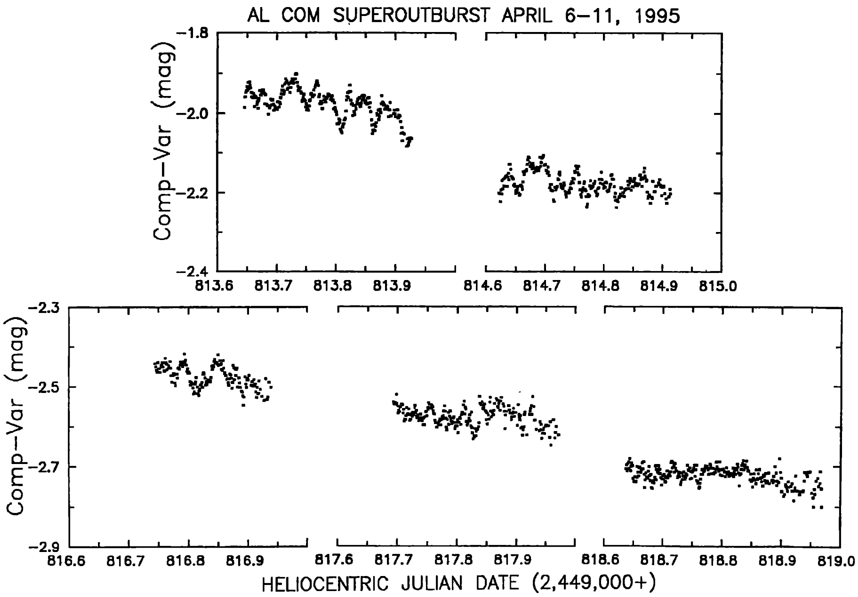

FIG. 2—Nightly light curves obtained during the early decline phase, showing the rapid disappearance of the outburst orbital hump. The comparison star is estimated to have $V=10.39$.

The light curve shows most of the features commonly found in the superoutbursts of SU UMa stars. The star rose very rapidly (at a rate of 7 mag d^{-1}) through the night of April 5, and was at maximum light when CCD observations started on April 6.2. During April 6–11 the star declined at an average rate of 0.15 ± 0.01 mag d^{-1}, and during April 12–29 this flattened to 0.111 ± 0.004 mag d^{-1}. On April 29.4 the star commenced falling into a "dip" 2 mag deep, then recovered and resumed declining at 0.11 mag d^{-1}. During egress from the dip, a transient brightening of ~1 mag occurred. A steep decline signifying the end of the eruption started 42 d after maximum light, and proceeded at a rate of 0.9 mag d^{-1}.

2.3 Nightly Light Curves

Nightly light curves during the first 6 days of eruption are shown in Fig. 2. The initial fairly rapid decline is seen here, as well as periodic waves which rapidly decline in amplitude.

On April 11 the periodic waves were nearly gone, and a brief observation on April 14 again showed nothing periodic. But the next observation on April 16 showed an obvious signal with full amplitude 0.23 mag, growing rapidly through the night. This signal continued to be plainly visible for the next 10 days, with slowly decaying amplitude. Nightly light curves during this interesting segment are shown in Fig. 3.

2.4 Period Analysis

To search for periodic signals, we removed the mean and trend from each night's observation, appended the nights to form long time series, and then calculated the power spectrum of the light curve from the discrete Fourier transform.

2.4.1 1995 April 6–11

The result for April 6–11 is shown in the upper frame of Fig. 4, indicating signals at 17.61 and 35.32 (±0.02) c d^{-1}. These signals are nearly in a 1:2 ratio, but not exactly. We summed the light curve at a frequency of 17.635 c d^{-1} (as a compromise between these two slightly discrepant estimates) and found the mean wave form shown in the lower frame of Fig. 4. The ephemeris for this photometric wave (which we shall call an "outburst orbital hump") is given by

$$\text{Primary maximum} = \text{HJD } \underset{(1)}{2449813.674} + \underset{(6)}{0.05670}E. \quad (1)$$

On this ephemeris, primary minimum occurs at phase 0.35.

2.4.2 1995 April 16–27

We did the same for the interval April 16–27, when a much larger periodic hump was visible in the light curve. The power spectrum in the top frame of Fig. 5 shows significant peaks at 17.438 and 34.927 (±0.009) c d^{-1}. The structures surrounding these peaks arise from the windowing of the light curve. Again the two signals are nearly in a 1:2 ratio, but not exactly. The higher-frequency signal occurs at a frequency $0.15\pm0.06\%$ higher than the exact first harmonic of the fundamental. We then summed at 17.438 c d^{-1} (because much more power exists at this frequency) and obtained the mean light curve shown in the lower frame of Fig. 5. The ephemeris for this photometric wave (which we shall identify as a "common superhump") is given by

$$\text{Primary maximum} = \text{HJD } \underset{(1)}{2449823.631} + \underset{(3)}{0.05735}E. \quad (2)$$

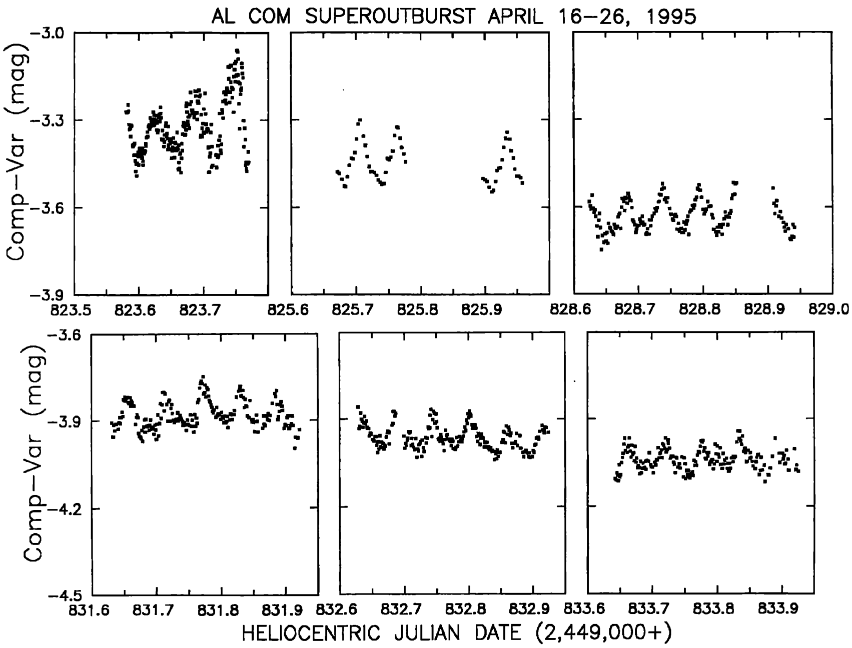

FIG. 3—Nightly light curves obtained during mid-decline, prior to the dip. A "common" superhump was suddenly born on April 16 (HJD 2449823), and slowly declined in amplitude over this 11-day interval.

Minimum light on this ephemeris occurs at phase 0.57.

