V729 Sgr: A long period dwarf nova showing negative superhumps during quiescence

Gavin Ramsay\textsuperscript{1}, Matt A. Wood\textsuperscript{2}, John K. Cannizzo\textsuperscript{3,4}, Steve B. Howell\textsuperscript{5}, Alan Smale\textsuperscript{6}

\textsuperscript{1}Armagh Observatory & Planetarium, College Hill, Armagh, BT61 9DG, UK
\textsuperscript{2}Department of Physics and Astronomy, Texas A&M University–Commerce, Commerce, TX 75429, USA
\textsuperscript{3}CREST and Astroparticle Physics Laboratory NASA/GSFC, Greenbelt, MD 20771, USA
\textsuperscript{4}Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA
\textsuperscript{5}NASA Ames Research Center, Moffett Field, CA 94095, USA
\textsuperscript{6}NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

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\section*{ABSTRACT}
We report \textit{K2} observations of the eclipsing cataclysmic variable V729 Sgr which covered nearly 80 days in duration. We find five short outbursts and two long outbursts, one of which shows a clear plateau phase in the rise to maximum brightness. The mean time between successive short outbursts is \(\sim 10\) d while the time between the two long outbursts is \(\sim 38\) d. The frequency of these outbursts are unprecedented for a CV above the orbital period gap. We find evidence that the mid-point of the eclipse occurs systematically earlier in outburst than in quiescence. During five of the six quiescent epochs we find evidence for a second photometric period which is roughly 5 percent shorter than the 4.16 h orbital period which we attribute to negative superhumps. V729 Sgr is therefore one of the longest period CVs to show negative superhumps during quiescence.

\textbf{Key words:} accretion, accretion discs – stars: dwarf novae – stars: individual: V729 Sgr – novae, cataclysmic variables

\section*{1 INTRODUCTION}
After the second of the \textit{Kepler} satellite’s reaction wheels failed in May 2013, the space mission was re-purposed and renamed \textit{K2}. Unlike the original mission which continuously monitored a 115 square degree field north of the Galactic plane between Cygnus and Lyra for 4 years, \textit{K2} monitors fields along the ecliptic plane, each pointing lasting \(\sim 70–80\) days (see Howell et al. 2014). \textit{K2} has been used to study a wide variety of astronomical sources including exoplanets, galaxies, solar system objects, and cataclysmic variables (e.g., Dai et al. 2016; Kennedy et al., 2016).

Briefly, cataclysmic variables (CVs) are interacting binaries in which a low mass star (typically a K/M dwarf) fills its Roche lobe and the material which flows through the L1 point forms an accretion disk around the more massive white dwarf (if the white dwarf has a magnetic field \(\gtrsim 1\)MG the disk is either partially or completely prevented from forming). In the dwarf-nova sub-class of CVs, eruptions are seen every few weeks or months where the brightness of the system increases by \(\sim 1-5\) mag. These outbursts, arising from instabilities in the accretion disk, are excellent sources with which to study the physics of interacting binaries and accretion processes.

\textit{K2} observations during Campaign 9\textsuperscript{1} took place towards the end of 2015 and one of the sources observed was EPIC 214539533, the CV V729 Sgr. This star was first identified as being variable in 1928 with further observations made by Ferwerda (1934) showing it to be an irregular variable with successive maxima being separated by 12–17 days. Although being fairly bright (\(V \sim 14\)) during outburst, V729 Sgr has not been particularly well studied, apart from that of Cieslinski et al. (2000). These authors confirmed its CV nature and found that V729 Sgr was an eclipsing system with a period of 4.16 hrs. In this paper, we report on the \textit{K2} observations of V729 Sgr.

\section*{2 OVERVIEW OF THE \textit{K2} OBSERVATIONS}
\textit{K2} observations of V729 Sgr were made between MJD = 57301.0–57382.4 (2015 Oct 5 – 2015 Dec 26) and were obtained in Short Cadence (SC) mode which yields an effective exposure time of 58.8 sec. Since the \textit{K2} raw light curves of sources need to be photometrically corrected for instrumental effects caused by minute changes to its pointing (van

\textsuperscript{1}https://keplerscience.arc.nasa.gov/k2-fields.html
Figure 1. Top Panel: The K2 short cadence light curve of V729 Sgr. Lower panel: the orbital phase of the eclipse where 6–8 successive eclipses have been averaged to determine the eclipse mid-point.

