ACCRETION-DISK PRECESSION IN UX URSAE MAJORIS

by

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ABSTRACT

We report the results of a long campaign of time-series photometry on the novalike variable UX Ursae Majoris during 2015. It spanned 150 nights, with ~1300 hours of coverage obtained on 113 separate nights. The star was in its normal "high state" near magnitude *V* = 13, with slow waves in the light curve and eclipses every 4.72 hours. Remarkably, the star also showed a nearly sinusoidal signal with an amplitude of 0.30 mag and a period of 3.70+-0.03 days. We interpret this as the signature of a retrograde precession (wobble) of the accretion disk. The same period is manifest as a ±23 s wobble in the timings of mid-eclipse, indicating that the disk's center of light moves with this period. The star also showed strong "negative superhumps" at frequencies of ω_o+N and $2\omega_o$+N, where ω_o and N are respectively the orbital and precession frequencies. It is possible that these powerful signals have been present, unsuspected, throughout the 60+ years of previous photometric studies.

1. INTRODUCTION

UX Ursae Majoris is one of the oldest and most thoroughly studied of the cataclysmic variables (CVs). Among noneruptive CVs, it's probably the champion in both respects. Visual and photoelectric photometry showed it to be an eclipsing binary with a remarkably short period of 4.7 hours (Zverev & Kukarkin 1937; Johnson, Perkins, & Hiltner 1954), and Walker & Herbig (1954) proposed a model in which the hot star in the binary is surrounded by a large ring of gas on which a bright region ("hot spot") resides. The hot spot became a key feature of the basic model for understanding CVs, in which the spot is interpreted as the region where the mass-transfer stream impacts the outer edge of the accretion disk.

The spectrum of UX UMa closely resembles that of dwarf novae in eruption: a blue continuum with broad, shallow hydrogen absorption lines, and narrow H emission contained within these absorption troughs. He I and weak He II emission are sometimes also present. The distance is 345±34 pc (Baptista et al. 1995, 1998). Recent spectroscopic studies have been reported by Linnell et al. (2008) and Neustroev et al. (2011). The out-of-eclipse mean *V* magnitude is ~13.0, but this is adversely affected by interstellar extinction (~0.2 mag) and the geometrical projection of a fairly edge-on disk (~1.0 mag: Paczynski & Schwarzenberg-Czerny 1980). After these corrections, the angle-averaged $<M_v>$ is about +4.1. That's just about right for the “high state” of a dwarf nova with an orbital period of 4.7 hours (Figure 1 of Patterson 2011). Thus the spectrum and brightness are consistent with interpretation as a dwarf nova in the high state.

In addition, UX UMa shows another phenomenon which is highly characteristic of dwarf novae: very rapid (~30 s) oscillations in its optical and UV brightness (Nather & Robinson 1974, Knigge et al. 1998). These oscillations are seen in practically every dwarf nova near the peak of eruption, and are consequently called "dwarf nova oscillations" (DNOs; Patterson 1981, especially the abstract and Figure 17). Their presence in UX UMa is yet another reason why the star is commonly regarded, and described, as essentially a "permanently erupting dwarf nova".

UX UMa vaulted to the world's attention from a program of time-series photometry in the 1940s. We launched a more intensive program in 2015, and discovered several additional periodic signals, which we describe in this paper and interpret as signifying the *retrograde precession of the accretion disk*.

2. OBSERVATIONS

We conducted this campaign with our global network of small photometric telescopes, the Center for Backyard Astrophysics. Details regarding the instrumentation and observing methods are given by Skillman & Patterson. (1993), along with the summary observing log in Table 1. We adopted our usual technique of differential photometry with respect to a nearby comparison star or stars, using overlaps of the various time series to calibrate each on a common instrumental scale. That scale is roughly a “V” magnitude, but usually differs from a true *V* since most of our data is unfiltered, to improve signal-to-noise. In the present case, we obtained sufficient data with a true *V* filter to apply a *V-C* correction and thereby reduce the systematic error to ~0.1 mag.

