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Cataclysmic variables from the Catalina Real-time Transient Survey

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ABSTRACT

We present 855 cataclysmic variable candidates detected by the Catalina Real-time Transient Survey (CRTS) of which at least 137 have been spectroscopically confirmed and 705 are new discoveries. The sources were identified from the analysis of five years of data, and come from an area covering three quarters of the sky. We study the amplitude distribution of the dwarf novae cataclysmic variables (CVs) discovered by CRTS during outburst, and find that in quiescence they are typically 2 mag fainter compared to the spectroscopic CV sample identified by the Sloan Digital Sky Survey. However, almost all CRTS CVs in the SDSS footprint have *ugriz* photometry. We analyse the spatial distribution of the CVs and find evidence that many of the systems lie at scale heights beyond those expected for a Galactic thin disc population. We compare the outburst rates of newly discovered CRTS CVs with the previously known CV population, and find no evidence for a difference between them. However, we find significant evidence for a systematic difference in orbital period distribution. We discuss the CVs found below the orbital period minimum and argue that many more are yet to be identified among the full CRTS CV sample. We cross-match the CVs with archival X-ray catalogues and find that most of the systems are dwarf novae rather than magnetic CVs.

Key words: stars: distances – stars: dwarf novae – novae, cataclysmic variables – galaxies: stellar content.

1 INTRODUCTION

Cataclysmic variables (CVs) are a common state of evolved compact binary systems. Such systems consist of a main-sequence, sub-giant or brown dwarf star that is filling its Roche lobe and transferring mass on to a white dwarf (Warner 2003). The accretion process can be either directly on to a strongly magnetic white dwarf or by way of an intervening accretion disc. Many CV systems with accretion discs undergo thermal instabilities within their discs (Meyer & Mayer-Hofmeister 1981) that give rise to outbursts of up to 8 mag, and make up the CV sub-class termed dwarf novae (e.g. Patterson et al. 1981; Howell, Szkody & Cannizzo 1995). These outbursting events in dwarf novae-type CVs can last from days to weeks (e.g. Szkody & Mattel 1984). Apart from their role in binary star evolution, understanding such systems is important for cosmology, since CVs remain possible progenitors to Type-Ia supernovae explosions (Immer et al. 2006; Patat et al. 2007; Zorotovic, Schreiber & Gänsicke 2011; Kafka, Honeycutt & Williams 2012).

Historically, the discovery of dwarf nova type CVs has been in large part due to serendipitous detection and subsequent follow-up studies (Gänsicke 2005). More recently, confirmation of dwarf nova candidates has been undertaken routinely by a large network of small telescopes (Kato et al. 2009). The discovery of these systems is aided by the large intrinsic variations of the sources. However, the lack of deep synoptic wide-field surveys has meant that most historical CV discoveries have been either relatively bright nearby CV systems, or fainter systems undergoing very large outbursts. An exception to this discovery method has been the Sloan Digital Sky Survey (SDSS), which undertook a spectroscopic survey of more than a hundred thousand QSO targets (Schneider et al. 2010; Paris et al. 2012). Due to the similar optical colours of QSOs and CVs, besides large numbers of QSOs, a few hundred CVs were discovered (Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007,

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2009, 2011). Since these CV systems were identified from quiescent spectra rather than optical variation, this survey presented an unprecedented insight into the variety of system properties within the CV population, and led to the firm detection of the predicted accumulation of CVs near the orbital period minimum (Gänsicke et al. 2009). However, as spectroscopic observations require more flux than photometry, the SDSS CV sample was limited to sources with $i < 19.1$ (although later work followed some targets as faint as $i = 20.2$; Richards et al. 2002).

The fact that dwarf novae brighten by many magnitudes during their outbursts enables the discovery of CV systems that are very faint in quiescence. However, intrinsically faint systems have lower accretion rates and less frequent outbursts compared to bright sources, thus introducing a bias in variability-based searches (Wils et al. 2010). To find large numbers of the faintest CV systems, it is necessary to repeatedly survey large areas of the sky.

A number of surveys have begun to systematically explore the astronomical time domain in order to discover optical transient events, such as CV outbursts. These projects include the Catalina Real-time Transient Survey (CRTS; Drake et al. 2009a; Djorgovski et al. 2011), the Panoramic Survey Telescope and Rapid Response System (PanSTARRS; Hodapp et al. 2004), the Palomar Transient Factory (PTF; Law et al. 2009) and the La Silla Quest survey (LSQ; Rabinowitz et al. 2011). All these surveys are capable of discovering hundreds of intrinsically faint CVs during outbursts. However, among these surveys only CRTS openly reports the discovery of CVs. Future surveys such as SkyMapper (Keller et al. 2007), *Gaia* (Perryman et al. 2001) and the Large Synoptic Survey Telescope (LSST; Ivezic et al. 2008) are also expected to detect numerous CVs.

In this paper we describe the CV systems that were detected by CRTS in data taken by the Catalina Sky Survey between 2007 November 8th and 2012 July 31st. We will then investigate the basic properties of these systems and outline areas where additional work is required to better understand their nature.

2 OBSERVATIONAL DATA

The Catalina Sky Survey[1] began in 2004 and uses three telescopes to repeatedly survey the sky between declination $\delta = -75$ and $+65^{\circ}$ in search of Near-Earth Objects (NEOs) and Potential Hazardous Asteroids (PHAs). In addition to asteroids, all the Catalina data are analysed for transient sources by CRTS (Drake et al. 2009a; Djorgovski et al 2011).

Each of the survey telescopes is run as separate sub-surveys. These consist of the Catalina Schmidt Survey (CSS), the Mount Lemmon Survey (MLS) and the Siding Spring Survey (SSS). In this paper we analyse data taken by all three telescopes, namely the 0.7-m CSS telescope and the 1.5-m MLS telescope in Tucson, AZ, and the 0.5m (SSS) Uppsala Schmidt at Siding Spring Observatory, Australia. Transient processing of CSS data by CRTS began on 2007 November 8, while for MLS data it began on 2009 November 6, and for SSS on 2010 May 5.

Each telescope currently has a 4k × 4k CCD camera, which for the CSS, MLS and SSS cover 8.2, 1.1 and 4 $\deg^2$, respectively. In general each telescope avoids the Galactic latitudes less than 10 to 15° due to reduced source recovery in crowded stellar regions. Because of its smaller field-of-view the MLS 1.5-m telescope predominately observes only ecliptic latitudes $-10^{\circ} < \beta < 10^{\circ}$, whereas the CSS covers $-30^{\circ} < \delta < 65^{\circ}$ and the SSS mainly covers $-75^{\circ} < \delta < 0^{\circ}$. In total, ∼30 000 $\deg^2$ of the sky are surveyed by the three telescopes.

Observations are taken during the darkest 21 nights per lunation in sets of four images each separated by 10 min. Exposures typically last for 30 s. All images are taken unfiltered to maximize throughput. Photometry is carried out using the aperture photometry program SExtractor (Bertin & Arnouts 1996) and is transformed to V using standard stars as noted by Drake et al. (2013).

[1] http://www.lpl.arizona.edu/css/

3 TRANSIENT SELECTION

The CRTS project is aimed at the discovery of astrophysical sources such as CVs and supernovae that undergo transient brightness variations. Details of the transient detection procedures in CRTS are given by Drake et al. (2009a). In short, transient sources are identified by comparing them with detections in past photometric catalogues including CSS, USNO (Monet 2003) and SDSS DR8 (Aihara et al. 2011). For selection as a transient, an object must be a point source. It also must either not be present in previous catalogues, or be present and have varied with a high significance.

Objects detected within archival catalogues qualify as transients in CRTS when they increase in brightness by at least three times the observed scatter at the source brightness provided there is a minimum increase of 0.65 mag. Transient sources must be present in at least three of the four observations within a set of observations. The 0.65 mag threshold is a significant change from Drake et al. (2009a), and was adopted after careful consideration of transient discoveries and the variations of common periodic variable stars. For example, almost all of the RR Lyrae detected by Drake et al. (2013) in Catalina data vary by less than 1.3 mag peak-to-peak. Therefore, they generally fall below the 0.65 mag threshold when compared to their median magnitudes. Among the ∼6200 transient sources discovered by CRTS before 2012 July, only a couple of dozen periodic variable stars (mainly halo LPVs) have met the transient detection criterion, thereby demonstrating that this threshold is effective in both removing periodically variable stars and catching low-amplitude transients.

In addition to the variability threshold, transient selection requires a number of filters to remove artefacts and artificial variations. Additional filters are run on the images containing transient candidates to remove objects that are detected as transients, but were missing from the input catalogues due to source blending and bad image data. Moving objects such as asteroids and comets are analysed by the CSS NEO survey and are removed based on known Minor Planet Center sources as well as based on any motion over the 30 min between sets of four observations. Transient candidates are also compared with sources from archival data from the SDSS, the Digital Sky Survey (DSS), and the Palomar-Quest (PQ) survey in order to classify the sources and remove any possible remaining artefacts. All the transient candidates that pass the filtering stages are visually inspected and classified using their light curves along with information from archival surveys.

In the case of CV transients, there are a number of factors that can affect the detection sensitivity in various ways. For example, the efficiency of detecting frequently outbursting CVs is lower than one might expect. This is because objects that were in outburst in the comparison catalogues cannot reach the detection threshold. Many of the CVs detected by Wils et al. (2010) were in outburst in USNO data and thus would not meet our transient criteria. Furthermore, bright CVs may become saturated during outburst and go undetected, while in contrast, CVs with faint quiescent magnitudes can only be detected during very large outbursts.

4 THE CRTS CATACLYSMIC VARIABLES

4.1 CV candidates

Among the ~ 6200 CRTS transient sources detected before 2012 July 31, 1062 were identified as CV candidates. The classification as CV candidate relies on several different lines of evidence. Transients that exhibited outbursts in prior CSS, PQ, DSS or other archival sources were deemed to be very good CV candidates and so were objects with blue PSF-like counterparts in SDSS or *GALEX* photometry (provided there was no radio flux present).

