Kepler observations of the eclipsing cataclysmic variable
KIS J192748.53+444724.5

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ABSTRACT
We present results from long-cadence Kepler observations covering 97.6 d of the newly discovered eclipsing cataclysmic variable KIS J192748.53+444724.5/KIC 8625249. We detect deep eclipses of the accretion disc by the donor star every 3.97 h. Additionally, the Kepler observations also cover a full outburst for this cataclysmic variable, making KIS J192748.53+444724.5 the second known eclipsing cataclysmic variable system in the Kepler field of view. We show how in quiescence a significant component associated with the hotspot is visible preceding the eclipse, and that this component is swamped by the brightness increase during the outburst, potentially associated with the accretion disc. Furthermore, we present evidence for accretion disc radius changes during the outburst by analysing the out-of-eclipse light levels and eclipse depth through each orbital cycle. We show how these parameters are linearly correlated in quiescence, and discuss how their evolution during the outburst suggests disc radius changes and/or radial temperature gradient variations in the disc.

Key words: accretion, accretion discs—binaries: close—stars: individual: KIS J192748.53+444724.5—stars: individual: KIC 8625249.

1 INTRODUCTION
Cataclysmic variables (CVs) are interacting close binary systems where a late-type star transfers material to a white dwarf (WD) companion via Roche lobe overflow. With a system orbital period in the range of hours, the transferred material from the secondary star forms an accretion disc surrounding the WD. As angular momentum is transported outwards in the disc, material will approach the innermost regions close to the WD in the absence of strong magnetic fields, and eventually accrete on to the compact object. Eclipsing CVs are particularly useful not only because the system parameters can be recovered (such as the masses of the two stars), but also because modelling the eclipses allows us to study in great detail the physics of the accretion disc (see Horne 1985; Feline et al. 2004). In total, 208 eclipsing systems are known (Ritter & Kolb 2003 version 7.12). In this Letter, we report on the discovery of an eclipsing dwarf-nova-type CV within the Kepler field of view (FOV): KIC 8625249/KIS J192748.53+444724.5 (hereafter KIS J1927). This is the second known eclipsing CV in the Kepler field, after V447 Lyr (Ramsay et al. 2012).

KIS J1927 was first discovered as a CV by Scaringi et al. (2013) via spectroscopic follow-up of sources from the Kepler-INT Survey (Greiss et al. 2012) displaying both Hα and blue colour excess.

Soon after the discovery, the Kepler satellite began monitoring this object (Kepler passband magnitude of $Kp = 18.4$) with a timing resolution of 29.4 min [long-cadence (LV) mode]. Only seven CVs have been observed and studied with Kepler (Cannizzo et al. 2010; Still et al. 2010; Wood et al. 2011; Barclay et al. 2012; Cannizzo et al. 2012; Osaki & Kato 2012, 2013; Ramsay et al. 2012; Scaringi et al. 2012a,b; Kato & Maehara 2013; Kato & Osaki 2013), but an additional eight have recently been monitored.

In Section 2, we introduce the Kepler satellite and the available observations, and present the orbital light curve of KIS J1927. In Section 3, we provide an ephemeris for the system, whilst in Section 4 we discuss the folded light curve on the orbital period. Section 5 discusses how the Kepler photometry provides evidence for accretion disc radius changes and/or radial temperature gradient variations during the observed outburst of KIS J1927, and places our observations in the context of previous work. Our conclusions are drawn in Section 6, and prospects for future Kepler observations of KIS J1927 are discussed.
FOV. The shutterless photometer (with a response function covering the wavelength range 4000–9000 Å) has a 116 deg² FOV and makes use of 6.02 s integrations (plus an additional 0.52 s for CCD readout). Only pixels containing pre-selected targets are saved due to telemetry bandwidth and onboard memory constraints. Up to 170 000 targets can be observed in LC mode, where 270 integrations are summed onboard the spacecraft for an effective 29.4 min exposure, and up to 512 targets can be observed in short-cadence (SC) mode, where 9 integrations are summed for an effective 58.8 s exposure. Gaps in the photometric light curves are the result of quarterly data downlinks, as well as Kepler occasionally entering anomalous safe modes. During such events no data are recorded, and for a few days following these events the data are always correlated due to the spacecraft not being in thermal equilibrium. Further details of artefacts within Kepler light curves can be found in the Kepler Data Release Notes 20 (Thompson et al. 2013). Here, we make no attempt to correct these artefacts, but simply remove them from the light curve.

