Publications of the Astronomical Society of the Pacific, **115**:37–42, 2003 January

Five Dwarf Novae with Orbital Periods below Two Hours[1]

John R. Thorstensen and William H. Fenton

Department of Physics and Astronomy, 6127 Wilder Laboratory, Dartmouth College, Hanover, NH 03755-3528; john.thorstensen@dartmouth.edu, william.h.fenton@dartmouth.edu

Received 2002 August 14; accepted 2002 September 9

ABSTRACT. We give mean spectra and report orbital periods P_{orb} based on radial velocities taken near minimum light for five dwarf novae, all of which prove to have $P_{orb} < 2$ hr. The stars and their periods are KX Aql, 0.06035(3) day; FT Cam, 0.07492(8) day; PU CMa, 0.05669(4) day; V660 Her, 0.07826(8) day; and DM Lyr, 0.06546(6) day. The emission lines in KX Aql are notably strong and broad, and the other stars' spectra appear generally typical for short-period dwarf novae. We observed FT Cam, PU CMa, and DM Lyr on more than one observing run and constrain their periods accordingly. Differential time-series photometry of FT Cam shows strong flickering but rules out deep eclipses. Although dwarf novae in this period range generally show the superhumps and superoutbursts characteristic of the SU UMa subclass of dwarf novae, none of these objects have well-observed superhumps.

1. INTRODUCTION

In this paper, we continue determining orbital periods P_{orb} for SU UMa type dwarf novae and candidate SU UMa stars. The SU UMa stars are dwarf novae, generally with $P_{orb} < 3$ hr, which occasionally undergo bright and long-duration eruptions, called superoutbursts. During superoutburst, they show quasi-periodic photometric oscillations, called superhumps, which have periods a few percent *longer* than P_{orb}. Warner (1995) gives an excellent discussion of these stars (and cataclysmic binaries in general). At this time, the most compelling explanation of the superhump clock invokes precession of an eccentric accretion disk (Whitehurst 1988). Such disks are expected to develop in low mass-ratio (hence short-period) cataclysmic binaries.

The stars reported on here all prove to have $P_{orb} < 2$ hr, yet to our knowledge none of them have well-observed superhumps or superoutbursts. Most of the stars in this sample should show superhumps in the future. The superhump periods can then be combined with the independently determined orbital periods to compute the superhump period excess $\epsilon = (P_{sh} - P_{orb})/P_{orb}$, which in turn appears to correlate well with the mass ratio $q = M_2/M_1$ (Patterson 2001).

2. OBSERVATIONS

The time-resolved spectra are from the MDM Observatory 2.4 m Hiltner telescope at Kitt Peak. Table 1 gives a journal of the observations. We used the modular spectrograph, a 600 line mm^{-1} grating, and a 2048^2 thinned Tektronix CCD as the detector. The spectra covered from 4200 to 7500 Å at almost exactly 2 Å pixel^{-1}, with a slightly undersampled spectral resolution of ∼3.5 Å FWHM. Individual exposures were generally ≤8 minutes to avoid phase smearing at short orbital periods, and frequent comparison exposures maintained the wavelength calibration. Observations of flux standard stars yielded a relative flux scale, but an unmeasurable and variable fraction of the light was lost at the 1″ spectrograph slit, and the sky was not always photometric, so the accuracy of the absolute flux calibration is probably ±∼30%. The time-averaged, flux-calibrated spectra appear in Figure 1, and Table 2 gives measurements of the emission lines.

We used convolution methods (Schneider & Young 1980) to measure velocities of the Hα emission lines (Table 3). The velocity uncertainties in Table 3 were computed by propagating the counting-statistics estimates of the errors in each spectrum channel through the convolution.

Figure 2 shows results of period searches on these velocities, computed using the "residualgram" method described in Thorstensen et al. (1996). Table 4 gives parameters of sine fits of the form

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

and the rms scatter σ around the best fits. In cases where they can be checked, cataclysmic binary emission lines seldom reflect the velocity amplitude of the white dwarf accurately, so we caution against using these parameters to compute masses. Note that zero phase occurs at apparent inferior conjunction of the emission-line source. Figure 2 also shows the velocities folded on the adopted periods with the best-fitting sinusoids superposed.

