An intensive CCD photometry campaign to observe DW Ursa Majoris

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Abstract

We report on a coordinated observing campaign in April and May 2008 to study the eclipsing dwarf nova DW Ursa Majoris. This belongs to the group of SW Sex stars, novalike variables containing accretion disks which exhibit superhumps in their light curves suggesting that their accretion disks are elliptical and precessing on time scales of a few days due to tidal interactions with the companion star. It has been suggested that the changing geometry will cause the depth of eclipses to be modulated on the accretion disk precession period. The aim of this campaign was to provide for the first time sufficient continuous photometric coverage of an eclipsing superhumper to test this hypothesis. 26 experienced amateur CCD photometrists in 7 countries participated in the project and altogether made almost 55,000 magnitude measurements over a 4 week period, keeping DW UMa under observation for more than 50% of the time. The results provide direct measurements of the orbital, superhump and disk precession periods, confirming unambiguously that the superhump signal is a beat between the orbital and precession periods. They also reveal modulation not only of the eclipse depth but also of the eclipse time of minimum and width on the accretion disk precession period. The project is a good example of cooperation between the amateur and professional communities to address an open research issue.

1. SW Sex stars

These are an unofficial class of cataclysmic variables (CVs), not in the GCVS, which was first proposed by Thorstensen et al. (1991) with the comment "…these objects show *mysterious* behaviour which is however highly *consistent* and *reproducible*.". The four original SW Sex stars were PX And, DW UMa, SW Sex, V1315 Aql. The class now includes around 50 members of which about half are definite members and the others either probable or possible based on observed characteristics. Hoard (2009) maintains an on-line list of SW Sex stars.

2. Observed characteristics of SW Sex stars

These are novalike variables with bright accretion disks showing occasional VY Scl-type low states and no observed nova or dwarf nova outbursts. There are circumstantial similarities between SW Sex stars and VY Scl stars. SW Sex stars are often eclipsing systems with V-shaped eclipses and periods mostly in the range 3-4 hours. They may exhibit positive and/or negative superhumps. Spectroscopically they show single-peaked Balmer, HeI and HeII emission lines which may not be fully eclipsed, not double peaked lines as expected in bright edge-on CVs. Superimposed on the emission lines is a transient narrow absorption feature around phase 0.5. Phase offsets are observed between the radial velocity and eclipse ephemerides. There is much variation in detail between individual systems.

3. Possible physical interpretation

Predominantly (~50%) but not exclusively these are high inclination systems. It is possible a selection effect is at work here so our interpretation of these objects may be influenced by their inclination. They are likely to have a high sustained mass transfer rate which keeps the accretion disk full and bright, but sometimes the accretion process turns off altogether causing the low states. They are thought to have an eccentric accretion disk which may be flared at the edge and/or tilted. The accretion stream is possibly punching through the edge of the disk and flowing over the disk creating a bright spot where it impacts the disk, but this bright spot is weaker than that observed in most dwarf novae. The single-peaked emission may be due to the relative dominance of a single bright spot on the disk. The absorption feature superimposed on the emission lines is possibly caused by light from the back of the disk passing through the accretion stream or bulges on the front disk edge. There may also be a strong accretion disk wind from the inner region of the disk. Current models have difficulty explaining all the observed properties.

There is also a suggestion that some SW Sex stars may be intermediate polars in which the white dwarf has a weak magnetic field. An example is LS Peg as reported by Rodrıguez-Gil et al. (2001). This would result in a truncated inner disk with the accretion stream flowing onto the magnetic poles of the white dwarf. One consequence of this should be circular polarisation and/or rapid coherent modulation in X-ray and UV light curves. There is evidence of these in some SW Sex stars.

The bottom line is that we really don't know what mechanisms operate in SW Sex stars, particularly in relation to the accretion disk, and how they relate to other CVs with similar periods. But as they constitute about 50% of CVs with periods in the range 3-4 hrs they are important and need further study.

4. Understanding more about accretion disks in SW Sex stars

In eclipsing SW Sex stars the eclipses should be a good diagnostic tool for probing the accretion disk. Stanishev et al. (2002) suggested a correlation between the depth of eclipses and the precession phase of the accretion disk in the SW Sex star PX And, but their coverage was insufficient to be able to say anything definite. Stanishev et al. (2004) noted a variation in depth of eclipses in DW UMa but they also had insufficient data to be able to analyse the variation.

DW UMa is an eclipsing SW Sex variable with a mean V magnitude outside eclipse of 14.5, an orbital period of 3 hr 17 min and an accretion disk precession period of about 2 days To gain sufficient data to be able to verify a correlation between the depth of eclipses and the accretion disk precession phase would ideally require continuous observation of DW UMa for several days. This is something which professional astronomers would find difficult to achieve with time-limited access to a telescope at a fixed longitude.

