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Orbital Periods for the SU UMa-Type Dwarf Novae UV Persei, VY Aquarii, and V1504 Cygni[1]

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ABSTRACT. We present mean spectra of three SU UMa-type dwarf novae and report orbital periods based on radial velocities taken near minimum light. For UV Per we find $P_{\rm orb}=0.06489\pm0.00011$ d ($=93.44\pm0.16$ min); for V1504 Cygni, 0.06951 ± 0.00005 ($=100.10\pm0.07$ min), and for VY Aqr, 0.06309 ± 0.00004 d ($=90.85\pm0.06$ min). The period for VY Aqr is slightly shorter than the period determined by Augusteijn from velocities during outburst, and is more consistent with expectations based on the superhump period. For UV Per we also present time-series photometry obtained on two nights. A weak modulation may be present at a period near, but formally distinct from, the orbital period. A magnitude sequence is presented.

1. INTRODUCTION

The SU UMa stars are dwarf novae which show occasional bright and long-lasting outbursts, called superoutbursts, in addition to their normal outbursts. During superoutbursts, the SU UMa stars develop oscillations in brightness, called superhumps, with periods $P_{\rm sh}$ a few percent *longer* than the orbital period, $P_{\rm orb}$. Molnar and Kobulnicky (1992) review models accounting for this phenomenon, the most promising of which invoke the precession of an eccentric accretion disk (Whitehurst 1988).

Independently determined orbital periods are needed to continue verifying the disk-precession model, and in the framework of this model, the superhump period excess may provide a means of measuring binary mass ratios. Here we use emission-line radial velocities taken near minimum light to determine the orbital periods of three SU UMa stars, namely UV Per, VY Aqr, and V1504 Cyg. Downes and Shara (1993) give finding charts and accurate coordinates for these stars.

2. OBSERVATIONS

We obtained time-resolved *spectra* of all three stars using the Michigan-Dartmouth-MIT Observatory (MDM) 2.4-m Hiltner telescope and modular spectrograph on observing runs in 1995 October and 1996 September/October. A 600 line mm^{-1} reflection grating and a 2048^2 Loral CCD gave a resolution of 3.2 Å FWHM (full width at half maximum) over most of the 4300–6800 Å spectral range, with some degradation of focus short of Hβ. The observing protocols, data reduction, and analysis were nearly identical to those described in Thorstensen et al. (1996).

For brevity we indicate to the reader here the major results of our spectroscopy, reserving discussion of individual stars for Sec. 3. Our time-averaged, flux-calibrated spectra appear in Fig. 1. Table 1 gives radial velocities of Hα, measured by convolution methods (Schneider and Young 1980), and Fig. 2 shows the period searches of these velocity time series. As usual, these diagrams show daily cycle-count aliases. To assess the confidence with which we could choose among these correctly, we computed the *discriminatory power* and the *correctness likelihood*, which are Monte Carlo statistics defined by Thorstensen and Freed (1985). The chance of an incorrect alias choice proved to be small in every case considered here. Table 2 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. We caution that in cases where they can be checked, cataclysmic binary emission lines seldom reflect the velocity amplitude of the white dwarf accurately, so we recommend that these parameters not be used to compute masses. Finally, Fig. 3 shows the velocities folded on the adopted periods with the best-fitting sinusoids superposed.

We obtained some direct CCD *photometry* of UV Per (only) on 1995 October 11 and 12 UT, using the MDM 1.3-m McGraw–Hill telescope and a STIS 2048^2 CCD cropped to 1024^2 0.″445 pixels. We extracted instrumental magnitudes from the pictures using IRAF's *apphot* routines, and calibrated using 15 observations of 61 Landolt (1992) standards taken over five nights. Exposure times on UV Per were 300 s in the V passband. The fit to the standards gave a rms residual of ~0.03 mag and a negligible color term. Figure 4 shows the UV Per field, and the figure caption gives V magnitudes of the indicated stars based on our calibration. For the two stars we have in common with Misselt (1996), we find our magnitudes to be systematically 0.12 mag fainter than his, a modest but formally significant difference for which we have no ready explanation.