There is also an unlabeled feature near the main signal in this power spectrum, at 17.84 c d^{-1}. Although it looks promising, our attempt to highlight it by "cleaning" the power spectrum (subtracting the main signal) was unsuccessful. A peak remained, but moved to 17.56 c d^{-1}, a frequency not present in the original power spectrum. This is the sort of uninterpretable result typically obtained when the subtracted signal (of constant frequency and amplitude) is a poor description of what is actually present in the star. (We list these

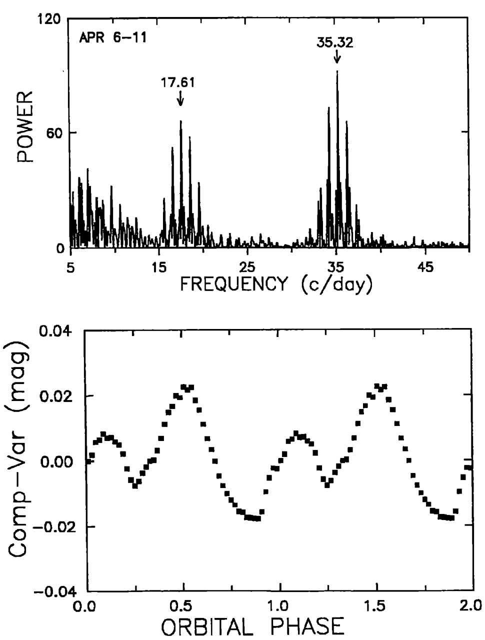

FIG. 4—*Upper frame*, power spectrum of the light curve in early decline. The two significant peaks are labeled with their frequencies in c d^{-1}. The frequencies are nearly in a 1:2 ratio. *Lower frame*, mean light-curve at the indicated fundamental frequency (17.635 c d^{-1}). Errors are about equal to the symbol size.

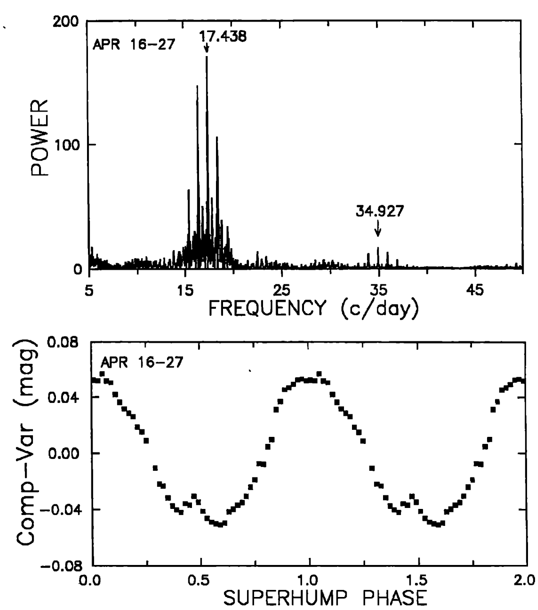

FIG. 5—*Upper frame*, power spectrum of the light curve in mid-decline, showing the common superhump: signals at 17.438 and 34.927 (±0.010) c d^{-1}. The frequencies are nearly in a 2:1 ratio, but not exactly. *Lower frame*, mean light curve during this interval, synchronously summed at 17.438 c d^{-1}. The actual light curve is slightly different (maxima more pointed), but a little phase wander hides sharp features somewhat.

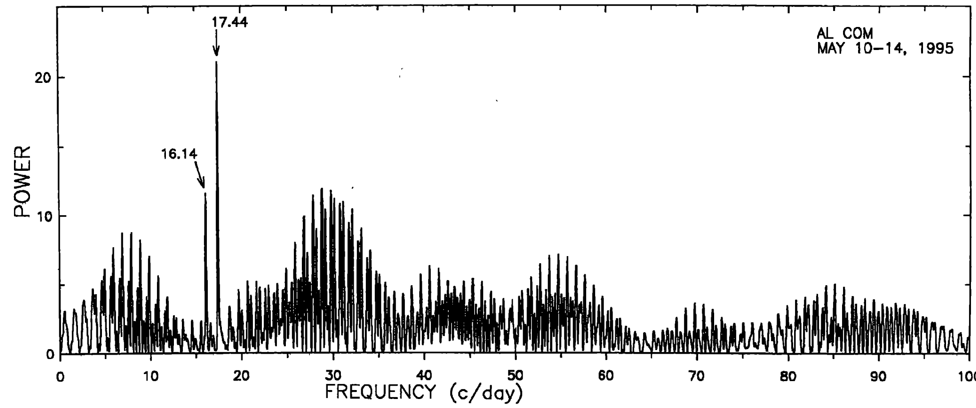

FIG. 6—Power spectrum during May 10–14. The obvious main signal occurs at 17.44(4) c d^{-1}, evidently the common superhump. We show the original "dirty" power spectrum to permit evaluation of the noise level, but include a "cleaned" region around the superhump to show the possible presence of a 16.14 c d^{-1} signal. The features near 8 and 30 c d^{-1} are also of borderline significance.

frequencies solely for the benefit of readers who may have other datasets on this star.)

2.4.3 1995 May 10–14

We obtained another dense data set during May 10–14, so we merged it and analyzed the time series. The light curves show mainly erratic variations, but with a probable weak signal at ~1.4 hr. The power spectrum, seen in Fig. 6, sheds considerable light on this. The main signal is again at 17.44 c d^{-1}, evidently the common superhump. Additional marginal signals appear near 30, 8, and 16.14 (or possibly 17.14) c d^{-1}. We show a partially cleaned power spectrum in which the window patterns in the vicinity of the 16.14 and 17.44 c d^{-1} signals have been removed, but the original noisy power spectrum is otherwise left intact, to permit evaluation of the noise level.

2.4.4 1995 May 20–25

We also obtained six consecutive nights of coverage at the end of the outburst, with the last four occurring near quiescence at $V\sim19$ (see Table 1). In the upper frame of Fig. 7 we show the power spectrum of this light curve, indicating the continuance of the common superhump, at 17.38(3) c d^{-1}.

Another feature appears in the power spectrum, at 4.37(3) c d^{-1}. The wave forms of these two signals are shown in the lower frame of Fig. 7. The complex and possibly four-peaked profile of the low-frequency signal arises from the fact that the two frequencies are consistent with the ratio 1:4.

3. SPECTROSCOPY

We obtained spectroscopic coverage during outburst, from April 17 to April 21, with the modular spectrograph mounted on the 2.4-m telescope of MDM Observatory. No obvious changes were seen over the several dozen spectra recorded. The grand average spectrum is shown in the upper frame of Fig. 8. Weak Hα absorption and weak Hβ emission are typical of dwarf novae slightly after outburst maximum. The breadth of Hβ absorption (FWZI=100 A) indicates velocities of at least 3000 km s^{-1} in the line-forming region of the accretion disk.

On June 1, with the star at $V\sim19$, we obtained an exposure with the R-C spectrograph mounted on the KPNO 4-m telescope. The lower frame of Fig. 8 shows the spectrum, containing strong H emission lines [EW(Hβ)=60 A] on a cool continuum—a typical spectrum for a low-$\dot{M}$ dwarf nova near quiescence. The apparently double-peaked line profiles are usually interpreted as a sign of moderately high binary inclination. The cool continuum slope limits any possible contribution from an underlying hot white dwarf to <35% of the V light.

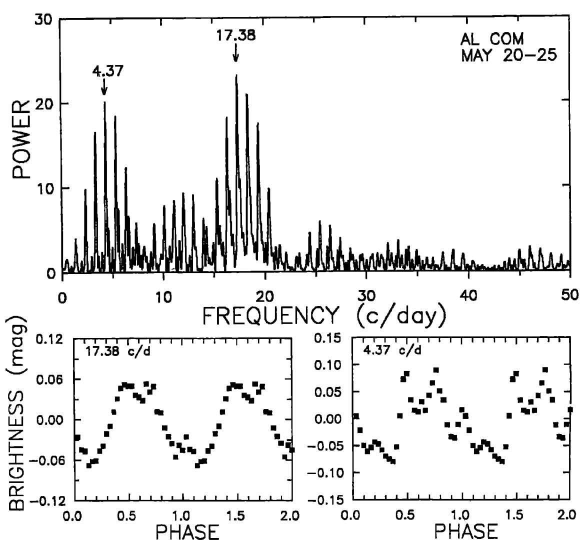

FIG. 7—*Upper frame*, power spectrum during the final decline (May 20–25). The dominant feature is still the common superhump at 17.38(3) c d^{-1}. There is also a possible signal at 4.37(3) c d^{-1}. *Lower frame*, wave forms of these signals. Zero phase is the beginning of the time series at HJD 2449857.5244.