5. A pro-am collaboration project

We saw a good opportunity for pro-am collaboration by involving the global amateur community in trying to address this challenging observational goal. At the joint BAA/AAVSO meeting at Cambridge University in the UK in April 2008, we proposed a project which sought to engage amateur observers distributed around the world with the aim of keeping DW UMa under as near as possible continuous photometric observation for one month. Guidelines for observing including recommended comparison stars, exposure times, S/N goals, and filters were circulated to the amateur community via a Google group through which observers could also submit their data and receive feedback on progress with the project.

During the next 4 weeks, 26 observers in 7 countries around the world observed DW UMa whenever their skies were clear. Together they made 155 observing runs, observing DW UMa for a total of 27.7 days. They submitted almost 55,000 images of DW UMa, each of which provided a magnitude measurement and estimated error. Most observers ran unfiltered but some V and R filtered data was taken. 109 of the 219 eclipses during this period were observed, some by as many as 8 observers. DW UMa was being observed somewhere in the world for a total of 15.4 days during the 30-day period, more than 50% of the time. Regular feedback via the Google group was an important factor in the success of the project by keeping people motivated.

The contributing observers are listed in Table 1.

Observer	Country	Equipment used	Total observation time (hr)
Amigo	Spain	0.25-m f/6.3 SCT + ST-7XME CCD	2.6
Arranz	Spain	0.35-m f/5 SCT + MX716 CCD	8.2
Boyd	UK	0.35-m f/5.3 SCT + SXV-H9 CCD	18.3
Brady	USA	0.4-m reflector + ST-8XME CCD	84.1
Castellano	Spain	0.2-m f/3.3 SCT + ST-7 CCD	3.2
dePonthiere	Belgium	0.2-m f/6.3 SCT + ST-7XMEI CCD	50.8
Dubovsky	Slovakia	VNT 1000/9000 f/3.3 + ST9-XE CCD Hugo 265/1360mm + DSI Pro CCD	59.6
Fernandez	Spain	0.4-m SCT + ST8 CCD	1.5
Gomez	Spain	0.2-m f/10 SCT + ST-8XME CCD	1.7
Krajci	USA	0.28-m SCT + ST-7 CCD	74.7
Miller	UK	0.35-m SCT + SXVF-H16 CCD	50.8

Nakajima	Japan	0.25-m f/5 SCT + Mutoh CV-04 CCD	35.9
Naves	Spain	0.3-m SCT + ST8-XME CCD	8.3
Oksanen	Finland	0.4-m RCT + STL-1001E CCD	37.9
Pickard	UK	0.3-m SCT + SXV-H9 CCD	13.8
Pinilla	Spain	0.25-m f/4 SCT + ST7XME CCD	4.6
Reina	Spain	0.25-m f/3.3 SCT + ST-7 CCD	1.5
Rodriguez	Spain	0.2-m f/7 SCT + ST-9 CCD	2.7
Sanchez	Spain	0.35-m f/10 SCT + ST-9 CCD	5.8
Shears	UK	0.28-m SCT + SXV-H9 CCD	9.7
Staels	Belgium	0.28-m f/6.3 SCT + MX-716 CCD	72.1
Stein	USA	0.35-m f/7 SCT + ST10XME CCD	45.4
Vandenabbeel	Belgium	0.2-m f/5.7 SCT + ST7-XME CCD	1.2
Vanmunster	Belgium	0.35-m f/6.3 SCT + ST-7XME CCD	47.2
Virtanen	Finland	0.2-m SCT + ST-7XME CCD	12.0
Yoshimura	Japan	1-m RCT	11.3

Table 1. Contributing observers.

6. Aligning light curves

The first step in the analysis was to align the individual observers' light curve segments. This was achieved by a careful iterative process of comparing the out-of-eclipse portions of light curves obtained at the same time by different observers and applying a constant magnitude adjustment for each observer to bring the overlapping regions of all light curve segments into mutual alignment. Most observers used the same comparison stars throughout and we found the same adjustment factor could be applied for all their runs, but if they changed comparison stars different adjustments were needed. With care, mutual light curve alignment could be achieved to better than 0.02 mag. This alignment was crucial to the subsequent analysis as we were investigating persistent modulation in the out-of-eclipse light curve of the order of 0.1 mag. The resulting integrated 30 day light curve is shown in Figure 1. This shows that DW UMa exhibits continuous flickering with an amplitude of around 0.2 mag. We think it unlikely that such dense coverage of a variable star has been achieved before.