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[1] Based on observations obtained at the Michigan-Dartmouth-MIT Observatory.

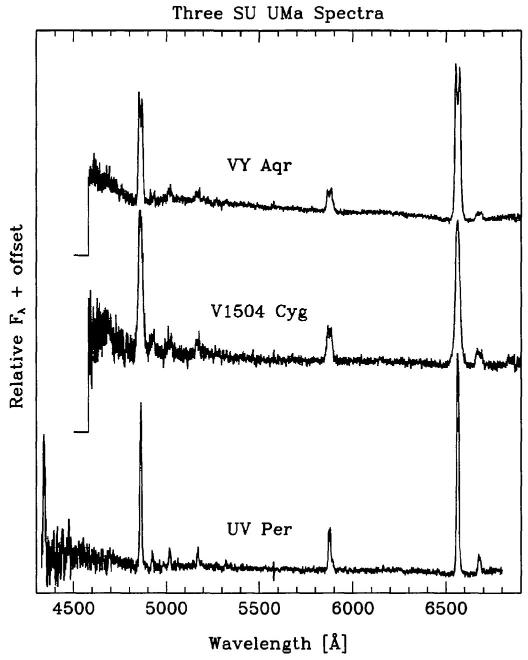

FIG. 1—Mean spectra of three SU UMa-type stars. The flux scales are adjusted individually to fit the traces on the plot. The zero point of the lowermost spectrum (UV Per) is the bottom of the plot, and the zero points of the other two spectra are indicated by the short horizontal line segments on their blue ends.

3. NOTES ON INDIVIDUAL STARS

3.1 UV Persei

UV Per outbursts rarely, but Udalski and Pych (1992) did observe a superoutburst photoelectrically in 1989 October, and determined an unambiguous superhump period of 95.6 minutes (0.066407±0.000038 d). Szkody (1985) obtained a spectrum at minimum light showing strong emission [E.W.(Hβ)~95 Å], and photometry on successive nights giving V=16.65 and V=16.85; Udalski and Pych found UV Per at V=17.5 on a single night in 1992 January. Kato (1990) detected a candidate photometric period of 89.9 min at minimum light, but the more sensitive observations of Udalski and Pych (1992) do not confirm this, and it is shorter than expected given the superhump period.

Figure 5 shows time-resolved photometry obtained 1995 October, and Fig. 6 gives results of a period search on these data. The orbital period determined in this paper is indicated by a vertical line. There appears to be modulation at a period slightly different from $P_{\rm orb}$, but there is heavy aliasing at ~1 cycle d^{-1} intervals because the photometric observations covered a small range of hour angle, so we cannot unambiguously determine the photometric period. Also, in view of the small redundancy of the data, we cannot be certain of the modulation's reality, and the nonrandom nature of the underlying noise process makes simple quantitative confidence estimates unreliable. Nonetheless, we thought it worthwhile to report this result because of the well-observed *negative* superhump period displayed by V503 Cyg in quiescence (Harvey et al. 1995). The strongest alias in the pho-