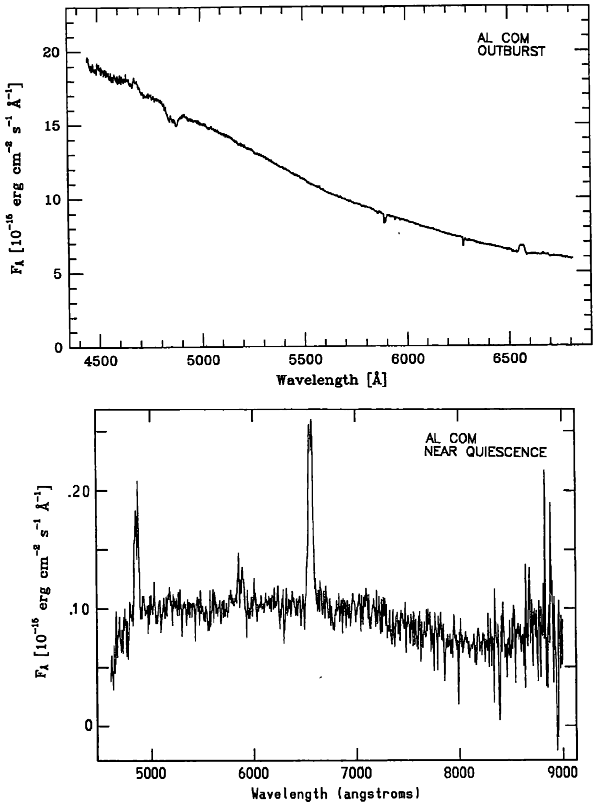

FIG. 8—*Upper frame*, spectrum in outburst (averaged over April 17–21). The sharp absorptions at 5900 and 6300 A are of terrestrial origin. FWHM resolution is ~4 A. *Lower frame*, spectrum just after the return to near-quiescence (V~19, June 1). The sharp downturn at short wavelength is of instrumental origin. FWHM resolution is ~6 A.

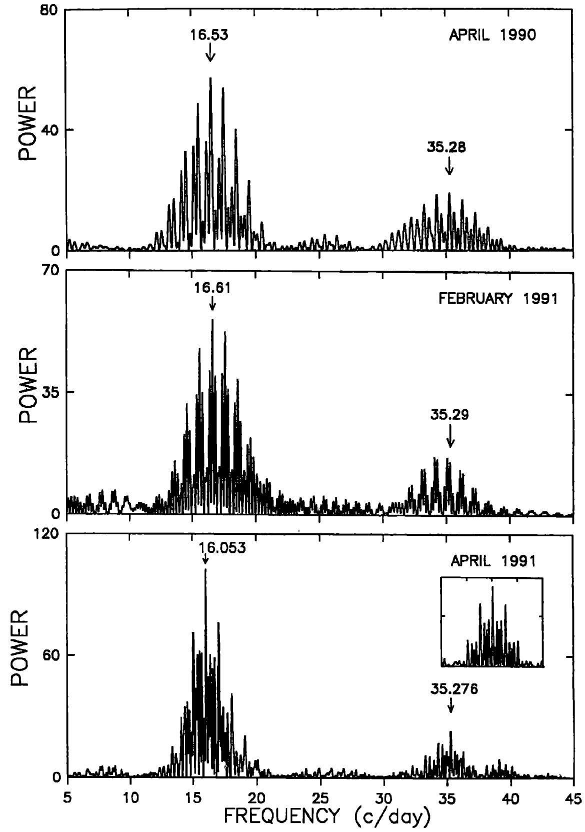

FIG. 9—Power spectra of the three time series in quiescence, with significant peaks labeled with their frequencies in c d^{-1}. A peak exists at 35.28 c d^{-1} in each frame, indicating a possibly stable signal. The inset in the lowest frame shows the spectral window, the power spectrum of an artificial signal sampled exactly like the actual data. The close resemblance to the two actual peaks in this frame shows that the labeled peaks are the correct frequencies, not the flanking aliases.

4. PHOTOMETRY IN QUIESCENCE

4.1 Rough Period Finding

The long nightly observations in superoutbursts eliminated the ± 1 c d^{-1} alias problems which frequently afflict period finding on a rotating Earth. We hoped that the hindsight afforded by these precise periods would enable us to make progress in understanding the period structure in quiescence (previously discussed by Abbott et al. 1992). Therefore we reanalyzed the 1989–1991 photometry reported by Abbott et al. We estimate the star's mean brightness during these observations as $V=20.0\pm0.3$.

The light curves themselves are shown in Fig. 5 of Abbott et al. There are three main clusters, in 1990 April, 1991 February, and 1991 April. For each of these we removed mean and trend from each night, and appended the nights to form three time series. The power spectra of these time series are shown in Fig. 9, with significant peaks labeled with their frequencies in c day^{-1}. The errors in the frequency estimates, top to bottom, are 0.03, 0.02, and 0.014 c d^{-1}. In the lowest frame (1991 April), the inset figure shows the power-spectrum window; the window is entirely consistent with the observed power spectra, indicating that the correct peaks are the labeled ones, not any of the surrounding aliases. The other frames show aliases competitive with the labeled peaks, and hence do not by themselves give unique frequency solutions. Nevertheless, we note that the high-frequency signal occurs at the same location in each power spectrum, and we conclude from this that there is a persistent signal at 35.280 ± 0.012 c d^{-1}. The other signal definitely occurs at a frequency lower than the subharmonic of 35.280, and definitely moves in frequency.[1]

4.2 Precise Period Finding

We then explored the hypothesis that the higher-frequency signal is stable. By combining the 1991 February and April data, we found two allowed solutions, at 35.2742 and 35.2930 (±0.0020) c $d.^{-1}$. Bridging back to the 1990 April and 1989 May data eliminated the former solution, and refined the estimate for the other candidate to 35.2930 ±0.0003 c d^{-1}.

This very stable signal is presumably the first harmonic of the orbital frequency, since the latter should be fairly close to

[1]Actually, the 1991 February signal could perhaps be at the subharmonic, if we have chosen the wrong alias. But this is not possible for the other two epochs.

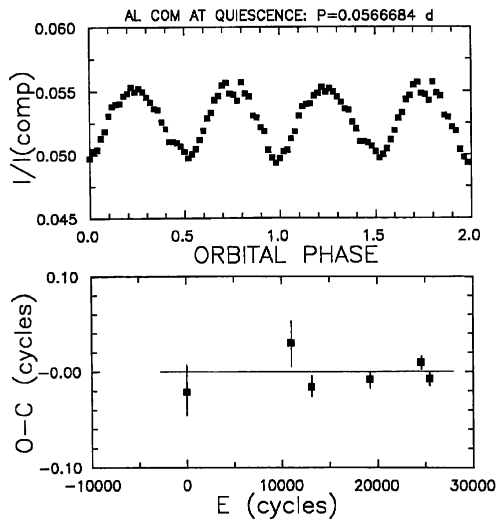

FIG. 10—*Upper frame*, mean light curve of AL Com in quiescence, relative to Eq. (3). *Lower frame*, O−C diagram of the timings of minimum light, listed in Table 4. The very small scatter indicates that this is truly a stable period. The flat line is Eq. (3).

the superhump frequency. We then synchronously summed the three time series on the putative orbital frequency of 17.6465 c d^{-1} (after first removing the large low-frequency signal), added the 1989 May data, and found the mean light curve shown in the upper frame of Fig. 10.