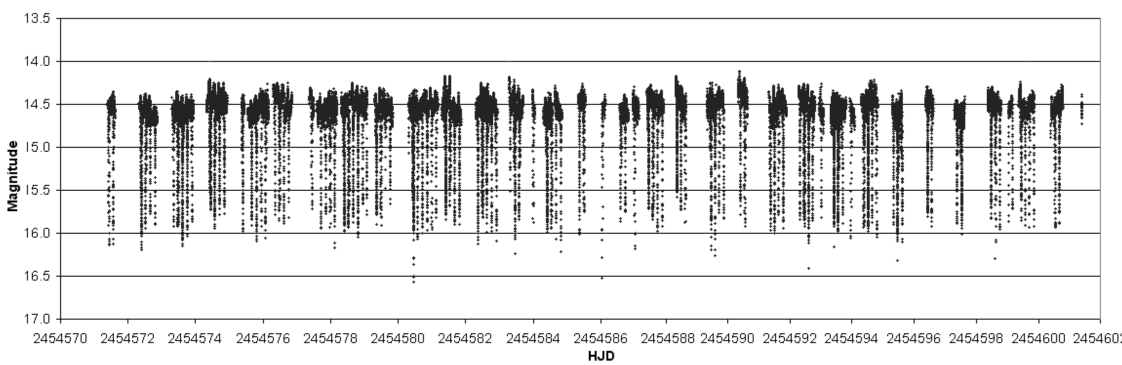

Figure 1. Combined 30 day light curve for DW UMa.

We checked the internal consistency of this light curve alignment procedure for 6 observers who submitted unfiltered measurements of the four comparison stars. Knowing V magnitudes and B-V colours of the comparison stars, a linear colour-dependent transformation was computed for each observer to bring the response of their equipment approximately onto the standard V magnitude scale. Knowing the colour of DW UMa, this transformation was then used to find the adjustment needed to bring their unfiltered measurements of DW UMa approximately onto the V magnitude scale. We found the relative adjustments derived from this analysis for all 6 observers were consistent to a std dev of 0.017 mag with the magnitude adjustments made to align the light curves of the same observers.

7. Light curve period analysis

We first determined the main signals in the light curve by removing the eclipses and carrying out a Lomb-Scargle period analysis on the remainder of the light curve. The resulting power spectrum is shown in Figure 2.

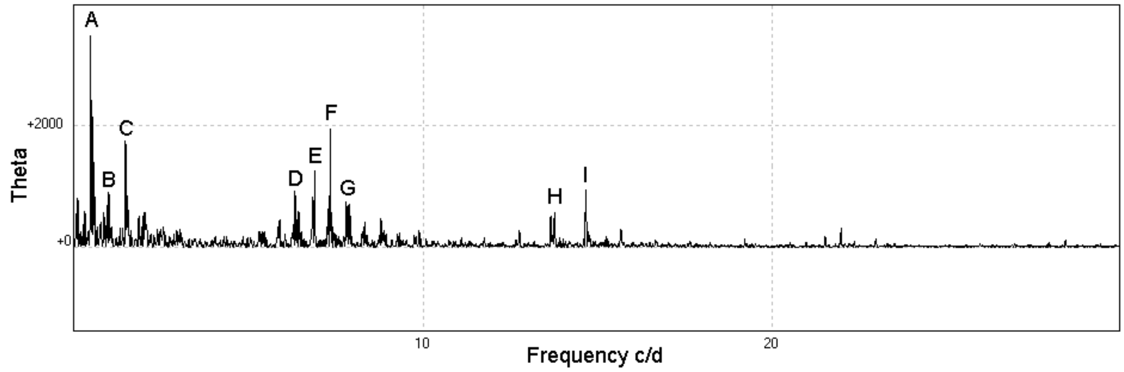

Figure 2. Power spectrum from Lomb-Scargle analysis of the combined light curve after removing eclipses.

Signal A is the accretion disk precession period P_{prec} = 2.22(2) days, signal F is the orbital period P_{orb} = 0.1366(1) days and signal E is the superhump period P_{sh} = 0.1455(2) days. This confirms that the superhump period is the beat between the orbital and precession periods with the relationship

$$1/P_{sh} = 1/P_{orb} - 1/P_{prec}$$

This superhump period is consistent with the positive or apsidal superhumps seen by Patterson et al. (2002) and Stanishev et al. (2004). However we see no sign of the negative or nodal superhumps found by Patterson during 1996.

8. Measurement of the eclipse ephemeris

Times of minimum and estimated errors were found for all well-recorded eclipses from a 2^{nd} order polynomial fit to the lower half of each eclipse. This gave 209 eclipse timings for 109 distinct eclipses. Timings for the same eclipse were averaged. Orbit numbers were assigned to each eclipse and a weighted linear ephemeris computed as

$$\text{HJD (minimum)} = 2454564.46465(4) + 0.1366062(3) * E \qquad (1)$$

No convincing evidence was found for a quadratic ephemeris. The orbital period of 0.1366062(3) days from this eclipse analysis is consistent with the value of 0.1366(1) days from period analysis. An O-C plot with respect to this linear ephemeris is shown in Figure 3. The rms scatter in O-C is 22.9 sec. This looks linear as expected for a constant orbital period, but it isn't quite as we shall see.

