The eclipsing intermediate polar V597 Pup (Nova Puppis 2007)

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ABSTRACT

Photometric observations of V597 Pup made in 2008, 9.1 mag below maximum, 4 months after eruption, showed no certain orbital modulation but exhibited a quintuplet of oscillations centred on a period 261.9 s and uniform splitting at a frequency $\sim$2.68 $h^{-1}$. One year later, the system had fallen in brightness by a further 2.5 mag, showed deep eclipses with a period of 2.6687 h, and the 261.9 s modulation at a reduced amplitude. There is often power near the ‘subharmonic’ at 524 s showing that the shorter periods observed are actually first harmonics.

V597 Pup is thus an intermediate polar, and is in the ‘orbital period gap’. Furthermore, it is the first to show a prominent secondary eclipse, caused by passage of the optically thick disc in front of the irradiated side of the secondary star.

Key words: binaries: close – stars: individual: V597 Pup – novae, cataclysmic variables – stars: oscillations.

1 INTRODUCTION

V597 Pup was discovered as a nova at $V \sim 7.5$ on 2007 November 14 (Pereira, McGaha & Rhoades 2007), reaching $V \sim 6.2$ at maximum and declining smoothly for at least 5 mag as a very fast nova, with $t_2 = 2.5$ d (Naik, Banerjee & Ashok 2009), which is nearly the shortest recorded (only V838 Her and MU Ser are shorter: table 5.2 of Warner 1995). Its infrared red spectra and X-Ray emission (as a super-soft source) in early stages of decline are discussed by Naik et al., who classify it as a He/N nova and deduce that it has a white dwarf mass close to the Chandrasekhar limit. By 2008 March, it had reached $V \sim 15.3$; our later observations place it (out of eclipse) at $\sim$17.7 in 2009 February and $\sim$17.9 a month later. No post-eruption spectra have been published. A possible pre-eruption image at $V \sim 20$ is present on the Digitized Sky Survey (Pereira et al. 2007).

A finding chart prepared from one of our CCD images is given in Fig. 1. The position of V597 Pup appears to coincide with the proposed pre-eruption image.

In Section 2, we give the results and an initial analysis of our observations. In Section 3, we look at the overall geometry of V597 Pup. Section 4 expands on the analysis by treating V597 Pup as an eclipsing intermediate polar (IP), and Section 5 summarizes our interpretation of this interesting cataclysmic variable.

2 OBSERVATIONS

We used the University of Cape Town CCD photometer, as described by O’Donoghue (1995), in frame transfer mode and with white light, on the 1.9-m (74-in) reflector at the Sutherland site of the South African Astronomical Observatory (SAAO). Table 1 contains a detailed observing log. Our magnitude scale was derived using hot white dwarf standards, but because of the non-standard spectral distributions of the spectrum of the nova remnant, and the use of white light, our magnitudes approximate a $V$ scale only to $\sim$0.1 mag.

2.1 Light curves on the orbital time-scale

The light curves from the 2008 data are shown in Fig. 2, aligned in phase with the orbital period that we deduce below. A repetitive hump with an amplitude $\sim$0.2 mag is seen, but no obvious eclipse features; unfortunately, our light curves had lengths not much greater than the (then unknown) orbital period. The Fourier transform (FT) of the combined light curves is shown in Fig. 3. The highest peak has a frequency of 91.8 $\mu$Hz, but there are aliases of almost equal amplitude either side at 80.3 and 103.3 $\mu$Hz (periods of 3.46, 3.03 and 2.69 h). There is also a set of frequencies which could be first harmonics, at 173.7, 185.2, 196.7 and 208.1 $\mu$Hz. The uncertainties on these figures are $\sim$0.5 $\mu$Hz.