We then extracted a timing of minimum light from each cluster of observations, and added two more obtained by digitizing published light curves. In the lower frame of Fig. 10 we present the O–C diagram of these timings (listed in Table 2), relative to the best ephemeris of

$$\text{Minimum light} = \text{HJD } 2{,}446{,}912.8929 + 0.0566684E. \quad (3)$$
$$\qquad\qquad\qquad\qquad (7) \qquad\qquad (1)$$

The lack of curvature in the O–C implies period stability with $|\dot{P}|<4\times10^{-10}$.

4.3 The Quiescent Superhump

A photometric signal with a period slightly discrepant from $P_{\rm orb}$, and which is slightly unstable in period, is often called a "superhump" (see Warner 1985 for a review of the most common type of superhump, that of dwarf novae in superoutburst). The superhump of the quiescent AL Com at $\sim$16 c d^{-1} is very unusual among cataclysmic variables, and we shall discuss possible physical origins in Sec. 8. We here use the term "quiescent superhump" for it.

Having solved for the period and wave form of the signal at $P_{\rm orb}$, we then subtracted it from the original data, in order to isolate the other variation. Each of the wave forms (not shown) was a fairly good sinusoid.

5. PERIOD CHANGES

We studied all the periodic signals for evidence of period change. Table 3 collects timings of maxima and minima

TABLE 2
Timings of Minimum Light at Quiescence

HJD (2440000+)	Source
6912.9200	Howell & Szkody 1988
7535.9352	Szkody et al. 1989
7655.6746	Abbott et al. 1992
8002.75686	Abbott et al. 1992
8304.85852	Abbott et al. 1992
8355.63338	Abbott et al. 1992

Note 1: Timings not published, but measured from published light curves.

Note 2: Last three timings are averages over several nights.

available from this work and the literature. Previously published timings are cited as given, but we only cite our own timing if we feel it is accurate to <0.003 d; this means that some timings are averages over a night, or even over two nights. In Fig. 11 we show O−C diagrams of these timings. The top frame refers to the outburst orbital hump; stability over 5 days of observation yields $|\dot{P}|<4\times10^{-5}$. The middle frame shows the "common superhump" during April 16–29. Some wiggles are present, as are commonly seen in SU UMa stars. But there is no systematic $\dot{P}$ over the 13-day observation; a formal fit to the original data (not the condensed version shown in the figure) yields $\dot{P}=+1.2(\pm1.5)\times10^{-5}$.

The bottom frame includes all the timings during the 40-day apparition of the common superhump. The sampling becomes very poor in the second half, leading to some possibility of cycle count error. But, we consider this unlikely, since the frequencies during May 10–14 and May 20–25 are well determined and agree with the frequency during April 16–27. Again there is no systematic $\dot{P}$ seen. A formal fit to the points yields $\dot{P}=+2(\pm4)\times10^{-6}$, but if we correct for the extreme clustering of the coverage, the result changes to $\dot{P}=-2(\pm3)\times10^{-6}$.

We applied the same test to the three apparitions of the quiescent superhump in 1990–1991. None show curvature over the $\sim$4-day baselines; this sets a limit $|\dot{P}|<2\times10^{-4}$. A lower limit is also set by the changes from 1991 February to 1991 April; this indicates that the clock is capable of $|\dot{P}|>4\times10^{-5}$.

6. A DOUBLE OUTBURST?

Many SU UMa stars show dips in their eruption light curves a few magnitudes below maximum (see Richter 1992 for examples). The present coverage of AL Com establishes two additional facts:

(1) There were superhumps throughout the post-dip light curve.
(2) The recovery from the dip showed a 1.5 mag brightening which lasted about 1 day and did not show clear superhumps.

These two facts lead us to describe the post-dip light curve as essentially a second superoutburst (rather than, say, a single outburst which resumes after an unexplained hiatus). We interpret the 1-day brightening as a normal outburst which triggers the second, fainter superoutburst. Thus, in the terminology of Marino and Walker (1979; see also Fig. 1 of

TABLE 3
Timings of Superhump Maxima/Minima

A. OUTBURST ORBITAL HUMP

(HJD 2,449,000+) T(sharp minimum)	Source	(HJD 2,449,000+) T(sharp minimum)	Source
813.525	DeYoung 1995	814.880	this paper
813.7507	this paper	815.051	Kato 1995
813.8094	"	815.111	"
813.8638	"	815.168	"
813.9195	"	815.224	"
814.654	"	815.278	"
814.714	"	816.756	this paper
814.770	"	817.715	"
814.822	"	818.682	"

B. COMMON SUPERHUMP

T(maximum)	Source	T(maximum)	Source
823.5693	Howell et al. 1996	831.6564	this paper
823.6311	this paper	832.3995	Pych & Olech 1995
825.7069	"	832.458	"
825.7631	"	832.687	this paper
825.9355	"	832.745	"
827.5925	Howell et al. 1996	832.802	"
827.6525	"	832.861	"
827.9313	this paper	833.4360	Pych & Olech 1995
828.3345	Pych & Olech 1995	833.4915	"
828.3931	"	833.5489	"
828.6784	this paper	833.6065	Howell et al. 1996
829.3636	Pych & Olech 1995	833.663	this paper
829.4200	"	833.722	"
829.4778	"	833.777	"
829.5928	this paper	833.833	"
829.5961	Howell et al. 1996	834.5843	Howell et al. 1996
829.6562	"	834.700	this paper
829.6491	this paper	836.5970	Howell et al. 1996
829.7064	"	836.710	this paper
829.7623	"	838.705	"
830.4536	Pych & Olech 1995	843.5732	Howell et al. 1996
830.5084	"	847.7625	this paper
830.5677	"	847.8165	"
830.6275	this paper	850.804	"
831.4293	Pych & Olech 1995	857.5544	"
831.4850	"	859.5228	"
831.5422	"	861.5257	"

Warner 1995a), the first superoutburst is of type S1–5, while the second is of type S8. These studies, based on many visually observed superoutbursts of VW Hyi, also show that type-S8 eruptions are fainter and shorter—in agreement with the observed behavior in AL Com.

Based strictly on the observed light curve, this interpretation is not compelling. It is attractive to us because it does not require any fundamentally new hypotheses, merely invoking *twice* the standard theory of superoutbursts (which posit normal eruptions to trigger the superoutbursts).

This interpretation really needs help from studies of *other stars*. Since many SU UMas show dips at the end of their superoutbursts, increased vigilance at this stage is needed to specify the subsequent behavior. This is particularly an issue for the stars most intrinsically faint at quiescence.

7. COMPARISON WITH WZ SAGITTAE

The most famous SU UMa star of long recurrence period is WZ Sagittae, often cited as the prototype of a separate class (see below in Sec. 8). It is not yet clear if this fine slicing of variable-star types is useful, but it does seem clear that whatever class name we assign to WZ Sge, that is the right one for AL Com as well. Let us explore this comparison.

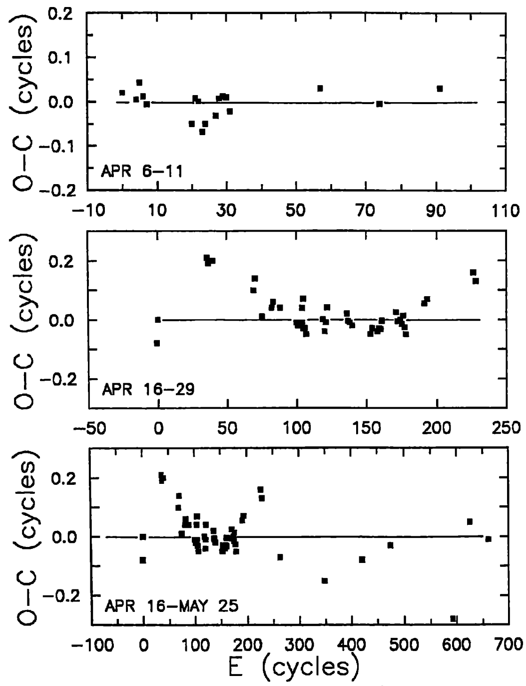

FIG. 11—O−C diagrams of periodic signals in outburst. Each frame is labeled with the dates spanned. The test period for the outburst orbital hump (*top frame*) is 0.05667 d. The test period for the common superhump (*middle and lower frames*) is 0.05733 d. No secular period change is present in any frame, although the common superhump wiggles a bit. There is some uncertainty about cycle count in the lower frame, discussed in the text. Timing uncertainties are about 2–3 times the size of the points.

