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Harnessing optical transient surveys for accretion studies

Elmé Breedt*
University of Cambridge
E-mail: ebreedt@ast.cam.ac.uk

Transient surveys are a proven method for uncovering the faint end of the accreting white dwarf population, including rare types of transients. Gaia Science Alerts, the transient survey based on the repeated Gaia scans, is ideal for this purpose, scanning the full sky at Hubble-like resolution and to a depth of $G < 20.7$. Here I show what the outburst properties of a transient-selected sample of cataclysmic variables can reveal about the population and discuss the advantages of Gaia Alerts for a variety of accreting objects.

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*Speaker.

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1. Introduction

Cataclysmic variables (CVs) consist of white dwarfs accreting from Roche lobe-filling companion stars, typically M–K dwarfs. The majority of systems have non-magnetic or weakly magnetic white dwarfs, and for these the accretion occurs via an accretion disc. CVs share many properties with other accreting systems, such as disc outbursts [5, 11], a linear rms-flux relation [20] and radio jets [6], but they are more common and typically brighter than e.g. systems with a neutron star or black hole as accretor, making them the ideal for accretion studies in general. For a detailed review of Cataclysmic Variables, see [23].

2. CVs discovered as transients

Over the past few years transient surveys have become very popular, driven in part by systematic searches for supernovae, but also as a by-product of photometric surveys with a different primary objective. For example, the Catalina Sky Survey (CSS) and the Asteroid Terrestrial-impact Last Alert System (ATLAS) monitor near-earth objects but have sparked the Catalina Real-time Transient Survey (CRTS, [7]) and ATLAS transients project [22] respectively; the All-Sky Automated Survey (ASAS, [19]) monitors variable stars and form the basis of a dedicated supernova search, ASAS-SN [16]; the Mobile Astronomical System of the Telescope Robots (MASTER, [18]) and the Gravitational-wave Optical Transient Observer (GOTO, [8]) are involved in electromagnetic follow-up of gravitational wave events; and Gaia's all-sky astrometric measurements form the basis of Gaia Photometric Science Alerts ([13]). Dedicated transient surveys like the Zwicky Transient Facility (ZTF) exist as well, all building up to the Large Synoptic Survey Telescope (LSST; [15]), which is expected to produce 10 million transients per day when it starts operations in 2022.

CVs are commonly detected in these transient surveys. Their accretion discs are subject to a thermal instability, which cause outbursts of several magnitudes that last for a few days. The time between successive outbursts vary from system to system and can be anything from weeks to decades. It depends primarily on the mass transfer rate from the donor star and the size of the accretion disc.

Because of these large amplitude outbursts, we can reliably discover CVs that are much fainter in quiescence than the detection limit of the survey. Rapid follow-up allows us to go much further than just discovery: we can measure their orbital periods too. Most of the dwarf novae with orbital periods shorter than 2 hours show superoutbursts, which last longer and are brighter than normal outbursts. During superoutbursts, the light curves of these CVs display photometric modulations known as 'superhumps', resulting from the dynamical interaction between the disc and the donor star. The superhump period is closely related to the mass ratio of the two component stars. It is a few per cent longer than the orbital period, and a good proxy for the evolutionary state of the binary.

3. The faint end of the accreting white dwarf population

The Sloan Digital Sky Survey (SDSS) revealed a large population of CVs with short orbital periods ($81 < P_{\rm orb} < 90$ min) whose optical spectra are dominated by the white dwarf, rather than

