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Optical precursors to X-ray binary outbursts

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Disc instability models predict that for X-ray binaries in quiescence, there should be a brightening of the optical flux prior to an X-ray outburst. Tracking the X-ray variations of X-ray binaries in quiescence is generally not possible, so optical monitoring provides the best means to measure the mass accretion rate variability between outbursts, and to identify the beginning stages of new outbursts. With our regular Faulkes Telescope/Las Cumbres Observatory (LCO) monitoring we are routinely detecting the optical rise of new X-ray binary outbursts before they are detected by X-ray all-sky monitors. We present examples of detections of an optical rise in X-ray binaries prior to X-ray detection. We also present initial optical monitoring of the new black hole transient MAXI J1820+070 (ASASSN-18ey) with the Faulkes, LCO telescopes, and Al Sadeem Observatory in Abu Dhabi, UAE. Finally, we introduce our new real-time data analysis pipeline, the "X-ray Binary New Early Warning System (XB-NEWS)" which aims to detect and announce new X-ray binary outbursts within a day of first optical detection. This will allow us to trigger X-ray and multiwavelength campaigns during the very early stages of outbursts, to constrain the outburst triggering mechanism.

KEYWORDS

X-rays: binaries – accretion – accretion disks – black hole physics – stars: neutron

1 | INTRODUCTION

X-ray transients appear when they brighten considerably—their X-ray intensity increases by a factor of up to $\sim 10^8$ (e.g., Chen et al. 1997). The exact mechanism that triggers these X-ray outbursts remains uncertain, despite more than 50 years of observational studies (for a timeline of key discoveries, see Shaw & Charles 2013). These X-ray transients are low-mass X-ray binaries (LMXBs)—binary systems containing a compact object—either a black hole (BH) or a neutron star (NS), and a low-mass companion star that is filling its Roche lobe so that material falls toward the compact object. In LMXBs, matter flows from the companion star onto the compact object via an accretion disk. LMXBs in our Galaxy often lay dormant, spending years-to-decades in a state of quiescence (being faint, feeding at low accretion rates, with X-ray luminosities of $\sim 10^{29}$–$10^{33.5}$ erg s^{-1}). They are (largely) only discovered when they enter an outburst and are detected by X-ray all-sky monitoring satellites, which can typically detect sources above $\sim 10^{35}$–10^{36} erg s^{-1}. During these shorter periods of intense activity called outbursts, the X-ray emission is much higher (up to $\sim 10^{38}$ erg s^{-1}) and may approach the Eddington luminosity limit, L_{Edd} (e.g., Chen et al. 1997).

In quiescence, the X-ray luminosity is so low that only the most sensitive, state of the art X-ray satellites such as *Chandra*, *XMM-Newton,* and *NuSTAR* can observe them. Even when detected, the X-ray spectrum is not well characterized due to the low number of photons detected, but can be described by a simple power law with a photon index of ∼2 (e.g., Plotkin et al. 2017). The X-ray emission is produced close to the compact object, toward the inner radius of the accretion disk, which is truncated. This cooler, fainter disk (compared to higher luminosities, during outbursts) cannot be detected at X-ray energies in quiescence; however, because its inner regions are cooler than during outburst, it emits predominantly at ultraviolet (UV) and optical wavelengths. In fact, a large fraction of quiescent LMXBs is easily detectable at optical wavelengths using moderate-size ground-based telescopes, even when they are in quiescence (e.g., Zurita et al. 2003). Evidence for emission from the accretion disk (and the companion star) can be found using ∼0.4- to 4-m class optical telescopes. Given the sensitivity limits of X-ray telescopes, it is usually only possible to detect the initial stages of a new outburst by performing regular monitoring using optical telescopes.

2 | WHAT CAUSES OUTBURSTS?

The process of accretion is responsible for the extreme heat and luminosity in the disk. Some aspects of the accretion process are fairly well understood (Frank et al. 2002) but many pressing questions remain unanswered:

- What is the structure of the accretion flow in quiescence?
- Where and how exactly are LMXB outbursts triggered?
- What *causes* outbursts, and their recurrence times?
- Do outbursts start differently in BH and NS systems?

An outburst itself is initiated due to an instability in the accretion disk. In quiescence, a cold disk fills up with matter until at some radius, its temperature reaches a critical value, ionizing hydrogen and triggering an outburst. This is described by the thermal-viscous disk instability model (DIM; Lasota 2001). Heating fronts propagate through the disk until it is in a hot, bright state, reaching X-ray luminosities approaching L_{Edd}. The DIM, modified to include irradiation of the disk by X-rays from the inner regions, can broadly explain the LMXB outburst cycle (Coriat et al. 2012) only if the inner disk is truncated during quiescence (Dubus et al. 2001). However, exactly where and when the mechanism responsible for triggering an outburst is operating remains elusive, due to the lack of data during the initial rise stages.