Light curves from the 2009 observations are shown in Fig. 4, where it is clear that the drop in system brightness by $\sim$2.5 mag over one year has revealed broad eclipses $\sim$0.6 mag deep with respect to the out-of-eclipse level away from the reflection region (see below). The fundamental and harmonics in the FT of these light curves provide an orbital period of 2.6687 h (104.089 $\mu$Hz), which shows that the orbital modulation, with first harmonic, was present in the 2008 light curves. The ephemeris for minimum light is

$$\text{HJD}_{\text{min}} = 2454888.3280 + 0.111119 E.$$  (1)

If the drop in brightness (by a factor of $\sim$10) between the two sets of observations was due largely or entirely to the dispersal and cooling of nova ejecta far from the central binary, the eclipses and their related humps could well have been present even in the earlier
Figure 1. CCD image of V597 Pup (indicated by the markers) taken on 2009 March 18 (out of eclipse). The field of view is $50 \times 34$ arcsec$^2$, north is up and east is to the left-hand side.

Table 1. Observing log of photometric observations.

| Run   | Date of obs. (start of night) | HJD of first obs. (+2450000.0) | Length (h) | $t_{in}$ (s) | $V$ (mag) |
|-------|-------------------------------|---------------------------------|------------|-------------|----------|
| S7807 | 2008 March 15                 | 4541.2615                       | 2.77       | 6           | 15.2     |
| S7808 | 2008 March 16                 | 4542.24472                      | 3.53       | 6           | 15.2     |
| S7810 | 2008 March 17                 | 4543.27429                      | 3.82       | 6           | 15.3     |
| S7812 | 2008 March 18                 | 4544.25449                      | 3.30       | 6           | 15.3     |
| S7828 | 2009 February 25              | 4888.26865                      | 7.30       | 30          | 17.8$^\dagger$ |
| S7830 | 2009 February 26              | 4889.28184                      | 6.95       | 30          | 17.7$^\dagger$ |
| S7832 | 2009 February 27              | 4890.26684                      | 7.39       | 30          | 17.7$^\dagger$ |
| S7834 | 2009 February 28              | 4891.25647                      | 4.29       | 30          | 17.7$^\dagger$ |
| S7840 | 2009 March 03                 | 4894.30579                      | 1.15       | 30          | 17.7$^\dagger$ |
| S7842 | 2009 March 18                 | 4909.24058                      | 5.42       | 30          | 17.9$^\dagger$ |
| S7843 | 2009 March 19                 | 4910.23990                      | 5.51       | 30          | 17.9$^\dagger$ |
| S7856 | 2009 March 23                 | 4914.29437                      | 1.68       | 30          | 17.9$^\dagger$ |

$^\dagger$ Out of eclipse.

Figure 2. The 2008 light curves of V597 Pup phased on the orbital ephemeris given in equation (1). The light curves of runs S7808, S7810 and S7812 have been displaced by 0.4, 0.8 and 1.2 mag, respectively, for display purposes.

Figure 3. The low-frequency FT of the combined 2008 observations of V597 Pup.

Figure 4. The 2009 light curves of V597 Pup phased on the orbital ephemeris given in equation (1). The light curve of run S7828 is displayed at the correct magnitude, the others have been displaced vertically for display purposes only.

light curves – there are some features that resemble such diluted structures.

The 2009 light curves for February and March averaged over the binary period are seen in Fig. 5 and show repetitive structures between the primary eclipses. Remembering that these are of a fast nova only 15 months after outburst, we would perhaps expect the white dwarf primary still to be very hot, so that at the small distance from the secondary implied by the short orbital period a strong reflection effect could be present. Between eclipses, there is indeed what may be described as a reflection effect which would be 0.3 or 0.4 mag in amplitude, were it not suppressed either side of phase 0.5 by a secondary eclipse of total width equal to that of primary eclipse. In Fig. 6, we sketch what we suggest would be the reflection effect without any secondary eclipse; the asymmetry, namely the early fall in brightness before the start of primary eclipse is probably caused by partial obscuration of the bright face of the companion star by the gas stream passing from it to the outer edge of the disc. The reflection effect and secondary eclipse are similar, but of greater amplitude, to what we saw in the nova remnant DD Cir (Woudt & Warner 2003), where we ascribed a shallow secondary eclipse.
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2.1 Optical variability

The average light curves of V597 Pup for the 2009 February and March observations, plotted separately.