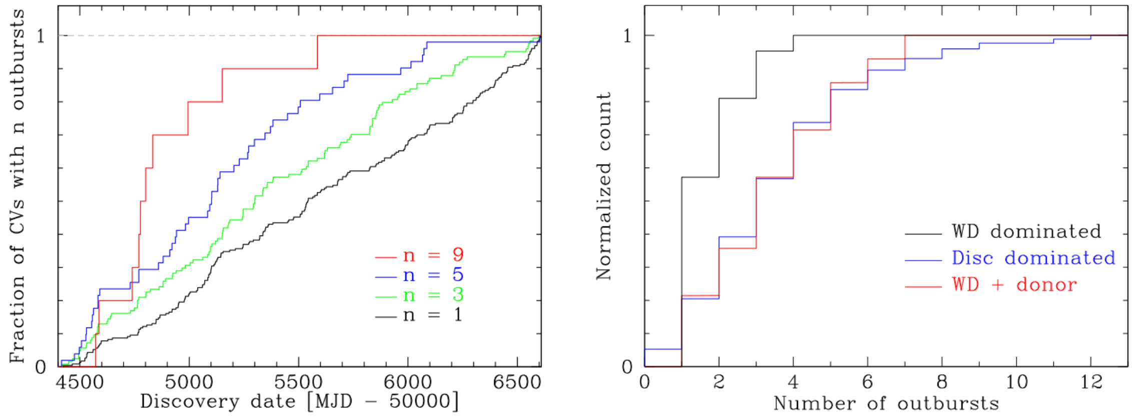

Figure 1: *Left:* Cumulative distribution of CSS CVs with one (black), three (green), five (blue) and nine (red) outbursts observed by CRTS. The number of CVs with a single observed outburst continues to increase at a steady rate. Dwarf novae with high accretion activity, and hence a large number of outbursts, were discovered early in the survey (steep initial rise). Their distributions also flatten off early, suggesting that most dwarf novae with an accretion rate high enough to produce one outburst per year have already been found. *Right:* A comparison between the number of outbursts observed from CVs whose spectra reveal the white dwarf (black), both the white dwarf and the donor star (red) and those where the white dwarf is not seen in the spectrum (blue). The white-dwarf-dominated sample show significantly different outburst behaviour than the disc-dominated sample.

by the accretion disc as in the majority of CVs [9]. They were interpreted as intrinsically faint systems with low accretion rates, too faint to be observed in previous surveys.

Transient surveys allow us to explore this notion at even fainter magnitudes. The left hand panel of Fig. 1 shows the cumulative distribution of CVs discovered by CRTS, split by the number of outbursts detected over 6 years of CRTS operations. The number of systems discovered by CRTS with just one observed outburst (black line) increases at a steady rate, and this increase is likely to continue for another few years before most dwarf novae are found and the slope will flatten off. In contrast, CVs with a large number of outbursts, like the $n = 9$ case (red line), rise steeply in the early part of the survey, but also flattens off early. Due to their high levels of accretion activity, most of these systems have been discovered and future observations will simply see more outbursts from the same systems, rather than finding many new CVs with similarly high accretion rates. The cumulative distribution suggest that the majority of dwarf novae in the CRTS survey area, with an accretion rate high enough to produce an average of one outburst per year, have already been found. Most future CRTS discoveries of dwarf novae will be systems with a lower accretion rate [2].

The outburst activity suggest that the CV population has a large fraction of low accretion rate systems which are still to be discovered. This idea is further supported by the fact that 83% of the CVs detected by CRTS were new systems, never before observed.

To compare the result more directly with the SDSS results we collected all available spectra of CRTS CVs and classified them as white dwarf dominated, accretion disc dominated or systems in which features from both the white dwarf and the donor star were visible. We compare their outburst properties (in terms of the number of outbursts) in the right hand panel of Fig. 1. Those

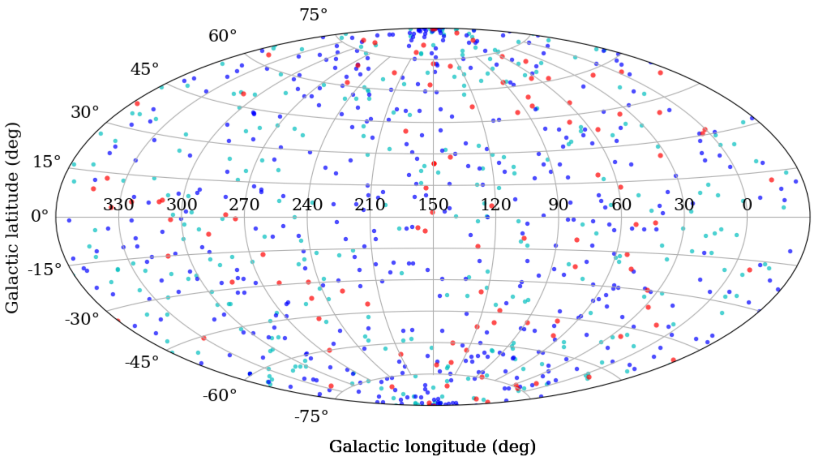

Figure 2: Sky distribution in galactic coordinates of previously known or confirmed CVs (red) and CV candidates (blue) and hostless blue transients (cyan) detected by Gaia Science Alerts. We expect the majority of the hostless transients to be CVs as well, although some may be supernovae.

with white dwarf dominated spectra (black line) show significantly fewer outbursts in their CRTS light curves than the remainder of the sample, in agreement with the interpretation of white dwarf dominated CVs as low accretion rate systems. For high accretion rates, the accretion disc is bright enough to dominate the optical luminosity so that the white dwarf is not visible in the spectrum. In addition, [24] found that the CVs with just a single outburst tend to have short orbital periods, giving further support to the notion that this is an old, evolved population with little accretion activity [9].

Transient surveys are also an efficient way to uncover faint and rare objects, due to the high event rates. For example, CRTS revealed 3 new AM CVn systems (ultracompact helium-accreting white dwarf binaries) as well as the first AM CVn progenitor among the (randomly selected) systems followed up spectroscopically [1, 2].