The cycle time (integration + readout) between points in the various time series was usually near ~60 s. We made no correction for differential (color) extinction, although such a correction is in principle necessary, since all CVs are bluer than field stars. But in a long time series, such effects are always confined to the same frequencies (very near 1.00 and 2.00 cycles per sidereal day), so the resultant corruption is easily identified and ignored. In the present case, it is also mitigated by the northern latitudes of observers and the far-northern declination of the star (51 degrees), which made it possible to obtain long runs within our self-imposed limit of 1.7 airmasses. Finally, we just prefer to keep human hands off the data as much as possible.

As detailed in Table 1, the campaign amounted to 266 separate time series on 122 nights, distributed over a span of 150 nights. The total coverage was 1278 hours, essentially all from sites in Europe and North America. This longitude span permitted many ~14 hour runs, which eliminated all possibility of daily aliases – the usual bugaboo of single-longitude time series.

3. LIGHT CURVES AND ECLIPSES

Two nightly light curves are shown in Figure 1, and are similar to essentially all light curves in the literature (e.g. Warner & Nather 1972, Walker & Herbig 1954): flickering, regular eclipses, plus a roughly “orbital” hump, although the latter varies markedly – and interestingly! – from one night to the next. The upper frame of Figure 2 shows a sample 23-day light curve, which suggests the presence of a slow wave with a period near 3.7 days. And the bottom frame shows a 98-day light curve (with eclipses removed), which confirms the apparent stability of this slow wave.

We measured the times of mid-eclipse in two ways: by the traditional “bisection of chords” method, and by fitting a parabola to the bottom half of the minimum. We then averaged these two methods to obtain an estimated time of mid-eclipse. These times are given in Table 2. As we shall see below, these times appear to be modulated by the 3.7 day period described above.

The orbital light curve is significantly contaminated by flickering, the 3.7 day variation, and the “superhump” variations described below. Making no attempt to remove these effects, and simply averaging over the ~1300 hours of coverage, we found the mean orbital light curve seen in Figure 3. This appears to be the first mean orbital light curve published for this venerable, oft-observed star.

4. PERIODIC SIGNALS IN THE LIGHT CURVE

Our primary analysis tool for studying periodic waves is power spectra, calculated by Fourier methods. Of course the sharp eclipses severely contaminate analysis by Fourier methods, since the latter represent time series as sums of sinusoids. So to prepare the light curves for study, we first removed the eclipse portion of the light curves, viz. the phase interval 0.9-1.1. Then we calculated the power spectrum of the densely sampled portion of the light curve (a baseline of 51 days). The low-frequency portion is shown in Figure 4, where the significant peaks are labeled with their frequencies in cycles/day, and alias peaks marked with "A". The orbital frequency ω_o = 5.0846 c/d is present, but the most powerful signal occurs at 0.268(1) c/d, which we denote as N, in anticipation of identifying it with nodal precession of the accretion disk. In addition to ω_o and N, other signals appear in the vicinity of ω_o and $2\omega_o$.

We summed at 0.268 c/d, and found a highly sinusoidal waveform with a full amplitude of 0.27 mag. This is shown in Figure 5. We then subtracted the sinusoids corresponding to N and ω_o, and recalculated the power spectrum of that 51-day time series. The results are shown in the upper frame of Figure 6, which reveals obvious signals at 5.3530(10) and 10.4355(10) c/d. These are consistent with identifications as ω_o+N and $2\omega_o$+N, which are expected at 5.3524(10) and 10.4370(10) c/d, respectively. The lower frames of Figure 6 show the mean light curve at these two frequencies. They are both rather pure sinusoids. These upper sidebands of the orbital frequency are known as *negative superhumps* in variable-star nomenclature, because in period (rather than frequency) language, their period excesses over P_{orb}, 0.5 P_{orb}, etc. are *negative*.

The transition from Figure 4 to Figure 6 looks odd. Of course the one-day aliases, along with the main peaks, disappear when the N and ω_o signals are subtracted from the time series. But in Figure 4 there are also strong and unlabeled peaks at 4.814(1) and 9.899(1) c/d, which also disappeared. That's surprising. But these frequencies are exactly equal to ω_o–N and $2\omega_o$-N, so a good possibility is that the N signal severely modulates the orbital signal, producing artificial flanking peaks at ±N. The effects described below in §5 support this. Only the +N sidebands – the negative superhumps – survive the subtraction.