TABLE 1
Hα Radial Velocities

HJD[a]	V (km s^{-1})	HJD[a]	V (km s^{-1})	HJD[a]	V (km s^{-1})
UV Per:					
0.7930	−35	1.7142	7	1.9706	−18
0.7983	−10	1.7189	26	1.9753	23
0.8031	6	1.7235	23	1.9800	−8
0.8077	20	1.7282	43	2.6101	−36
0.8124	32	1.7427	25	2.6148	−9
0.8171	28	1.7474	18	2.6195	7
1.6189	10	1.7521	−14	2.6242	−7
1.6236	11	1.7567	−25	2.6289	−2
1.6334	−4	1.7614	−17	2.6336	26
1.6380	5	1.7661	−11	2.6382	46
1.6427	−9	1.7708	−30	2.6429	35
1.6474	15	1.7755	−23	2.6508	22
1.6545	−8	1.7837	2	2.6554	−27
1.6592	19	1.7884	17	2.6601	−29
1.6639	33	1.7931	38	2.6648	−19
1.6686	61	1.7978	36	2.6695	−12
1.6733	48	1.8025	34	2.6742	−29
1.6779	18	1.8071	25	2.6788	−36
1.6826	18	1.8118	23	2.6835	−44
1.6873	−0	1.8165	6	2.9703	29
1.6955	20	1.9519	−26	2.9750	4
1.7001	−24	1.9566	−27	2.9797	−1
1.7048	−20	1.9613	−35	2.9844	5
1.7095	−0	1.9660	−18	2.9890	−2
VY Aqr:					
353.7134	−13	357.8180	−21	358.7898	−52
353.7195	−49	357.8240	−69	358.7959	−26
353.7255	−42	357.8301	−76	358.8019	12
353.7316	−46	357.8361	−84	358.8100	20
354.7681	42	358.6129	15	358.8160	−0
354.7742	3	358.6190	30	358.8221	−1
357.7735	−87	358.6250	25	358.8281	−30
357.7795	−65	358.6311	13	358.8342	−32
357.7856	−30	358.6371	−24	359.7883	−61
357.7916	−18	358.6432	−59	359.7944	−47
357.7977	8	358.7717	−84	359.8004	−51
357.8037	43	358.7777	−90		
357.8119	1	358.7838	−59		
V1504 Cyg:					
354.6163	−163	359.6360	−75	360.6471	−111
354.6210	−122	359.6421	−65	360.6532	−110
354.6257	−164	359.6512	−17	360.7354	−158
354.8103	−125	359.6573	−11	360.7415	−146
354.8163	−170	359.6633	−37	360.7475	−70
354.8224	−105	359.6754	−93	360.7536	−86
354.8284	−149	359.6815	−90	360.7596	−45
354.8345	−151	359.8099	−57	360.7657	−43
355.6397	−47	359.8159	−109	360.7743	−48
358.7412	−33	359.8220	−114	360.7804	−61
358.7472	−31	359.8281	−111	360.7864	−106
358.7533	−12	359.8341	−103	360.7925	−76
358.7593	−57	359.8382	−147	360.7985	−91
359.6118	−156	360.6229	−76	360.8046	−147
359.6178	−165	360.6290	−57		
359.6239	−173	360.6350	−60		
359.6300	−191	360.6411	−50		

[a] Heliocentric JD of midintegration minus 2450000.

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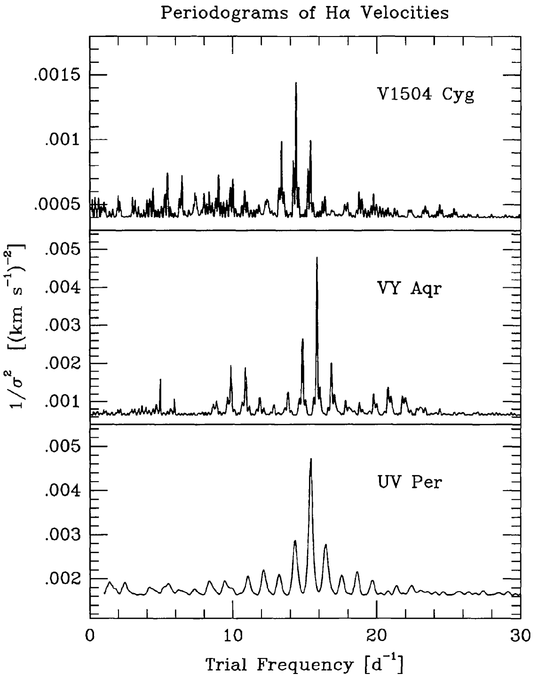

FIG. 2—Periodograms of the Hα radial velocities, computed as the inverse mean-square residual around sinusoidal fits at each trial frequency. The vertical scale is arbitrary.

tometry is at 12.84 d^{-1}, while the aliases flanking the orbital frequency (15.411 d^{-1}) occur at 14.72 and 15.68 d^{-1}.

