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. Approximately 1000 hours of coverage were obtained on 103 (over a span of 132) 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 ±22 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 2ω_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, Linnell 1949), 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 a. 1995). 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, Smak 19xx). After these corrections, the angle-averaged $\langle M_V \rangle$ 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 2 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 *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 ranged from 30 to 80 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 narrow frequencies (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 191 separate time series on 111 nights, distributed over a span of 132 nights. The total coverage was 1088 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 appear quite similar to essentially all light curves in the literature (e.g. Warner & Nather 1971, Walker & Herbig 1954): flickering, regular eclipses, plus a roughly "orbital" hump, although the latter varies markedly 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 lower-frequency feature.

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. With no attempt to remove these effects, and simply averaging over the ~1000 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 labelled with their frequencies in cycles/day..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 N.

To study the latter, we removed the sinusoids corresponding to N and wo, and recalculated the power spectrum of that 51-day time series. The results are shown in Figure 5, 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. Figure 5 also shows the mean light curve at these two frequencies. They are both rather pure sinusoids. These upper precessional sidebands of the orbital frequency are known as *negative superhumps* in astronomical nomenclature, because in period (rather than frequency) language, their period excesses over P_{orb}, 0.5 P_{orb}, etc. are *negative*.

The purely sinusoidal waveforms of all four signals (N, ω_o, ω_o+N, $2\omega_o$+N) are impressive, and probably indicate that none of these signals are affected by the eclipse itself. UX UMa would probably show these effects at any binary inclination.

5. 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 astronomical 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 6.

A significant peak is present at 0.2705(20) c/d, or 3.70+-0.03 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 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 4-month campaign.) A fold of the residiuals on the 3.72 d period yields the result seen in the lower frame of Figure 6: a possibly asymmetric wiggle with a semi-amplitude of 23+-4 s.

6 et seq. INTERPRETATION AND DISCUSSION

N signal. About 12 CV s show this effect – table in Armstrong et al. At least 4 XRBs show it too, most famously HZ Her/Her X-1 and SS 433/V1343 Aql. In those cases there's strong evidence that the effect comes from a (retrograde) wobbling accretion disk. Strong partly because the effect is actually spatially ***resolved***. For CVs it's not so strong, but suppoted by...

wo+N and 2wo+N.... “negative superhump”... history of such things... about 25 CVs show it - basically all high-Mdot stars. Theories of how the disks might be driven out of the plane.

Can't be “rigid-body” planes, but somehow manages to act like one. Is this related to the spiral waves??

Has this term (3.7 d) always been there? Yes, very possibly. We got interested in UX U Ma because previously published light curves showed slow waves which did not repeat regularly from night to night. Sounded “superhumpy” to us, so we decided to look.

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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, likely orbital humps, and a possible 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 labelled with their frequencies (+-0.001) in cycles/day, and alias peaks are designated “A”. The strongest signal by far, at 0.268 c/d, rises off-scale to a power of 1900.

Figure 5. *Upper frame*: power spectrum of the light curve, after the strong orbital and precessional effects are subtracted. The two obvious signals occur at ω_o+N and 2ω_o+N – “negative superhumps”. *Lower frame*: mean light curves at the two superhump frequencies.

Figure 6. *Upper frame*: the power spectrum of the departures of the eclipse timngs from the ephemeris mid-eclipse = HJD 2,457,102.70075 + 3.72 E. A significant peak occurs at 0.2705(20) c/d, the same frequency as the large variations in light seen in Figures 2 and 4. *Lower frame*: fold of these residuals about the 3.72 period, showing a periodic effect with a semi-amplitude of 22±3 s..

TABLE 1 – LOG OF OBSERVATIONS

Observer	CBA Station	Nights/hours
Starkey	Indiana 0.4 m	23/101
Barrett	La Marouzeau (France) 0.2 m	19/90
Menzies	Massachusetts 0.35 m	9/60
Campbell	Arkansas 0.4 m	7/45
de Miguel	Huelva (Spain) 0.35 m	13/80
Jones	Oregon 0.4 m	12/99
Ulowetz	Illinois 0.25 m	34/166
Koff	Colorado 0.35 m	6/40
Vanmunster	Belgium 0.35 m	12/58
Dvorak	Rolling Hills (Orlando) 0.25 m	8/38
Stein	Las Cruces 0.35 m	9/45
Morelle	France	4/26
Ogmen	Cyprus	2/10
Cejudo	Spain	29/144
Hambsch	Belgium 0.28 m	7/29
Goff	Sutter Creek (California) 0.3 m	9/48
Boardman	Wisconsin 0.35 m	6/35
Lemay		4/18
Collins		4/16
Cook	Newcastle (Ontario)	4/20
Richmond	Rochester (New York)	

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
116.6631	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		

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