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Kepler observations of V447 Lyr: an eclipsing U Gem Cataclysmic Variable

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ABSTRACT

We present the results of an analysis of *Kepler* data covering 1.5 yr of the dwarf nova V447 Lyr. We detect eclipses of the accretion disc by the mass donating secondary star every 3.74 h which is the binary orbital period. V447 Lyr is therefore the first dwarf nova in the *Kepler* field to show eclipses. We also detect five long outbursts and six short outbursts showing V447 Lyr is a U Gem-type dwarf nova. We show that the orbital phase of the mid-eclipse occurs earlier during outbursts compared to quiescence and that the width of the eclipse is greater during outburst. This suggests that the bright spot is more prominent during quiescence and that the disc is larger during outburst than quiescence. This is consistent with an expansion of the outer disc radius due to the presence of high viscosity material associated with the outburst, followed by a contraction in quiescence due to the accretion of low angular momentum material. We note that the long outbursts appear to be triggered by a short outburst, which is also observed in the super-outbursts of SU UMa dwarf novae as observed using *Kepler*.

Key words: accretion, accretion discs – stars: dwarf novae – stars: individual: V447 Lyr – novae, cataclysmic variables.

1 INTRODUCTION

Cataclysmic variable (CV) binary systems contain a white dwarf primary star that accretes mass from a Roche lobe-filling late-type main sequence secondary star. Mass-loss from the secondary through the inner Lagrange point (L1) forms an accretion disc about the primary, and viscosity within the accretion disc acts to transfer angular momentum outward in radius allowing mass to migrate inward to the surface of the white dwarf. The disc and bright spot associated with the accretion stream impact point are typically the brightest components in a CV system (Warner 1995; Hellier 2001; Frank, King & Raine 2002). The mean disc luminosity is ultimately provided by the release of gravitational potential energy as the material migrates inward through the disc and is given by $L_{\rm disc} \sim GM_1\dot{M}_1/R_1$, where $\dot{M}_1$ is the mass transfer rate on to the primary of mass M_1 and radius R_1. The mass flow rate through L1 is governed by the long-term evolution of the binary separation and the secondary star itself, but the mass flow rate through the disc and on to the primary is a function of the viscosity of the disc – the higher the viscosity, the higher the inward mass flow rate.

V447 Lyrae (KIC 8415928, $r = 18.4$, Brown et al. 2011) is a little-studied CV in the NASA *Kepler* field of view. Its sky coordinates are $\alpha = 19^{\rm h}\,00^{\rm m}\,19\overset{\rm s}{.}92$, $\delta = +44^\circ\,27'\,44\overset{''}{.}9$ (2000.0). It was discovered and announced as GR 247 by Romano (1972) who noted a maximum photographic magnitude of 17.2 and a minimum fainter than 18.5. These observations were included in Downes, Webbink & Shara (1997) but the system was noted as undetected in the 2MASS survey (Hoard et al. 2002) nor is it a known X-ray source.

This work is the fifth in a series of publications focusing on the CVs in the *Kepler* mission field of view. In Still et al. (2010), we presented preliminary results for the periods observed in the Q2 data for V344 Lyr, a previously little-studied CV in the *Kepler* field. In Cannizzo et al. (2010), we presented results of the thermal viscous disc instability model for CVs applied to the Q2–Q4 V344 Lyr outburst time-series data. In Wood et al. (2011), we presented a detailed analysis of the orbital and super-hump periods present in the V344 Lyr Q2–Q4 time-series data. In Cannizzo et al. (2012), we discussed the outburst properties of V1504 Cyg and V344 Lyr over the first two years of *Kepler* observations, and most recently (Barclay et al. 2012) we have reported the serendipitous discovery

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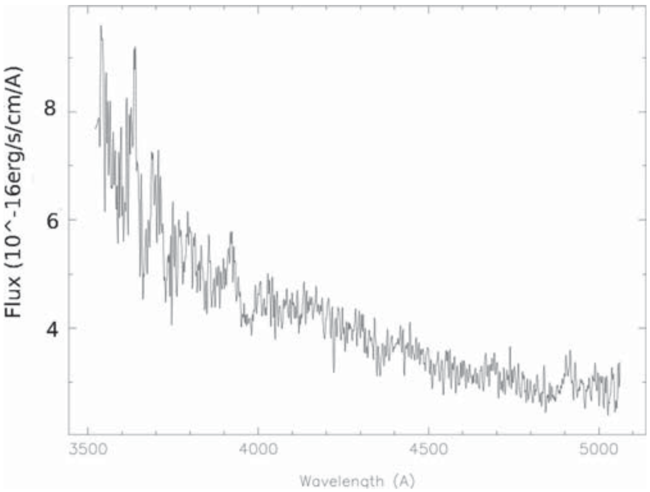

Figure 1. An optical spectrum of V447 Lyr taken using the Palomar 200 inch telescope on 2011 June 6 when it was in a long outburst.

of an SU UMa dwarf nova within 7 arcsec of a G-type star. Here we report *Kepler* observations of V447 Lyr covering 1.5 yr.