The average spectrum (Fig. 1) shows the very strong Balmer emission typical of SU UMa stars at minimum light. The equivalent widths of Hα and Hβ are, respectively, 170 and 64 Å . The emission lines are narrower than in a typical SU UMa star; Hα has a FWHM = 14 Å = 640 km s^{-1}, and a FWZI = 48 Å = 2215 km s^{-1}. There is a hint of broad absorption around Hα, which might arise in an underlying white dwarf. He I emission lines appear, as does a feature near λ5169 usually attributed to Fe II (Taylor and Thorstensen 1996). The continuum level suggests $V\sim 18.0$, with at least ±0.5 mag uncertainty, in reasonable agreement with the contemporaneous CCD photometry.

Because UV Per was near our limit, we measured velocities using the derivative of a Gaussian as the convolution function, and therefore included information from near the line center, which makes our velocities even less reliable for dynamics than usual. The velocities do span over 9 hr of hour angle, so the Monte Carlo test gives a discriminatory power of 1000/1000 — the daily cycle count is secure. Combining the spectroscopic period (93.45±0.20 min) with Udalski and Pych's (1992) superhump period yields

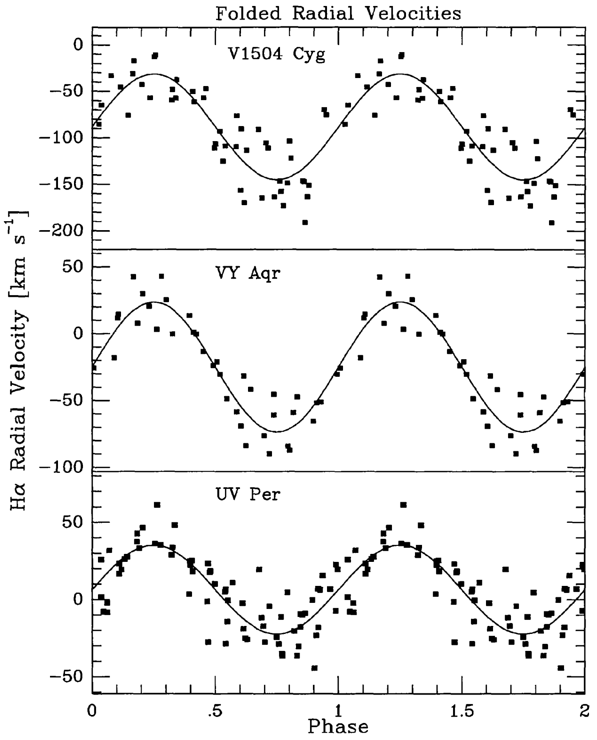

FIG. 3—Hα radial velocities folded on the adopted periods with best-fit sinusoids superposed. All data are plotted twice for continuity.

$$\epsilon=(P_{\rm sh}-P_{\rm orb})/P_{\rm orb}=0.023\pm0.002,$$

while the relationship derived by Thorstensen et al. (1996) predicts 0.0251. This puts UV Per squarely among the normal SU UMa stars.

While we reiterate our cautions about taking the velocity measurements too literally, both the rather small K velocity and the narrow lines suggest that the orbital inclination is rather low. With nominal component masses of 0.6 $M_\odot$ and 0.12 $M_\odot$ (the latter derived from the period and the semiempirical $M_2-P_{\rm orb}$ relationship of Patterson 1984), the observed K velocity would imply $i=21°$. Udalski and Pych (1992) reach a similar conclusion from the lack of a photometric orbital modulation at minimum light; our weak detection of a periodicity does not compel a high inclination.

TABLE 2
Fits to Radial Velocities

Star	T_0[a]	P (d)	K (km s^{-1})	γ (km s^{-1})	σ (km s^{-1})
UV Per	1.9760±0.0012	0.06489±0.00014	29±4	6±3	15
VY Aqr	357.7860±0.0009	0.06309±0.00004	49±4	−25±3	15
V1504 Cyg	358.7357±0.0014	0.06951±0.00005	57±7	−88±5	26

[a] Apparent emission-line inferior conjunction, HJD −2450000.