The waveforms of all four signals (N, ω_o, ω_o+N, $2\omega_o$+N) are impressively sinusoidal, and probably indicate that none of these signals rely on the deep eclipse for their existence. UX UMa would probably show these effects at any binary inclination, although the amplitude may well depend on inclination.

5. DEPARTURES FROM STRICT COHERENCE

5.1 Periodic Effects in the Mid-Eclipse O-C

As we examined the many eclipses, we noticed some which were distinctly asymmetric, confounding the effort to derive a precise timing of mid-eclipse. We adopted one particularly good eclipse timing and the well-known binary period of 0.19667128 d, and calculated the scatter (the O-C, in variable-star lingo) of the other 170 timings. Departures from the mean ranged up to ~80 s, but seemed to be systematic with time. So we calculated the power spectrum of the O-C residuals, and found the result seen in the upper frame of Figure 7.

A significant peak is present at 0.2705(20) c/d, or 3.70(3) d. This is consistent with the period found in the photometry. Apparently the center of light, or at least the center of eclipsed light, wanders back and forth on this period. And since the eclipsed light of UX UMa is dominated by the accretion disk, we conclude that the disk's photometric center moves about with this period. (Presumably the true orbital period, set by the laws of dynamics, can be relied on to stay immoveable during this 5-month campaign.) A fold of the residiuals on the 3.70 d period yields the result seen in the lower frame of Figure 7: a possibly asymmetric wiggle with a semi-amplitude of 23±4 s.

5.2 The 3.7 Day Clock

We also estimated the timings of maximum light in the 3.7 day cycle, and present these timings in Table 3. Figure 8 shows an O-C diagram of these timings with respect to the mean period, and the curvature indicates some period change during the 150 days spanned. It appears that the period changes smoothly from 3.75(2) to 3.66(2) d over a baseline of ~100 d.

5.3 The 0.18681 Day (Negative Superhump) Clock

We tried to time individual maxima in the negative-superhump cycle by picking out local maxima after removing the 3.7 day and orbital signals. Table 4 shows the resultant timings, and the upper frame of Figure 9 shows an O-C diagram of these timings with respect to the mean period of 0.18681 d. The downward curvature of the O-C mirrors that of Figure 8, verifying that the observed superhump frequency changes in lockstep with the observed precession frequency. The relation $\omega = \omega_o + N$ remains valid in the short term, not just for the whole season.

The departures from a smooth curve are quite large – up to 45 minutes, whereas we estimate a typical measurement error of 10-15 minutes. But the dispersion in timings on individual nights is much smaller, so we suspected that some other effect contributes to that variance. The lower frame of Figure 9 shows a power spectrum of the residuals, and the peak at 0.273(2) c/d indicates that the precession term is responsible for this effect, even though its direct photometric signature – the 3.7 day signal – has been accurately subtracted.

6. DISCUSSION

Most cataclysmic variables show a periodic signal at P_{orb}, either from an eclipse – pretty obvious! – or from some other effect of high or moderate inclination, e.g. the periodic obscuration of the mass-transfer "hot spot" as it wheels around the disk. Many (~100) also show a photometric period a few percent longer than P_{orb} (*postitive superhumps*). Most of the latter are short-period dwarf novae, which sprout these signals for 1-4 weeks, during their long outbursts ("supermaxima"). This is now understood as arising from the apsidal precession of the accretion disk, rendered eccentric at the 3:1 resonance in the disk. A few stars which are not dwarf novae also show this effect, but these are all short-period (<3.5 hr) novalike variables, which in many ways can be seen as permanently erupting dwarf novae. These signals are known as "permanent" superhumps (Patterson & Richman 1991).