2 OPTICAL SPECTROSCOPY

Fig. 1 shows the blue spectrum of V447 Lyr obtained using the double-beam spectrograph on the Mt. Palomar 200 arcsec telescope and confirms its CV nature. The spectrum was reduced in the usual manner using IRAF 2D and 1D spectral reduction tools. The relative fluxes were provided by an observation of the spectrophotometric standard star Feige 92 obtained 35 min prior to the V447 Lyr spectrum. The night was not photometric, having thin to moderate thick clouds passing by; thus, the fluxes are approximate. The red spectrum, obtained simultaneously, has low signal-to-noise ratio but shows that Hα is also in emission.

This single 900 s spectrum was recorded for approximately two days into a long outburst of V447 Lyr (LO4 in Table 2) and reveals complex line profiles in the hydrogen lines. The lines of Hβ, Hγ, Hδ and beyond show a broad absorption component with a slightly off-centre narrow emission line during this near-outburst-peak spectrum. In addition, a broad redshifted emission bump is observed, the overall shape producing P Cyg-like line profiles. These line profiles are similar to those observed in Hα early into a super-outburst of LL And (Howell & Hurst 1996), with the complex Hα line structure quickly disappearing one night later. The optically thick wind outflow observed at this time has an average velocity offset from the absorption line centre of 3700 km s^{-1} and a velocity width (full width zero intensity) of 1200 km s^{-1}, similar to the line profiles and wind signatures observed in the ultraviolet spectra of SW UMa, BC UMa and TV Cor (Howell et al. 1995) during super-outburst.

3 *KEPLER* PHOTOMETRIC OBSERVATIONS

The primary science objective of the *Kepler* mission is to discover Earth-sized planets in the habitable zone of Sun-like stars (Borucki et al. 2010; Haas et al. 2010). The spacecraft is in an Earth-trailing orbit allowing it a continuous view of the target field over the planned 3.5 yr mission lifetime (recently extended for at least a further two years). The shutterless photometer has a 116 deg^2 field of view and makes use of 6.54 s integrations, but only pixels containing pre-selected targets are saved due to bandwidth and memory constraints. Bandwidth limits impose that only up to 170 000 targets can be observed in *long cadence* (LC) mode, where 270 integrations are summed for an effective 28.4 min exposure, and up to 512 targets can be observed in *short cadence* (SC) mode, where nine integrations are summed for an effective 58.8 s exposure. Gaps in the *Kepler* data streams result from, for example, 90° spacecraft rolls every 3 months (called quarters), monthly data downloads using the high-gain antenna as well as unplanned safe-mode and loss of fine point events. For further technical details see Haas et al. (2010), Koch et al. (2010) and Caldwell et al. (2010).

Kepler data are provided as quarterly FITS files by the Science Operations Center after being processed through the standard data reduction pipeline (Jenkins et al. 2010). After the raw data are corrected for bias, shutterless readout smear and sky background, time series are extracted using simple aperture photometry. The start and end times of each quarter of *Kepler* data which are used in this study are shown in Table 1. (We note that when SC mode data are obtained, LC are also obtained.)

We show the LC light curve for V447 Lyr obtained over quarters Q6–Q11 in Fig. 2. The light curve shows 11 outbursts: 6 of these have a ‘short’ duration clustered around a mean of 6.6 d and 5 have a ‘long’ duration clustered around a mean of 12.3 d (Table 2). The ratio of the duration of the long outbursts to short outbursts is 1.9 and is consistent with that seen in systems with long orbital periods (and hence high mass transfer rates, e.g. Warner 1995). Indeed, it is very similar to that seen in U Gem ($P_{\rm orb} = 4.25$ h) whose short and long outbursts have a typical duration of 5 and 12 d, respectively (Cannizzo, Gehrels & Mattei 2002). The mean recurrence time between successive long outbursts is 118 d (the mean recurrence time in U Gem is ~120 d, Szkody & Mattei 1984). There are only two successive short outbursts and they were separated by 30 d.