For FT Cam, we also obtained differential time-series pho-

[1] Based on observations obtained at the MDM Observatory.

TABLE 1
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Date (UT)	N	HA Start (hh:mm)	HA End (hh:mm)
KX Aql			
2001 Jun 24	3	+1:21	+1:35
2001 Jun 26	2	+0:35	+0:46
2001 Jun 30	20	−3:07	+2:36
2001 Jul 1	26	−4:11	+2:52
FT Cam			
2002 Jan 22	31	+0:11	+5:54
2002 Jan 23	34	−0:51	+5:58
2002 Jan 24	8	+0:14	+1:00
2002 Feb 20	2	+1:46	+1:52
2002 Feb 21	4	+2:22	+4:19
PU CMa			
2002 Jan 20	17	−2:47	+2:45
2002 Jan 21	22	−3:07	+2:48
2002 Jan 22	4	+1:19	+1:36
2002 Jan 23	18	−3:11	+3:38
2002 Feb 19	2	+0:28	+0:38
2002 Feb 20	4	−0:25	+1:43
V660 Her			
2001 Jun 24	4	−0:41	+2:56
2001 Jun 25	5	−1:50	−1:12
2001 Jun 26	20	−1:33	+4:13
2001 Jun 27	15	−2:21	−0:23
2001 Jun 28	5	+2:04	+2:39
2001 Jun 29	6	−0:20	+0:23
2001 Jul 1	3	+3:52	+4:10
DM Lyr			
1999 Jun 4	3	−0:38	+0:27
1999 Jun 9	9	+0:59	+1:57
1999 Jun 10	19	−4:49	+2:11
1999 Jun 11	6	−0:25	+0:14
1999 Jun 12	12	+0:46	+2:17
1999 Jun 13	12	−2:44	−0:56
1999 Jun 14	6	−1:17	−0:33
2001 Jun 27	16	−0:59	+2:27
2001 Jun 28	5	−3:39	−3:04

tometry with the MDM McGraw-Hill 1.3 m telescope. A Schott BG38 filter and a thinned SITe CCD yielded a nonstandard broad blue-visual passband. Each image had 256^2 binned (2×2) pixels, with an image scale of 1″.018 per binned pixel. We obtained 223 exposures of 30 s each, spanning 135 minutes. The reduced images were measured using the IRAF[2] implementation of DAOphot, and the instrumental magnitudes from individual exposures were adjusted to correct for transparency variations. No absolute calibration was attempted. An automated routine matched star images in the pictures to objects

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

TABLE 2
EMISSION FEATURES

Feature	EW[a] (Å)	Flux[b] (10^{-15} ergs cm^{-2} s^{-1})	FWHM[c] (Å)
KX Aql			
Hγ	104	225	27
Hβ	128	213	26
He I λ4921	10	15	28
He I λ5015	14	22	28
Fe λ5169	12	19	29
He I λ5876	52	58	32
Hα	227	225	30
He I λ6678	23	23	37
He I λ7067	14	15	34
FT Cam			
Hγ	54	376	29
He I λ4471	15	91	35
He IIλ4686	7	39	46
Hβ	85	418	31
He I λ4921	10	47	41
He I λ5015	11	53	38
Fe λ5169	9	42	35
He I λ5876	37	132	38
Hα	145	483	36
He I λ6678	17	53	41
He I λ7067	14	41	45
PU CMa			
Hγ	68	1637	23
He I λ4471	20	386	26
He II λ4686	11	198	44
Hβ	108	1784	25
He I λ4921	9	147	30
He I λ5015	9	131	27
Fe λ5169	4	59	27
He I λ5876	38	455	30
Hα	151	1674	27
He I λ6678	19	201	34
He I λ7067	14	139	36
V660 Her			
Hγ	52	125	26
He I λ4471	14	27	24
He II λ4686	15	24	55
Hβ	88	133	26
He I λ4921	9	13	31
He I λ5015	10	15	27
Fe λ5169	6	8	30
He I λ5876	24	29	28
Hα	107	122	27
He I λ6678	12	14	35
He I λ7067	9	10	42
DM Lyr			
Hγ	86:	61:	15
He I λ4471	15:	14:	21
Hβ	78	79	18
He I λ4921	8	8	18
He I λ5015	8	8	19
Fe λ5169	8	8	18
He I λ5876	27	24	23
Hα	95	82	20
He I λ6678	13	11	23
He I λ7067	9	7	25

[a] Emission equivalent widths are counted as positive.
[b] Absolute line fluxes are uncertain by a factor of about 2, but relative fluxes of strong lines are estimated accurate to ∼10%.
[c] From Gaussian fits.