The DIM model predicts that for an LMXB outburst, the instability is triggered at some radius within the inner part of the accretion disk, and propagates outwards. This is coined an “inside-out” outburst (Lasota 2001; Ludwig & Meyer 1998; Smak 1984); it does not start exactly at the inner disk edge, and heating fronts propagate both ways. In dwarf nova outbursts (accreting white dwarfs), and in a few LMXB outbursts an alternative triggering process is suggested, an “outside-in” outburst (e.g., Shahbaz et al. 1998; Warner 2003). This is triggered by a thermal instability in the outer disk, which creates a heating front that propagates inwards to smaller radii.

In both inside-out and outside-in outbursts, the heating fronts propagate with a speed αc_{s}, where c_{s} is the sound speed. Eventually, the inner disk fills in on the viscous timescale, resulting in X-rays from the hot disk—this predicts a delay of several days in the rise to outburst of the X-ray emission *from the disk* with respect to the optical emission (see discussion in Hameury et al. 1997; Dubus et al. 2001; Bernardini et al. 2016). However, during the decay of outbursts, near quiescence the disk is considered to be truncated, and the X-rays originate in the hot inner flow. To compare to this, it is not clear at what stage the disk fills in during the rise of an outburst. The movement of matter through the radiatively inefficient inner flow is rapid compared to the viscous timescales of the disk filling in, so in the case of a truncated disk, we may expect a shorter X-ray delay (less than a few days) if the X-rays originate in this inner flow. Optical and X-ray detections are needed at the beginning stages of an LMXB outburst, in order to tell if outbursts are triggered inside-out or outside-in, and to measure how long it takes (and to what extent) for the inner disk to fill in during the initial brightening. Only if this can be tested on a number of LMXB outbursts, will we truly understand what triggers these outbursts.

It is notoriously difficult to detect the initial stages of a new LMXB outburst, due to the sporadic nature of their start times and the lack of regular monitoring. Nowadays, X-ray all-sky monitors still do not have the sensitivity to detect LMXBs during the initial rising stages. The limiting sensitivities of the X-ray monitors such as *MAXI* (The Monitor of All-sky X-ray Image; Matsuoka et al. 2009) and *BAT* (Burst Alert Telescope) on *Swift* (Krimm et al. 2013) are several orders of magnitude greater than the quiescent fluxes of most Galactic LMXBs. If it is possible to obtain both optical and X-ray monitoring during the very early stages of an outburst, we will be in a position to answer the question “*Where, and how exactly are LMXB outbursts triggered?*”

3 | LMXB OPTICAL MONITORING

Currently, the only way that regular monitoring can be used to detect the start of new outbursts is with optical telescopes. Queue-scheduled facilities are needed to monitor sources continuously, and robotic telescopes provide the best setup for this purpose because observations can be performed remotely and do not require real-time human interaction. A few outburst rises have been detected at optical wavelengths before X-ray detection, and claims have been made from some of these that the optical rise preceded the X-ray rise (e.g., Bernardini et al. 2016; Buxton & Bailyn 2004; Orosz et al. 1997), but the initial rise of the X-ray emission was never detected because they were fainter than the detection limit of the X-ray instruments during the initial brightening, in all cases. X-ray observations have never been triggered quick enough for the early X-ray rise out of quiescence to be seen.

Many LMXBs can be detected with small optical telescopes in only a few minutes of exposure time. We have been monitoring ~40 LMXBs for >10 years using the 2-m Faulkes Telescope North (Maui, Hawaii) and 2-m Faulkes Telescope South (Siding Spring, Australia; http://www.faulkes-telescope.com/xrb/; Lewis 2018). The Faulkes Telescopes (http://www.faulkes-telescope.com/) are the largest telescopes in the Las Cumbres Observatory (LCO; https://lco.global/), a global robotic telescope network that also comprises a suite of 1 and 0.4-m telescopes distributed over six continents (Brown et al. 2013). We typically observe each LMXB once per week when they are visible (above the horizon at night) in three filters: V, R, and i′. The main aims of our monitoring campaign are to characterize the quiescent variability of LMXBs, gather multiwaveband light curves of outbursts to be included in multiwavelength campaigns, and to detect new outbursts (Lewis et al. 2008b). In addition, in the last few years, the LCO 1-m network has become available to us. The 1-m network currently comprises of nine identical 1-m telescopes, mostly in the southern hemisphere, making it possible to perform high cadence monitoring of sources in outburst, for example, GS 1354–64 (Koljonen et al. 2016).