7.1 Distance, Luminosity, Limits on Secondary

Both stars fail to provide the sort of evidence needed for good distance measures (a nova shell, or detection of the secondary). Thus we must resort to less accurate and less reliable estimates.

(1) WZ Sge has a nearby "companion" (7″ away) of similar proper motion and colors resembling an M5 star. Such stars have $M_v = +11.0$. Recent (1995 July) photometry yields $V = 15.29$ and 13.93 for WZ Sge and its companion, respectively. This yields a distance of 55 pc.

(2) For the white dwarf in WZ Sge, we know the temperature fairly well from the line strengths in the blue and UV (15,000 K long after the eruption), and by extrapolating the white-dwarf flux a short distance to the V band we can estimate $V_{wd} = 15.8$ in quiescence. For a 0.5 $M_\odot$ white dwarf of this temperature, the luminosity is 3×10^{31} erg s^{-1}, or $M_v = +11.7$ after applying the bolometric correction. This yields a distance estimate of 65 pc.

(3) There is a correlation between M_v of a dwarf nova in outburst and its P_{orb}, arising chiefly from the fact that the disk *areas* correlate with P_{orb}. Warner's (1987) relation gives

$$M_v(\max) = 5.74 - 0.26 P_{orb}(\mathrm{hr}),$$

yielding $M_v(\max) = 5.4$ for the two stars. The apparent magnitudes at maximum were ~8.3 for WZ Sge and 12.3 for AL Com, suggesting distances of 45 and 330 pc.

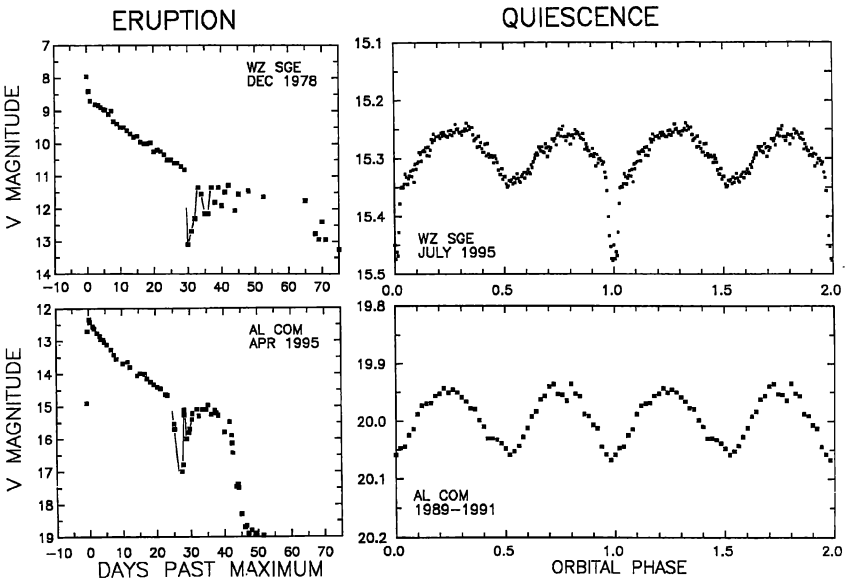

FIG. 12—*Left frames*, the best-observed eruption light curves for WZ Sge (in 1978) and AL Com (in 1995), on a common scale (day 0=maximum light). *Right frames*, the quiescent light curves of both stars on a common scale. Data for WZ Sge are averaged over 20 orbits in 1995 July. Both stars show a double sinusoid of full amplitude 0.12 mag, but WZ Sge has a notch ("eclipse") which defines phase zero. The broadband detectors and filters produce some uncertainty in the magnitude calibration; we estimate ±0.3 mag for AL Com and ±0.1 mag for WZ Sge. Random errors are about equal to the symbol size.

(4) There is also a rough relation connecting M_v at quiescence with $P_{\rm orb}$ and with T_n, the recurrence time between normal outbursts. Warner (1987) states the relation as

$$M_v(\min)=7.1+1.64 \log T_n(\mathrm{d})-0.26P_{\rm orb}(\mathrm{hr}),$$

giving $M_v=13.44$ for WZ Sge and 11.80 for AL Com. These imply distance estimates of 50 and 550 pc, respectively (although this requires using the relation well outside the range of the calibrating stars!).

(5) Both stars have very strong emission lines in quiescence; we estimate Hβ to have an equivalent width of >100 A (after subtracting the estimated white dwarf contribution to the continuum light), and this implies a disk with $M_v>+11$ according to a 1984 calibration (Patterson 1984). We estimate V of the disks to be 16.2 (WZ Sge) and 20.2 (AL Com), implying distances of <110 and <700 pc, respectively.

While none of these methods give accurate distances, all results are consistent. For WZ Sge we adopt a compromise of 60±15 pc, and for AL Com we adopt 430±150 pc. Thus the accretion disk absolute magnitudes in quiescence are both about +12.2±0.5.

What do we know about the secondary stars in these binaries? We know that they are not seen in the visible and near-IR spectra; and this is quite a stringent limit, since very cool stars always sport strong TiO bands. From the absence of such bands in the 6000–8000 A region we estimate these limits for the secondary: $V>17.7$ for WZ Sge, and $V>21.6$ for AL Com. The corresponding limits for M_v are >13.7 and >13.5, respectively.

Thus all of the available luminosity clues give results in agreement. Both are intrinsically very faint binaries, with the disk ranging from $M_v=+12.2$ to +5.4, and the secondary fainter than +13.5.

7.2 Comparison with Smak's Results

The most complete study of WZ Sge in quiescence is that of Smak (1993). Mostly we agree with his results, stated in his Table 1. However, we have chosen not to distinguish "bright spot" and "disk" luminosities, since that distinction is not available for the vast majority of CVs (which we depend on for the calibration of the above arguments). The other significant difference is that we take the $K_1=49$ km s^{-1} measurement (Gilliland et al. 1986) as an upper limit only, since it yields a phase of orbital motion conflicting with other evidence from photometry and spectroscopy. Smak used it to constrain the mass ratio $q=M_2/M_1=0.15$, whereas we favor $q\lesssim 0.06$.

7.3 Superoutburst

On the left of Fig. 12 we show on the same scale the best-observed superoutburst light curves for each star, showing great similarity. In both cases, the star rose ~7.5 mag from quiescence in about 1 day. WZ Sge promptly fell by 0.6 mag in 2 d, then declined at a slowly decreasing rate, from 0.12 to 0.07 mag d^{-1}. AL Com did not seem to suffer that quick fall, but declined at a rate progressing from 0.15 to 0.11 mag d^{-1}. A principal dip of 2.4 mag occurred at day 29 of the WZ Sge outburst; the main dip of AL Com was 2.3 mag deep and occurred at day 27. This dip lasted 4 d in WZ Sge, and 5–7 d in AL Com. After rising from the dip, each star probably broke into oscillations of ~0.4 mag; in AL Com we know that common superhumps persisted in this interval, but no such information is available for WZ Sge. The final rapid decline occurred on day 45 in AL Com, and somewhere in the interval day 75–100 in WZ Sge.