The presence of photometric variations in follow-up data and Balmer emission lines in spectroscopic observations was also used to classify some of the systems as good CV candidates. In contrast, if no prior outburst was seen, or the colour and extent of the quiescent source was unclear, the transient source was deemed ambiguous. These objects are rejected from our sample of CV candidates. This selection excludes 235 sources with significant outbursts, but no additional evidence that they were CVs. The remaining 855 objects are hereafter identified as good CV candidates. Among these sources, 150 systems were known to be CVs prior to their detection by CRTS. Ongoing photometric and spectroscopic follow-up of CRTS CV candidates suggests that our selection process has >95 per cent accuracy at identifying CV systems (e.g. Kato et al. 2009, 2010; Kato, Maehara & Uemura 2012a; Thorstensen & Skinner 2012; Woudt et al. 2012; Kato et al. 2013).

In Table 1, we present the parameters of the 855 good CV candidates detected by CRTS before 2012 August 1. The table presents the number of times the source was detected in outburst by CRTS up to this date. A large fraction of the objects have additional outbursts in Catalina photometry that was taken before CRTS began searching these data for transients. For completeness, we have included the 64 CV candidates discovered between 2007 November 8 and 2008 May 14 that were presented by Drake et al. (2009a). Many of these systems have now had additional outbursts and a few have been spectroscopically confirmed. We also include the 150 previously known sources, many of which are well characterized by published follow-up observations. The detection of these sources demonstrates the overall sensitivity of CRTS.

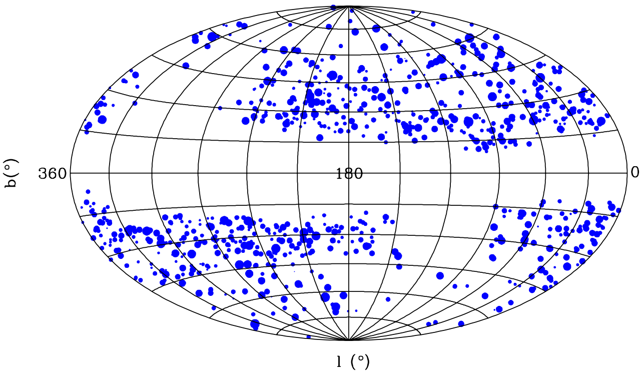

Figure 1. The distribution of CRTS CV candidates in Galactic coordinates (Aitoff projection). The radii of the points are proportional to the peak magnitude with the brightest points largest. Gaps are present in the regions not observed by Catalina, i.e. near the celestial poles and in the galactic plane.

In Fig. 1, we present the Galactic distribution of CV candidates and outburst brightnesses. In Fig. 2, we plot the distribution of these sources as a function of Galactic latitude. As expected, the number of sources drops significantly at high Galactic latitudes, whereas near the Galactic plane few sources are detected due to reduced survey coverage.

4.2 Other outbursting transients

In addition to CV systems, the outbursting optical transients discovered by CRTS also include blazars and supernovae. Most known

Table 1. CRTS CVs.

CRTS ID	RA	Dec. (J2000)	Mag_O	Mag_Q	N_{det}	Prior ID	Reference
CRTS_J000024.7+332543	00:00:24.67	+33:25:43.0	15.7		2	CSS100910:000025+332543	
CRTS_J000130.5+050624	00:01:30.47	+05:06:23.6	15.3	20.2	2	CSS101127:000130+050624	
CRTS_J000659.6+192818	00:06:59.59	+19:28:17.8	17.5	>21.0	2	CSS100602:000700+192818	
CRTS_J000720.7+200722	00:07:20.74	+20:07:21.7	17.1		1	CSS110921:000721+200722	
CRTS_J000938.2−121017	00:09:38.25	−12:10:16.7	14.5		1	CSS101007:000938−121017	
CRTS_J000945.5+402928	00:09:45.46	+40:29:28.0	17.9		1	CSS091120:000945+402928	
CRTS_J001019.3+410455	00:10:19.31	+41:04:54.9	15.6	19.5	1	CSS091120:001019+410455	
CRTS_J001158.3+315544	00:11:58.28	+31:55:44.0	17.3		1	CSS101111:001158+315544	
CRTS_J001310.6+212108	00:13:10.63	+21:21:8.1	18.0	>20.4	3	CSS101201:001311+212108	
CRTS_J001339.6+332124	00:13:39.58	+33:21:23.5	17.9	>19.9	2	CSS101111:001340+332124	
CRTS_J001449.5−523215	00:14:49.55	−52:32:15.4	16.9		1	SSS110916:001450−523215	
CRTS_J001538.3+263657	00:15:38.26	+26:36:56.8	13.3	17.7	2	CSS090918:001538+263657	
CRTS_J001636.9+185615	00:16:36.88	+18:56:15.2	18.6		2	CSS080202:001637+185615	
CRTS_J001828.4+215519	00:18:28.36	+21:55:19.4	18.7	>21.5	1	CSS101107:001828+215519	
CRTS_J001952.2+433901	00:19:52.24	+43:39:1.4	15.6		1	CSS120131:001952+433901	

The full table will be available in the online version. Col. (1) presents the CRTS identifier. Cols. (2) & (3). present the right ascension and declination, respectively. Col. (4) presents the observed peak *V* magnitude. Col. (5) presents the CRTS quiescent magnitude or limit (if known). Col. (6) presents the number of outbursts detected by CRTS. Col. (7) presents the detection ID from CRTS or other prior IDs when previously known. Col. (8) presents the reference for spectroscopic follow-up from the following list. [I]Szkody et al. (2002, 2003, 2004, 2005, 2006, 2007, 2009, 2011), [II]Thorstensen & Skinner (2012), [III]This work, [IV]Quimby et al. (2008), [V]Levitan et al. (2013), [VI]Garnavich et al. (2012), [VII]Breedt et al. (2012), [VIII]Woudt et al. (2012), [IX]Wright et al. (2012), [X]Wils et al. (2010), [XI]Croom et al. (2001), [XII]Jones et al. (2004). [XIII]Drake et al. (2009a).

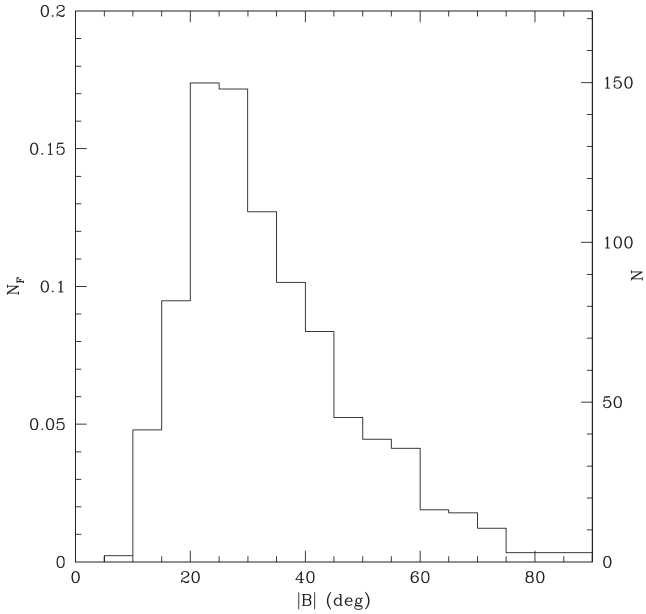

Figure 2. The Galactic latitude distribution of CRTS CV candidates.

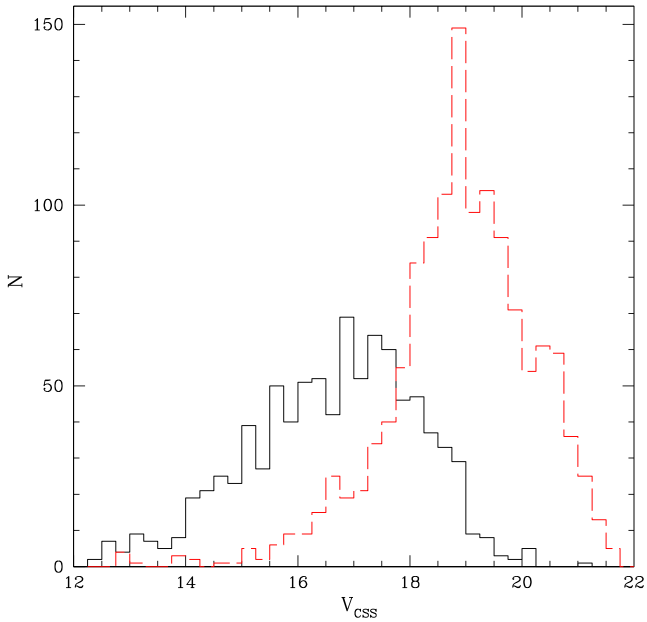

Figure 3. A histogram of the detection magnitudes of CRTS CVs and SN. CVs are given by the solid line, while SN are given by the dashed line.

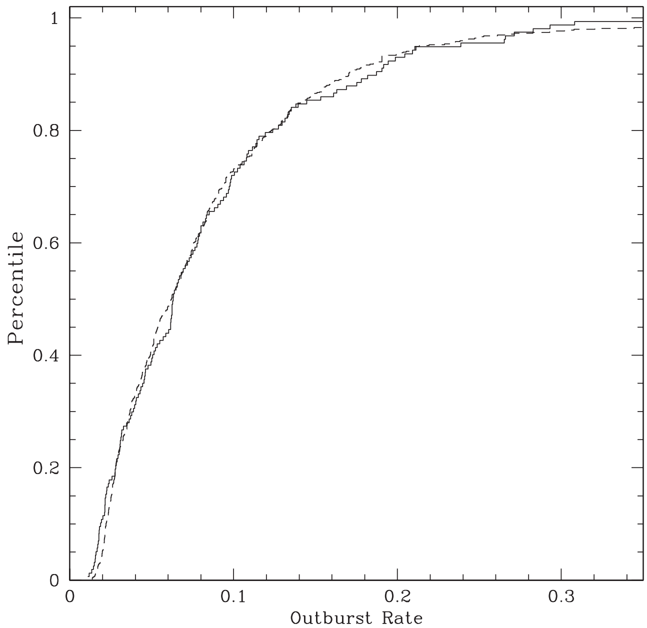

Figure 4. The cumulative distribution of CV outburst rates. We define the outburst rate as the ratio of the number of nights observed in outburst to the number of nights of observation. The previously known CVs are given by the solid line, whereas the new sources are given by the dashed line.

blazars have been discovered as flat-spectrum sources in radio survey data (Healey et al. 2007; Healey et al. 2008). Unlike blazars, CVs are generally not radio sources with a few notable exceptions (e.g. Mason & Gray 2007; Kording et al. 2008; 2011). Thus CVs and blazars can be separated based on radio data. For this purpose we have used observations from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), the Faint Images of the Radio Sky at Twenty-cm (FIRST; Becker, White & Helfand 1995), and the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003). The entire survey region of CRTS is covered by one or more of these radio surveys. The NVSS survey covers the sky at 1.4 GHz in the region $\delta > -40°$. The SUMSS survey covers the entire sky at latitudes $\delta < -30°$ for $|b| > 10°$ at 843 mHz, and the FIRST survey covers the 10 000 deg^2 around the Galactic poles at twenty centimetres. To reduce the possibility of misclassifying blazar sources as CVs, we routinely inspected the images generated by these surveys.