Around 30–50% of the LMXBs in our monitoring program are bright enough to be regularly detected in quiescence. However, we have not been able to detect most new outbursts as soon as they occur, because we have not had a real-time data analysis pipeline. The nature of issues with the data, and their evolution over the years, has generally required manual inspection of the data. As such, the data from only some of the sources, typically the more active ones, have been published to date. This has unfortunately resulted in missing a number of outburst brightenings, even though the data were taken.

We typically detect a new outburst a few days to a few weeks before the first X-ray detection by an X-ray all-sky monitor. However, only in a few cases (e.g., Al Qasim et al. 2017; Lewis et al. 2008a, 2012; Russell & Lewis 2009) were we able to report the detection of the new outburst in order to trigger multiwavelength follow-up observations. Clearly, for this to occur regularly, an automated system is required. Based on the detection of an outburst from our Faulkes optical monitoring before the first X-ray detection in 15 of 17 outbursts, we estimate that with such a system set up, we will detect the initial optical rise of ~80–90% of all outbursts from sources that we are monitoring (that are visible at the time of initial brightening). Having the light curves of all ~40 LMXBs (including quiescent sources that we do not usually detect, but for which we would if an outburst occurred) updated automatically, daily, will allow us to detect the early stages of outbursts at multiple wavelengths.

4 | EXAMPLES OF OPTICAL RISES BEFORE X-RAY DETECTIONS

In Figure 1, we show the optical and daily X-ray all-sky monitor (*MAXI* and *BAT* on *Swift*; Matsuoka et al. 2009; Krimm et al. 2013) light curves of the initial stages of four LMXB outbursts. The purple bars indicate the epochs at which the rise into outburst was first detected at optical and X-ray (3σ detections) wavelengths. For the NS systems Aql X–1 and MAXI J0556–332, the optical rise of the outbursts was detected by our Faulkes monitoring about a week before the X-ray flux brightened to sufficient fluxes to be detected by the all-sky monitors (Russell et al. 2010a, 2016b; Russell & Lewis 2016). For the BH LMXB Swift J1357.2–0933 (Russell et al. 2018a), the X-ray all-sky monitors did not detect the outburst at all (except one single *MAXI* point 26 days after the first optical detection).

The new X-ray transient, MAXI J1820+070 (Figure 1; lower right panel), was discovered in March 2018 by *MAXI* (Kawamuro et al. 2018). However, it was soon realized that a new optical transient, ASASSN-18ey, discovered 5 days earlier by the All-Sky Automated Survey for SuperNovae (ASAS-SN), was in fact the same source (Denisenko 2018). We have been monitoring this bright LMXB with the Faulkes Telescopes and the LCO 1-m network in g', r', i', y-band filters, and we used some of the initial data to infer that the system likely contains a BH, and not a NS (Baglio et al. 2018). We have also been monitoring MAXI J1820+070 with a Meade LX850 16-inch (41-cm) telescope using Baader LRGB CCD filters (similar central wavelengths to g', V, R-bands) at Al Sadeem Observatory (http://alsadeemastronomy.ae/) (Owner/Cofounder Thabet Al Qaissieh, Director/Cofounder Alejandro Palado, Resident Astronomer Aldrin B. Gabuya), located in Al Wathba South, outside the city of Abu Dhabi in the United Arab Emirates (Russell et al. 2018b). The light curve of MAXI J1820+070 in Figure 1 represents one of the best sampled rises into outburst at optical wavelengths of a LMXB to date (we also include some magnitudes published in *ATels*; Denisenko 2018; Littlefield 2018; Gandhi et al. 2018), and shows that the X-ray flux started to flatten and decay slightly, before the optical reached peak flux. MAXI J1820+070 provides evidence that we are