4. The Gaia advantage

As part of its main goal of measuring the parallaxes of 10^9 stars in the Milky Way, Gaia is repeatedly scanning the full sky to a depth of $G < 20.7$. This allows us to construct a light curve for each object, composed of an average of ~ 300 measurements over the (recently extended) 7 year mission lifetime. These light curves are processed to reveal transient variability and the discovered events are published as a public alerts stream, known as Gaia Science Alerts[1].

Gaia Science Alerts will allow us to extend the study of the CV population to the full sky. Gaia has numerous advantages compared to ground-based transient surveys. Its space-based location means that biases due to weather or variable seeing are dramatically reduced and the well-defined scanning law allows one to measure and account for the detection efficiencies of different types of transients. It covers the full sky at high spatial resolution (~0.1 arcsec) and photometric precision

[1] `http://gsaweb.ast.cam.ac.uk/alerts/alertsindex`

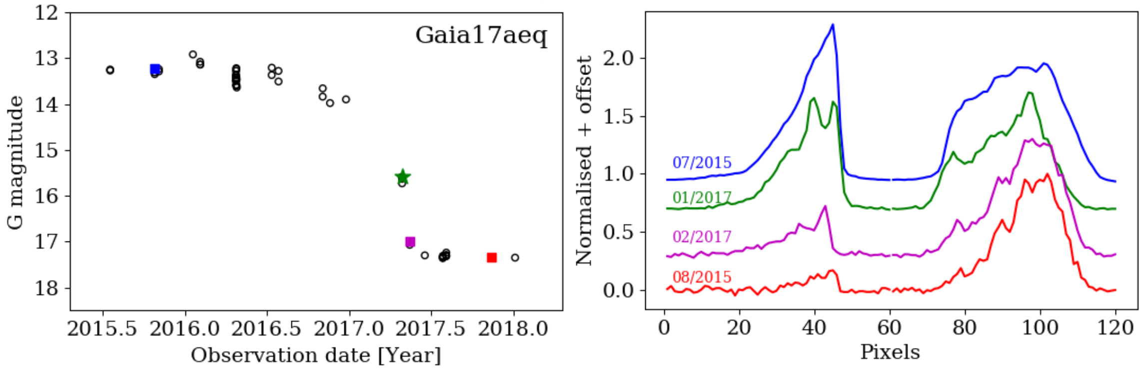

Figure 3: Light curve and colour variation of the YSO ASASSN-13db/Gaia17aeq. The points in the light curve are all Gaia measurements, and those corresponding to the BP/RP spectra shown on the right are indicated with filled, coloured squares. The Gaia alert was issued when the target faded, at the point indicated by the green star symbol.

(0.1% at $G = 15$, 3% at $G = 20.5$), including the Galactic plane which ground-based surveys usually have to avoid because of crowding.

Gaia Alerts has been operational for 4.5 years, and for all published alerts the red photometer–blue photometer (BP/RP) spectra and the full light curve, from both before and after the alert, is already publicly available. So far it has detected 7359 transients (February 2019), including 211 confirmed (or previously known) CVs, 872 CV candidates and 629 hostless blue transients, the majority of which we believe to be CVs as well. Their distribution on sky is shown in Fig. 2. Gaia Alerts has already discovered two new AM CVn binaries [4, 3] and caught several previously known AM CVn systems in outburst, including the first observed outburst of SDSS J080710.33+485259.6 = Gaia19atk [17].

5. Other accreting transients in Gaia Science Alerts

Accretion is an inherently variable process, and many types of accreting sources appear as transients in Gaia Alerts. Highlights include the young stellar objects Gaia17aeq [21] and Gaia17bpi [12]. Gaia17aeq illustrates another unique characteristic of Gaia as a transient survey: alerts can also be issued on objects that fade significantly. The outburst of this EXor variable was already underway when Gaia's nominal observations started; it was originally detected by the ASAS-SN survey, as ASASSN-13db. Gaia Alerts detected the accretion state change when it started to fade again towards quiescence (star symbol in Fig. 3). The time-series BP/RP spectra clearly illustrate the dramatic colour/spectral changes that accompany the flux variation in accretion events like these. ASASSN-13db/Gaia17aeq is the lowest mass star known to show outbursts like these [14].

Gaia has also detected the optical outbursts of the X-ray binaries MAXI J1820+070, MAXI J1348-630 and RX J0535.6-6651 (called Gaia18asi, Gaia19aqe and Gaia19bpr respectively), albeit after the detection of the outburst by X-ray observatories. Almost all neutron star and black hole binaries have been discovered as a result of their high energy emission, but the Gaia detections are of great help for localisation of the transient and further follow-up observations [10].

6. Summary

Accretion variability account for a large fraction of transients detected by currently running photometric surveys. The all-sky coverage, high spatial resolution and great depth delivered by Gaia and Gaia Alerts make it the ideal survey for statistical studies of transient populations. Rapid follow-up observations of these transients have demonstrated the discovery potential for rare and unusual objects.

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