Correlation study of multi-wavelength transient emission of selected CRTS cataclysmic variables

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Abstract. A sample of cataclysmic variable systems, showing high levels of transient emission, have been identified in the Catalina Real-Time Transient Survey archive. This study involved the identification of rapidly varying transient sources which met the criteria for intensive multi-wavelength follow-up studies. The selection criteria are discussed, as well as the PSF photometry process that was used to obtain light curves for the selected sample. The follow-up studies will be aimed at better understanding the processes driving thermal and non-thermal transient phenomena in several disc-fed and disc-less cataclysmic variable sources. Further optical observations will include photometric observations with the UFS/Boyden 1.5-m telescope at the Boyden Observatory and spectroscopic observations with the SAAO 1.9-m telescope, located at the South African Astronomical Observatory (SAAO).

1. Introduction

The Catalina Real-Time Transient Survey (CRTS) is aimed at discovering sources that undergo transient variations in brightness, e.g. cataclysmic variables (CVs), supernovae and blazars [1]. It provides a detailed survey that includes extremely faint sources of up to 20 magnitudes. The CRTS makes use of three dedicated telescopes which, combined, cover ~ 30000 deg^2 of sky in the declination range of $-75^\circ < \delta < 65^\circ$. The telescopes run separate sub-surveys which are known as the Catalina Schmidt Survey (CSS), the Mount Lemmon Survey (MLS) and the Siding Spring Survey (SSS), respectively [2]. The CRTS started operating in 2007 and has since identified more than 1300 CV candidates, making it the largest sample of CVs from a single survey to date. Due to the survey's success, it is the ideal database to mine for sources that show high levels of transient emission, e.g. the CVs.

CVs are close binary systems in which a Roche lobe filling low-mass star (secondary) transfers matter to a white dwarf (WD) primary [1, 3]. These are compact systems, with a separation of ~ 1 R$_\odot$ between the binary components, and with orbital periods ($P_{\rm orb}$) of a few hours or less [4]. The intensity of the WD's magnetic field determines the accretion process. CVs where the primary has a weak magnetic field ($B_\star < 1$ MG), are known as non-magnetic CVs (NMCVs) and material is accreted via an accretion disc. If the primary has a strong magnetic field, then the CV is either an Intermediate Polar (IP) ($B_\star \sim 1 - 10$ MG) or a Polar ($B_\star \sim 10 - 150$ MG) [5]. Polars channel material towards the magnetic poles and IPs accrete material via a disrupted accretion disc and an accretion stream to the primary's poles.

Many CVs exhibit dramatic outbursts, which are classified according to the outburst recurrence time and magnitude range. These outbursts are essentially caused by either runaway

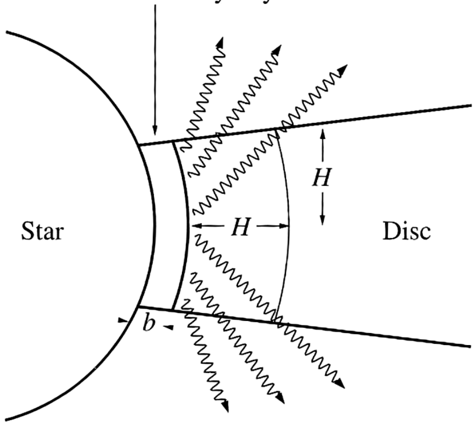

Figure 1. Schematic illustration of an optically thick boundary layer. The secondary's Roche lobe overflow is accreted by the WD with a weak magnetic field (Adopted from [8, p. 156, Fig. 6.2].

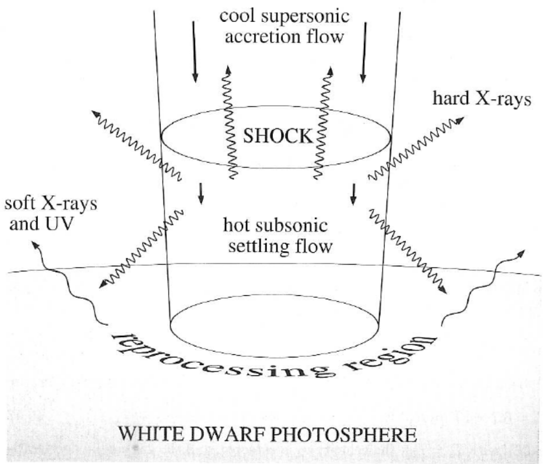

Figure 2. Schematic illustration of the accretion column typically seen in a Polar. The WD has a strong magnetic field causing accretion material to channel through the magnetic poles. (Adopted from [8, p. 178, Fig. 6.11].

thermonuclear burning of the accreted material on the WD's surface, as in classical novae (CNe) and recurrent novae (RNe), or a release of gravitational energy caused by a temporary increase in the mass transfer rate of the accretion disc, as in dwarf novae (DNe) [6]. The vast majority of these eruptive systems are NMCVs, as outbursts in magnetic CVs are rare events. V1500 Cyg (novae outburst in 1975) [7], and GK Per (dwarf nova outburst in 2015) [8], are two magnetic CVs who exhibited such eruptive behaviour. In a fourth class of systems, the so-called nova-likes, large eruptions as in novae or DNe have not been observed.