In contrast to CVs, supernova explosions give rise to a single brightening event that typically lasts for a few months. The host galaxies of supernova explosions are usually visibly extended in archival images. Furthermore, supernovae, like blazar outbursts, are roughly isotropically distributed over the sky. Both supernovae and blazars have different quiescent colours than CVs (i.e. which tend to be blue). Lastly, supernovae generally give rise to smaller increases in brightness relative to the brightness of their host galaxies and have fainter apparent magnitudes. To demonstrate this, we present a histogram of the CV and supernova detection magnitudes in Fig. 3. The distribution of CV outburst magnitudes is offset towards brighter apparent magnitudes from supernova explosions. The incidence of bright supernova explosions is limited to a small number of events that occur each year in nearby galaxies.

5 CV ACTIVITY

In order to investigate the CV outburst frequency of the candidates, we divided the number of outbursts detected by the number of nights the sources were observed. As most locations are only sampled every few weeks, individual outbursts are generally only observed on one night. Therefore, this ratio gives the approximate outburst rate. In Fig. 4, we plot the cumulative distribution of rates for the entire set of CVs detected by CRTS. We separate the previously known CVs from new discoveries to investigate whether the CV outburst rates vary because of differences in selection, etc. Performing a KS test on the two sets of rates we find a *D*-statistic of 0.068, corresponding to a *P*-value of 0.58. Therefore, we find no significant evidence for a difference in the distributions of outburst rates for the known (and generally brighter) CVs compared to the newly discovered CVs. This result is in slight disagreement with the findings of Gänsicke et al. (2009), based on SDSS CVs, and the results of Wils et al. (2010). However, we do find a very large number of CVs in the sample have low outburst rates in agreement with these authors. This is reflected in the fact that 55 per cent of the good CV candidates have only been detected in outburst once. There is insufficient data to quantify rates for the sources where outbursts occur <3 per cent of the time.

6 COMPARISON WITH SDSS DATA

As CSS images are taken without filters there is very little information regarding the colours of candidates. However, the SDSS DR8 data set provides photometry in five filters and spans approximately half of the area covered by CRTS (14 555 deg^2). We cross-matched the CV candidates with the SDSS DR8 photometric data base and found 416 common objects. In Fig. 5, we present the colours and magnitudes of the CV candidates with SDSS photometry. As expected, the CV candidates detected by CRTS have significantly bluer $(u-g)_0$ colours than normal main-sequence stars. The distribution of SDSS i_0 magnitudes clearly shows that the CVs discovered by CRTS are much fainter than the SDSS spectroscopic CV sample. Since CVs are in outburst for only a small fraction of the time, in most cases the SDSS photometry was taken when the CVs are in quiescence. However, by comparing CSS magnitudes with SDSS ones, there are a few cases where SDSS imaging was clearly taken during an outburst. In Fig. 6, we present the spatial distribution of CRTS CVs in SDSS i-band photometry and apparent brightness.

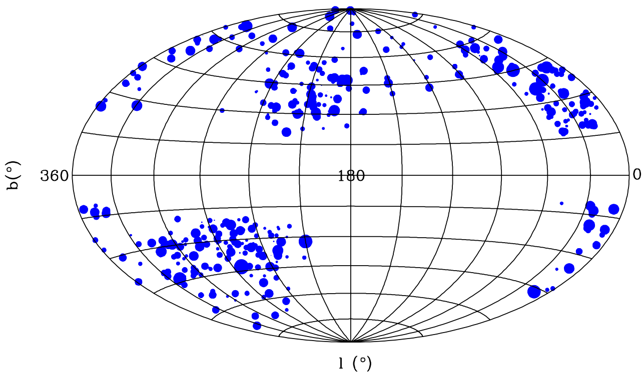

Figure 6. The Galactic coordinates of CRTS CV candidates with SDSS photometry (Aitoff projection). The radii of the points are proportional to their SDSS i-band magnitudes. The brightest sources are largest.

In Fig. 7, we compare the SDSS colours of CVs with those of supernova hosts galaxies and blazars. For the blazars, in addition to the presence of radio emission, we can see that these sources are generally redder than CVs, both in their $(g-r)_0$ and the $(r-i)_0$ colours. They also form quite a tight group. The supernova hosts

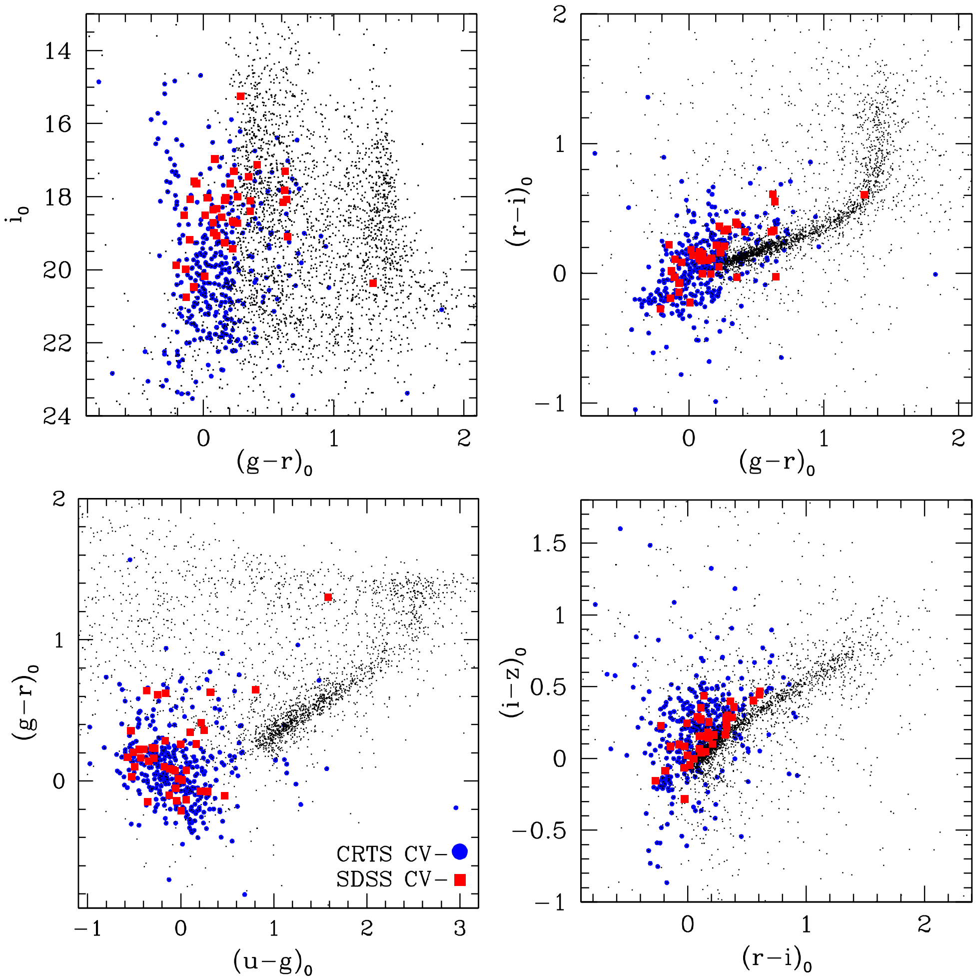

Figure 5. The colour and brightness distribution of CRTS CV candidates. CV candidates are large blue dots. Red squares are sources with SDSS spectra. The black points are the point sources (stars, QSOs and other unresolved sources) from the SDSS that lie within an arcmin of each CV candidate.

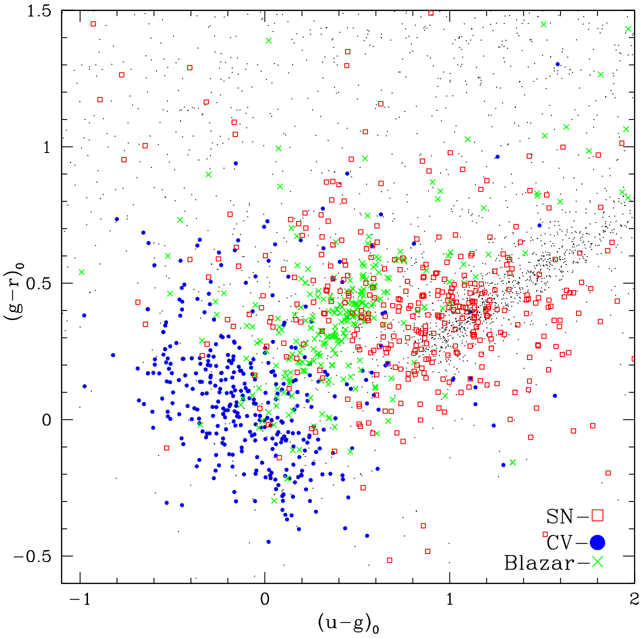

Figure 7. The colours of CRTS CV candidates compared with other transient sources. CVs are large blue dots. Red boxes are supernova hosts. Green crosses are *Fermi* and CRTS blazars. Small black dots are point sources within 1 arcmin of each CV.

have a much more diverse range of colours than CVs and blazars, and are also clearly redder than quiescent CVs.

As SDSS photometry is much deeper than Catalina data, SDSS photometry enables us to assess quiescent source colours and magnitudes to levels below our detection threshold. In addition, a comparison between Catalina *V* magnitudes and SDSS photometry reveals a relatively close match to SDSS *i*-band magnitudes. This is likely due to the red sensitivity of unfiltered Catalina data. We investigated the transformation of the SDSS photometry[2] and found poorer results.