Figure 5. The average light curves of V597 Pup for the 2009 February and March observations, plotted separately.

The average light curves of V597 Pup as in Fig. 5 – the 2009 March light curve is shifted vertically by 0.18 mag to match the 2009 February average magnitude – with overplotted the expected sinusoidal variation of a strong reflection effect (dashed line) of \(\sim 0.54\) mag peak-to-peak amplitude. The depth of the deepest secondary eclipse is an indication of the approximate minimum brightness at secondary eclipse, marked by the horizontal dotted line.

Figure 6. The average light curves of V597 Pup as in Fig. 5 – the 2009 March light curve is shifted vertically by 0.18 mag to match the 2009 February average magnitude – with overplotted the expected sinusoidal variation of a strong reflection effect (dashed line) of \(\sim 0.54\) mag peak-to-peak amplitude. The depth of the deepest secondary eclipse is an indication of the approximate minimum brightness at secondary eclipse, marked by the horizontal dotted line.

There is great variability in the profile and depth of the secondary eclipse, as it could be expected from a disc of rapidly changing structure. Figs 5 and 6 show that the 0.2 mag decrease in brightness from 2009 February to March has resulted in a deeper primary eclipse as the fading ejecta reduce the amount of in-fill.

Inspection of the individual light curves in Fig. 4 shows that during primary and secondary eclipses there is flickering similar to that seen out of eclipse, so at least one flickering source is still visible during eclipse. Apart from that, certainly the secondary and possibly the primary eclipse appear flat bottomed as in a total eclipse or a transit.

2.2 Short period optical oscillations

The FT of the combined 2008 light curves is shown in Fig. 7. There is red noise at low frequencies, associated with flickering and with harmonics of the orbital modulation, but an isolated cluster of peaks in the vicinity of 3800 \(\mu\)Hz is evident. On detailed examination, five components are found, with the frequencies and amplitudes listed in Table 2, found from a 5 sinusoid simultaneous least squares fit. Uncertainties of the frequencies are all \(\sim \pm 0.5\) \(\mu\)Hz and of the amplitudes are \(\pm 0.7\) mmag. The phases (with arbitrary zero point) are quoted as fractions of cycles. The largest amplitude signal is at 261.9 s.

As further evidence for the significance of these signals we produce in Fig. 8, an observed–calculated phase diagram relative to the central frequency and comparison with the same diagram produced by a simulation using the five sinusoidal signals listed in Table 2.

The mean splitting between the components in 2008 is 104.15 \(\mu\)Hz, which, within errors, is the same as the orbital frequency. It is therefore clear that in 2008 a quintuplet of frequencies was present with internal splitting equal to the orbital frequency \(\Omega\), which is the characteristic signature of an IP where the white dwarf primary’s frequency \(\omega\), and/or its reprocessed signal \(\omega - \Omega\), acquires orbital sidebands. This occurs through reprocessing of a rotating beam of high energy radiation, emitted from the accretion zone(s) on the primary, off regions of varying cross-section or varying visibility rotating in orbit (Warner 1986). This shows that the central binary was free from obscuration during the 2008 observations and therefore that much of the luminosity came from distant ejecta and not an optically thick wind close to the primary. The apparent amplitude of the oscillations should be increased by a factor of at least 10 to remove the diluting effect of these bright

| Frequency (\(\mu\)Hz) | Ampl. (mmag) | Phase | Frequency (\(\mu\)Hz) | Ampl. (mmag) |
|------------------------|--------------|-------|------------------------|--------------|
| 3610.0                 | 2.2          | \(-0.05 \pm 0.09\) | 3714.6                | 2.7          |
| 3713.4                 | 2.0          | \(-0.37 \pm 0.10\)  | 3817.8                | 6.3          |
| 3818.2                 | 3.4          | \(-0.21 \pm 0.06\)  | 3922.4                | 1.6          |
| 3922.4                 | 1.6          | \(-0.45 \pm 0.12\)  | 4026.8                | 2.3          |
| 4026.8                 | 2.3          | \(+0.24 \pm 0.08\)  | 4027.3                | 3.1          |

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Figure 8. Phase variations (observed–calculated) of the 3818 μHz signal in the 2008 data (observed: top panel; simulated (see text for details): bottom panel). Different symbols represent data from different nights. Each dot represents ~6 cycles of the 3818 μHz modulation, with a 50 per cent overlap.