Only a disk large enough to reach the 3:1 resonance can suffer this instability (Whitehurst & King 1991, Lubow 1991), and that is presumably the reason that positive superhumps are only found in short-period stars. But some stars show photometric signals with $P<P_{orb}$ – the *negative* superhumpers. Much less is known about them. The early papers on these phenomena (Bonnet-Bidaud et al. 1985, Patterson et al. 1993, Harvey et al. 1995) postulated the existence of a *tilted* accretion disk, which is forced to precess slowly backwards (relative to the orbit) by the torque from the secondary. The angular relation between the secondary (including its structures, viz. the mass-transfer stream) and the disk then repeats with a period slightly less than P_{orb}. This is a negative superhump. Roughly 20 CVs show negative superhumps (see Table 2 of Montgomery 2009), and roughly half of these (see Table 5 of Armstrong et al. 2013) *also* show a photometric signal at the postulated precession period. The latter is a strong point in support of the theory, since a wobbling disk should present an effective area which varies with the wobble period.

Our data demonstrate that UX UMa joins this club. We hypothesize that its accretion disk wobbles about the orbital plane with a period of 3.70 d, and we see its effective area varying on that period. But the orbiting secondary – not in the inertial frame! – sees the disk with a slightly shorter recurrence period, such that $1/P = 1/P_{orb} + 1/(3.70\ d) = 5.435$ c/d. The effect is identical to the famous tropical/sidereal year effect in the Earth-Sun system, or the draconic/sidereal month effect in the Earth-Moon system. Montgomery (2009) discusses this analogy in great, and fascinating, detail.

The cause and maintenance of disk tilt is not known. No actual short-period dwarf novae show negative superhumps, although their closest cousins – novalike variables with P_{orb}<3.5 hours – frequently do (Patterson et al. 1993, Armstrong et al. 2013). It's possible that the 3:1 resonance is again involved, but with the tilt instability growing so slowly that only a "permanent" dwarf nova, which is in a high-viscosity state for a long time, can develop sufficient tilt.

UX UMa is not a typical member of this club. Most members belong to the "SW Sex" subclass, which have shorter P_{orb} (3-4 hours), occasional excursions to very low states, and only the $\omega_o + N$ feature (lacking $2\omega_o + N$). They also commonly show radial-velocity signals of high amplitude, presumably indicative of the mass-transfer stream overflowing the disk (because of the tilt). Maybe CV zoology needs to be adjusted somewhat, in order to fit these oddities.

Finally, why did we find all these new effects in a star which has been closely studied for 60 years? Did they first arise in 2015? It seems unlikely; the mean brightness and eclipse depths were not exceptional this year. We selected the star for observation partly because previously published light curves showed variations in the orbital waveform – suggesting that a signal at some nearby frequency might be present. But to actually reveal these effects, an extensive campaign is required, and no such campaign has ever been reported. So it's a decent bet, though by no means sure, that these superhump effects have been lurking, unsuspected, in many previous observations of UX UMa.

7. SUMMARY

1. We report a long photometric campaign during 2015, with coverage on 118 of 150 nights, totalling ~1300 hours. The star displayed a 0.3 magnitude sinusoidal signal with a mean period of 3.70(2) days, or a frequency 0.270(2) c/day. We identify the latter as N, the accretion disk's (putative) frequency of retrograde nodal precession. Figure 7 shows that the period varied smoothly from 3.75(2) to 3.66(2) d during the campaign.

2. Figure 1 shows that the orbital waveform is highly variable from day to day, but not from orbit to orbit. Power-spectrum analysis shows that this arises from signals noncommensurate with P_{orb}, namely "negative superhumps" with $\omega = \omega_o + N$ and $2\omega_o + N$.

3. The 3.70 d period is strongly manifest in essentially every quantity we studied. The eclipse times wobble on this period with an amplitude of 23+-3 s, probably because the disk's (projected) center of light moves with that period. The superhump times also wobble with that period, as do the eclipse depths (in magnitude units).

4. Figure 7 shows that the precession period changed slightly during the campaign: from 3.75(2) to 3.66(2) d over the ~100 days. As it did, the superhump frequency changed accordingly, maintaining $\omega = \omega_o + N$.