In Fig. 8, we compare the Catalina *V* magnitudes with SDSS *i*-band photometry. We only compare the 220 candidates that have both a Catalina quiescent magnitude values and SDSS photometry. A number of the SDSS magnitudes are significantly offset from the Catalina measurements. As noted above, some of the SDSS sources were imaged while they were in outburst. For a few sources the SDSS magnitudes are much fainter. This is likely to be due to the Catalina images having lower resolution than SDSS. Multiple SDSS sources can contribute to a single CSS object and thus make CSS source appear brighter.

For comparison purposes we note that the photometric uncertainties of individual CSS observations vary from 0.03 to 0.5 mag. However, the measured dispersion in measurements for the CV is typically much larger than this because of variability. For the SDSS photometry $\sigma_i < 0.1$ mag for most sources. After removing the outliers that typically differ by more than two sigma (1.1 mag), we were left with a sample of 184 CVs with SDSS and Catalina magnitudes. For these objects we find an average difference between *i*-band and Catalina *V* of −0.01 mag with $\sigma = 0.33$ mag. This level of scatter is much larger than derived by Drake et al. (2013) for horizontal-branch stars observed by both Catalina and SDSS. We

[2] http://www.sdss.org/dr7/algorithms/sdssUBVRITransform.html

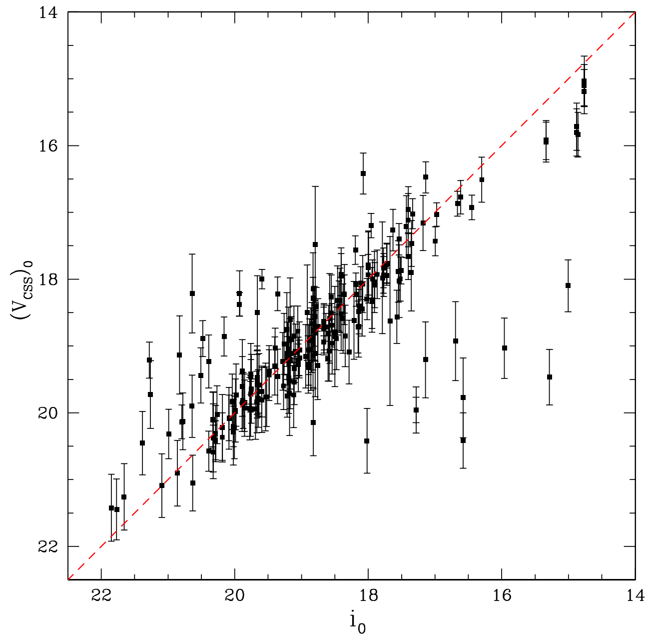

Figure 8. A comparison between the CSS *V* and SDSS *i* magnitudes, for the 220 CV candidates with SDSS photometry and a measurement of quiescent magnitude in Catalina data.

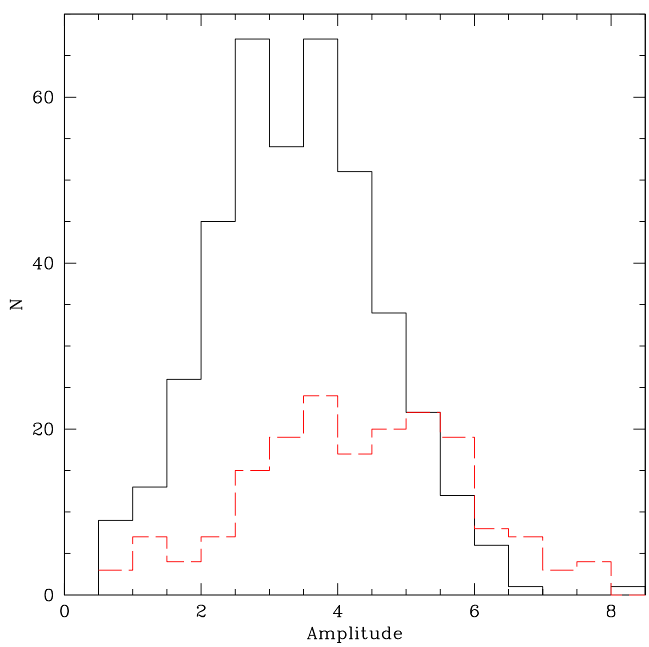

Figure 9. Histograms of the outburst amplitudes for CRTS CVs. The solid line presents the distribution for 416 sources where the quiescent magnitude was bright enough to measure in Catalina data. The dashed line shows the distribution for 196 fainter sources where their SDSS *i*-band magnitude is assumed to be equivalent to the $V_{\rm CSS}$ quiescent brightness.

believe this is due to two main sources, namely variations between the SEDs of the CVs, and the intrinsic variability of CVs.

By comparing the SDSS *i*-band magnitudes with the Catalina outburst magnitudes we can estimate the outburst amplitudes of faint sources. In Fig. 9, we present histograms of the CV outburst amplitudes. For bright CVs we measure the difference between the average quiescent brightness ($M_{\rm Q}$) and the average peak measured

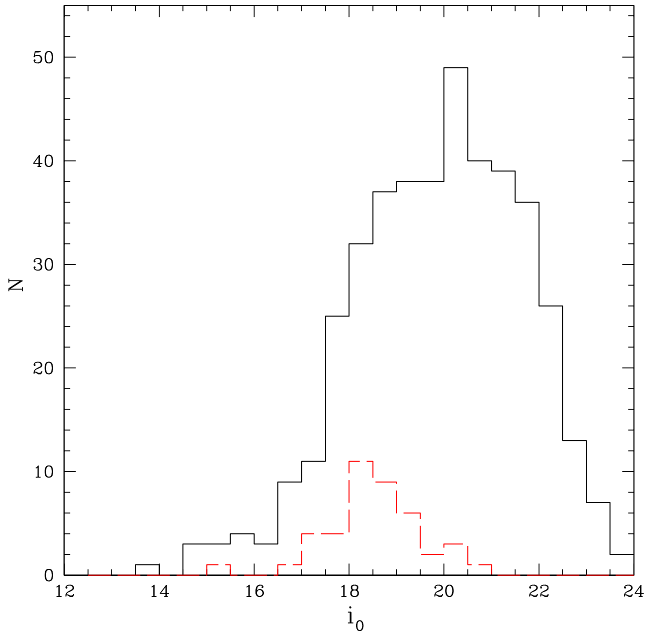

Figure 10. The distribution of SDSS *i*-band magnitudes for CRTS CVs. All CVs with SDSS photometry are given by the solid line, while CVs that have spectra taken by SDSS are given by the dashed line.

brightness (M_O). For CVs with faint quiescent states, and SDSS photometry, we determine the difference between the peak outburst magnitude and the SDSS *i*-band magnitude. CVs with fainter apparent magnitudes clearly exhibit, on average, larger amplitude outbursts, i.e. these faint CVs exhibit a large number of outbursts greater than 5.5 mag. However, this distribution is subject to selection effects, as only large amplitude outbursts can be detected by CRTS for faint CVs. Furthermore, some of the CVs detected in quiescence in CSS data may be missed when they become saturated during large amplitude outbursts.

In Fig. 10, we present the distribution of SDSS *i*-band magnitudes. The figure demonstrates how the CRTS CV detections go well beyond the limits of SDSS spectroscopy and thus probe a larger volume. In addition, it shows that many of the bright CVs found by CRTS within the SDSS imaging fields do not have SDSS spectra. These sources are therefore missing from the SDSS CV catalogues (Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007, 2009, 2011). However, SDSS spectroscopy involved complex target selections largely aimed at QSOs (Richards et al. 2002) and BHB stars (Yanny et al. 2009), rather than CVs. It is also possible that a number of these sources come from areas where spectroscopy was either not undertaken or completed by SDSS.

SDSS obtained spectra of 285 CVs (Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007, 2009, 2011) and of these 184 were new discoveries. Among the 285 CVs from SDSS, 33 are classified as polars, seven as intermediate polars, six as Nova-like, and 70 dwarf novae. The remaining 169 do not have clear type classifications. CRTS covers almost all of the area observed by SDSS and is mainly sensitive to dwarf novae. Therefore, assuming the overall fraction of dwarf novae in SDSS is the same as among the classified fraction (60 per cent), we would expect to have detected 170 of the SDSS CVs as dwarf novae having outbursts in CRTS (assuming 100 per cent detection completeness). However, only 64 SDSS CVs were detected by CRTS during outburst. This suggests that only a third of the dwarf novae in the SDSS area have been classified as such. The total fraction of dwarf novae in the SDSS spectroscopic sample is likely to be higher since many of the systems have not been monitored extensively, but the above numbers suggest that many of the SDSS CVs suspected to be dwarf novae have rare outbursts. Clearly a large number of dwarf novae are yet to be detected within the SDSS coverage area.

7 PHOTOMETRIC FOLLOW-UP

Since the CRTS survey began, all optical transient discoveries have been made public within minutes of their detection. Rapid follow-up is particularly important for CVs since the outbursts may only last for a few days. As CSS only observes the same sources every two to four weeks, and CVs typically have shorter rise times than decline times (Cannizzo et al. 2010), outbursts were caught more often declining than rising when they were discovered. Notification of transient detections was made by way of project web pages. Additionally, since 2009 September 21, every new CRTS transient discovery included a *CRTS Circular* that was linked to webpages as well as posted to the SkyAlert service (Williams et al. 2010) and the LSST/CRTS iPhone alert app.[3] In some cases, notifications were also sent as Astronomer's Telegrams (Astron. Telegrams; e.g. Drake et al. 2009b,c,d, 2011a).

Following the first spectroscopically confirmed CV discovered by CRTS (Djorgovski et al. 2008), photometric follow-up began with the Variable Star Network project (VSNet; Kato et al. 2009, 2010, 2012a, 2013). Projects undertaken by VSNet largely involve photometric time series of bright CVs in outburst with small telescopes reaching limiting magnitudes of $V = 16$ to 17. To enable such follow-up we created specific webpages (one for each Catalina telescope) where CVs brighter than $V = 17$ were posted as soon as they were classified.[4] Additionally, since some CVs exhibit lower-amplitude variability that is missed by our detection software, we also created a watch-list based on the Ritter & Kolb (2003) catalogue of known CVs. For each of the objects observed by CSS data we extracted the existing archival photometry. Then we set up software to automatically update the light curves of those known CVs whenever they were observed.[5] Since known CVs require no detection filtering these updates occur immediately. This service produces a snapshot of the activity level for more than 1000 CVs with a couple of hundred known CVs covered each night. Notably, Mukadam et al. (2011) used this information to discover the only known outburst of CV SDSS J074531.92+453829.6. Similarly, Southworth et al. (2009) used the data to find and constrain the rate of outbursts for eclipsing CV SDSSJ100658.40+233724.4.