The most common CV type detected is DNe, since most CVs accrete material onto the WD via an accretion disc [2]. During an outburst, a DN shows a typical increase in brightness of 2 - 5 magnitudes. The outburst can last for a few days and recurs on a timescale of days to years [6]. DNe are sub-divided into three distinct types, namely U Gem, Z Cam and SU UMa stars. SU UMa stars occasionally have superoutbursts which last $\sim$ 5 times as long as an ordinary outburst. The knowledge gained from monitoring CVs and studying the physical processes related to gravitation, viscosity and magnetic fields, will contribute to the understanding of e.g. planet formation and larger accreting systems, such as Active Galactic Nuclei (AGNs).

CVs emit energy almost across the whole electromagnetic spectrum [9]. The regions where the strongest emission occurs in non-magnetic and magnetic CVs are illustrated in figure 1 and figure 2, respectively. In NMCVs, the accretion disc often dominates the luminosity of the system, making the primary and secondary almost invisible in the optical spectrum. The boundary layer, which is the transition region between the accretion disc and the WD, is the region where particles decelerate to match the surface velocity of the WD. Soft X-rays and extreme ultraviolet (EUV) emission are detected from this region when the boundary layer is optically thick [6]. An optically thin boundary layer emits hard X-rays. Infrared radiation comes from the outer regions of the disc. In magnetic CVs, high energy radiation, such as hard X-rays, are emitted from a region in the accretion column where supersonic accretion flow produces a stand-off shock. Soft X-rays and ultraviolet radiation are emitted where the hot subsonic settling flow interacts with the WD's photosphere. Radio emission is also observed due to synchrotron

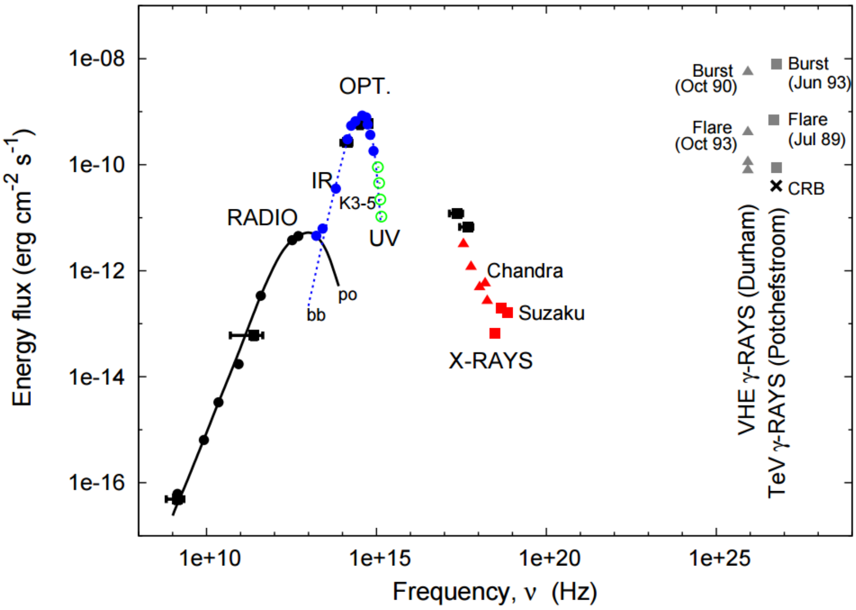

Figure 3. SED of AE Aqr (Adopted from e.g. [9, p. 645, Fig. 4]).

or cyclotron radiation (e.g. [2]). A fascinating magnetic CV in its propeller phase, AE Aqr, is one of a few CVs to date that have been studied from radio to TeV gamma-rays [11]. Figure 3 shows the spectral energy distribution (SED) of AE Aqr. Multi-wavelength studies are therefore essential to fully understand the different processes in these systems.

For this study in general, the parameters we want to determine are the orbital periods and WD spin periods, the accretion rate, and particularly the fraction of accretion power that may be channelled into non-thermal flares or outbursts. A sample of CVs, showing high levels of transient emission, have been identified in the CRTS. In the following sections, the selection criteria for the sample are discussed, as well as the necessary photometric process to obtain accurate light curves for the CRTS data. The light curves of three DN SU UMa sources are also presented.