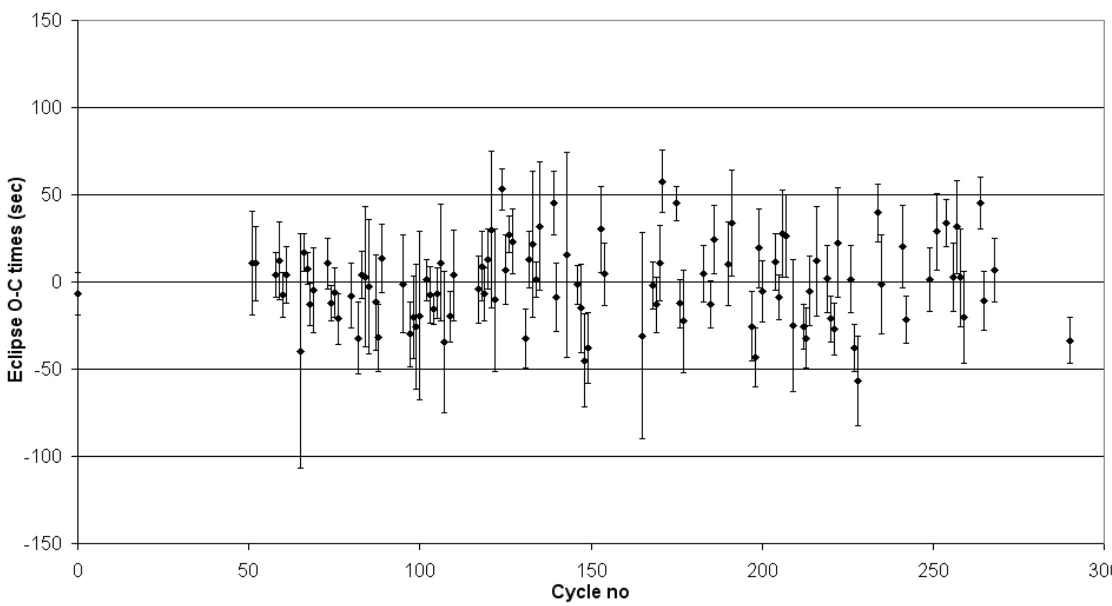

Figure 3. O-C times for 109 eclipses relative to the ephemeris in eqn (1).

9. Previous eclipse timings

We also researched previously published eclipse timings for DW UMa and found 146 measurements made between 1983 and the start of this project. Most of these did not specify a measurement error so we calculated the following unweighted eclipse ephemeris

HJD (minimum) = 2446229.0068(1) + 0.136606531(3) * E

The orbital period of 0.1366062(3) days measured during the project is consistent with its mean value over the last 25 years.

10. Superhump period excess and mass ratio

Our measured values of the orbital and superhump periods give a superhump period excess $\varepsilon = 0.065(1)$ in agreement with the value $\varepsilon = 0.064(2)$ in Patterson et al. (2005). Using Patterson's empirical relationship $\varepsilon = 0.18q + 0.29q^2$, this gives a mass ratio $q = 0.256(3)$ which is at the lower end of the range $q = 0.39(12)$ proposed by Araujo-Betancor et al. (2003).

11. Variation of brightness with the disk precession phase

To investigate this further we applied sine fits to the out-of-eclipse light curve for a range of assumed precession periods and looked at the residuals as a function of precession period. We found the best fit occurred at a precession period of 2.231 days, confirming and refining the result from period analysis. Figure 4 shows the combined light curve folded on a precession period of 2.231 days together with the best fit sine curve. The full amplitude of variation over the precession phase is 0.12 mag. Removing the precession signal and folding on the superhump period of 0.1455 days reveals the superhump phase shown in Figure 5 with an amplitude of 0.1 mag.

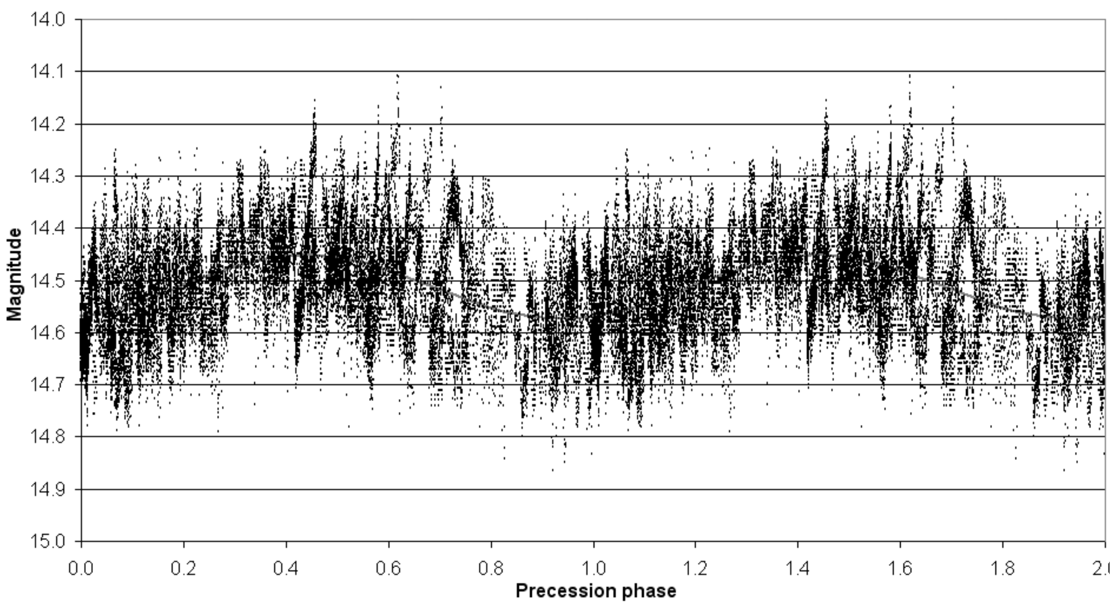

Figure 4. Combined light curve folded on a precession period of 2.231 days.