Cleve et al., 2016), Andrew Vanderburg very kindly supplied the corrected SC light curve using the techniques outlined in Vanderburg & Johnson (2014).

We show the light curve of V729 Sgr in the top panel of Figure 1 and note that it is characteristic of a CV showing regular outbursts. There are seven outbursts, two of which have higher peak fluxes and significantly longer duration than the other five: we call these ‘long’ outbursts and the others ‘short’ outbursts. On average there is an outburst every 12.7 d, with short outbursts lasting ~6.4 d and long lasting ~10.4 d. The mean time interval between successive short outbursts is 10.0 d and the time interval between the two long outbursts is ~38 days. The orbital period of V729 Sgr (4.16 h) is similar to that of the prototype dwarf nova U Gem (4.25 h). U Gem also shows short and long outbursts with a mean outburst recurrence time of ~110 d (Szkody & Mattei 1984), is much longer than V729 Sgr.

The second long outburst is shown in Figure 2. After the initial rise from quiescence, the flux remains roughly constant for nearly 2 days (a feature which we call a ‘plateau’ phase), after which there is a further increase in flux which is the long outburst. In Figure 2 we show this long outburst, superposed with the profiles of the five short outbursts. We have shifted the short outbursts in time by-eye so that each outburst profile has its ‘zero’ point coinciding with the peak of the outburst and the start of the plateau phase of the long outburst. We find that while there is a spread of ~10 percent in the average short outburst amplitude, the amplitude and rise time of the short outbursts are very similar to that of the initial rise in the long outburst.

This behaviour is similar to the superoutbursts observed in the SU UMa dwarf novae (which tend to have shorter orbital periods, \( \lesssim 2 \) h) and the long outbursts seen in U Gem-type dwarf novae, both types of systems which have been observed in detail using Kepler (e.g. V447 Lyr, Ramsay et al. 2012). Indeed, it appears that all super and long outbursts seen in dwarf nova have a short outburst precursor (see Cannizzo 2012). The first long outburst does not show such a clear plateau phase as the second, (perhaps due to residual imperfections in the corrections applied to the raw light curve), but appears to be broadly consistent with such a view.

3 THE ECLIPSE

To investigate the light curve of V729 Sgr in more detail we extracted sections during quiescence and fit each of these with a linear plus Gaussian function. We then took the mid-point of each observed eclipse (the times are given in Appendix 1) and determined a linear fit to these times giving the ephemeris:

\[
To = BMJD57300.5183(5) + 0.173405(2)E
\]

where the numbers in parentheses give the standard error on the last digits. Our determined period, 4.1617 h, is consistent with that found by Cieslinski et al. (2000) and we take this to be the orbital period of V729 Sgr.

We then detrended the light curves covering the short and long outbursts (i.e., the effects of the outbursts have been removed) and determined the time of the eclipses from these data. Taking the individual eclipse times and converting these to orbital phase using equation 1, we find an indication that the mid-point of the eclipse occurs earlier during outburst compared to quiescence. To reduce noise in the eclipse profile, we formed the mean profile using 6–8 eclipses.
4 SUPERHUMPS

CVs show a range of periodic and quasi-periodic behaviour in their light curves. In the absence of eclipses and/or phase resolved spectra it can sometimes be difficult to determine the origin for periods identified in power spectra. This is due to the fact that in addition to there generally being a signature of the orbital period in the light curve, CVs quite often show signatures of ‘superhumps’. The ‘positive’ superhumps are due to torsional disc oscillations and have periods slightly longer than the orbital period (e.g., Wood et al. 2011), whereas the ‘negative’ superhumps result from a tilt and retrograde precession of the accretion disc (e.g., Wood, Thomas, & Simpson 2009). In the latter case, the accretion stream bright spot transiting the face of the tilted disc provides the negative superhump signal. For CVs with orbital periods shorter than ~2 hrs, positive superhumps are seen in almost all CVs found in superoutburst (e.g., Patterson et al. 2005). The ‘period excess’ over the orbital period has been used to estimate the orbital period of many CVs.

There are a small number of CVs where negative superhumps have been detected including during quiescence (e.g., Wood et al. 2011 reported negative superhumps in the Kepler observations of V344 Lyr, and Osaki & Kato 2013 reported the detection of negative superhumps over a full supercycle using Kepler observations of V1504 Cyg). The physical origin of the tilt of the disk negative superhumps has not been firmly established, but Thomas & Wood (2015) adapted the results of Lai (1999) in smoothed particle hydrodynamic simulations to find that a magnetic field on the primary can tilt the disk out of the orbital plane.