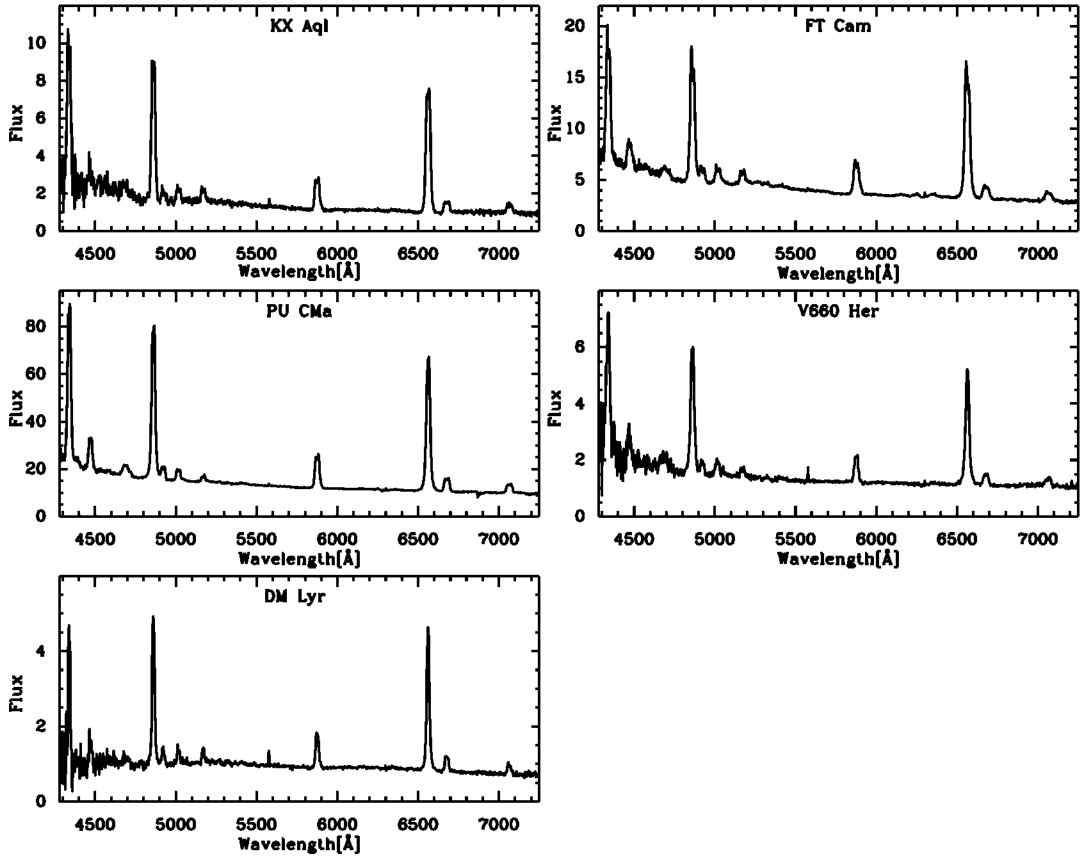

FIG. 1.—Averaged spectra. The vertical axes are in units of 10^{-16} ergs cm^{-2} s^{-1} $Å^{-1}$, but the flux scales are uncertain by at least 20%.

in the USNO-A2.0 catalog (Monet et al. 1996) and generated astrometric plate solutions accurate to ∼0″.3.