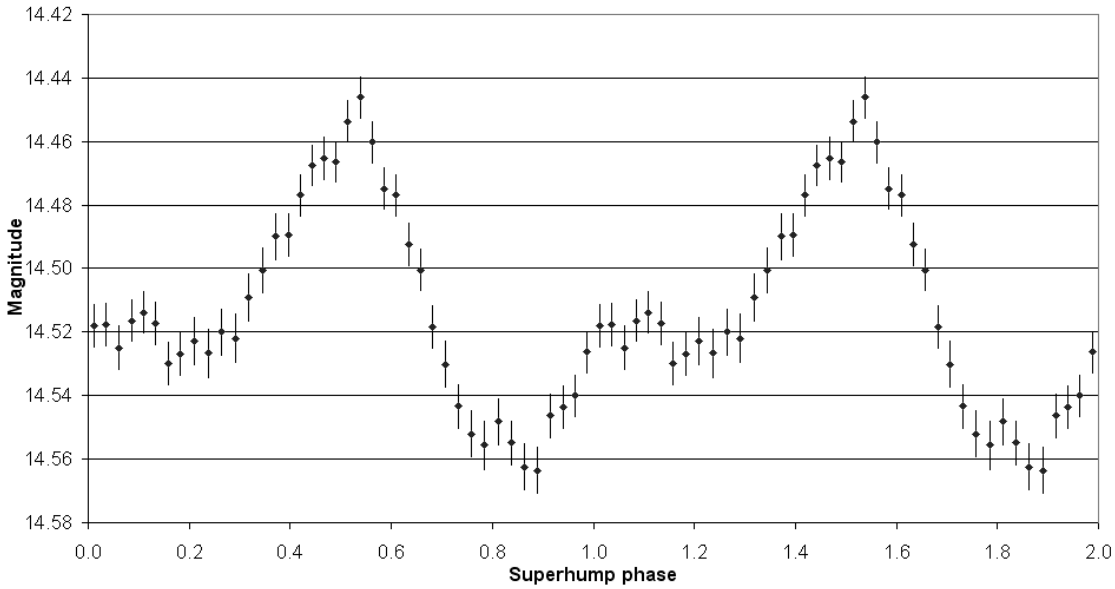

Figure 5. Superhump signal folded on a period of 0.1455 days.

12. Variation of the eclipse time with the disk precession phase

This had not been predicted but we thought it worth investigating. To do this we applied sine fits for a range of periods to the eclipse O-C times derived from the linear ephemeris in eqn (1) and examined the residuals. The best sine fit occurred at a period of 2.231 days, exactly the same as the disk precession period. This offers convincing evidence that the eclipse time of minimum is also correlated with the disk precession phase. Figure 6 shows the eclipse O-C times plotted against precession phase for a precession period of 2.231 days along with the best sine fit. The amplitude of variation is ±13.5 sec about the orbital period of 3h 17m. Binning the data and calculating means and standard errors yields a chi-sq probability for a sine fit of 0.10 whereas for a linear fit it is $\sim 10^{-10}$.