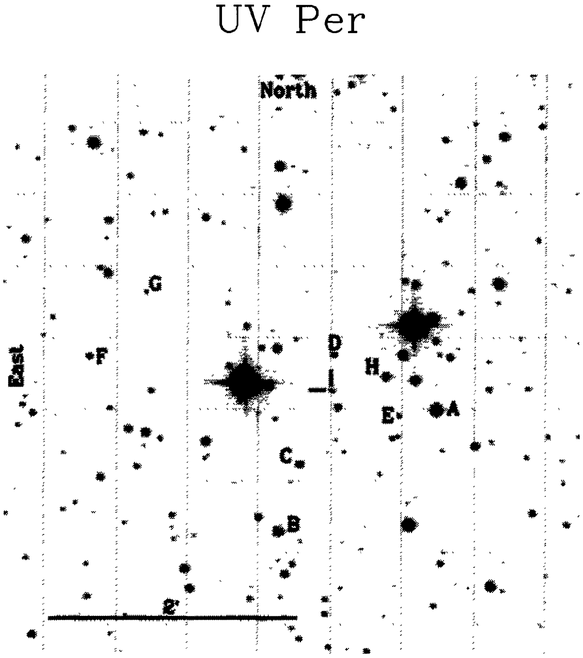

FIG. 4—Average of several V-band CCD exposures, with UV Per (short lines) and secondary photometric standards indicated. We find the following V magnitudes for the marked stars: A, 13.63; B, 14.61; C, 15.97; D, 17.14; E, 17.84; F, 16.75; G, 18.28; and H, 15.27. North is at the top and east at the left.

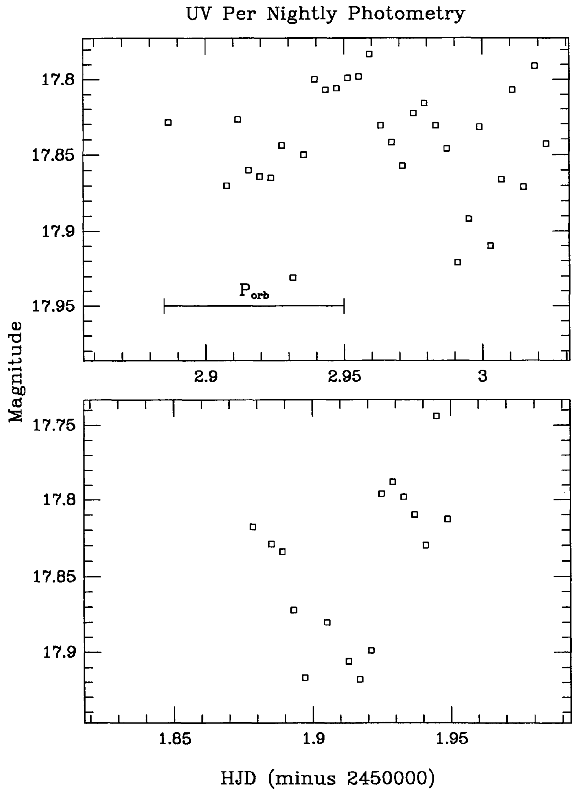

FIG. 5—Time-series photometry of UV Per. The orbital period is indicated.

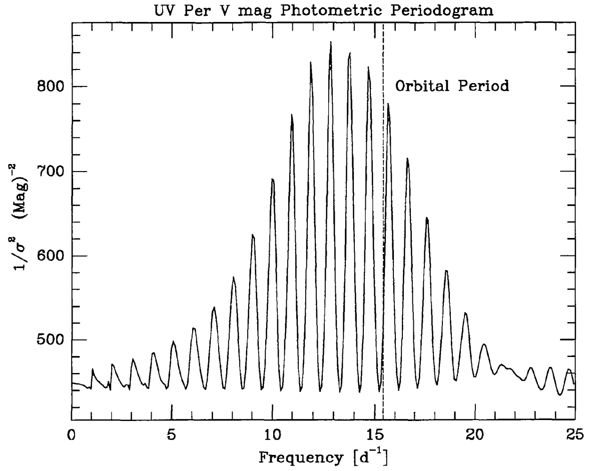

FIG. 6—Periodogram of the UV Per time series photometry. The orbital period is indicated.