3. NOTES ON INDIVIDUAL STARS

3.1. KX Aql

Tappert & Mennickent (2001) obtained a spectrum of KX Aql showing strong, broad emission lines. The large outburst amplitude (12.5 to fainter than 18), emission-line morphology, and absence of a secondary absorption spectrum led them to suggest that KX Aql is a short-period, SU UMa type system. Kato, Sekine, & Hirata (2001a) list it as a candidate WZ Sge type star. The period we find, 86.91(3) minutes, is rather longer than WZ Sge and its ilk. Also, there is not any clear sign of absorption around Hβ from the underlying white dwarf, as is found in WZ Sge and GW Lib at minimum light (Thorstensen et al. 2002).

3.2. FT Cam

FT Cam was discovered by Antipin (1999), who designated it Var 64 Cam and found a range from 14.0 to fainter than 17.6 in *B*. Definite variations were noted around minimum light. Kato, Uemura, & Yamaoka (2001b) reported photometry through an outburst, pointed out that the known outbursts have all been rare and short in duration, and derived a proper motion of ∼0″.02 yr^{-1}. Superoutbursts and superhumps have not been detected.

The line spectrum appears typical for a dwarf nova, with a slight doubling of the emission lines; the peaks of Hα are

TABLE 3
Hα Radial Velocities

Time (HJD −2,400,000)	v (km s^{-1})	σ[a] (km s^{-1})
KX Aql		
52084.92859	−66	9
52084.93335	−39	9
52084.93810	−4	8
52086.89135	19	20
52086.89883	16	25
52090.72698	−20	10

NOTE.—Table 3 is published in its entirety in the electronic edition of *PASP*. A portion is shown here for guidance regarding its form and content.

[a] Standard deviation estimated from counting statistics.