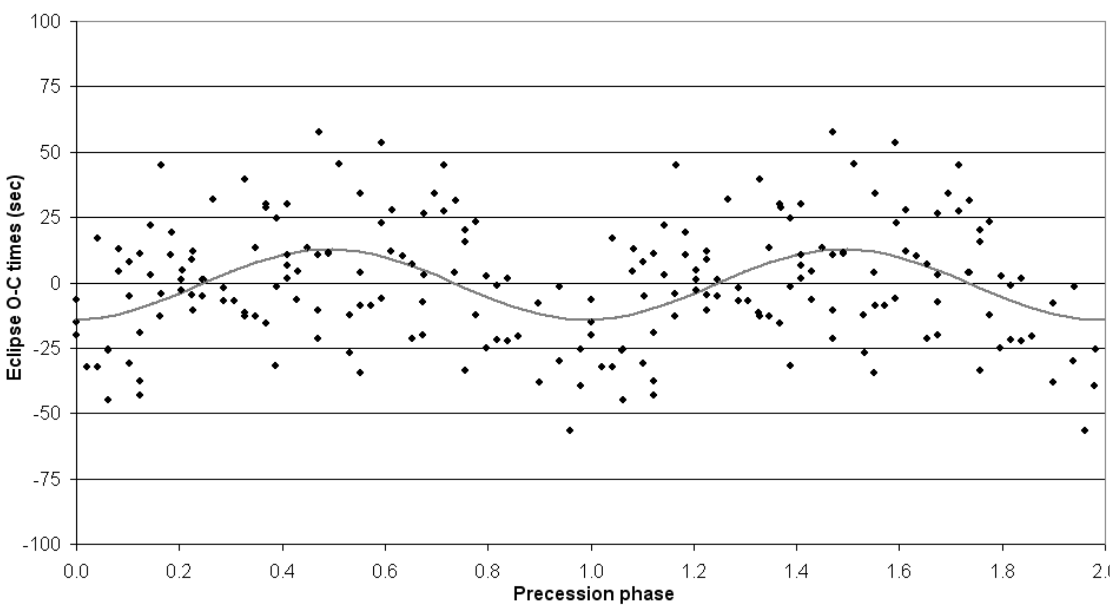

Figure 6. Variation of eclipse O-C times with accretion disk precession phase assuming a precession period of 2.231 days.

13. Variation of the eclipse depth with the disk precession phase

To investigate the suggestion that eclipse depth varies with the disk precession phase, we first had to extract eclipse depth information from the light curve. Figure 7 shows our method of doing this for a typical eclipse.

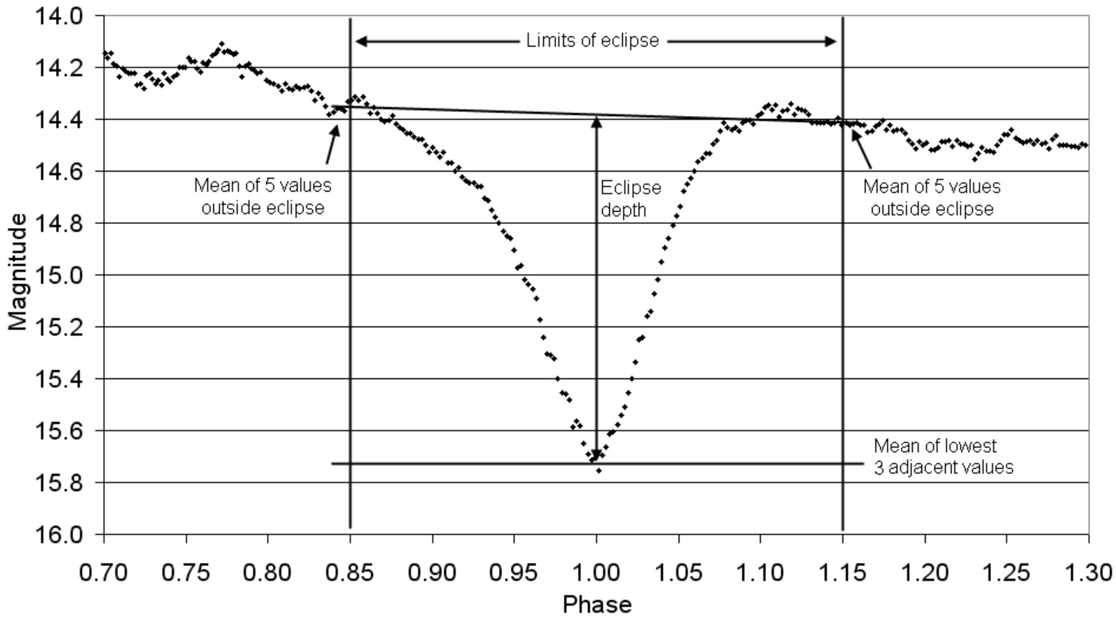

Figure 7. Method of measuring eclipse depth.

Eclipses measured with different filters had different mean depths.

Filter band	Mean eclipse depth (mag)	No of eclipses measured
V	1.43(13)	32
Unfiltered	1.33(09)	172
R	1.21(14)	5

These results are consistent with unfiltered CCD cameras having a mean response between V and R. Eclipses reduce the light intensity by 73% in the V band and 67% in R, implying the eclipsed source is bluer than the average colour outside eclipse. On average 29% of the light intensity is not eclipsed. We investigated the variation of depth with precession phase using the unfiltered eclipses and only eclipses for which both the beginning and the end were observed were included in the analysis.

We repeated the same procedure applying sine fits for a range of periods to the eclipse depth measurements and looked at the residuals. The best sine fit again occurred close to the disk precession period, supporting the previous suggestion that eclipse depth is correlated with the precession phase of the accretion disk. Figure 8 shows a plot of eclipse depth against precession phase for a precession period of 2.231 days along with the best sine fit. The variation is ±0.044 mag on a mean eclipse depth of 1.33 mag. Binning the data and calculating means and standard errors yields a chi-sq probability for a sine fit of 0.16 whereas for a linear fit it is 0.003.