Figure 9. The high frequency FT of the combined 2009 February observations of V597 Pup around 3818 μHz. The vertical bars correspond to the frequencies listed in Table 2.

Figure 10. The high-frequency FT of V597 Pup around 1905 μHz of the combined 2009 February observations (top panel), and the combined 2009 March observations (lower panel). The vertical bars correspond to the selected frequencies listed in Table 3.

Table 3. The high frequencies (fundamentals) in V597 Pup.

| Frequency (μHz) | Ampl. (mmag) | Frequency (μHz) | Ampl. (mmag) |
|----------------|--------------|----------------|--------------|
| 1930.8 ± 0.3  | 11.3 ± 2.8   | 1919.2 ± 0.3   | 11.1 ± 2.8   |
| 1909.9 ± 0.3  | 9.2 ± 2.8    | 1907.5 ± 0.5   | 8.9 ± 2.0    |
| 1907.5 ± 0.6  | 8.9 ± 2.0    | 1896.1 ± 0.5   | 8.0 ± 0.5    |

†Aliases are given in italics.

3 THE STRUCTURE OF V597 PUP

The drop in luminosity from 2008 to 2009 revealed an IP in the orbital period gap (Warner 1995), with a rotation period of 8.7 min. The reduction in amplitudes of the spin modulations over the year is probably the result of diminishing \( \dot{M} \) as the primary cools and lessens its irradiation of the secondary.

It is not possible, with the flickering and variations from orbit to orbit, to give precise values for eclipse ingress and egress timings, but we can show the effect in the light curve of the various components. First, a simple calculation shows that the measured widths of the eclipses imply an unusually large disc radius. From the expected high mass for a very fast nova, and the mass and radii relationships for secondaries in cataclysmic variables (Warner 1995), we adopt \( \dot{M}(1) = 1.3 \, M_\odot \), \( \dot{M}(2) = 0.22 \, M_\odot \), \( R_2 = 1.9 \times 10^{10} \) cm. These lead to a separation \( a = 7.82 \times 10^{10} \) cm, a radius \( R(L) \) of the Roche lobe of the primary of \( 4.2 \times 10^{10} \) cm, and expected radius of a high \( M \) disc of \( R_d = 0.7 \, R(L) = 2.9 \times 10^{10} \) cm. The first and last contact phases \( \pm \phi \) of eclipses, relative to phase 0, assuming an inclination near 90° is found from \( \sin \phi = [R(2) + R]/a \), where \( R \) is selected from above. For the usual \( R = R_2 \), we find \( \phi = 0.10 \), but for \( R = R(L) \) we have \( \phi = 0.14 \), which is close to the observed \( \phi \sim 0.15 \). The disc in V597 Pup fills the primary’s Roche lobe to its...
maximal possible extent. The radius of the disc is considerably larger than that of the secondary star, which results in the flat bottomed secondary eclipse.

The phases of first and last contact in the secondary eclipse, as the secondary star (made visible by irradiation from the hot primary) is eclipsed by the disc, relative to phase 0.5, are also ±φ and the phases between second and third contact are ±(φ − θ), where sin θ = |R(L) − R(2)|/a, which are ±0.09, in reasonable agreement with what is observed for the emergence of the secondary, but immersgence takes longer than predicted, possibly because at that phase the illuminated gas stream is also being eclipsed by the disc.

The general agreement between observed and expected time-scales of the secondary eclipses adds weight to our interpretation of this unusual light curve.