The data for KIS J1927 discussed in this Letter are that of the first quarter with available and reduced observations (Quarter 15: 2012 October 04–2013 January 06) obtained in LC mode. KIS J1927 resides in a crowded field with a number of close neighbours identified, including the $K_\text{p} = 17.4$ object KIC 8625243. The archived simple aperture photometry is based upon the summation of two collected pixels with CCD module 13.3 coordinates (271, 859) and (272, 859). We expect these two pixels to be contaminated by the point-spread-function (PSF) wings of near neighbours, and the correction for contamination in the archived pre-search conditioning data is overly simplified, resulting in the eclipse depths to be underestimated in the archived simple aperture photometry. To rectify this situation, we extract new photometry from the archived target pixels using PSF photometry. The PSF model was downloaded from the Mikulski Archive for Space Telescopes (MAST\textsuperscript{1}). A more precise PSF distribution was obtained by interpolation over the position of KIS J1927 and this model was fitted to the target pixels, at each photometric time stamp. A fit adopting three significant sources within the target mask proved sufficient to reduce the residuals to an acceptable level (Pearson’s $\chi^2 = 173$ for 26 degrees of freedom). The resulting photometric time series for the target star is provided in Fig. 1. A typical fit to the pixels collected from a single time stamp is provided in Fig. 2. The median eclipse depth (relative to the out-of-eclipse light) within the simple aperture photometry was 90.3 electrons s\(^{-1}\), whereas the median eclipse depth within the PSF photometry was 161.2 electrons s\(^{-1}\).

The light curve in Fig. 1 shows a large-amplitude outburst starting shortly after the beginning of the observations, similar to the

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\textsuperscript{1} http://archive.stsci.edu/kepler/fpc.html
outbursts observed in dwarf-nova-type CVs (see Cannizzo et al. 2010, 2012; Still et al. 2010; Wood et al. 2011; Kato & Maehara 2013). The Fourier transform of the quiescent interval (BJD > 245 6226 d) is shown in Fig. 3, where the orbital period is clearly visible, as well as higher harmonics due to the non-sinusoidal light curve shape through each orbit. Also alias periods are present, which are due to the close proximity of integer multiples of the sampling frequency to the system orbital period. The most notable aspect of the light curve is the eclipses occurring every 3.97 h as the binary inclination angle is high enough to cause the donor star to eclipse the accreting WD and/or its associated accretion disc and hotspot.

3 ECLIPSE TIMINGS

We estimated the arrival times of the eclipse minima by fitting a spline function independently to each orbital cycle, and determining the time of minimum flux within the fitted curve. In order to obtain the eclipse ephemeris, we then fitted a linear curve to the observed mid-eclipse times for every observed cycle. The accuracy of the ephemeris is then assumed to be the small scatter around the fit, which is mainly caused by the aliasing of the sampling frequency to the orbital period. The mid-eclipse ephemeris is then

\[ \text{BJD}_{\text{min}} = 245 6206.0845(17) + 0.165 \times 3077(49) \times N, \]

where \( N \) is the cycle number. The 1σ uncertainty for the parameters is given in parentheses for the last digits.

4 FOLDED LIGHT CURVE

Fig. 4 shows the light curve folded on the orbital period of 3.97 h during the quiescent interval (BJD > 245 6226 d). The median eclipse depth relative to the out-of-eclipse flux is 34 per cent. However, this value is most likely underestimated as a result of the data cadence. Future observations with a faster cadence may better resolve each orbital cycle and reveal the eclipses to be deeper than what is observed here. The increase in flux at the orbital phase just preceding the eclipse (\( \phi \approx 0.8 \pm 0.9 \), where \( \phi \) is the orbital phase) can be explained by the hotspot (where the accretion stream from the donor star impacts the outer edges of the accretion disc) being observed nearly face-on (Wood et al. 1986). It is also possible that the hotspot itself is also being eclipsed by the donor star. This would explain the observed flux descent after the eclipse (\( \phi \approx 0.1 \pm 0.3 \)) as a continuation of the hotspot emission, and would imply that the maximum hotspot brightness occurs during the eclipse.

Assuming that we can derive the mass ratio of the system, we can place constraints on the system inclination. To do this, we use the semi-empirical donor tracks of Knigge, Baraffe & Patterson (2011) to infer the mass of the secondary star of \( M_2 = 0.32 \, M_\odot \) from the observed orbital period. Since the mass ratio \( q = M_2 / M_1 \) has to be smaller than 2/3 for stable mass transfer to occur (Warner 2003), and since the mass of the primary can at most be the Chandrasekhar limit (1.4 \, M_\odot), we infer a mass ratio range of 0.23 < \( q < 0.67 \). We note however that the mass ratio might be larger than 0.35 for this system as no superhumps are detected during outburst (although this might be caused by the low sampling rate), but we employ a larger conservative range. By fitting a Gaussian function to the folded eclipse profile (between 0.85 < \( \phi < 1.1 \)), we also infer a full width at half-maximum of the eclipse of \( \Delta \phi = 0.095 \). We then employ the method of Horne (1985) to deduce an inclination of \( i > 80^\circ \).