2. Selection criteria

The criteria used to select CV candidates from the CRTS database for further study were: 1.) they were observed for more than a year by the CRTS, and 2.) exhibit variability of more than 2 magnitudes. In order to perform follow-up studies of the sample, which includes optical photometric observations with the UFS/Boyden 1.5-m telescope at the Boyden Observatory, the sources must have a V magnitude less than 19 and a declination less than +30°.

The light curves provided by the CRTS only provide a rough estimate of a source's variability, as they were produced by an aperture photometry pipeline [2]. Part of the CRTS photometric processing included transforming unfiltered magnitudes to standard (Johnson) V magnitudes using Landolt photometric standards. Aperture photometry is not the ideal photometric process to apply on all the sources as some of the sources are in crowded fields. One of the key factors of the selection criteria was to identify rapidly varying transient sources that have the potential to be selected for intensive multi-wavelength follow-up studies. We therefore preferred to produce light curves by applying point spread function (PSF) photometry and differential photometry on the available CRTS fits files. This enabled us to get a better of idea the sources' variability and to obtain a more accurate magnitude range.

3. PSF photometry

The Image Reduction and Analysis Facility (IRAF) package is freeware that is mainly used for general image processing (reduction and analysis) of astronomical data [13]. It includes packages to do accurate photometric processing. A Python- and PyRAF-based script was developed which automated PSF photometry in IRAF. The standard routines of the DAOPHOT package were used. By automating PSF photometry, the PST package in DAOPHOT automatically identifies stars to create a PSF. The problem with the CRTS data is that some of the stars in the images are saturated and cannot be used to create a PSF. This was overcome by setting a maximum detection value in the DAOFIND package to ensure that the saturated stars were not identified and used to create a PSF.

A differential photometry method largely based on the method described by Everett and Howell [14] was included in the automated script. For the purpose of differential photometry, three comparison stars were chosen near the source. Another pitfall of the CRTS data is that the source is not centred in the images and have an extreme positional shift between frames. This limited the number of comparison stars that could be used for differential photometry, as the chosen comparison stars are not in the field of view for all the frames. The script was programmed to identify the comparison stars that were visible in most of the frames and that had the lowest corrected magnitude variance values. This helped to eliminate the possibility that the chosen comparison stars are also variable stars and ensured that the best differential photometry results were obtained.

Figure 4 shows the light curves (with error bars) obtained for SSS J202948-155437, CSS J163121+103134 and CSS J152614+081802. All three sources are classified as SU UMa DNe and show prominent outbursts. During quiescence, the sources vary by ~ 1 magnitude, which is a clear indication that there must be other processes at hand that cause variability, other than the release of gravitational energy. This lower magnitude range variability is visible when the light curves are compared to the reference lines (dashed lines) included in the plots. The error bars are extremely small, indicating the high degree of accuracy associated with the PSF photometry process. All three sources are included in the sample and further observations will assist in narrowing down the causes of variability.

The sample of sources that was selected for intensive multi-wavelength follow-up studies is discussed in the next section.

4. The sample from CRTS

The CRTS CV sample that was chosen for the multi-wavelength follow-up study is given in table 1. The CV classifications and the orbital periods $P_{\rm orb}$ were obtained from the Outburst catalogue of cataclysmic variables [15], accessible through the CDS Vizier website [16]. The V magnitudes are the values specified by the CRTS [1]. CDS Vizier was also used to determine in which wavelengths the CVs have been observed or detected. This is for an indication of how extensive the multi-wavelength studies can potentially be.

5. Prospects for future work

Optical observations of the sample will be undertaken, and other archives, e.g. GALEX, WISE, XMM-Newton and Fermi, will be investigated in an attempt to match outbursts detected by CRTS. The new observations will include photometric observations with the UFS/Boyden 1.5-m telescope at the Boyden Observatory, and spectroscopic observations with the SAAO 1.9-m telescope, located at the South African Astronomical Observatory (SAAO). The increased sensitivity of instruments, such as the currently constructed MeerKAT, will increase the number of radio detections in CVs. In the near future, we wish to utilise MeerKAT, more specifically ThunderKAT (The HUNt for Dynamic and Explosive Radio transients with MeerKAT), to help us better understand the processes causing non-thermal outbursts in the system.