Between 2008 August 4 and 2011 October 25 the VSNet project sent follow-up requests for 132 bright CVs discovered by CRTS. Of these, 57 were followed sufficiently to determine that they are SU UMa-type dwarf novae, and their superhump periods were used to estimate orbital periods (Kato et al. 2009, 2010, 2012a, 2013). Additionally, Woudt & Warner (2010) and Woudt et al. (2012) together report high-speed photometric observations of 22 CRTS CVs. Woudt et al. (2012) note that 115 CRTS CVs have had periods determined and almost all of these lie below the CV period gap. Wils et al. (2010) combined SDSS, *GALEX* and CRTS data along with astrometric catalogues to discover 64 new CVs. Their results indicated that besides systems that are faint because they are farther

[3] http://www.lsstcorp.org/transientevents/index.html
[4] http://nesssi.cacr.caltech.edu/catalina/BrightCV.html
[5] http://nesssi.cacr.caltech.edu/catalina/CVservice/CVtable.html

away, there also exists a population of intrinsically faint dwarf novae with rare outbursts. This result was supported by Thorstensen & Skinner (2012).

8 CV SPECTRA

Of the 855 *good* CV candidates detected by CRTS, more than 137 have already been spectroscopically confirmed. This number excludes historical CVs which have largely already been followed spectroscopically (e.g. TY PsA; Warner, O'Donoghue & Wargau 1989, and TT Boo; Bruch & Schimpke 1992). As noted above, 64 of these systems were either discovered, or spectroscopically confirmed by the SDSS (Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007, 2009, 2011). Recently, 36 additional systems were spectroscopically confirmed by Thorstensen & Skinner (2012). Additionally, CRTS CVs have been confirmed by Woudt et al. (2012), Wright et al. (2012), Levitan et al. (2013), Breedt et al. (2012), and Littlefield et al. (2013).

From our own observations we have confirmed 33 CRTS CV candidates using spectroscopy with the Palomar 5 m (P200), Keck, and SMARTS telescopes. All of these sources were followed during regular spectroscopic confirmation of CRTS optical transients. Since our follow-up targets were generally transient sources of uncertain nature, the CVs we observed are mainly sources where there was no evidence for a blue point source within archival images from SDSS or DSS. In Table 2, we present the CVs that were confirmed during our CRTS follow-up. The table is presented in chronological order of discovery.

We classified CRTS transients as CVs based upon the detection of strong, broad hydrogen absorption or emission lines detected in our follow-up spectroscopy. As many of the sources were observed shortly after they were detected in outburst, the sample is biased towards systems exhibiting absorption lines from an optically thick accretion disc. This is in contrast to spectroscopically confirmed CVs from SDSS, which are mainly systems observed during quiescence when strong emission lines are observed. In Fig. 11, we present examples of the Palomar DSBS spectra, and in Fig. 12, we present examples of Keck LRIS spectra of CRTS CVs.

We complemented our own follow-up observations with spectroscopy of four CRTS CV candidates observed by the Six-Degree Field survey (6dF; Jones et al. 2004) DR3 spectra (Fig. 13). We also matched the objects with the Two-Degree Field survey (2df; Croom et al. 2001), and found spectra for another three CRTS CVs (Fig. 14). The sources having SDSS spectra have already been analysed by Szkody et al. (2002, 2003, 2004, 2005, 2006, 2007, 2009, 2011).

9 MAGNETIC CV SYSTEMS

Magnetic CVs form a subset of 10 per cent to 20 per cent of all known CVs (Wickramasinghe & Ferrario 2000, Scaringi et al. 2010). These objects are either polars (AM Her stars), or intermediate polars (IPs or DQ Her stars). Intermediate polars have weaker magnetic fields and may form partial accretion discs, while polars accrete directly from the secondary on to the white dwarf. In these systems, material is magnetically accreted on to the pole of the white dwarf giving rise to soft (polars) or hard (IPs) X-rays that are modulated at the spin period of the white dwarf (Warner 2003). The detection of X-ray flux is thus one means of separating IP and polar CV candidates from the more common dwarf novae.

To provide a more complete view of the X-ray properties of the CRTS CVs, we have matched the *ROSAT* X-ray catalogue positions

Table 2. CVs confirmed by CRTS during transient follow-up.

Detection ID	Telescope+instrument	Reference
CSS080130:021110+171624	P200+DBSP	I,II,III,IV
CSS080227:112633−100210	P200+DBSP	I
CSS080505:163121+103134	P200+DBSP	V
CSS080606:164147+121026	P200+DBSP*	VI
CSS080606:162322+121334	P200+DBSP	
CSS081026:023839+355648	P200+DBSP*	
CSS090416:164413+054158	P200+DBSP*	
CSS090826:223958+231837	Keck+LRIS	VII
CSS090910:223418−035530	SMARTS+RCSpec	VIII
CSS090917:221344+173252	SMARTS+RCSpec	VIII
CSS091024:042229+161430	Keck+LRIS†	
CSS100108:081031+002429	P200+DBSP	
CSS100313:085607+123837	P200+DBSP	
CSS100911:022648+152539	P200+DBSP	
CSS100916:215226−012850	Keck+LRIS	
CSS110114:091937−055519	P200+DBSP	
CSS110208:135717−093238	P200+DBSP*	
MLS100313:131245−064047	P200+DBSP	
CSS100507:164354−131525	Keck & P200	VII
MLS101203:050253+171041	P200+DBSP	
CSS110501:094825+204333	P200+DBSP	
CSS110610:134306+520843	P200+DBSP†	
CSS110623:173517+154708	P200+DBSP	
CSS110628:220857+200440	P200+DBSP*	
CSS111003:054558+022106	Keck+LRIS	
CSS111022:205145+075305	Keck+LRIS	
CSS111027:075959+211936	P200+DBSP	
CSS120526:165741−055625	Keck+LRIS	
CSS120113:040822+141516	P200+DBSP	
CSS120610:135419+273603	Keck+LRIS	
CSS120612:173245+094746	Keck+LRIS	
CSS120613:212655−012054	Keck+LRIS	

Objects marked with '*' have featureless spectra. Objects marked with '†' have noisy identifying spectra. [I]Glikman et al. (2008), [II]Djorgovski et al. (2008), [III]Drake et al. (2009a), [IV]Kato et al. (2009), [V]Mahabal et al. (2008), [VI]Djorgovski et al. (2009) [VII]Djorgovski et al. (2010). [VIII]Drake et al. (2009b).

(Voges et al. 1999, 2000). In total, 42 of the CVs match the position of *ROSAT* X-ray sources within 2σ. Of these, 22 are CRTS CVs and 20 are previously known CVs. In Table 3, we present the *ROSAT* X-ray source matches to new CRTS CVs.

During the course of the CRTS survey, most new optical transient discoveries were investigated using the Datascope service.[6] This VO resource aggregates astronomical data covering a given location, so that optical sources can be compared with prior detections in radio, X-ray, infrared and other wavelengths. Sources that were found to match prior X-ray detections were noted on CRTS discovery webpages. Our rapid alerting system enabled optical follow-up of a number of the potential magnetic CV systems. For example, Schwope & Thinius (2012) combined Catalina data with additional photometry and found that CSS091109:035759+102943 is a candidate polar with an orbital period of 114 min. Ten of the sources classified as CVs by CRTS were flagged as possible X-ray sources (e.g. Drake et al. 2009a).

Among the X-ray sources followed, CSS090219: 044027+023301 was found to be associated with 1RXS J044027+023300 and was spectroscopically confirmed as a CV

[6] http://heasarc.gsfc.nasa.gov/vo

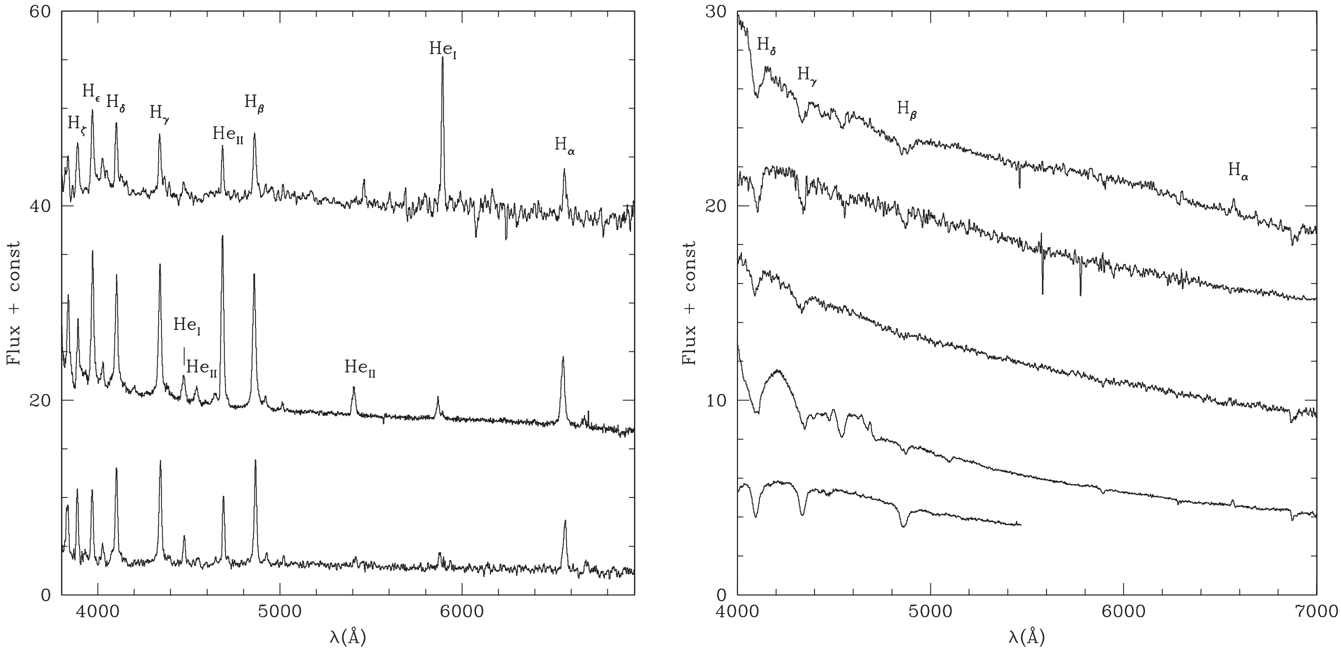

Figure 11. Palomar 5-m spectra of CRTS CVs. In the left panel (top to bottom), we show spectra of three CVs (CSS100108:081031+002429, CSS110114:091937−055519, CSS100313:085607+123837) exhibiting strong hydrogen and helium emission lines typical of CVs near quiescence. In the right panel (top to bottom), we show the spectra of CRTS CVs that were observed during outburst (CSS120113:040822+141516, CSS100507:164354−131525, CSS110623:173517+154708, CSS080606:162322+121334, CSS110501:094825+204333).