However, perhaps the most notable aspect of the light curve is that an eclipse is observed every 3.74 h (Fig. 3). This feature is seen because the binary inclination angle is high enough to cause the physically larger mass-donating secondary star to eclipse the white dwarf (if the inclination is close to 90°), or the accretion disc and

Table 1. Journal of observations. The start and end MJD and UT dates are the mid-point of the first and final cadence of the LC time series for each quarter, respectively.

Quarter	Start MJD	Start UT	End MJD	End UT
Q6 (LC)	553 71.947	2010 June 24 22:46	554 61.794	2010 Sept. 22 19:04
Q7 (LC)	554 62.673	2010 Sept. 23 16:10	555 52.049	2010 Dec. 22 01:09
Q8 (SC)	555 67.855	2011 Jan. 06 20:42	556 34.856	2011 March 14 20:15
Q9 (SC)	556 41.007	2011 March 21 00:23	557 38.434	2011 June 26 10:13
Q10 (LC)	557 39.343	2011 June 27 08:16	558 32.766	2011 Sept. 28 18:24
Q11 (SC)	558 33.696	2011 Sept. 29 16:58	559 30.837	2012 Jan. 04 20:48

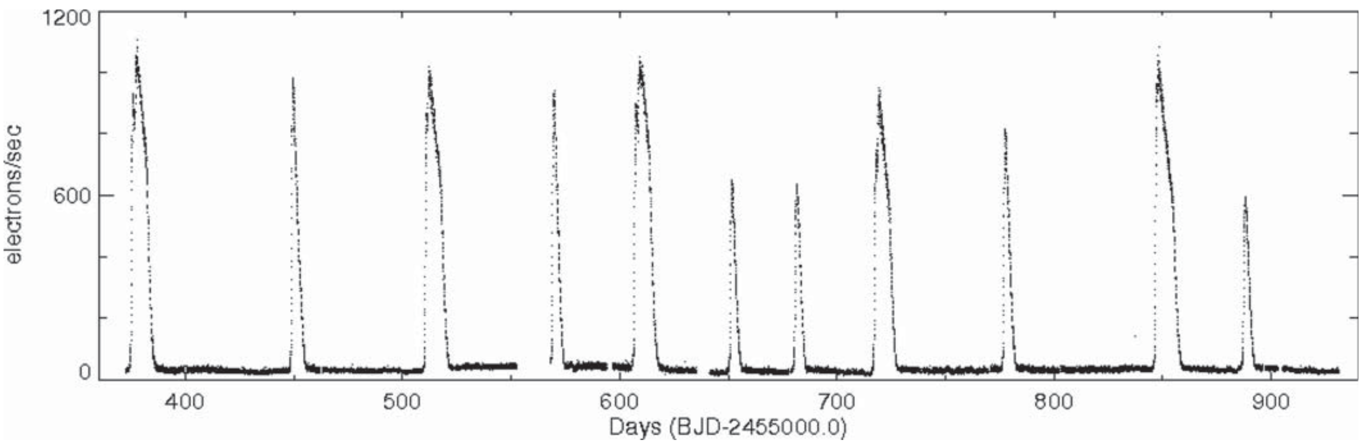

Figure 2. Long cadence *Kepler* Q6–Q11 light curve of V447 Lyr in flux units. The time unit is in BJD 245 5000.0.

Table 2. A summary of outbursts observed in *Kepler* data of V447 Lyr. LO indicates a 'long' outburst and SO a 'short' outburst. The start date is the time of the rise to outburst where the date is BJD 245 5000.0. The duration of the outburst is given in days and the amplitude in mag.

Outburst	Quarter/ Cadence	Start date	Duration (days)	Amplitude (mag)
LO1	Q6/LC	374.3	11.8	3.5
SO1	Q6/LC	448.1	7.3	3.8
LO2	Q7/LC	509.6	12.4	3.8
SO2	Q8/SC	568.3	6.5	3.2
LO3	Q8/SC	605.5	12.7	3.5
SO3	Q9/SC	650.1	6.4	3.5
SO4	Q9/SC	679.7	6.5	3.2
LO4	Q9/SC	716.1	11.8	4.0
SO5	Q10/LC	776.1	6.6	3.3
LO5	Q11/SC	845.7	13.0	3.5
SO6	Q11/SC	886.3	6.1	2.9