We detrended the light curves for the short and long outburst intervals seen in V729 Sgr and then obtained Lomb Scargle Power Spectra and also Discrete Fourier Transforms (DFT) of these light curves. The short or long outbursts show no evidence for a period in the light curve other than \( P_{\text{orb}} \) (which we know precisely from the eclipses). However, we find evidence for a period which is shorter than the orbital period in five out of the six quiescent epochs. To investigate this in more detail we pre-whitened the light curves by removing the orbital period and its three harmonics and then obtained a DFT. We show the DFT of the six detrended light curves in Figure 4. These DFT show clear peaks at a period which is shorter than the orbital period in five of the six quiescent light curves: we identify these peaks as a signature of a negative superhump. We indicate the period of these peaks in Table 1 and also the negative super-hump excess \( \epsilon = (P_{\text{orb}} - P_{\text{sh}})/P_{\text{orb}} \). We also did the same analysis using a single light curve made up of the individual detrended Q2-Q6 quiescent light curves, and find a strong peak at 237.4 min. We folded each of the quiescent light curves in Figure 2, and instead a minimum is seen at \( \phi \sim 0.7-0.8 \). In addition, the eclipse becomes deeper from quiescence to short outburst and into long outburst, which may indicate that the system brightness is concentrated close to the white dwarf (perhaps the boundary layer between the accretion disk and white dwarf). The eclipse is also broader during outburst and indicates (as was seen in V447 Lyr) that the disk has a greater extent compared to quiescence.

5 DISCUSSION

5.1 General Characteristics

The upper panel of Fig. 1 indicates that V729 Sgr has characteristics which are typical of CVs, showing frequent short
Figure 3. The folded and binned light curves of V729 Sgr during quiescence (top panel); short outburst (middle panel) and long outburst (bottom panel). In the right hand panels we highlight the profile of the eclipse.

| Quiescence Section | $P_{+sh}$ (min) | $\epsilon^+$ |
|--------------------|-----------------|-------------|
| Q2                 | 238.18          | 0.046       |
| Q3                 | 236.30          | 0.054       |
| Q4                 | 237.46          | 0.049       |
| Q5                 | 237.60          | 0.048       |
| Q6                 | 237.31          | 0.050       |

Table 1. We show the period identified in each of the six quiescent epochs and indicate whether they are likely negative superhumps ($P_{-sh}$) or positive superhumps ($P_{+sh}$) and note the positive $\epsilon^+$ and negative $\epsilon^-$ super-hump excess.

and long outbursts. The light curve also shows eclipses, allowing the orbital period to be unambiguously determined, (4.16 hr), placing it above the orbital period gap. By determining the phase of the mid-eclipse we find that the eclipse center occurs earlier in phase during an outburst compared to quiescence (lower panel of Fig 1). This is consistent with observations of other CVs, and is due to the differing relative contribution of the bright spot to the overall optical brightness in outburst compared to quiescence. The duration of the short outbursts seen in V729 Sgr are also typical of sources with similar orbital period, whilst the duration of the long bursts are marginally shorter (we caution that we have a sample of only two long outbursts) than other CVs with similar orbital period (see Fig 17 and 18 of Otulakowska-Hypka et al. 2016).

5.2 The frequency of outbursts

However, there are two features of the K2 light curve of V729 Sgr which make this CV rather unusual. The first is the high frequency of the outbursts, which is $\sim$10 d for successive short outbursts and 38 d between the two long outbursts (which by necessity we assume is typical of the rate of long outbursts in this system). In Figure 6 we plot the recurrence times of short and long outbursts for the 17 CVs with values reported in Ritter & Kolb (2003) (all systems have an orbital period less than 2.1 hrs) and we add the values for V729 Sgr and V447 Lyr (Ramsay et al. 2012). The general trend, which was noted by Warner (1995), is that the short outburst rate is proportional to the super or long outburst rate.

The *Kepler* observations of V447 Lyr (orbital period 3.74 hr) show it is only a marginal outlier compared to the short period systems, but V729 Sgr is clearly an outlier and falls into the lower left of Fig 2 of Warner (1995), which has only 3 systems in this part of the distribution. These systems are the ER UMa systems (a sub-class of CVs which also includes V1159 Ori and RZ LMi, see Kato et al. 2016) which show outbursts every handful of days and superoutbursts every month or so. This is unexpected (and so far not adequately explained) since a short recurrence time is predicted to be due to a high mass accretion rate. However, the known ER UMa CVs all have periods below the orbital period gap at 2 hrs (RZ LMi has an orbital period of $\sim$83 min) and are therefore expected to have relatively low mass transfer rates. In the case of V729 Sgr we have a CV above the period gap (and hence higher mass transfer rate) which shows frequent outbursts.