5 VARYING ACCRETION DISC RADIUS

Fig. 1 shows the Kepler light curve of KIS J1927 as a function of orbital cycle, with insets displaying zoomed portions of the light curve during outburst and quiescence. It is clear from Fig. 1 that there are significant changes in the eclipse profiles as the system switches between outburst and quiescence. Most notably, the increase in flux at \( \phi \approx 0.8 \pm 0.9 \) associated with the hotspot is much less pronounced during the outburst. This potentially suggests that during the outburst, the optical light is dominated by the accretion disc and the bright spot makes a significantly smaller contribution to the total optical flux as compared to quiescence, and/or that the hotspot emitting region has changed from a small, compact, region to a larger structure over the disc. Additionally, the eclipse depth relative to the out-of-eclipse light changes from 34 per cent in quiescence to 58 per cent in outburst.

The Kepler observations of KIS J1927 displayed an increase in brightness of 2.5 mag during the outburst. Fig. 5 shows the relation between the out-of-eclipse brightness and the eclipse depth. Studies on how these variations are correlated in eclipsing CVs have been presented by Groot et al. (1998) and Walker (1963). These studies found that during quiescence the out-of-eclipse light is linearly correlated with the eclipse depth, but also that deviations are observed from this correlation, namely the ‘Walker branch’ (as these excursions were first noted by Walker 1963) and the ‘Shallow branch’ (naming after fig. 2 of Groot et al. 1998). The explanation for the linear correlation between the out-of-eclipse light and the eclipse depth is simple geometry, where the same part of the disc is eclipsed during every orbital cycle, assuming that the radial temperature gradient of the disc remains constant. If the accretion disc brightens by say 1 mag (but does not increase in size), then the eclipse depth will also increase by the same amount. In principle, during each
observations of KIS J1927

Kepler observations of KIS J1927

During the outburst evolution, a decrease in the radial temperature gradient (say from \( T \approx R^0 \) to \( T \approx R^{-3/4} \)) is expected. This will cause observations to lie above the ‘line of maximal eclipse’ in the case where the innermost edges of the disc are being eclipsed during each cycle. The only way to then explain our observations is by increasing the radial size of the disc during the outburst. If the innermost edges of the disc are not being eclipsed, then an increase in the radial temperature gradient could explain our observations. However, we note that CV accretion discs are theoretically expected to expand in radius, and the temperature gradient is theoretically expected to decrease, during outbursts (Anderson 1988; Frank, King & Raine 2002). Furthermore, many CVs display this expansion in their observational properties (e.g. U Gem, Smak 1984; Z Cha, O’Donoghue 1986).

6 CONCLUSION

We have reported on LC Kepler observations of the eclipsing CV KIS J1927. The system has an orbital period of 3.97 h, and displays an \( \approx 2.5 \text{ mag.} \) 10 d-long outburst during the 97.6 d-long observation. The quiescent folded light curve displays a significant contribution from the hotspot, which is swamped during the outburst, potentially by the bright accretion disc. We have also reported on evidence for accretion disc radius changes during the outburst of this system by studying the out-of-eclipse light levels versus the eclipse depth during the outburst. We find that the eclipse depth and out-of-eclipse light levels are linearly correlated in quiescence, and that this correlation is offset during outburst. This result suggests that the accretion disc increases in radius and/or temperature during the outburst. Similar implications on the other eclipsing CV in the Kepler field (V447 Lyr; Ramsay et al. 2012) have also been deduced, as well as previous work using ground-based observations (Rutten et al. 1992; Groot et al. 1998).

The main drawback from our analysis has been the light curve cadence, which coarsely samples the eclipses. SC Kepler observations of this object, with a sampling time-scale of 58.5 s, would potentially allow us to model the light curve via eclipse mapping and to separate out each individual contribution of the light curve for every orbital cycle (accretion disc, hotspot, WD and secondary star). Furthermore, eclipse mapping on SC data will allow us to locate the physical origin of flickering in CVs (Baptista & Bortletto 2004; Scaringi et al. 2012a) with unprecedented precision. Additionally, eclipse mapping of this system using SC data will potentially allow us to track the disc evolution during the outburst, and to infer both radius and temperature changes during the rise and fall of the outburst. If additional observations by Kepler become viable after investigation of further two or three reaction wheel operations, KIS J1927 is a valuable potential target for SC observations.

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