5. About a dozen other CVs show this basic triad of frequencies (ω_o, N, and ω_o+N). Most are so-called “SW Sex” stars. Because the physics which underlies this category is probably the wobbling non-coplanar disk, it is likely that the credentialing scheme of that club (Thorstensen et al. 1991, Rodriguez-Gil et al. 2007) will have to change, in order to accommodate UX UMa. We note that Neustroev et al. (2011) has also, based on spectroscopic evidence, proposed that UX UMa has transient episodes of SW Sex behavior.

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FIGURE CAPTIONS

Figure 1. Representative light curves on two nights in the 2015 campaign.

Figure 2. *Upper frame*: a 23-night light curve, showing eclipses, possibly "orbital" humps, and a candidate 3.7 day variation (also apparent in the eclipse depths). *Lower frame*: the central 98 days of the campaign, with eclipses removed. The 3.7 day variation seems to endure throughout.

Figure 3. Mean orbital light curve over the ~100-night time series.

Figure 4. Power spectrum of the central 51-night portion of our light curve. The most significant peaks are labeled with their frequencies (+-0.001) in cycles/day, and one-day alias peaks are designated "A". The strongest signal by far, at 0.268 c/d, rises off-scale to a power of 1900. There are also unlabeled strong peaks at 4.814 and 9.899 c/d, which coincide exactly with ω_o-N and $2\omega_o$-N. These probably arise from modulation of the orbital signal by N, and they disappear in Figure 6 below.

Figure 5. Mean light curve on the 3.7 day period.

Figure 6. *Upper frame*: power spectrum of the light curve, after the strong orbital and "precession" (3.7 day) signals are subtracted. The two obvious peaks occur at ω_o+N and $2\omega_o$+N – "negative superhumps". *Lower frame*: mean

light curves at the two superhump frequencies.

Figure 7. *Upper frame*: power spectrum of the departures of eclipse timngs from the ephemeris mid-eclipse = HJD 2,457,102.70075 + 0.19667128 E. A significant peak occurs at 0.2705(20) c/d, the same frequency as the large variations in light seen in Figure 2. *Lower frame*: fold of these residuals on the 3.72 day period, showing a periodic effect with a semi-amplitude of 23±3 s..

Figure 8. O-C diagram of the timings of maximum light (Table 3) on the 3.7 d cycle. The curvature shows that the period changed slightly over the season, from 3.75(2) in early season to 3.66(2) d in late-season.

Figure 9. *Upper frame*: O-C diagram of the 0.18681 d superhump maxima, with respect to the test ephemeris HJD 2,457,102.795 + 0.18681 E. *Lower frame*: power spectrum of the residuals about the quadratic fit, showing a periodic effect at the 3.7 d period.

TABLE 1 – LOG OF OBSERVATIONS

Observer	CBA Station	Nights/hours
Ulowetz	Illinois 0.24 m	53/214
Cejudo	Madrid 0.25 m	29/144
Jones	Oregon 0.35 m	14/119
Koff	Colorado 0.25 m	14/94
Barrett	Le Marouzeau (France) 0.2 m	19/90
Boardman	Wisconsin 0.3 m	17/86
de Miguel	Huelva (Spain) 0.35 m	13/80
Menzies	Massachusetts 0.35 m	9/60
Slauson	Iowa 0.24 m	15/59
Vanmunster	Belgium 0.35 m	12/58
Goff	Sutter Creek (Calif.) 0.5 m	9/48
Dvorak	Rolling Hills (Orlando) 0.25 m	8/38
Stein	Las Cruces 0.35 m	9/45
Campbell/ Roberts	Arkansas 0.4 m	7/45
Costello	Fresno 0.35 m	6/42
Morelle	France 0.3 m	4/26

Hambsch	Belgium 0.28 m	7/29
Lemay	Quebec 0.25 m	4/18
Collins	North Carolina 0.35 m	9/25
Cook	Newcastle (Ontario) 0.3 m	4/20
Richmond	Rochester (New York) 0.25 m	2/7
Ogmen	Cyprus 0.3 m	2/10

TABLE 2 – TIMINGS OF MID-ECLIPSE (HJD 2,457,000+)