With the short orbital period, and mass ratio $M_2/M_1 = 0.22$ adopted here, we might have expected an elliptical disc and superhumps to be present (see chapter 3 of Warner 1995), but there is no evidence for them in the light curves and FTs. The reason may be that with an accretion disc of such large radius, greatly exceeding the 3:1 resonance radius that excites ellipticity, the resonance is ineffective: Osaki & Meyer (2003) have shown how in a disc of large radius the 2:1 Lindblad resonance can suppress the 3:1 resonance. Our estimate of φ ∼ 0.15 in fact puts the outer edge of the accretion disc very close to the 2:1 resonance radius.

4 V597 PUP AS AN INTERMEDIATE POLAR

Mukai (2008) lists over 30 bona fide IPs, among which there is none with relatively rapid rotations that possess deep eclipses suitable to provide detailed information about the structure of an IP. Eclipses are seen in XY Ari but it is an X-Ray source, hidden behind a dust cloud; DQ Her is far more favourable for observation but is not ideal as it has an inclination so high that much of the central region of the disc is hidden from view; DD Cen (Woudt & Warner 2003) is too faint to study fully. Thus, V597 Pup is the first relatively large disc the vertical gravity is very low), processing of high energy radiation emitted from accretion zones on the rotating binary (Chester 1979; Petterson 1980), and are a function of the relative amounts of direct radiation from the primary and those from the front and back portions of the accretion disc.

In V597 Pup, the phase behaviour of the 262 s signal in 2009 is of a kind that has not been observed before. Our initial impression was of a 360° increase in phase during eclipse – which might be thought to indicate that the primary rotates retrogradely in the system. But further investigation showed that Chester (1979) had anticipated the situation – he pointed out that if the phase of the first harmonic is measured in a high inclination system (where only the beam sweeping across the back surface of the disc is observable, as in DQ Her) then a 180° increase would be seen, followed by an instantaneous decrease of 360° and a recovery increase of 180°. There is of course an ambiguity in how to plot such observed phase shifts, but we have chosen to use Chester’s insight rather than claim a retrogradely rotating primary. The phase variations through eclipse are present in all the high quality light curves; these and their average are shown in Fig. 11.

There is no significant reduction in amplitude near phase 0, which may be the result of the ω − Ω signal having at least three sources (secondary and two regions of disc thickening). Furthermore, unlike DQ Her, where the radii of the secondary and disc are almost equal (Petterson 1980), in V597 Pup the secondary is considerably smaller and leaves much of the disc uncovered at phase 0.

As seen in Fig. 11, there are no significant phase changes associated with the secondary eclipse.

4.3 The phase variation of the 524 s modulation

The phase and amplitude variations of the 1907.5 μHz (524 s) fundamental modulation seen in our best light curves (runs S7842 and S7843 of 2009 March, both of which cover two orbits) are shown in Fig. 12. The results through the eclipses are not clear cut, which may result from varying contributions of different sources to the ω − Ω signal, but is largely due to the modulation period being comparable to the ingress and egress durations.
However, there is a DQ Her-like variation of phase centred on the first primary eclipse of S7842, not repeated in the second eclipse, and a suggestive rise in the second eclipse of S7843. In addition, there is a reverse phase change (also $\sim 180^\circ$) in the secondary eclipses of S7842 and a probably similar effect in the second secondary eclipse of S7843 (in the first of the secondary eclipses of this run, the amplitude of the signal is quite low). There are also some indications of lower amplitudes at the times of both primary and secondary eclipses.

5 CONCLUSION

V597 Pup is unique in several ways and will repay further photometric and spectroscopic investigation before it fades another 2 mag to its pre-eruption brightness. It is the first cataclysmic variable found to have a deep secondary eclipse – the result of a background generated by the temporary extra brightness of one face of the otherwise low-luminosity secondary star. Detailed study of this eclipse could reveal more about the structure of the outer parts of the accretion disc.

As an IP V597 Pup offers a rare opportunity to study reprocessing in a very high inclination system. It has some parallels with DQ Her, but the fundamental and first harmonics of the rotation and reprocessed signals are more complex.

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