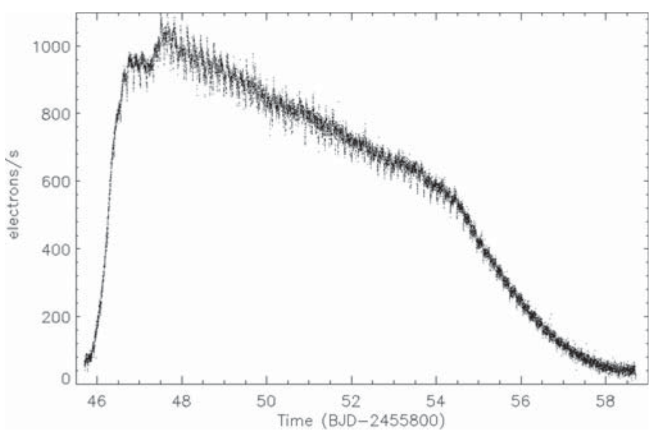

Figure 3. The light curve of long outburst 5 (see Table 2), showing an eclipse of the accreting white dwarf by the late-type main sequence star every 3.74 h.

bright spot (if the inclination is slightly less than 90°), once every orbital period leading to an apparent dimming in the light from the system. We show below that the likely inclination of this system is such that the white dwarf itself is not eclipsed. We therefore identify V447 Lyr as the first eclipsing dwarf nova in the *Kepler* field.

4 A PRECURSOR TO THE LONG OUTBURSTS

The short-duration outbursts show a sharp rise followed by an exponential type decay. In contrast, the long outbursts all show an initial sharp rise (as in the short outbursts) followed by a plateau lasting less than a day, and then an increase in flux (see Fig. 3), followed by a gradual decline in flux. This 'precusor' to the super-outburst has been seen in all of the super-outbursts of SU UMa CVs observed using *Kepler* (e.g. Still et al. 2010; Barclay et al. 2012). A normal (or short) outburst is thought to trigger a super- (or long) outburst when the material in the outer radii of the accretion disc becomes ionized.

This precursor has not been seen in long outbursts of U Gem-type CVs until very recently (Cannizzo 2012). We attribute this to the fact that the cadence of observations has not been high enough to resolve this precursor. However, given a precursor has been seen in super-outbursts and now in long outbursts, we suggest that this precursor is common to long outbursts from accreting CVs in general. Any model aiming to reproduce long/super-outbursts will have to account for this feature.

5 ECLIPSING TIMINGS

We initially estimated the time of the mid-eclipse in individual eclipses during each of the outbursts which were observed in SC mode. Given that the exposure time of each SC data point was nearly 1 min and the eclipse profile was rather noisy, the uncertainty on the eclipse times was relatively large. However, it allowed us to obtain a working eclipse ephemeris which we used to phase the SC light curve. To improve the signal-to-noise ratio of the eclipse profile we split up the light curve into sections consisting of 3 orbital cycles when the system was in outburst and up to 30 cycles during quiescence and phase folded and binned the data. This allowed us to refine the linear eclipse ephemeris so that during an outburst the eclipse mid-point was defined as $\phi = 0.0$. This gave the eclipse ephemeris:

$$T_o = \mathrm{BJD}\,245\,5569.4134(2) + 0.155\,6270(1)E, \quad (1)$$

where the numbers in parentheses give the standard error on the last digits.

6 FOLDED LIGHT CURVES

When we fold the light curve derived from intervals of quiescence we find a peak in the folded light curve at $\phi \sim 0.8$–0.9 (Fig. 4) which

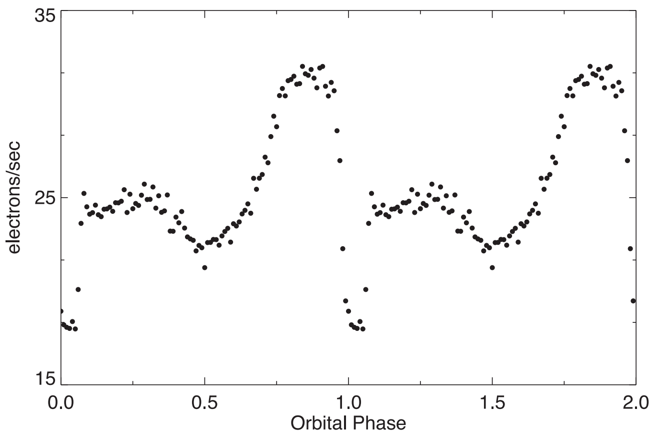

Figure 4. The folded light curve obtained from data taken during the quiescent interval MJD = 556 87.0–557 14.0, i.e. between outbursts SO4 and LO4 (see Table 2).

is due to the bright spot where the accretion stream hits the accretion disc and is seen approximately face-on at this phase angle (see Wood et al. 1986 for a breakdown of the predicted contribution from the white dwarf, accretion disc and bright spot as a function of the orbital phase). The full width at half-maximum of the eclipse profile is $\Delta\phi \sim 0.08$. Assuming we can derive the mass of the secondary star ($M_2 = 0.27$) from the mass–period relationship (Patterson et al. 2005) and a mass of $M_1 = 0.6$ for the white dwarf ($q = 0.45$) we predict an inclination angle $i = 80°$ (or $i = 82.5°$ for $M_1 = 0.8$), using fig. 2 of Horne (1985).