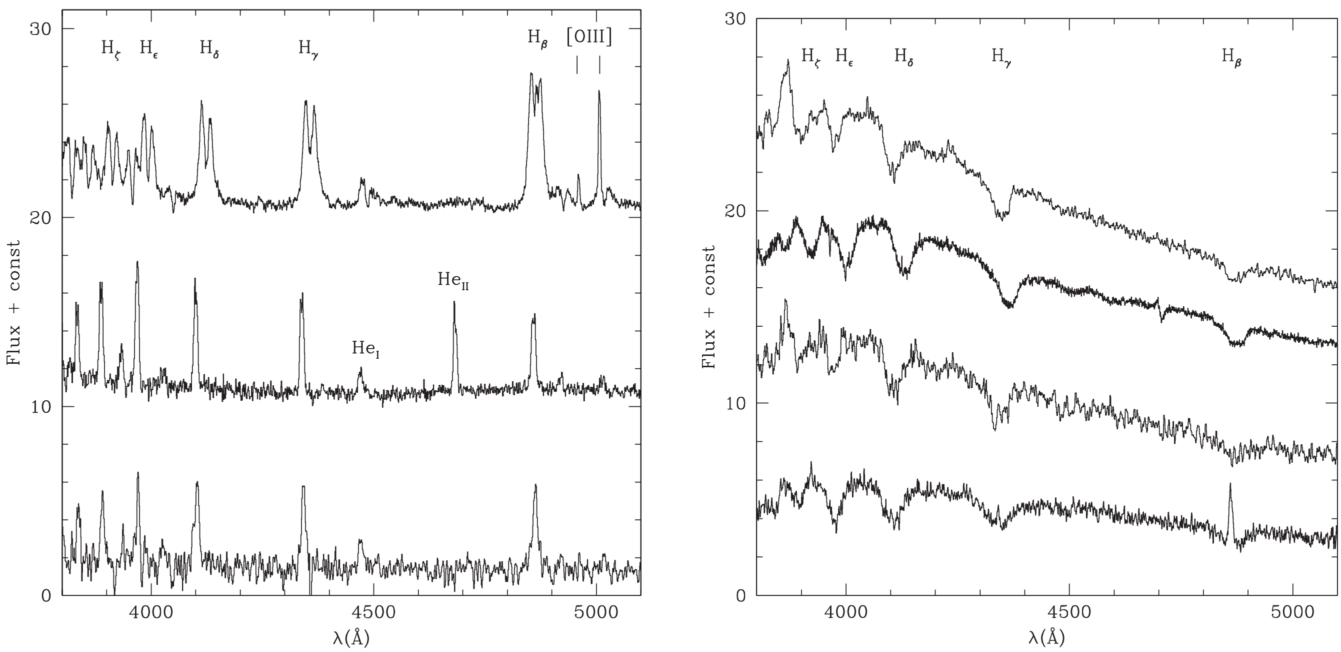

Figure 12. Keck spectra of CVs. In the left panel (top to bottom), we show spectra for three CVs (CSS111003:054558+022106, CSS120526:165741−055625, CSS120613:212655−012054) with strong hydrogen and helium emission lines typical of CVs. CSS111003:054558+022106 lies within the shell of a planetary nebula PN Te 11 (Jacoby et al. 2010), clearly seen within SDSS images, and was found to have a period of 0.12 d by Miszalski et al. (2011). In the right panel (top to bottom), we show the spectra of four CRTS CVs that were observed during outburst (CSS120610:135419+273603, CSS120612:173245+094746, CSS111022:205145+075305, CSS100916:215226−012850).

by Thorstensen & Skinner (2012). CSS100217:104411+211307 was identified as a possible match to 1RXS J104409.6+211334. However, this source was found to exhibit superhumps by Maehara (2010), suggesting it is unlikely to be a magnetic system. In our CRTS Circular we noted CSS081231:071126+440405 to be an apparent eclipsing polar-type CV. This was found to be a magnetic low-accretion rate system by Thorne, Garnavich & Mohrig (2010). In contrast, CSS120101:105123+672528 was found to match 1RXS J105120.5+672550 and was independently detected by the MASTER project five hours after CRTS (Tiurina et al. 2012).

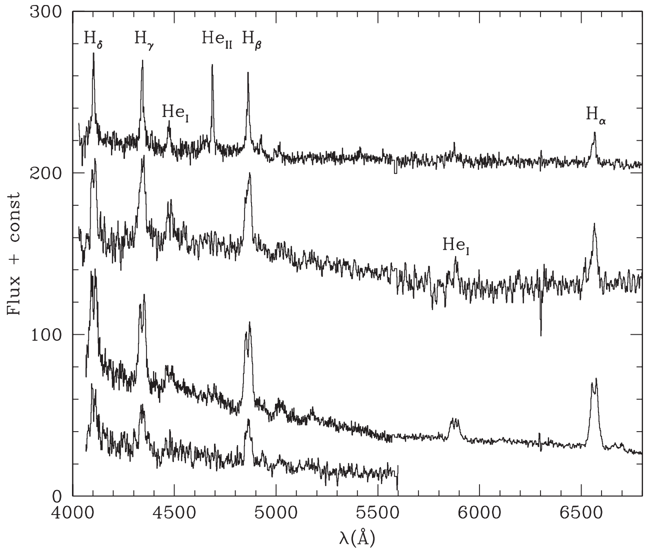

Figure 13. The 6dF survey spectra of four CVs. From top to bottom, TY PsA (SSS100716:224940−270653), CC Scl (SSS111103:231532−304848), YY Sex (CSS090301:103947−050658), and CSS120222:124602−202302.

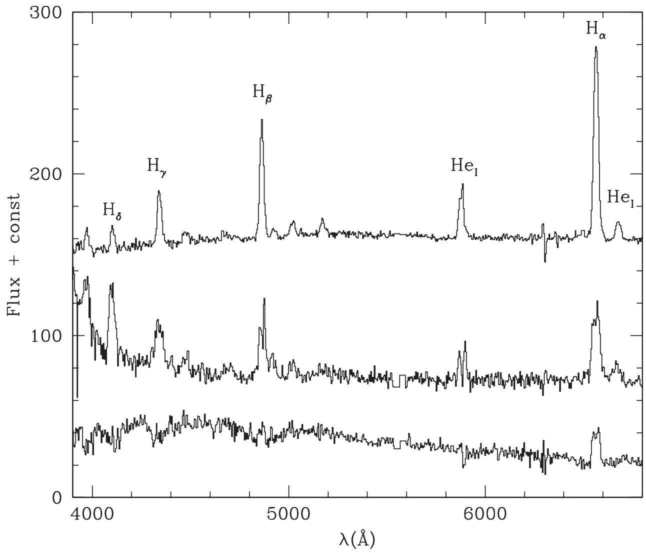

Figure 14. The 2dF survey spectra of CRTS CVs From top to bottom, HV Vir (CSS080227:132103+015329), OU Vir (CSS080329:143500−004606) and SSS100911:222416−292422.

Once again this was determined to be an SU UMa-type dwarf nova (Pavlenko et al. 2012), rather than a magnetic system. CSS120330:154450−115323, was also classified as a possible X-ray match with *ROSAT* source 1RXS J15444.5−115340. As the nature of the object was unclear, we initially only classified the object as a variable star. Optical spectroscopic follow-up observations along with ultraviolet and X-ray data revealed the source to be a likely dwarf nova (Wagner et al. 2012), rather than a magnetic system.

10 ECLIPSING CV SYSTEMS

CVs that exhibit eclipses are relatively common. More than 150 such systems are listed in the International Variable Star Index (VSX; Watson, Henden & Price 2006) data base. These systems are particularly valuable as they allow precise measurements of parameters such as orbital period (e.g. Littlefair et al. 2006, 2008; Savoury et al. 2011). Although we have not undertaken a specific search for these objects in the photometric data, a number of clearly eclipsing CVs were apparent from the light curves.

CSS110513:210846−035031 was a CV that we classified as an eclipsing system. This system shows outbursts up to $V \sim 15$ and eclipses to $V \sim 20$. In Fig. 15, we plot the light curve of CSS110513:210846−035031 along with the phase folded photometry. The eclipses of this object are observed over a span of ∼2000 d. Although the time of mid-eclipse is not well defined, the long baseline allows determination of a very accurate period. For this system we find an eclipse ephemeris of MJD $= 53500.131(5) + E \times 0.1569268(8)$. The figure clearly shows the eclipse both in the outburst and in the quiescent photometry. The eclipse itself lasts 27 ± 4 min.

Other eclipsing CVs include MLS120517:152507−032655, which we found to be a match to 1RXS J152506.9−032647. This exhibits deep (>2 mag) eclipses, as do MLS101226:072033+172437, CSS090622:215636+193242, CSS080228:081210+040352, and CSS080227:112634−100210. The light curves can be found on the CRTS website.[7] Seven of the CVs detected by CRTS are previously known eclipsing systems.

11 CV PERIODS

We matched the CVs detected by CRTS with those in VSX and in Ritter & Kolb (2003; 2012 July version), resulting in a sub-sample of 196 systems with known orbital period.