These are very detailed resemblances. Comparison with the other two historical outburst light curves of WZ Sge (Fig. 1 of Patterson et al. 1981) shows that AL Com replicated WZ Sge as faithfully as WZ Sge replicated itself.

The *nightly* light curves during outburst were also very similar. WZ Sge showed a dominant modulation at $P_{\rm orb}$ for the first 10 d, and AL Com showed a similar effect for the first 6 d (not provably with the same origin, but of the same period). Only one other SU UMa star, HV Virginis, has ever clearly shown such an effect (Leibowitz et al. 1994). In all three cases the light curve for the next 12–15 d was dominated by a common superhump. The period excess of that superhump was 0.8% for WZ Sge, 1.1% for HV Vir, and 1.1% for AL Com. These excesses are quite low, the three lowest known among dwarf novae. The period stability of the three superhumps was also higher than in any previously well-studied dwarf nova ($|\dot{P}|<2\times10^{-5}$ in all cases).

7.4 Quiescence

The resemblance at *minimum* light is also remarkable. At the right of Fig. 12 we show the average orbital light curve of both stars at quiescence. In both stars the dominant feature is a very symmetrical double hump of 0.12 mag full amplitude. They are the only two CVs known with an orbital wave form like this. WZ Sge has one extra photometric feature apparently not present in AL Com: a small sharp dip which defines phase zero (and is usually called an *eclipse* although its real origin is still not understood).

The quiescent orbital light curve of HV Vir is single humped (Leibowitz et al. 1994), and hence does not particularly resemble the other two stars.

7.5 Orbital Period, Mass Ratio, Binary Structure

Then there is the coincidence in the value of $P_{\rm orb}$: the period of AL Com is shorter by a scant 1.7 s. After waiting 33 years to find a dwarf nova of $P_{\rm orb}$ shorter than WZ Sge, we are finally greeted by a nearly indistinguishable star with a period only 1.7 s shorter! This, coupled with the large pileup of stars in the 81–85 min period range, seems to indicate fairly well the minimum $P_{\rm orb}$ attainable by a hydrogen-rich CV.[2] Thus it is plausible that these two stars are in the act of "turning around"—starting to evolve toward a *longer* period, with secondaries significantly less massive than a main-sequence star of the same radius. A very low-mass secondary would also explain why the fractional superhump period excesses are so low, about a factor of 2.5 lower than would be predicted from the general trend among SU UMa stars (Fig. 9 of Thorstensen et al. 1996).

Paradoxically, the *quiescent* superhump period excess of AL Com is very *high*, as much as 10%! Within the context of superhump theory, this implies a large perturbing force on the disk, and the only simple way to obtain this is to suppose that the disk extends far beyond the 3:1 orbital resonance (the resonance usually blamed for dwarf nova superhumps). *We conjecture that in quiescence the disks in AL Com and WZ Sge extend out to the 2:1 orbital resonance, and eccentricity instability there can produce a superhump with large period excess (since the approach to the secondary is then very close), and a dissipation pattern which manifests itself as two equal humps per orbital period.*

Why would these particular stars be able to reach the 2:1 resonance? The answer must lie in the extreme mass ratios. From Kepler's Third Law, the 2:1 resonance occurs at a radius of $0.63a$, where a is the binary separation. The Roche lobe around the primary has a radius given by $R=(0.38-0.2\log q)a$, and hence this requires q to be <0.05 for the 2:1 resonance to be accessible. This is difficult to reconcile with a main-sequence star ($M_2>0.08\ M_\odot$), and is most easily achieved when the secondary has a mass $<0.04\ M_\odot$ (since white-dwarf masses in CVs average about $0.7\ M_\odot$).

Lin and Papaloizou (1979) calculated the disk structure in the limit of very low-mass ratios, and actually found a spiral dissipation pattern which has two arms and hence is a good candidate for producing two photometric humps if the disk is sufficiently inclined. These spiral arms are in fact associated with the 2:1 resonance. The reason it is accessible is not merely that "there is room," but that the outer disk is normally expected to be truncated by tidal torques—which are quite weak for low mass ratios.

8. THE WZ SAGITTAE STARS

Dwarf novae with very rare outbursts were called "WZ Sge stars" by Bailey (1979) and Downes and Margon (1981). The term remains in use today, but has acquired the slightly more specialized meaning of "SU UMa stars with very rare superoutbursts, and few or no normal outbursts." Lists of candidate stars are given by O'Donoghue et al. (1991) and Warner (1995a,b).

8.1 Trouble in the Jungle

Howell et al. (1995, hereafter HSC) proposed instead the term "tremendous outburst amplitude dwarf novae" (TOADs). The definition of a TOAD by HSC was not entirely clear, but basically required an outburst amplitude >6 mag. This criterion is far more inclusive, and they listed 27 class members. To see if outburst amplitude can be used as a classifying criterion, we studied the amplitude distribution for all known dwarf novae. We used the Downes and Shara (1993) catalog but with (1) addition of recently discovered stars, (2) amendment where detailed studies have warranted it, and (3) subtraction of the luminous contribution of the secondary star and white dwarf (nonaccretion light).

The results are shown in Fig. 13. The amplitudes are in the range 1–9.5 mag, with no evidence for any bimodal distribution. Thus there appear to be no empirical grounds for labeling any threshold in amplitude as signifying the transition to "tremendous." Furthermore, the well-studied individual stars of large amplitude all acquire their large amplitude only by virtue of their great faintness in quiescence. The outbursts themselves are not particularly bright; in fact, they are slightly fainter than the outbursts of stars with amplitudes

[2] We omit the little-studied star V485 Cen, which shows good evidence of having an orbital period of 59 min (Augusteijn et al. 1993). This period is so far from the rest of the distribution that it cannot plausibly be considered part of the distribution. More likely it is a borderline AM CVn star, able to reach shorter periods by virtue of low hydrogen content (Augusteijn 1995).

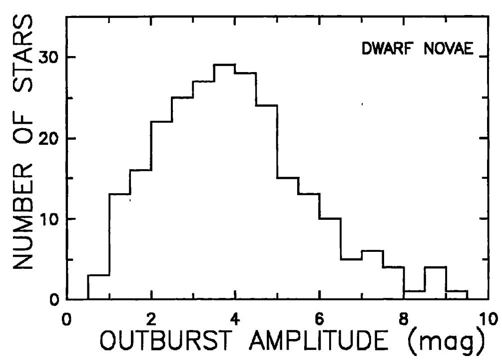

FIG. 13—Distribution of outburst amplitudes for dwarf novae. No evidence of two populations is seen.

<6 mag (erupting dwarf novae are moderately good standard candles, but the quiescent brightness ranges from $M_v \sim +6$ to $\sim +12$).

Therefore this suggested class name based on amplitude is not motivated by the data itself, and the adjective is misleading. "Very faint in quiescence" ($M_v \gtrsim +10.5$) and "seldom erupting" ($T \gtrsim 1000$ d) are really the key points.[3]

8.2 Low $\dot{M}$ or Low Viscosity?

An interesting question is, *what physically drives an SU UMa star into the WZ Sge subclass?* We think the primary answer is a very low mass-transfer rate. This will guarantee low luminosity in quiescence, and a very long interval between maxima since it will take a long time for sufficient matter to accumulate in the disk torus. This successfully reproduces the main features. However, the various disk-instability theorists who have studied this (Cannizzo et al. 1988; Smak 1993; Osaki 1995) suggest that the 33-yr time scale of WZ Sge can only be reproduced with a much lower assumed viscosity in quiescence. The basic idea is that for a sufficiently low $\dot{M}$, accumulation in the torus hardly matters, and the recurrence time scale is set only by diffusion in the disk ($T_{\rm diff} \sim 33$ yr, implying $\alpha_{\rm cold} \sim 0.001$, about a factor of 30 less than the most popular value for dwarf novae generally).