Dwarf novae exhibit a considerable scatter in outburst properties at a given orbital period (Patterson 1984, Knigge...
et al. 2011), indicating the mass transfer rate $M_T$ feeding into the outer disk can vary considerably from one system to another. This is presumably due to the fact that the secondary stars can have widely varying histories to end up at a given orbital period, as evidenced by the dispersion in stellar radii at given orbital period (Knigge et al. 2011; see their Figure 6). In the disk instability model, higher $M_T$ translates into a faster build-up of accretion disk material in quiescence, and therefore more frequent outbursts. Therefore V729 Sgr can be explained by invoking a higher-than-average $M_T$.

Superoutbursts are usually defined as long outburst exhibiting (positive) superhumps, and yet in V729 they are lacking. Our current understanding for superhumps is that they are due to a torsionally oscillating eccentric disk which undergoes prograde precession (Whitehurst 1988). Physical conditions in the disk allow for this to occur when the disk grows large enough so that the radius of 3:1 resonance with the binary orbital period is exceeded. Given that CV primary masses are $\sim 1 M_\odot$ and the secondary mass is $\sim 0.1 M_\odot (P_{\text{orb}}/1 \text{ hr})$, this means superhumps can only occur in short orbital period systems $P_{\text{orb}} < 3 \text{ hr}$. The mass ratio in V729 is probably not extreme enough to support superhumps during outburst because the point of 3:1 resonance lies beyond the last stable (i.e., non-intersecting) orbit. Van Paradijs (1983) carried out a study of long and short outbursts above and below the 2–3 hr period gap and concluded that superoutbursts in the SU UMa systems are consistent in their properties with long outbursts in systems above the period gap. In other words, dwarf novae in general exhibit alternating series of long and short outbursts. Systems below the period gap tend to have more short outbursts between two long outbursts. The lack of superhumps in the long outbursts in V729 Sgr and V447 Lyr indicates they are not required for long outbursts to occur.
5.3 The detection of negative superhumps

The second feature of V729 Sgr which make it unusual is the presence of negative superhumps during quiescence. Wood et al. (2009) list 21 CVs which have negative superhump excesses reported in the literature. The system with the longest orbital period was TV Col which has a moderately magnetic white dwarf (and is an intermediate polar). The next longest period system was LT Eri (SDSS J0407-0644) with $P_{\text{orb}}=4.08$ hrs. The Ritter & Kolb Catalogue 7.23 (2015 Dec) (Ritter & Kolb 2003) gives 27 sources which are reported as displaying negative superhumps. Three have orbital periods longer than V729 Sgr. AT Cnc ($P_{\text{orb}}=4.83$ h was reported to have negative superhumps with $P_{\text{orb}}=4.65$ h and 4.74 h made when it was in a bright standstill episode (Kozhevnikov 2004). Quasi-Periodic signals were seen in AY Psc ($P_{\text{orb}}=5.22$ h over three years which were ~5 percent shorter than $P_{\text{orb}}$ (Gülsen et al. 2009) and interpreted as negative superhumps (it is unclear whether these superhumps were seen in quiescence or outburst). Finally, KIC 9406652 ($P_{\text{orb}}=6.11$ h) was found to show a period of 5.75 hr (Gies et al. 2013) which although present over the whole of the Kepler observations its amplitude varied over time, making KIC 9406652 the longest period CV to show negative superhumps. V729 Sgr is therefore unusual (although not unique) in showing negative superhumps above the orbital period gap during quiescence.

6 CONCLUSIONS

V729 Sgr is worthy of further investigation since it shows outbursts on a more frequent basis than its orbital period indicates. Future observations should set out to identify further examples of long outbursts and determine their frequency. Higher cadence observations are encouraged at all accretion states to search for superhumps (both positive and negative) to determine how often the negative superhumps are observed in this system. It should shed important light on the nature of accretion disks in high mass transfer rate systems.