In Fig. 16 we plot the period distribution for the CVs detected by CRTS and the distribution for the 806 CVs in the Ritter & Kolb catalogue that were not detected by CRTS. For comparison we also plot the cumulative distributions. A similar analysis was performed by Woudt et al. (2012). This work also demonstrated that the sources with shorter periods had fewer outburst detections. However, the sample here is larger since Woudt et al. (2012) did not include periods for the bright CVs observed by VSNet that were also detected by CRTS. This clearly shows that CRTS detects a much larger fraction of CVs with short periods. A one-dimensional KS test gives the probability that the two samples are drawn from the same underlying distribution of $P < 0.001$.

11.1 Ultra-short-period systems

In comparison to the full CRTS CV sample, a modest number have been found to be ultra-short-period systems that lie below the orbital period minimum for normal CVs, which is near 80 min (Gänsicke et al. 2009). The dominant populations at such short orbital periods are AM CVn systems, and SU UMa dwarf novae with substellar or evolved companions (e.g. Augusteijn, van Kerkwijk & van Paradijs 1993; Thorstensen et al. 2002; Littlefair et al. 2007; Levitan et al. 2011; Uthas et al. 2011; Carter et al. 2013). Woudt & Warner (2010) discovered that CSS111019:233313−155744 is an eclipsing dwarf nova with a 61.7-min period while Woudt et al. (2012) found that CSS090331:102843−081927 is an ultra-short period CV (like V485 Cen and EI Psc), with a period of 52.1 min. Breedt et al. (2012) discovered that CSS100603:112253−111037

[7] http://crts.caltech.edu/

Table 3. *ROSAT* matches to CRTS CVs.

CRTS ID	HR1	HR2	Offset(arcsec)	Nσ	*ROSAT* ID
CRTS_J001538.3+2636057	0.68 (0.44)	−0.25 (0.38)	0.9	0.07	1RXSJ001538.2+263656*
CRTS_J003203.6+3145010	1.00 (0.26)	0.16 (0.41)	29.8	1.30	1RXSJ003204.2+314441
CRTS_J003304.0+3801006	0.55 (0.46)	1.00 (0.48)	23.9	0.99	1RXSJ003302.3+380118
CRTS_J013308.7+3832017	1.00 (0.92)	1.00 (9.99)	2.5	0.18	1RXSJ013308.9+383218
CRTS_J015051.5+3326022	1.00 (0.22)	0.73 (0.18)	3.4	0.29	1RXSJ015051.8+332622
CRTS_J020804.2+3732017	1.00 (0.24)	0.06 (0.39)	27.8	1.39	1RXSJ020802.6+373236
CRTS_J044027.1+0233001	1.00 (0.33)	1.00 (0.30)	2.2	0.20	1RXSJ044027.0+023300*
CRTS_J051922.9+1554035	1.00 (0.31)	0.37 (0.40)	14.7	0.73	1RXSJ051922.6+155421
CRTS_J053054.6−3357030	−0.09 (0.36)	−0.66 (0.51)	8.3	0.55	1RXSJ053054.5−335722
CRTS_J065128.5−4109018	1.00 (0.39)	0.20 (0.33)	8.9	0.56	1RXSJ065127.9−410913
CRTS_J073339.3+2122001	1.00 (0.58)	−0.51 (1.01)	21.0	1.50	1RXSJ073340.7+212208
CRTS_J094327.3−2720039	1.00 (0.40)	−0.14 (0.43)	16.0	0.80	1RXSJ094326.1−272035*
CRTS_J104411.4+2113007	0.69 (0.35)	0.91 (0.72)	37.1	1.95	1RXSJ104409.6+211334*
CRTS_J121924.7−1900024	0.58 (0.40)	1.00 (2.40)	12.1	1.01	1RXSJ121925.5−190022
CRTS_J135143.5−4430020	0.33 (0.43)	0.47 (0.57)	14.6	0.91	1RXSJ135142.2−443023
CRTS_J135915.2−3914052	0.57 (0.33)	−0.09 (0.44)	6.4	0.53	1RXSJ135915.6−391447*
CRTS_J152506.9−0326055	0.71 (0.20)	0.38 (0.25)	7.4	0.62	1RXSJ152506.9−032647*
CRTS_J172148.9−0517013	0.92 (0.27)	0.73 (0.22)	17.1	1.43	1RXSJ172148.4−051729
CRTS_J203214.0−1126001	0.07 (0.38)	0.33 (0.62)	6.8	0.52	1RXSJ203214.0−112554
CRTS_J221344.0+1732052	1.00 (0.21)	−0.32 (0.34)	9.8	0.75	1RXSJ221343.9+173301*
CRTS_J231909.2+3315040	0.95 (0.10)	0.32 (0.23)	9.9	0.76	1RXSJ231909.9+331544*
CRTS_J233003.0+3033000	1.00 (0.49)	1.00 (0.75)	22.0	1.29	1RXSJ233004.7+303305*

Objects marked with '*' were identified as X-ray matches in CRTS alerts. Col. (1) presents the CRTS identifier. Cols. (2) and (3) present the *ROSAT* X-ray hardness ratios HR1 and HR2, respectively. Col. (4) presents the offset between the CRTS and *ROSAT* sources. Col. (5) presents the offset in terms of *ROSAT* position error σ. Col. (6) presents the *ROSAT* identifier.

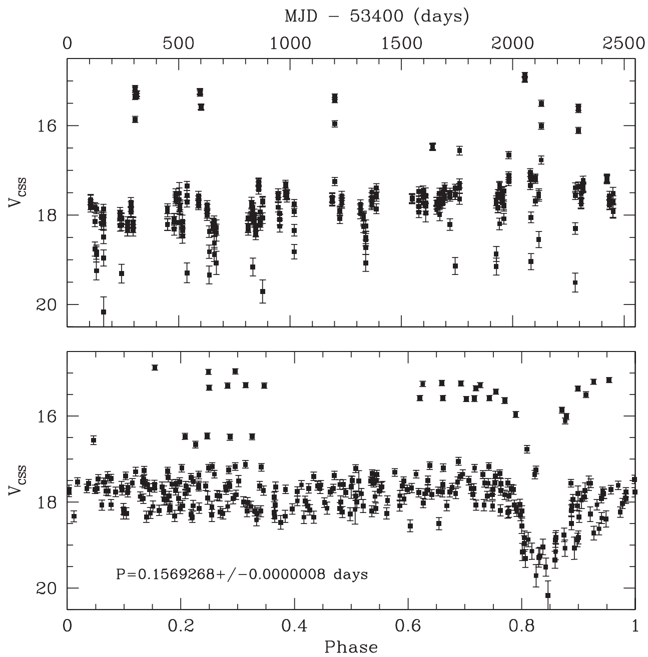

Figure 15. The light curve of eclipsing CV CSS110513:210846−035031. In the top panel we plot the observed light curve. In the bottom panel we plot the light curve when folded with the orbital period.

is a helium-rich dwarf nova with a 65-min orbital period. Interestingly, the authors noted that this object appears to be the first evidence for a dwarf nova evolving into an AM CVn system. Littlefield et al. (2013) discovered that CSS120422:111127+571239 is a similar hydrogen-depleted SU UMa-type CV below the period gap with a superhump period of 55.8 min. The AMCVn system SDSS J172102.48+273301.2 (Rau et al. 2010) was also detected by CRTS during outburst in 2012 July. Recently, Levitan et al. (2013) spectroscopically confirmed that CSS090219:043518+002941 and CSS110507:163239+351108 are AM CVn systems, yet did not determine their orbital periods.

12 CV DISTANCES

The absolute magnitudes of CVs are well known to vary significantly with their orbital periods. Short-period CVs typically have $M_V \sim 9.5$ in quiescence and $M_V \sim 5$ in outburst (Warner 1987). However, recent determinations of distances suggest that quiescent magnitudes near the period minimum can be much fainter, at $M_g = 11.6$ (Gänsicke et al. 2009), or perhaps even as faint as $M_V = 14$ (Sproats, Howell & Mason 1996), and it is those type of systems which are likely to dominated the Galactic CV population. In contrast, the determinations of CV outburst absolute magnitudes have remained relatively consistent with the values predicted by Warner (1987) (e.g. Thorstensen 2003; Harrison et al. 2004). The outburst absolute magnitudes are much better constrained than those in quiescence since the accretion disc completely dominates the emission during outburst. The brightness scales with the physical size of the disc, which itself scales with the orbital period. As the majority of CRTS CVs have periods around 1.7 h, if one was to assume the objects have outburst magnitudes that are consistent with the prescription of Warner (1987), the absolute magnitudes of most are expected to be $M_V(\mathrm{max}) \sim 5.5$.

In Fig. 17, we plot the distribution of CV distances. The agreement between distances derived from CRTS outburst magnitudes and SDSS quiescent magnitudes [assuming $M_g(\mathrm{min}) = 9.5$] is very good. For the two distributions we find scale heights of 1.1 kpc. This value is consistent with values for the scale height of the thick disc (e.g. Kerber, Javiel & Santiago 2001; Larsen & Humphreys