We have studied the arguments leading to this conclusion, but find them not compelling. The main difficulty is that we are required to accept the absence of normal eruptions as a fact, and this we are reluctant to do. Among reasonably well-observed stars, all appear to show normal eruptions except WZ Sge—and even for this star, the frequency of observation and the expected short duration of a normal outburst [~2 d, based on the Bailey (1975) relation] suggest to us that some normal outbursts could easily be missed. We think the observations probably require a recurrence time for normal outbursts >10 yr, but not necessarily as long as 33 yr.

A second difficulty in accepting low $\alpha_{\rm cold}$ is created by the X-ray observations of WZ Sge, which show a fairly strong hard-X-ray flux demonstrably originating from the vicinity of the white dwarf (Richman 1996). The luminosity in hard X rays is about equal to the bolometric luminosity of the bright spot ($\sim 3 \times 10^{30}$ erg s^{-1}), and showed no appreciable secular change during 1979–1991. This proves that some accretion flow (at least 10% of the total) proceeds throughout quiescence. At the very least it suggests the existence of a substantial "back door" for accretion flow, not described in the pure cold-disk models.[4]

Even in standard accretion disk theory, the recurrence time for normal outbursts scales (for low-$\dot{M}$ stars) approximately like

$$t_{\rm accum} \propto \dot{M}_{16}^{-2} \alpha_{\rm cold}^{-0.7},$$

where $\dot{M}_{16}$ is the mass-transfer rate in units of 10^{16} g s^{-1} (Osaki 1996). A typical SU UMa star is likely to have $\dot{M}_{16} \sim 1$, but WZ Sge probably has $\dot{M}_{16} \sim 0.1$ (Patterson 1984). The typical recurrence time is ~40 d, suggesting that WZ Sge should have a recurrence time of ~4000 d if $\dot{M}$ is the only variable. This is consistent with observational constraints. Thus we see no pressing need to invoke dramatic variations of $\alpha_{\rm cold}$ to account for the WZ Sge stars. We suspect that the most important distinguishing trait of these stars of very long recurrence time is simply low $\dot{M}$, with viscosity playing only a minor role.

8.3 Summary and Class Members

Therefore we regard the SU UMa stars as spanning the very wide range from the ever-erupting ER UMa subclass to the most sluggish of dwarf novae, the WZ Sge subclass. Probably it is a true continuum, with $\dot{M}$ being the key parameter determining where a dwarf nova resides on that axis (over the range $\dot{M}_{16}$=5 to 0.1).

Partly because we might be wrong, and partly because subclasses are useful terms for discussions among specialists, we think it is still desirable to retain the term "WZ Sge stars."

Which stars should be assigned to the (sub)class? WZ Sge and AL Com are obvious choices. HV Vir is a star with a long recurrence period (probably ~3000 d), no recorded normal ourbursts, an outburst orbital hump, a very small superhump period excess, and a small value of $P_{\rm sh}$. These are impressive credentials, sufficient to establish membership. The case for all other candidates is much weaker, because far less detailed information is available. A few more stars could be considered likely (e.g., V592 Her, RZ Leo, GW Lib) based mainly on the apparent infrequency of eruptions, but

[3]There is a well-known statistical correlation between amplitude and recurrence time, the Kukarkin–Parenago relation (Kukarkin and Parenago 1934). Therefore, roughly the same stars will be selected by amplitude and recurrence time criteria. But if the theory (low viscosity) cited by HSC to explain these stars is correct, then the important quantity for classification is *recurrence time* rather than amplitude (since viscosity sets the theoretical recurrence time in the low-$\dot{M}$ limit). The same is true if their theory is not correct, which we tend to suspect (see below, where we argue that $\dot{M}$ is probably the dominant physical variable). Amplitude is also a poorer choice because it is affected by factors not part of the accretion physics, mainly white-dwarf temperature and radius.

[4]A promising version of this is the evacuated inner disk suggested by Meyer and Meyer-Hoffmeister (1994; see also Lasota et al. 1995; Angelini and Verbunt 1989). Such models can make X rays through coronal emission, and tend to suppress normal eruptions because the inner disk (where "inside-out" eruptions would otherwise start) is missing; no assumption of very low viscosity is required.

we think it advisable to label them as candidates only until some of their properties in superoutburst have been measured (and until the constraints on outburst frequency improve; most suggested candidates are *very* sparsely observed stars).

8.4 Mass Ratio: Key to the Subclass?

Finally, why should some SU UMa stars have particularly low mass-transfer rates? The answer probably lies in the extreme mass ratio. The dipole formula for angular momentum loss due to gravitational radiation in a binary system is

$$\dot{J}_{GR} \propto (M_1 M_2)^2 (M_1+M_2)^{-2/3} P_{orb}^{-7/3}$$

(Shapiro and Teukolsky 1983). For very short P_{orb}, we will usually have $M_2 \ll M_1$, and therefore approximately

$$\dot{J}_{GR} \propto q^2 M_1^{10/3},$$

where $q=M_2/M_1$. The dependence on P_{orb} is minor since we are only exploring a limited period range, say, 80–90 min. The dependence on M_1 is strong, but for a given star M_1 does not actually change much once M_2 becomes small. Thus $\dot{J}_{GR}$ in this domain essentially varies as q^2. Now the mass-transfer rate $\dot{M}_2$ is given by

$$\dot{M}_2/M_2 = \dot{J}_{GR}/J,$$

so again in the limit of short P_{orb} and $q \ll 1$, we see that the important dependence is $\dot{M}_2 \propto q^2$ [this can also be seen in Warner's (1995b) Eq. 9.46]. More correctly, this holds for binaries around the period minimum (since P_{orb} is changing only very slowly there). AL Com and WZ Sge *define* the period minimum, so this should certainly apply to those stars.

Thus we expect that the mass-transfer rate should decline severely as binaries move through the period minimum. We earlier (Patterson 1984) estimated $\langle \dot{M}_2 \rangle = 5\times10^{15}$ g s^{-1} as an average figure for short-period SU UMa stars, and $\langle \dot{M}_2 \rangle$ = 10^{15} g s^{-1} for WZ Sge. So we expect q to be about a factor 2.2 smaller than other stars of slightly longer period. If the smallest main-sequence secondaries in CVs are near the 0.085 $M_\odot$ limit for core hydrogen burning (which is consistent with, though not demanded by, available data), then the secondaries in WZ Sge and AL Com should be ~0.04 $M_\odot$.

Let us put the essential physical point more succinctly. As CVs approach period minimum, the secondaries become distended relative to their main-sequence radii (because their thermal time scales become very long), and q therefore drops severely. This is quite a sharp effect; see, for example, Fig. 12 of Rappaport et al. (1982). Thus it should be no surprise that the shortest-period stars have substantially lower values of q and $\dot{M}_2$.

9. THE OUTBURST ORBITAL HUMP

What causes the outburst orbital hump in the three sure members of the WZ Sge class? In WZ Sge, Patterson et al. (1981) interpreted it as a brilliant mass-transfer bright spot, elongated in the downstream direction. Kato et al. (1996) interpreted it as an "immature superhump"—a sort of embryonic common superhump, not yet well developed since the tidal torques could be quite weak in these stars.