In the left-hand panel of Fig. 5 we show a set of folded light curves taken from a short outburst (SO4), where we have detrended the light curve to remove the effect of the decline from outburst, and have split the light curve into sections 0.7 d in length and then folded the light curve according to the ephemeris derived in the previous section. At outburst maximum the brightness out of eclipse is more uniform, and as the system approaches quiescence, a peak appears in the folded light curve at $\phi = 0.8$ due to the bright spot becoming progressively more prominent as the system approaches quiescence. During outburst the bright spot makes a relatively significantly smaller contribution to the optical light from the system compared to quiescence.

In the middle panel of Fig. 5 we show the results from a similar analysis of a long outburst (LO4). We find that at outburst maximum (the lowermost curve in Fig. 5), there is a peak in the folded light curve at $\phi \sim 0.55$. In contrast, in the right-hand panel of Fig. 5 we show the results of the same analysis for the next long outburst (LO5). At maximum brightness there is a prominent peak in the folded light curve shortly after the eclipse, while there is a minimum in the light curve at $\phi \sim 0.6$. Over the course of the outburst the brightness out of eclipse becomes more uniform (the analysis for L03 is very similar to LO5). We speculate that this evolution of the accretion disc (and the differences between the LO4 and that of LO3 and LO5) is due to the evolution of sprial shocks in the accretion disc as observed in U Gem (Groot 2001).

7 THE ECLIPSE PROFILE

We now turn our attention to the characteristics of the eclipse profile. As indicated in Section 5, we extracted three successive cycles of data during outbursts and phase folded and binned these data using the eclipse ephemeris. For intervals of quiescence we did this for up to 30 orbital cycles of data. We fitted the eclipse profiles using a model consisting of a linear trend plus a Gaussian profile and