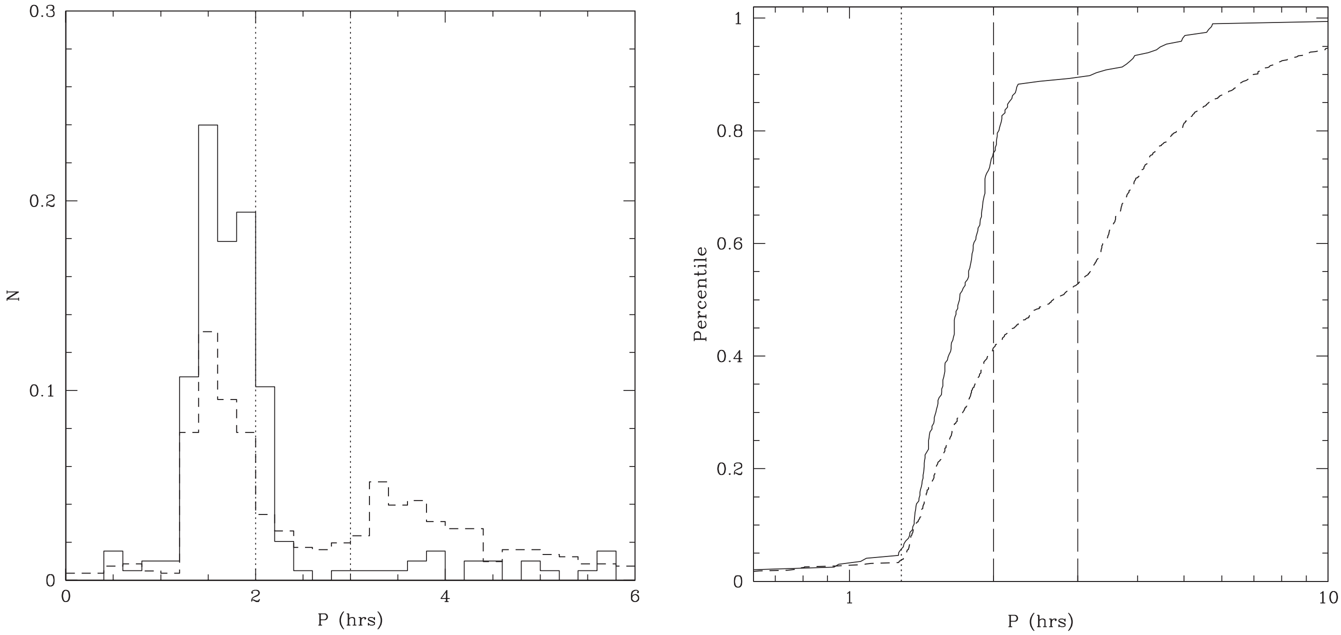

Figure 16. The normalized CV period distribution. On the left panel, we plot the distribution of CV periods for sources detected by CRTS (solid line) and the distribution of all CV periods given by Ritter & Kolb (2003, dashed line). On the right panel, we plot the cumulative distribution of CV periods. In the right panel CV, the period-minimum is plotted with a dotted line, while the period gap is indicated by the region between the two long-dashed lines.

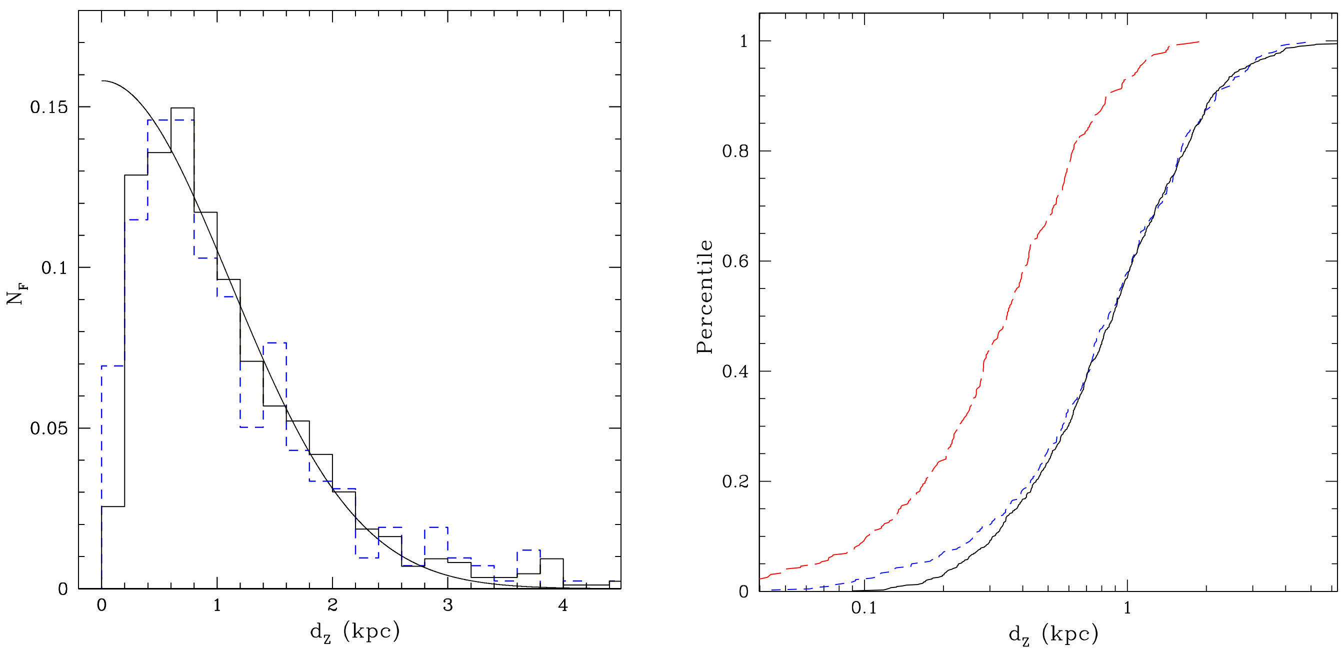

Figure 17. Normalized distribution of CV heights above the Galactic mid-plane. In the left panel we show the distances derived from 391 SDSS magnitudes assuming quiescent magnitudes of $Mg(\mathrm{min}) = 9.5$ as a dashed blue line. For the 855 CRTS CVs we plot the distances assuming $M_V(\mathrm{max}) = 5.5$ (solid black line). Gaussian fits to the distributions give a scale height of 1.1 kpc. In the right panel we plot the cumulative distribution of distances derived from SDSS magnitudes assuming $Mg(\mathrm{min}) = 9.5$ (blue short-dashed line), the CRTS peak outburst magnitudes assuming $M_V(\mathrm{max}) = 5.5$ (black solid line), and from the SDSS magnitudes adopting $Mg(\mathrm{min}) = 11.6$ (red long-dashed line).

2003; Du et al. 2006; Carollo et al. 2010) and suggests that the CVs are drawn from this distribution. However, if one adopts $M_g(\mathrm{min}) = 11.6$ as found by Gänsicke et al. (2009), the scale height is reduced to 420 pc. This value is still significantly larger than most values derived for the Galactic thin disc (e.g. Gould, Bahcall & Flynn 1997; Chen et al. 2001), but consistent with some results (e.g. Nelson et al. 2002).

Considering the survey is largely limited to sources with $|b| > 10°$, the faintest CRTS CVs are preferentially found at greater scale heights. Nevertheless, even with this bias there should be few thin disc sources beyond three times the scale height. However, we note that the distances derived using quiescent absolute magnitudes are clearly inconsistent with the distances derived from outburst magnitudes. Both sets of distances are inconsistent with

CVs coming from a population with a scale height of 190 pc, as found by Patterson (1984). This result is not surprising since the Patterson (1984) sample is based on nearby CVs. Only recent all-sky surveys are deep and wide enough to probe CV systems at thick disc distances. More recently, Pretorius, Knigge & Kolb (2007) considered a number of models of the CV distribution within the Galaxy and suggested that, given the different ages of the components of the Galaxy, the scale heights of CVs should depend on their age, and hence on their orbital period. From their model *A1* they found that CVs with $|b| > 20^{\circ}$ would be strongly concentrated towards the period minimum when sources with $V > 20$ were considered. The CRTS period distribution appears consistent with this model. Pretorius et al. (2007) also suggest that the flux-limited samples available at that time were not deep enough to reproduce the intrinsic population CVs, and thus that any comparison between the observed population and true population had to remain difficult. Nevertheless, the determination of the spatial density of CVs is an important means for understanding CV evolution. In a future paper we shall address this question for CVs detected by CRTS (Breedt et al., in preparation).

13 DISCUSSION

In this work we have catalogued 855 CV candidates detected by CRTS. Of these 705 are new discoveries and at least 137 are spectroscopically confirmed. These sources were primarily selected among CRTS optical transient sources using information about prior outbursts and their amplitudes, combined with archival information such as optical colours, and the presence of radio and X-ray sources. We have investigated the resulting outburst amplitude and colour distributions and confirm the expected differences from other common types of optical transients (such as supernovae and blazars). We find that the CRTS CV sample extends two magnitudes deeper compared to the CVs that were spectroscopically identified by SDSS (Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007, 2009, 2011).

In contrast to the recent work on quantifying the CV population based on CRTS data by Thorstensen & Skinner (2012), our analysis includes the additional CVs discovered using MLS and SSS telescopes, as well as more accurate details of the CRTS CV detection and classification. Nevertheless, given that only 45 per cent of the CRTS CVs have been detected in outburst more than once, we agree with the suggestion of Thorstensen & Skinner (2012) that a large fraction of the Galactic CV population must remain to be discovered.

While it is clear that the Galactic latitude limits of the Catalina survey ($|b| > 10^{\circ}$) create a bias towards sources at large-scale heights, the absolute magnitudes predicted from CV outbursts suggest a significant fraction of the CVs discovered have scale heights well beyond that expected for the Galactic thin disc. This strongly supports the idea that many of the CRTS CVs belong to a thick disc population.

Since CRTS detects CVs by searching for optical transient sources, this inherently biases the detections towards dwarf nova systems. To better understand the CV population we identified candidates that coincide with hard sources from X-ray catalogues. We find that most of the CV systems with X-ray matches appear to be non-magnetic systems. Nevertheless, CRTS has discovered both eclipsing systems and magnetic CVs. It is likely that more magnetic CVs remain to be identified.

By analysing the orbital periods of the CVs, we find that the period distribution of CRTS CVs includes a much more significant contribution from short-period systems compared to the bulk of the previously known CVs, which are, on average, both brighter, and have more frequent outbursts. This result is in agreement with prior analyses by Wils et al. (2010) and Woudt et al. (2012), and also with the work by Gänsicke et al. (2009) based on SDSS CVs, and Uemura et al. (2010) on WZ Sge stars. This underlines that new CV samples that have much deeper limiting magnitudes probe a different population of systems compared to the previously discovered bright CVs. However, in contrast to the orbital period distribution, we find no evidence for a difference in the outburst rates of the dwarf nova CVs.

Recent work on CVs from CRTS and other synoptic surveys has led to the discovery of a number of ultra-short-period CVs. These have been identified as AM CVn types (e.g. Woudt & Warner 2010; Levitan et al. 2013) as well as those that systems are evolving into AM CVns (e.g. Breedt et al. 2012), or have substellar companions (e.g. Garnavich et al. 2012). Given that less than quarter of the CRTS CVs currently have orbital period determinations, it is likely that a large number of ultra-short-period systems remain to be found.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. CRTS Cataclysmic Variables (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu639/-/DC1).

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