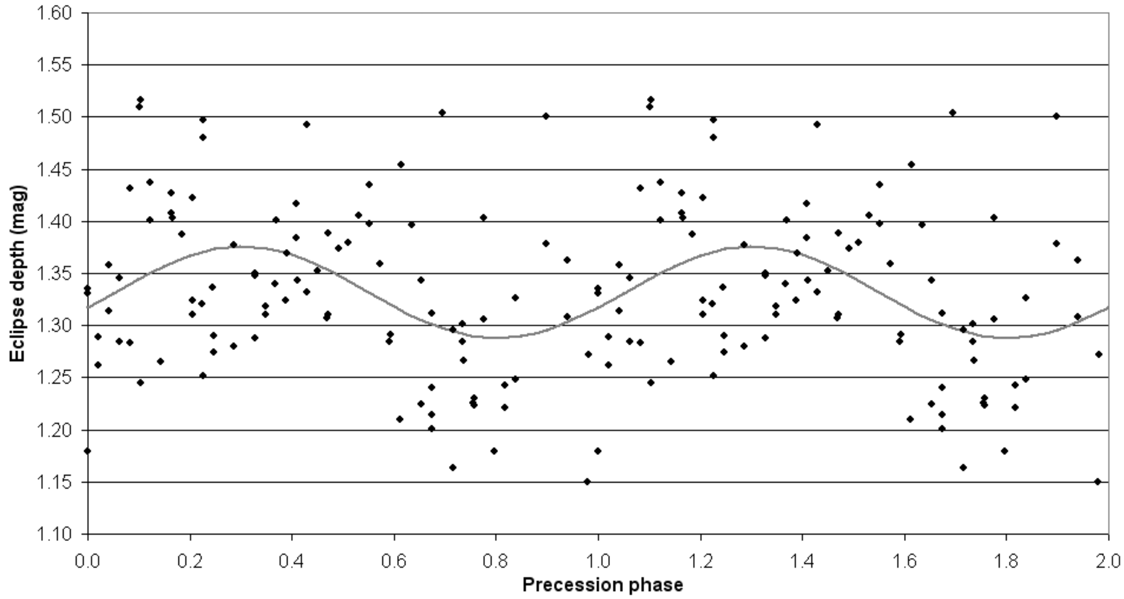

Figure 8. Variation of eclipse depth with accretion disk precession phase assuming a precession period of 2.231 days.

14. Variation of the eclipse width with the disk precession phase

Finally, we decided to investigate whether the eclipse width also varies with the disk precession phase. We obtained the eclipse width using the 2nd order polynomial fitted to the eclipse to obtain the time of minimum. The separation of the points on this polynomial at mid-depth of the eclipse was taken as the eclipse width. We again restricted our analysis to the unfiltered eclipses. We repeated the same procedure as before applying sine fits for a range of periods to the eclipse width data and looked at the residuals. The best sine fit again occurred close to the disk precession period indicating that the eclipse width is also correlated with the precession phase of the accretion disk. This result had not been expected. Figure 9 plots the eclipse width against precession phase for a precession period of 2.231 days along with the best sine fit. The variation is ±0.40 min on a mean eclipse width of 14.89 min. Binning the data and calculating means and standard errors yields a chi-sq probability for a sine fit of 0.50 whereas for a linear fit it is 0.43.

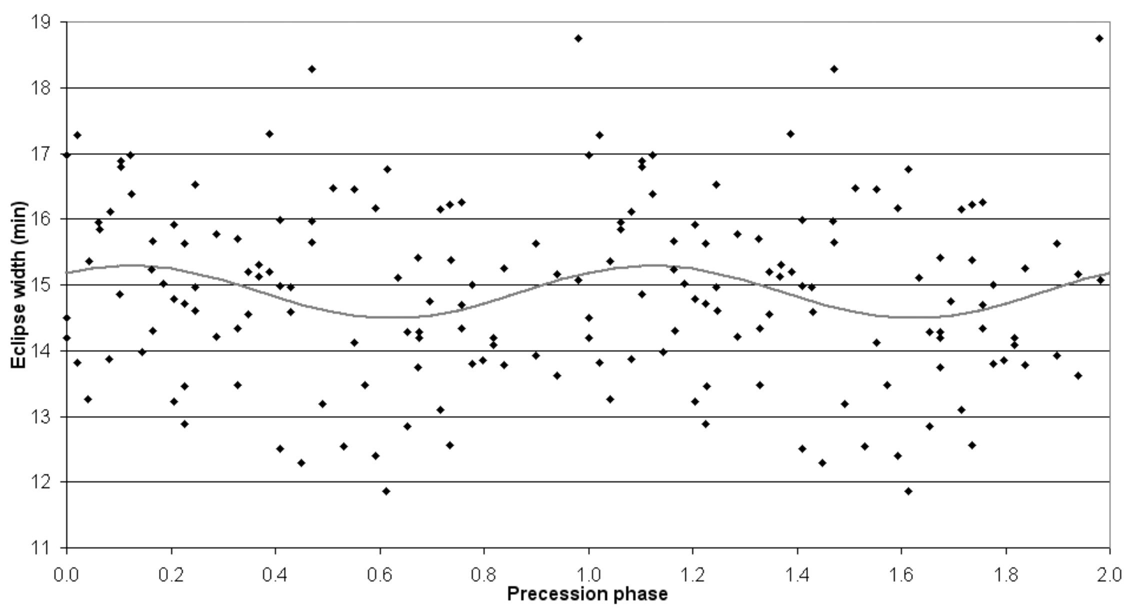

Figure 9. Variation of eclipse width with accretion disk precession phase assuming a precession period of 2.231 days.