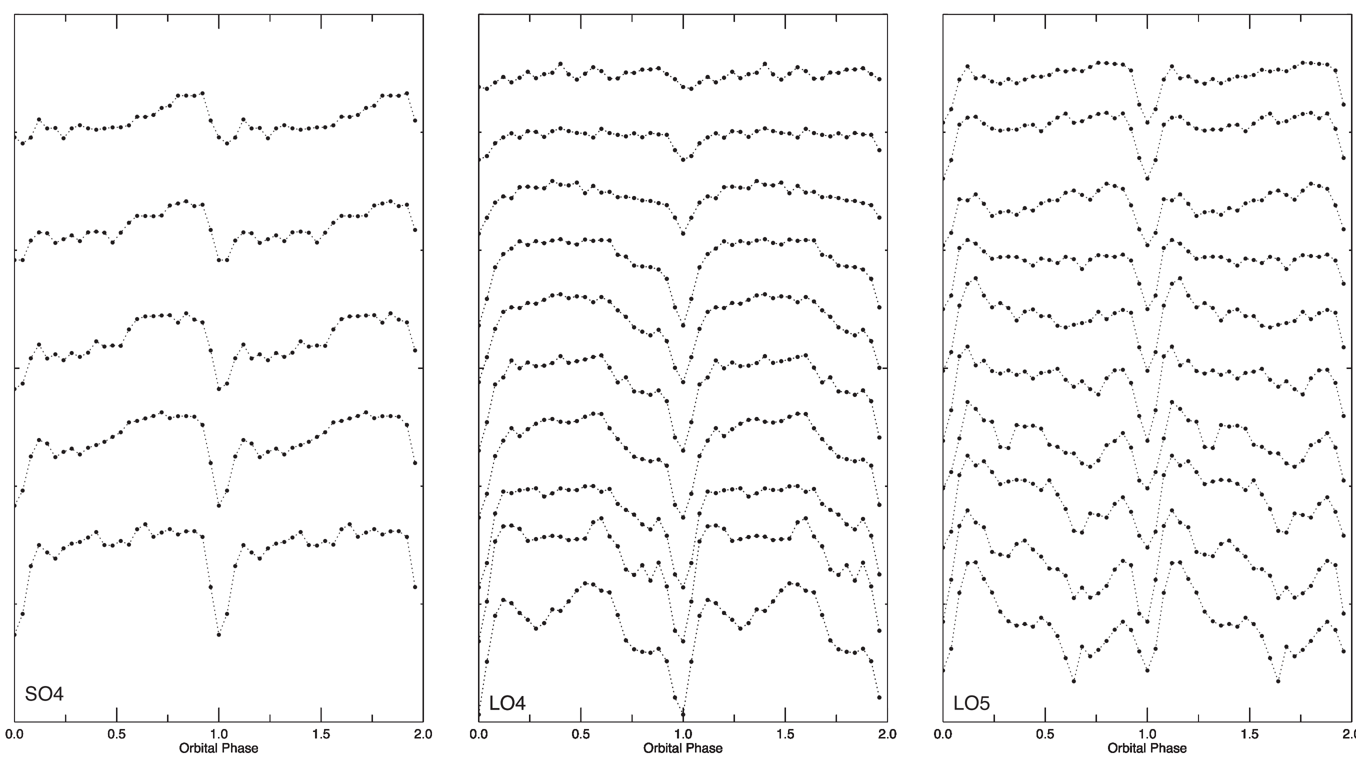

Figure 5. We show a set of folded light curves from a short outburst (SO4 in the left-hand panel) and two long outbursts (L04, middle panel and LO5, right-hand panel). We have detrended the light curve from each outburst and split the light curves into 0.7 d sections and then folded and binned each on the eclipse ephemeris – time increases upwards.