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APPENDIX A: ECLIPSE TIMES
Table A1. The time of the mid-eclipse (BMJD) is shown with the cycle number in the right hand column (see §3 for details).

| Time (BMJD) | Cycle | Time (BMJD) | Cycle | Time (BMJD) | Cycle |
|------------|-------|------------|-------|------------|-------|
| 57309.540  | 52    | 57338.492  | 219   | 57375.430  | 432   |
| 57309.707  | 53    | 57338.668  | 220   | 57375.605  | 433   |
| 57310.880  | 54    | 57339.016  | 222   | 57375.940  | 435   |
| 57310.050  | 55    | 57339.188  | 223   | 57376.130  | 436   |
| 57310.227  | 56    | 57339.360  | 224   | 57376.300  | 437   |
| 57310.574  | 58    | 57346.645  | 266   | 57376.470  | 438   |
| 57310.746  | 59    | 57346.816  | 267   | 57376.640  | 439   |
| 57310.926  | 60    | 57346.992  | 268   |              |       |
| 57311.094  | 61    | 57347.164  | 269   |              |       |
| 57311.270  | 62    | 57347.336  | 270   |              |       |
| 57311.445  | 63    | 57347.510  | 271   |              |       |
| 57311.613  | 64    | 57347.684  | 272   |              |       |
| 57311.790  | 65    | 57347.855  | 273   |              |       |
| 57311.965  | 66    | 57348.030  | 274   |              |       |
| 57312.137  | 67    | 57348.203  | 275   |              |       |
| 57323.586  | 133   | 57348.380  | 276   |              |       |
| 57323.750  | 134   | 57348.550  | 277   |              |       |
| 57323.930  | 135   | 57348.900  | 279   |              |       |
| 57324.100  | 136   | 57349.070  | 280   |              |       |
| 57324.277  | 137   | 57349.242  | 281   |              |       |
| 57324.453  | 138   | 57349.420  | 282   |              |       |
| 57324.620  | 139   | 57349.594  | 283   |              |       |
| 57324.797  | 140   | 57349.770  | 284   |              |       |
| 57324.970  | 141   | 57349.940  | 285   |              |       |
| 57325.140  | 142   | 57362.074  | 355   |              |       |
| 57325.316  | 143   | 57362.250  | 356   |              |       |
| 57325.490  | 144   | 57362.420  | 357   |              |       |
| 57325.660  | 145   | 57362.600  | 358   |              |       |
| 57325.840  | 146   | 57362.777  | 359   |              |       |
| 57326.010  | 147   | 57362.950  | 360   |              |       |
| 57326.180  | 148   | 57363.117  | 361   |              |       |
| 57326.355  | 149   | 57363.290  | 362   |              |       |
| 57326.527  | 150   | 57363.465  | 363   |              |       |
| 57326.703  | 151   | 57363.637  | 364   |              |       |
| 57326.875  | 152   | 57363.812  | 365   |              |       |
| 57327.047  | 153   | 57363.984  | 366   |              |       |
| 57327.223  | 154   | 57364.156  | 367   |              |       |
| 57327.395  | 155   | 57364.332  | 368   |              |       |
| 57327.570  | 156   | 57364.504  | 369   |              |       |
| 57327.742  | 157   | 57364.676  | 370   |              |       |
| 57327.914  | 158   | 57364.850  | 371   |              |       |
| 57328.090  | 159   | 57365.023  | 372   |              |       |
| 57328.260  | 160   | 57365.195  | 373   |              |       |
| 57328.438  | 161   | 57365.370  | 374   |              |       |
| 57328.610  | 162   | 57365.543  | 375   |              |       |
| 57328.785  | 163   | 57365.720  | 376   |              |       |
| 57328.957  | 164   | 57365.890  | 377   |              |       |
| 57336.418  | 207   | 57366.070  | 378   |              |       |
| 57336.586  | 208   | 57366.242  | 379   |              |       |
| 57336.766  | 209   | 57373.690  | 422   |              |       |
| 57336.934  | 210   | 57373.867  | 423   |              |       |
| 57337.105  | 211   | 57374.043  | 424   |              |       |
| 57337.280  | 212   | 57374.215  | 425   |              |       |
| 57337.453  | 213   | 57374.387  | 426   |              |       |
| 57337.625  | 214   | 57374.562  | 427   |              |       |
| 57337.797  | 215   | 57374.740  | 428   |              |       |
| 57337.977  | 216   | 57374.906  | 429   |              |       |
| 57338.145  | 217   | 57375.082  | 430   |              |       |
| 57338.320  | 218   | 57375.258  | 431   |              |       |