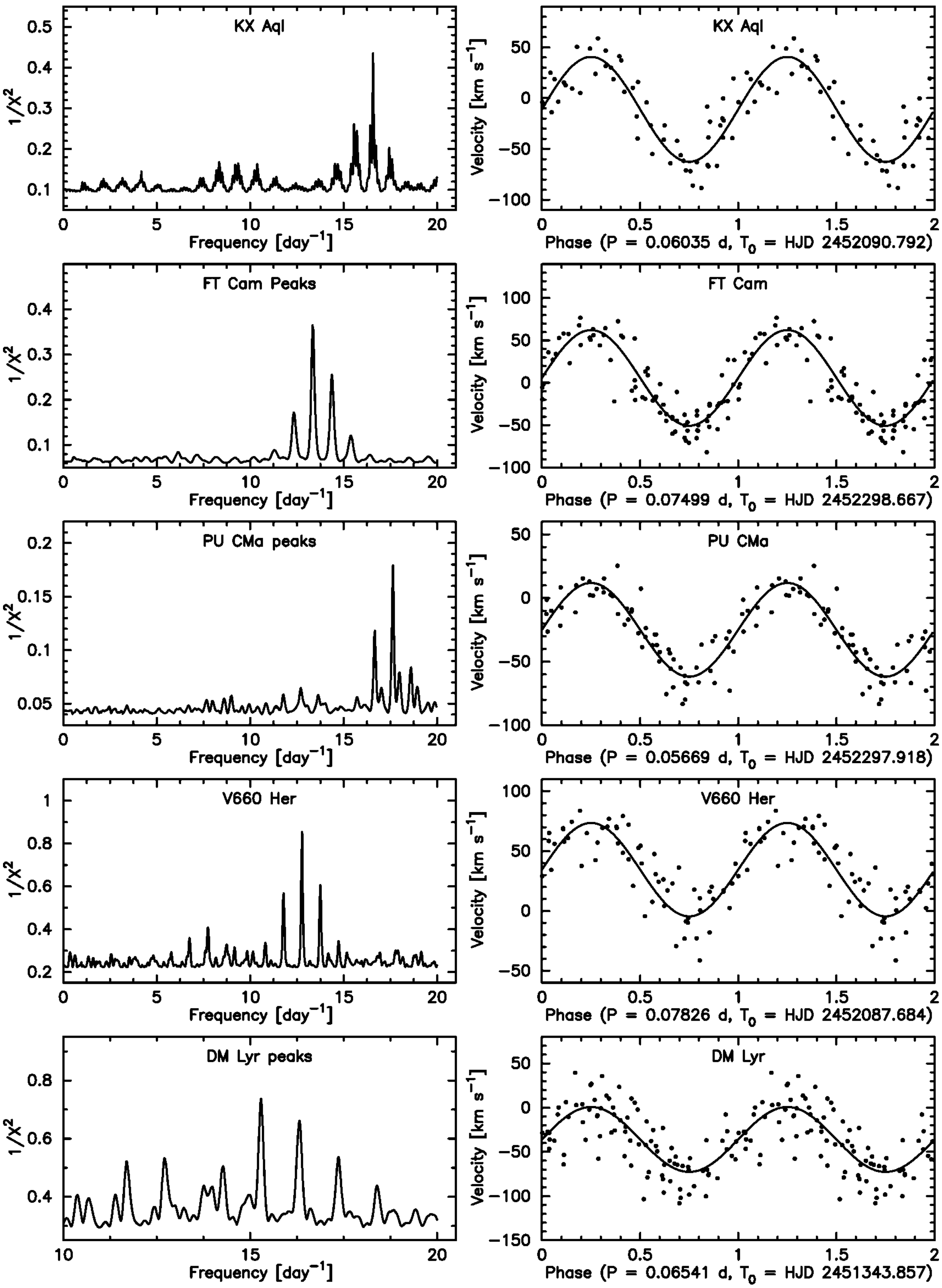

FIG. 2.—Period searches of the radial velocities (*left panels*) and radial velocities folded on the adopted periods (*right panels*). When data from several observing runs are combined, fine-scale ringing is present, and the function plotted is formed by joining local maxima of the function. In these cases, the choice of cycle count used in folding the data for the right panel is arbitrary. Two cycles are shown in the folds for continuity.

TABLE 4
FITS TO RADIAL VELOCITIES

Data Set	T_0[a]	P (days)	K (km s^{-1})	γ (km s^{-1})	σ (km s^{-1})	N	Function[b]	W (Å)	F (Å)
KX Aql	52090.7923(9)	0.06035(2)	52(5)	−11(4)	51	19	G	30	12
FT Cam	52298.6667(11)	0.074990(10)[c]	56(5)	6(4)	79	18	G	46	12
PU CMa	52297.9183(9)	0.056694(6)[c]	37(4)	−25(3)	67	14	G	44	12
V660 Her	52087.6838(17)	0.07826(8)	39(5)	35(4)	58	17	D	36	...
DM Lyr	51343.8565(15)	0.0654092(2)[c]	37(5)	−36(4)	88	21	G	30	10

[a] Blue-to-red crossing, HJD −2,400,000.
[b] Convolution function used in measurements; D indicates the derivative of a Gaussian, in which case W is the FWHM for which it is optimized, while G indicates positive and negative Gaussians of FWHM F separated by W.
[c] For these objects, the period and its error assume an uncertain choice of cycle count between observing runs. See text for discussion.

separated by ∼700 km s^{-1}. In the mean spectrum, the violet peaks of the lines are stronger than the red peaks, which may be an artifact of uneven phase coverage. The continuum level implies $V = 17.5$.

Our data are from two observing runs (see Table 1). The more extensive 2002 January data yield $P_{\rm orb} = 0.07492(8)$ day, but the number of cycle counts between this and the 2002 February run is ambiguous. Periods within 5 standard deviations of the best January period are given by $P =$ [29.621(4) days]/N, where $N = 395 \pm 2$ is an integer.

Figure 3 shows the time-series photometry of FT Cam. Very strong flickering is present, amounting to almost 1 mag peak to peak, but no eclipse is evident. The flickering is strong enough that a shallow eclipse might escape detection.

Comparing our direct images with the USNO-A2.0 yields a barely significant displacement of FT Cam corresponding to $\mu = 16$ mas yr^{-1} in position angle 353°, corroborating the proper motion found by Kato et al. (2001b).