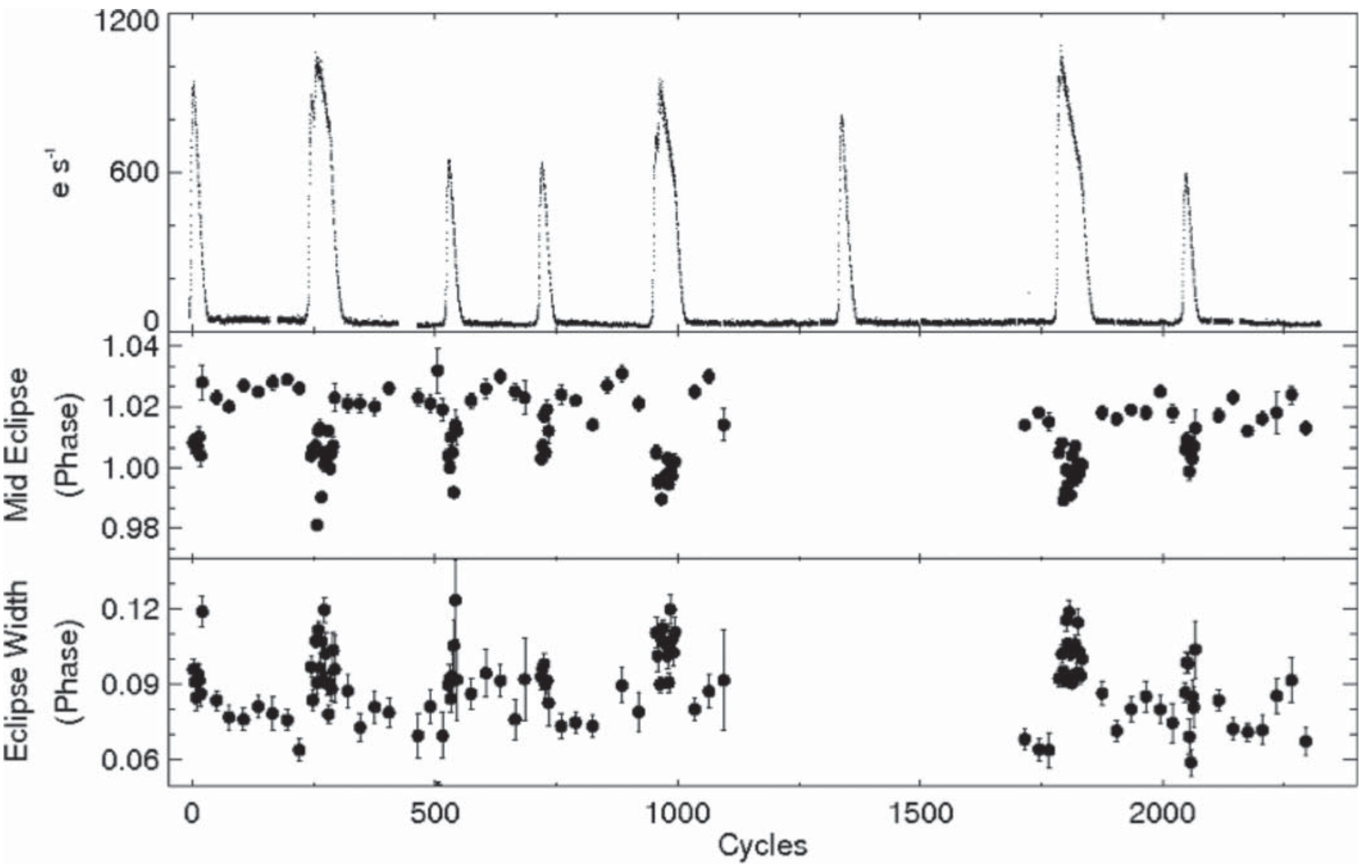

Figure 6. In the top panel we show the light curve derived from the LC mode data. In the middle panel we plot the phase of the mid-eclipse where $\phi = 0.0$ has been defined as the mid-eclipse time during outburst. The lower panel shows the eclipse width in units of orbital phase. (The results for the middle and lower panels were derived using SC data. The gap results from only LC data being obtained during the corresponding quarter.)

determined the mid-point and width of the eclipse. We show the results of this in Fig. 6.

The most obvious result is that during an outburst the phase of the mid-eclipse is centred near $\phi = 0.0$ (since that defined our ephemeris), whereas the phase of the mid-eclipse during quiescence occurs at later phases ($\phi = 1.02$–1.03). There is some suggestion that after a long outburst the phase of eclipse during short outbursts gets progressively later. During long outbursts the full width half-maximum of the eclipse is greater compared to quiescence and also compared to short outbursts. The difference between the results from quiescence and outbursts is largely due to the relative contribution of the bright spot which is seen strongly in the folded light curve from quiescence (Fig. 4) but not during outburst (Fig. 5). If it were only the accretion disc which was being eclipsed, then it would only be the eclipsed width which would change and not the eclipse phase.

To obtain a better overview of the differences between the short and long outbursts, we took each outburst and phased it such that $\phi = 0.0$ defined the start of the outburst, with the end phase being the start of the next burst. We then folded the points of mid-eclipse and the eclipse width for short and long bursts – we show the results of this in Fig. 7. This shows that there is a tendency for the orbital phase of mid-eclipse to be earlier (and with a larger eclipse width) in long outbursts compared to short outbursts, which we interpret as the accretion disc that has a tendency to be larger during a long outburst compared to a short outburst. In short outbursts there is some evidence that the point of mid-eclipse increases after the outburst followed by a decrease, which may suggest a decrease in the size of the disc followed by an increase leading up to the next outburst. During a long outburst the width of the eclipse tends to decrease after outburst. We explore the physical causes for these variations in Section 9.

8 SEARCHING FOR ADDITIONAL PERIODS

We searched for periodic signals (other than the orbital period) in the SC data. We did this by splitting up the data into sections which were taken from quiescent intervals and also individual outbursts, where we detrended the data to remove the effect of the general decline from outburst. The Lomb Scargle periodogram was used to obtain power spectra for each data section.

Power spectra taken from the quiescent data showed a strong signal at a period very close (within the error) to the orbital period. Similarly, power spectra of detrended light curves during outbursts also showed maximum power at a period consistent with the orbital period. We therefore found no significant evidence for super-humps in these data. The detection of super-humps in U Gem (Smak & Waagen 2004) is rather controversial (Schreiber 2007). However, we note that the novalike variable BB Dor has an orbital period only slightly shorter than V447 Lyr at 3.70 h (Rodríguez-Gil et al. 2012), and is reported to display super-humps with a period of 3.93 h. Continued monitoring of V447 Lyr to search for evidence of super-hump behaviour is therefore recommended since systems