102.70075	102.8971	103.6836	103.8801	104.4701
105.8459	106.8305	107.4204	107.6179	108.4307
108.6099	108.7970	108.9949	109.3870	109.5842
109.7803	109.9781	110.3708	110.5671	110.7640
111.7467	111.9436	112.5432	112.7302	112.9278
113.7145	114.5012	114.6974	114.8943	115.4829
116.6630	116.8611	117.8443	118.4344	118.6303
119,4172	119.6142	119.8108	120.5981	121.3847
121.5817	121.7781	122.7600	122.9571	123.7434
124.3342	124.5312	124.7278	125.3185	125.5147
125.7116	126.4978	126.6943	126.8922	127.4811
127.6764	128.4643	128.6617	128.8573	129.6444
129.8404	130.4309	130.6277	130.8241	131.0214
131.4149	131.8076	132.0052	132.3983	132.5946
132.7915	132.9885	133.3813	133,5772	133.7739
134.3641	134.5611	134.7574	135.5451	135.7411
135.9377	136.5280	136.7251	138.4936	138.6909
138.8884	139.6747	139.8719	140.6585	140.8540
141.4445	141.6413	141.8380	142.4279	142.6249
142.8218	143.4121	143.6080	143.8051	144.0017
144.3947	144.7882	145.7714	145.9679	146.7549
147.7390	148.5250	149.5085	149.7050	150.4918
150.6879	151.4757	151.6720	152.4581	152.8513
153.4415	153.6374	153.8346	154.4249	154.6215

155.4088	155.6055	155.8010	156.5880	156.7848
157.5718	158.5553	159.5388	160.5210	162.4895
163.4718	164.4553	165.4387	166.4209	166.6188
166.8150	167.4054	168.3883	168.5851	169.5698
170.5523	170.7487	172.5195	173.5024	175,4693
176.6493	177,4358	177.6322	183.7289	184.7126
190.4155	191.3998	192.5790	193.5624	194.5466
195.7268	196.5124	197.6938	198.4795	199.4624
201.6262	201.8225	202.4128	203.7890	206.5436
208.5087	209.4945	209.6898		

TABLE 3 – MAXIMUM LIGHT ON THE 3.7 DAY CYCLE
(HJD 2, 457,000+)

81.60	85.50	104.25	107.51	111.43
115.31	119.08	122.91	126.62	130.17
134.07	137.80	141.28	145.09	148.75
152.29	156.18	159.64	163.18	166.94
170.60	174.25	177.96	192.48	196.18
199.97	207.08	210.90	225.45	

TABLE 4 – MAXIMUM LIGHT ON THE 0.18681 DAY CYCLE
(HJD 2,457,000+)

102.795	102.962	103.893	104.490	107.450
107.654	108.573	108.766	108.942	109.667
109.871	110.441	110.610	110.814	111.736*
112.484	112.671	112.866	113.796	114.365*
114.726	115.503	115.670	116.807	117.726*
117.918	118.473	118.651	119.414*	119.611*
119.799	120.333	120.535	121.464	122.423
122.784	122.977	123.695	124.462	124.643
124.830	126.356	126.724	126.918	127.424
127.796	128.744	128.930	129.696	129.887
130.663	130.809	130.988	131.352	131.724
131.923	132.675	132.869	133.426	133.723

133.990 134.528 134.708 135.473 135.662
135.846 136.416 136.589 136.786 138.823
139.768 140.726 140.911 141.475 141.660
141.847 142.371 142.767 142.950 143.523
143.712 143.882 144.272 144.828 145.726
145.911 146.685 147.613 148.366 148.545
149.449 149.638 149.828 150.598* 151.528
152.480 152.849 153.548 153.750 154.509
155.472 155.660 155.840 156.610* 157.487
158.439 158.640 159.409 159.594 162.568
162.751 163.507 164.397 164.580 164.763
165.515 166.477 166.667 168.479 168.676
169.445 170.396 170.590 170.774 172.433
172.798 173.557 174.521 176.538 176.722
177.501 177.680 182.673* 183.615* 190.512
193.668 194.451 197.626 198.555 199.517
201.726* 202.496 203.821 208.426 222.427
222.801

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*Lower weight.