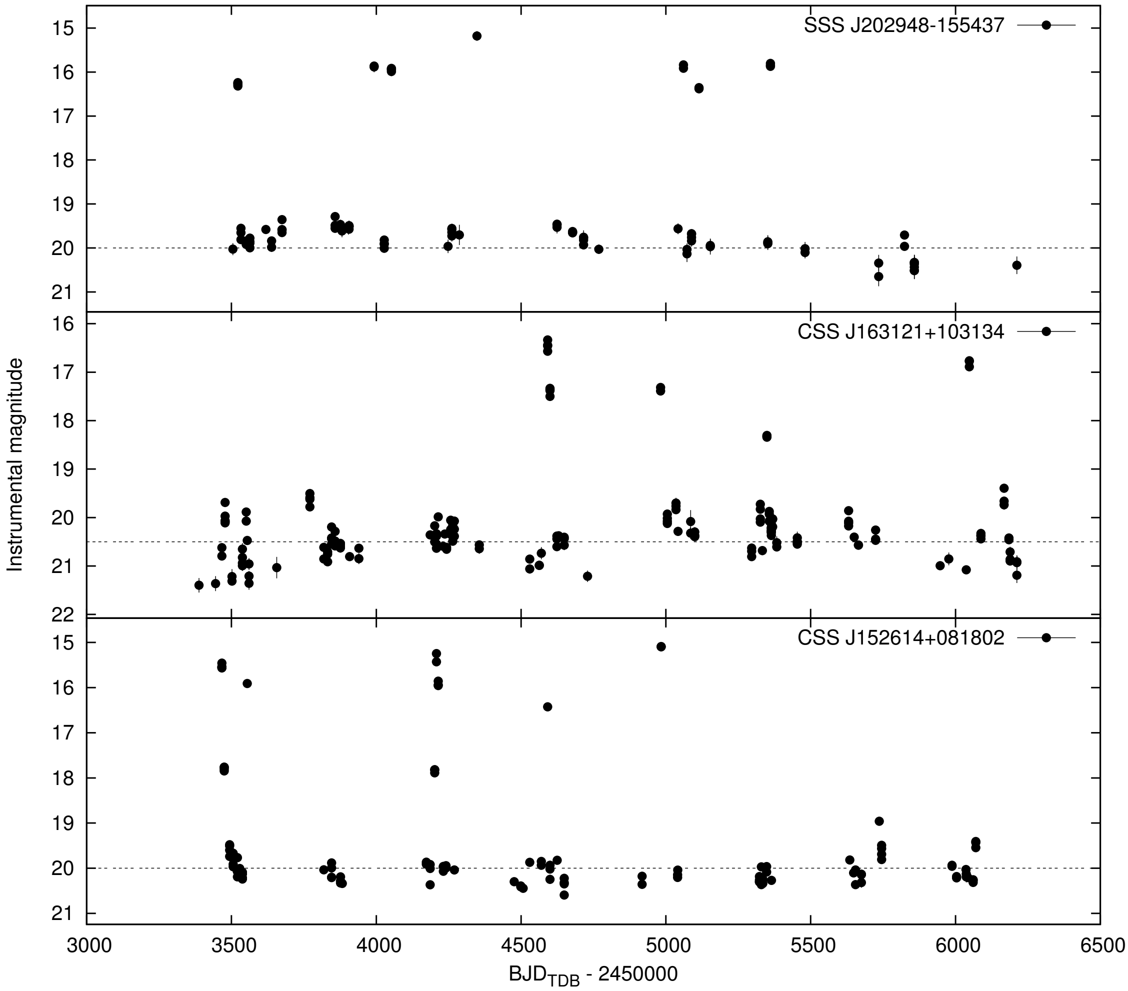

Figure 4. Light curves of three SU UMa CVs. The dashed lines at instrumental magnitudes 20 and 20.5 in the respective plots are only reference lines. Error bars are included for all the data points, but are smaller than the plotted data points in most cases.

Table 1. The sample of CRTS CVs selected for intensive multi-wavelength follow-up studies. The last column specifies in which wavebands the sources have been detected, namely Radio (R), Infrared (IR), Optical (V), Ultraviolet (UV) and X-ray (X).

CRTS Name	Type	$P_{\rm orb}$ (h)	$V_{\rm mag}$	Detected emission
MLS J022733+130617	Polar	3.79	16.5 - 18.4	IR, V, UV
CSS J034515-015216	DN	1.68	15.5 - 18.6	IR, V
CSS J054558+022106	DN	2.88	14.6 - 16.4	IR, V
CSS J103947-050658	IP	1.57	16.4 - 20.2	IR, V, X
CSS J152614+081802	DN SU UMa	1.78	12.6 - 17.7	IR, V, UV, X
CSS J162147-225310	IP	3.56	15.6	R, IR, V, X
CSS J163121+103134	DN SU UMa	1.5	14.1 - 18.1	IR, V, UV
SSS J202948-155437	DN SU UMa	1.5	13 - 17.9	IR, V
CSS J233003+303301	Non-DN	—	16.6 - 18.3	IR, V, UV, X

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