3.2 VY Aqr

Patterson et al. (1993) present spectroscopy and photometry of this object, which had at one point been thought to be a recurrent classical nova. They derive $P_{\rm sh}=92.70 \pm 0.12$ min (or possibly a period differing by one cycle per day), and find that $P_{\rm sh}$ grows slightly shorter as the superoutburst fades. The superhump, together with the spectroscopic similarity between VY Aqr and the large-outburst-amplitude SU UMa stars WZ Sge and WX Cet, establish its credentials as a *bona fide* SU UMa star. Augusteijn (1994), using cross-correlation radial velocities derived from spectra taken in outburst, found an orbital period of 0.06348(12) d ($=91.41\pm0.17$ min). Because of the possibility that this could have been affected by line-profile changes (the mean velocity shifted by 153 km $\rm s^{-1}$ between the two nights on which he obtained data), and because the superhump period excess ϵ appeared anomalously small, we thought it wise to check his period using velocities taken at minimum light.

Figure 1 shows the average spectrum observed 1996 September/October. Note the steep-sided, double-peaked emission profile in the mean spectrum, similar to spectra presented by Augusteijn (1994) and Patterson et al. (1993). The emission peaks of Hα are separated by 930 km $\rm s^{-1}$, the line FWHM is 1550 km $\rm s^{-1}$, and the FWZI is 3800 km $\rm s^{-1}$. The equivalent widths of Hα and Hβ are 140 and 49 Å, respectively. There is again, a slight hint of absorption underlying the Balmer lines, which (if real) may arise in the white dwarf photosphere.

Because conditions were sometimes marginal, we selected spectra of adequate signal-to-noise ratio before measurement. For the convolution function we used positive and negative Gaussians separated by 1940 km $\rm s^{-1}$, which emphasized the steep sides of the line profile. The best sinusoidal fit to our 37 velocities gives $P_{\rm orb}=0.06309\pm0.00004$ d ($=90.85\pm0.05$ min). The Monte Carlo test against the next-best alias gave a one-sided discriminatory power of 983/1000 and a correctness likelihood indistinguishable from unity, so the alias choice (which had been slightly uncertain in previous determinations) is now secure. Our period is only barely consistent with that of Augusteijn (1994), differing by 3.1 standard deviations. Again, because of the possibility of secular evolution of the lines in outburst, we believe our minimum-light value is likely to be more accurate than his value as well as slightly more precise.

Combining our revised period with the superhump period changes ϵ from 0.0141 ± 0.0023 to 0.0204 ± 0.0015. The mean $\epsilon-P_{\rm orb}$ relation from Thorstensen et al. (1996) predicts $\epsilon=0.0234$. The revised period is therefore more consistent with that expected from the superhump period.

3.3 V1504 Cygni

The spectrum (Fig. 1) appears typical. The Hα and Hβ lines show a FWHM of 1500 km s^{-1}. The equivalent width of Hβ is 53 Å, and that of Hα is 71 Å. The wings of Hα can be traced to ±2300 km s^{-1} from the line center. The Balmer lines appear single peaked, while the He I lines show incipient double peaks. The continuum level suggests $V\sim18$. We measured velocities in Table 1 using the derivative of a Gaussian for the convolution, so once again they are surely not suitable for dynamical solutions. While our 100.10 ±0.07 min period appears secure, with a (one-sided) discriminatory power of 972/1000 and a correctness likelihood again indistinguishable from unity, we were unable to find a superhump period in the literature for comparison.

4. DISCUSSION

None of these objects appears unique. Where we can check, all appear consistent with a normal ϵ-$P_{\rm orb}$ relation, and in the case of VY Aqr, the revision of $P_{\rm orb}$ results in an ϵ more consistent with the mean relation. This relation is easily understood as a function of mass ratio in the precessing disk model, so the precessing disk model continues to lead the pack of theories accounting for the superhump phenomenon.

The candidate periodic modulation in UV Per at minimum light, if confirmed, may be a second example of a "negative superhump," after V503 Cyg (Harvey et al. 1995).

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