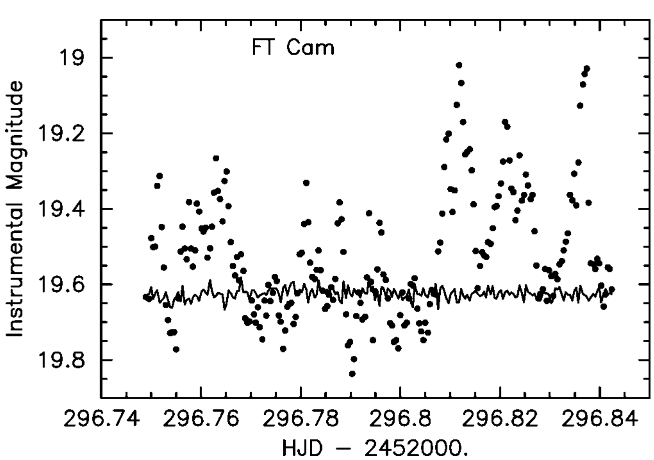

FIG. 3.—Time-series photometry of FT Cam. Instrumental magnitudes from each frame have been adjusted to account for transparency variations. The jagged line shows a comparison star at $\alpha = 3^{\rm h}20^{\rm m}58^{\rm s}.88$, $\delta = 61°05'13''.8$ (ICRS), that is, 113″ from FT Cam in P.A. 264°.

3.3. PU CMa

PU CMa is the optical counterpart of the ROSAT source 1RXS J064047.8−242305. Several outbursts have been seen, and in one outburst Kato and Uemura (VSNET alert 3980) suspected an oscillation that might have been the beginnings of a superhump.[3]

The emission lines are only slightly double-peaked in the average spectrum, indicating a rather low orbital inclination. The observed continuum implies $V = 16.2$, quite bright for a relatively unstudied object. The radial velocity data span a 6.8 hr range in hour angle, despite the unfavorable declination of −24°; this and the good signal-to-noise ratio resulted in an unambiguous period determination. The period, 81.63(6) minutes, is the shortest in the present sample and is essentially equal to that of WZ Sge. The low-velocity amplitude K (Table 3) also suggests a relatively low inclination.

As with FT Cam, the data set spans two observing runs, creating ambiguity in the long-term cycle count. The more extensive 2002 January data yield $P = 0.05669(4)$ day. Including the 2002 February data constrains the period to [29.5941(32) days]/N, where the integer $N = 522 \pm 1$.

3.4. V660 Her

Spogli, Fiorucci, & Tosti (1998) obtained photometry during an outburst which reached $V = 14.3$; at minimum, the magnitude is *estimated* as 19, so the amplitude is approximately 5 mag. A spectrum obtained by Liu et al. (1999) appears normal for a dwarf nova near minimum light. Our spectrum (Fig. 1) appears similar, with single-peaked Balmer lines that suggest a relatively low orbital inclination. The continuum indicates $V \sim 18.7$. The period, 112.60(12) minutes, is the longest in the present sample.

[3] VSNET home page: http://vsnet.kusastro.kyoto-u.ac.jp/vsnet/index.html.

3.5. DM Lyr

The emission lines are single-peaked, indicative of a low orbital inclination. DM Lyr is the only star in this sample for which we are aware of a superhump period, namely, 0.066 day listed by Nogami, Masuda, & Kato (1997) in their Table 1. However, the details of this determination remain unpublished, and the quoted accuracy is insufficient to compute an accurate superhump period excess ϵ. Our spectroscopy is from two observing runs separated by 2 yr, which yielded a weighted mean $P_{\rm orb} = 0.06546(6)$ day. Precise periods that fit both runs lying within 4 standard deviations of the weighted mean are given by [747.9533(25) days]/N, where the integer $N = 11{,}426 \pm 44$.

4. DISCUSSION

None of these five stars appears particularly unusual. They all prove to have periods in the range occupied by the SU UMa stars. Superhumps are evidently detected (but not well measured) in DM Lyr, and presumably they have not yet turned up in the other four stars only because the objects have not been observed long or intensively enough. If one or more of the other four objects proves after extensive monitoring *not* to be an SU UMa star, it will present an interesting anomaly.

We thank the NSF for support through AST 99-87334. Tim Miller obtained the direct images of FT Cam. This research made use of the Simbad database, operated at CDS, Strasbourg, France.

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