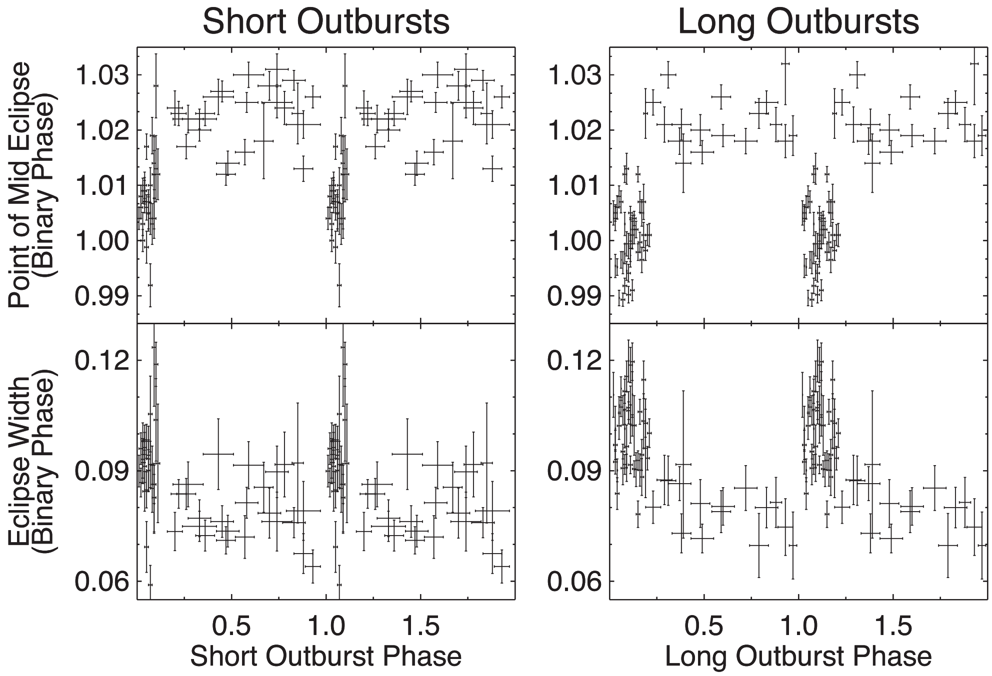

Figure 7. We phased outbursts such that $\phi = 0.0$ corresponded to the start of the outburst and $\phi = 1.0$ corresponded to the point just before the start of the next outburst. We then folded and binned the results for the mid-eclipse times and eclipse widths shown in Fig. 6 to show how these parameters vary over the course of a short outburst (left-hand panels) and a long outburst (right-hand panels).

with an orbital period just shorter than 4 h may define the edge of the super-hump instability strip in period space.

9 DISCUSSION

The cadence of our SC observations precludes us from resolving distinct binary components (e.g. white dwarf and accretion disc) in the eclipse profile. However, we have found a systematic difference in the orbital phase of the mid-eclipse as seen in quiescence and in outburst. We therefore caution that unless you can detect the eclipse of the white dwarf, mid-eclipse times determined from quiescence should not be mixed with times determined from outburst.

Detailed observations from eclipsing dwarf novae place strong constraints on the accretion disc radius as a function of time. Two well-studied systems are U Gem (Smak 1984) and Z Cha (O'Donoghue 1986). The disc expands dramatically during outburst, and then contracts exponentially. Anderson (1988) presents a simple disc model in which the sudden appearance of high viscosity material in outburst causes the rapid expansion, and the accretion of low angular momentum material from the secondary causes the slower contraction. Fig. 1 of Anderson shows a collection of all the U Gem data, which shows a variation of r_d/a between about 0.29 and 0.37. Thus the outburst radius expands by ∼30 per cent during outburst. Anderson infers a minimum mass in the outer accretion disc of $\sim10^{-9}\,M_{\odot}$. Ichikawa & Osaki (1992) examined the radius expansion question using a detailed numerical model for the accretion disc thermal limit cycle mechanism and confirmed Anderson's overall results.

Although the variation in the eclipse width shown in the bottom panel of Fig. 6 shows more variability than the results of Smak (1984), it is similar quantitatively to U Gem – which is apparently a near twin of V447 Lyr in many ways. It is more difficult with our data to state clearly what the form of the decay is, due to the scatter in the quiescent data, but in going from quiescence to outburst the disc expands from ∼0.08 to ∼0.12 in phase units, an increase of ∼50 per cent. Given the similar orbital periods of V447 Lyr and U Gem, a fit using a simple model like Anderson's should also produce a lower limit disc mass $\sim10^{-9}\,M_{\odot}$.

10 CONCLUSIONS

We report observations of V447 Lyr which show that it is the first dwarf nova in the *Kepler* field to show eclipses. It has an orbital period of 3.74 h and shows almost equal numbers of long and short outbursts, which makes it a near twin of the well-studied dwarf nova U Gem. By fitting the mean eclipse profile of three successive eclipses we find that the phase of the mid-eclipse occurs earlier during outbursts compared to quiescence and that the width of the eclipse is greater during an outburst. This suggests that the accretion disc has a larger radius during outburst compared to during quiescence and is consistent with an expansion of the outer disc radius due to the presence of high viscosity material associated with the outburst, followed by a contraction in quiescence due to the accretion of low angular momentum material. *Kepler* observations of dwarf novae outbursts have found that super-outbursts in the shorter orbital period dwarf novae appear to be triggered by a normal outburst. We find that long outbursts also appear to be triggered by short outbursts in V447 Lyr. This indicates that this is a general phenomenon found in CVs which any outburst model will have to reproduce.

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