Because we now have a long-term orbital ephemeris for AL Com, we can measure the phase of its outburst orbital hump. Primary maximum occurred at $\Phi_{orb}=0.69\pm0.10$. In WZ Sge, primary maximum occurred at $\Phi_{orb}=0.62\pm0.02$, but this would change to 0.58 ± 0.02 if we adopted an ephemeris based on the double sinusoid (as in AL Com). Thus we require the light center of the bright spot to be displaced in the forward direction by 0.17 ± 0.02 cycles in WZ Sge, and by 0.06 ± 0.10 cycles in AL Com (or 0.56; the quiescent light curve is symmetrical and shows no obvious eclipse, so we do not know which hump is "primary"). Therefore the phase shifts are compatible, and the arguments for interpreting the signal as evidence of a mass-transfer bright spot apply about equally well to both stars.[5] If this is true, it would *dramatically* distinguish the WZ Sge class from other SU UMa stars, which show little or no enhancement of their bright-spot luminosities in outburst. It could be that mass-transfer instabilities occur only in the WZ Sge secondaries, i.e., those of very low mass.

The immature superhump interpretation proposed by Kato et al. is also viable, but the very rapid observed growth of the *common* superhump on April 16 (see Fig. 3) seems somewhat hard to reconcile with this "slow to get organized" viewpoint.

10. UNDERSTANDING $\dot{P}$ OF THE COMMON SUPERHUMP

Most SU UMa stars show slowly decreasing superhump periods during decline from superoutburst. Available evidence suggests typical values of $\dot{P}=-6\times10^{-5}$, or $(1/P)dP/dm=-0.008$ mag^{-1} (Patterson et al. 1993). How does AL Com compare with these values?

To answer this we appeal to the April 16–29 interval only (see Fig. 11). Although the superhump persisted far beyond this, there is uncertainty in cycle count; and because there are no previous superhump observations in "second" superoutbursts, it is impossible to make comparisons. During April 16–29, a small wiggle indicative of a positive $\dot{P}$ existed; interpreted as an upper limit on $-\dot{P}$, the result is $-\dot{P}<10^{-5}$. Over that interval the star faded by 0.8 mag. Thus we obtain $(-1/P)dP/dm<0.002$ mag^{-1}. These values are lower than normal by a factor of >4.

How can we understand this? Well, conventional wisdom attributes the superhump to the 3:1 resonance in the disk, which occurs at $r=0.46a$, nearly independent of q. The precession period P_{prec} is given approximately by (Osaki 1985)

[5]Smak (1993) preferred to attribute the signal to the effect of reprocessing in the secondary star. We disfavor this alternative, because it leaves unexplained the restriction of such signals to this very small class of dwarf novae (reprocessing effects are suppressed because a smaller fraction of accretion light is intercepted by the small secondary), because reprocessing is ill suited to produce a *double-humped* variation as prominently seen in AL Com, and because it is difficult to reconcile with the observed phase of maximum light in WZ Sge (0.62 ± 0.02, compared with 0.44 ± 0.03 expected for the secondary's superior conjunction in the standard model of WZ Sge).

$$\frac{P_{\text{orb}}}{P_{\text{prec}}}=\frac{3}{4}\frac{q}{(1+q)^{1/2}}r^{3/2},$$

and the superhump period P is given by

$$P^{-1}=P_{\text{orb}}^{-1}-P_{\text{prec}}^{-1}.$$

Taking time derivatives we find that

$$-\dot{P}\propto qP_{\text{orb}}r^{1/2}\dot{r}.$$

Now $r^{1/2}$ is nearly constant, and $\dot{r}$ probably has some characteristic value, empirically estimated as $-0.006\ \text{day}^{-1}$ (Patterson et al. 1993). Thus the important dependence in this theory is really $-\dot{P}\propto qP_{\text{orb}}$. Most SU UMa stars probably have secondaries near the main sequence, which implies $q\propto P_{\text{orb}}$ and hence $-\dot{P}\propto P_{\text{orb}}^2$. But if the secondary is undermassive, then the expected value of $-\dot{P}$ will be proportionally less. Thus we interpret the measured low values of $-\dot{P}$ in AL Com and WZ Sge as *yet another indication of a very low-mass secondary* ($<0.04\ M_\odot$).

11. SUMMARY

(1) We report photometry of AL Com's 1995 superoutburst. The eruption light curve was interrupted by a brief "dip," and the recovery showed a short brightening which could be interpreted as a normal outburst triggering a second superoutburst. It would be very desirable to study the very late stages of superoutbursts of many SU UMa stars, since dips are commonly seen though poorly understood.

(2) The complexity of AL Com leads us to new terminology. We use "common superhump" to denote the periodic signal with $P=P_{\text{orb}}+\epsilon$ that is essentially a universal hallmark of SU UMa stars in superoutburst. We use "outburst orbital hump" to denote the signal with $P=P_{\text{orb}}$ that is transiently present early in the superoutbursts of a few SU UMa stars. We use "quiescent superhump" to denote the signal seen in quiescence with a period near but unequal to P_{orb}. Just for completeness, we note that there also exist such things as "negative superhumps" and "late superhumps." Happily for us, they are found in other parts of the CV zoo, not yet documented in the WZ Sge stars.

(3) An outburst orbital hump was seen for the first 5 days of superoutburst. We do not yet understand the origin of this signal, though it could well signify a mass-transfer burst from the secondary. It may be important that the three dwarf novae showing this behavior are the three stars showing the smallest period excesses in their common superhumps, probably arising from the very low mass of their secondaries. These stars (AL Com, WZ Sge, HV Vir) are the three certain members of the WZ Sge class of dwarf novae.

(4) On day 10 of the eruption, a common superhump was suddenly born, a signal with a period 1.1% longer than P_{orb}. This endured at least until day 49, by which time the star had faded to $V=19$. No superhump period change was seen, to a limit $|\dot{P}|<1\times10^{-5}$.

(5) In the middle of the "second superoutburst" (at magnitude 15), the star showed additional probable signals at 16.14 and $\sim$30 c d^{-1}, reminiscent of the strong superhumps shown by AL Com in quiescence.

(6) We reexamined the photometry of AL Com in quiescence, and found a persistent double-humped modulation during 1989–1991, with a fundamental period of 81.6025 min. This is very likely to be the orbital period, the shortest yet found among certified dwarf novae. The apparent pileup of stars in the range 81–84 min probably means that 81 min is the shortest P_{orb} attainable by a nonmagnetic hydrogen-rich CV.

(7) We consider several clues to the distance and luminosity of WZ Sge and AL Com, and converge on estimates of 65±15 and 430±150 pc, respectively. These imply similar estimates for the absolute visual magnitude of the accretion disk (+12.2 in quiescence and +5.4 in outburst), and similar limits for the secondary star ($M_v>13.5$).

(8) There are many clues suggesting an extreme mass ratio in AL Com and WZ Sge: the very short P_{orb}, demanding a small secondary; the stringent luminosity limit on the secondary; the very low fractional period excess of the superhump, indicating a weak gravitational perturbation on the disk; the very low value of $\dot{P}_{\text{sh}}$, indicating the same; and the stringent upper limit on the motion of spectral lines (known for WZ Sge, not yet studied for AL Com). The fact that the two stars sharing these traits should *also* show peculiar and very similar orbital light curves suggests that that peculiarity (two equal humps per orbit) may also arise from the extreme mass ratio. We suggest that these stars are distinguished by having large disks extending out to the 2:1 resonance, where an instability may act to produce luminous patches at opposite sides of the disk. The constraint on mass ratio requires the secondaries to be below the 0.08 $M_\odot$ limit for core hydrogen burning.

(9) It remains an open question as to how dwarf novae manage to become WZ Sge stars (mainly characterized by a very long recurrence time). We think that low $\dot{M}$ is the key requirement, whereas disk theorists cite the need for a very low value of α_{cold}. It may of course also be true that low $\dot{M}$ and low α_{cold} are causatively linked through some physics not yet understood, or are effects from the same cause (e.g., presence of a secondary star insufficiently massive for core hydrogen burning). To distinguish among these alternatives, it would be very desirable to expand the roster of class members, and see if any have moderate or high values of $\dot{M}$ in quiescence, which would rule out the interpretation we favor here.

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