15. Phase differences

The phase difference and corresponding angular differences between the phases of maximum eclipse delay, depth and width, and the phase of maximum brightness are listed in the table below.

	Phase difference	Angular difference
Maximum eclipse delay – maximum brightness	0.052	18.7°
Maximum eclipse depth – maximum brightness	-0.137	-49.3°
Maximum eclipse width – maximum brightness	-0.318	-114.5°

The phase relationship between these precession phases of maximum is relatively stable with respect to the assumed disk precession period as shown in Figure 10.

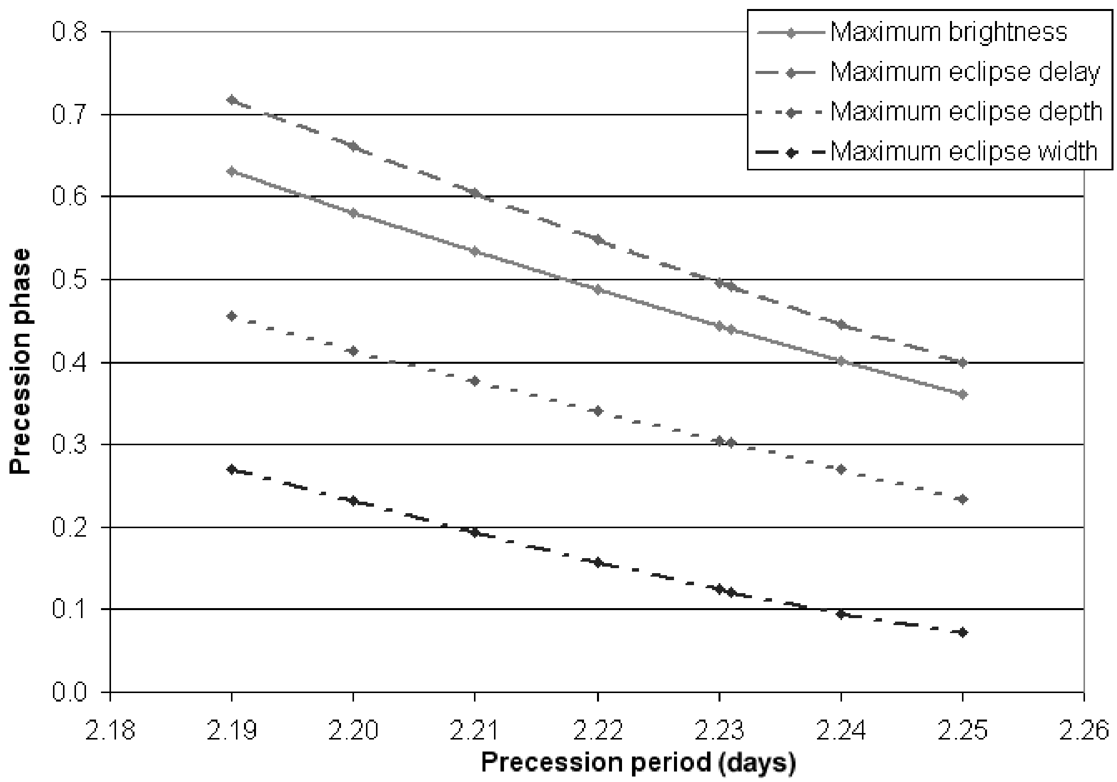

Figure 10. Variation of precession phases of maximum with precession period.

16. Conclusions

These results confirm that eclipses are a useful diagnostic tool for probing the precessing accretion disk in DW UMA and potentially other SW Sex stars. We have confirmed the suggestion that eclipse depth is correlated with the precession phase of the accretion disk. We have also found for the first time evidence of correlations between the disk precession phase and both the eclipse time of minimum and the eclipse width. The phase relationships we have found between the variations in brightness, eclipse time, eclipse depth and eclipse width with disk precession phase are not consistent with those expected for a simple geometrically flat, elliptical, precessing accretion disk. Additional factors, such as variations of the thickness and/or brightness of the disk rim, may dominate the observed behaviour.

17. Acknowledgements

We are very grateful to all those observers who freely gave their observing time to this project. Without their efforts these results could not have been achieved. This is a good example of pro-am collaboration in the pursuit of scientific progress. DB gratefully acknowledges support from the Royal Astronomical Society to attend the conference.

18. References

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