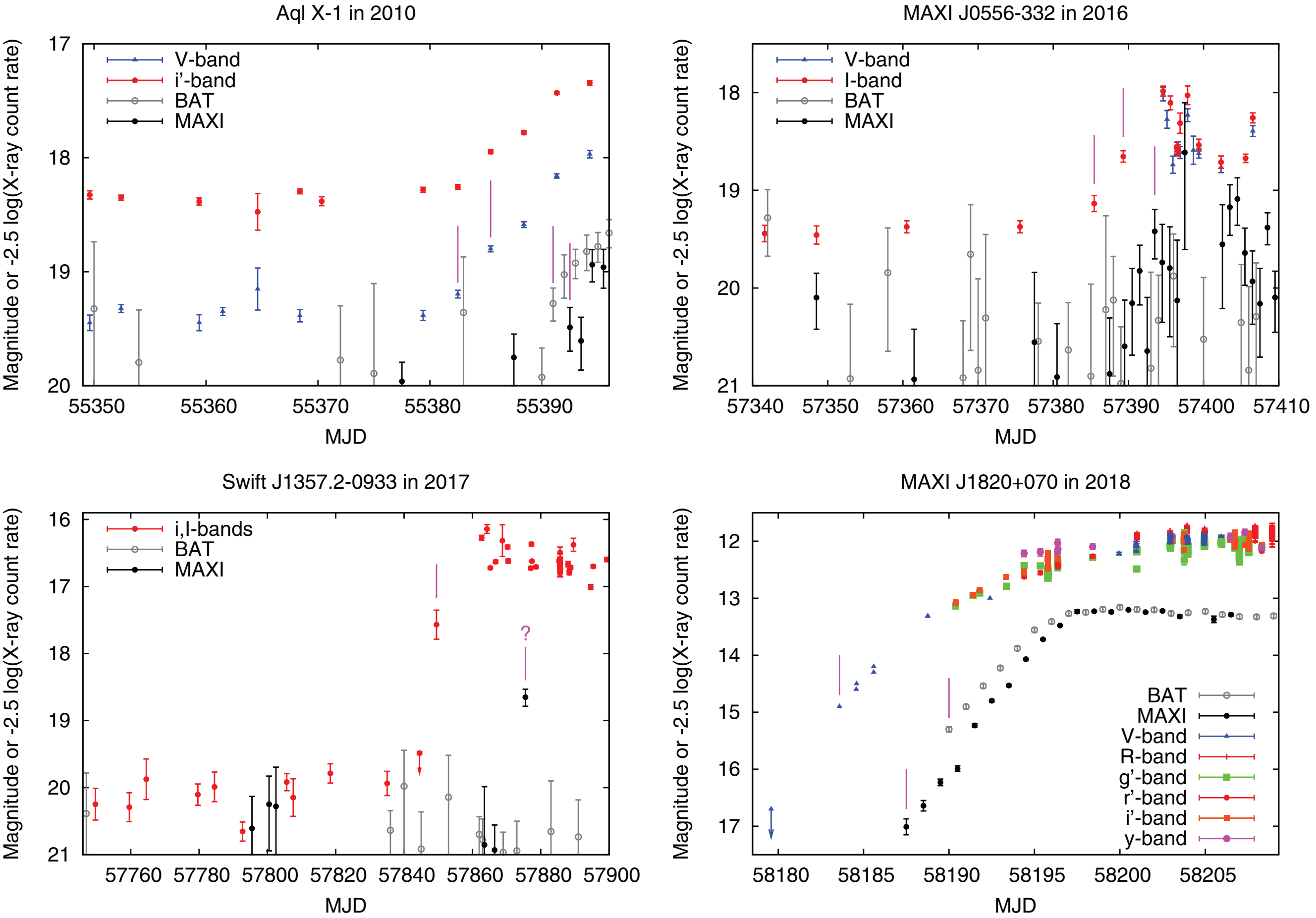

FIGURE 1 Examples of LMXB outbursts detected by optical telescopes before the first X-ray detections. Soft X-ray (2–20 keV) data from *MAXI* are shown in black and hard X-ray data (15–50 keV) from *BAT* on *Swift* are in gray. The purple vertical lines mark the dates of first significant detections at optical, then X-ray wavelengths. All were detected first with the Faulkes Telescopes except MAXI J1820+070, which was discovered as the optical transient ASASSN-18ey by the ASAS-SN survey

now entering an era in which *previously unknown* LMXBs are being discovered at optical wavelengths before X-rays. However, again the initial rise out of quiescence was missed, this time at both optical and X-ray wavelengths.

The short-lived 2015 outburst of V404 Cyg was the brightest LMXB outburst seen in decades. We detected the initial brightening of the outburst from our Faulkes Telescope monitoring—the optical precursor occurred a week before the first X-ray flare was detected (Bernardini et al. 2016). Because the X-ray rise was very rapid, the week delay suggests that the disk may have heated up before the X-ray outburst began. The X-ray delay is consistent with the time needed to refill the inner region and hence move the inner edge of the disk inwards, allowing matter to reach the central BH, finally causing the X-ray brightening. This may be the case for some of the other outbursts in which the optical rise was detected before X-ray confirmation (Figure 1), but for these we have no constraint on when the X-rays started rising out of quiescence. Even though we are detecting new outbursts regularly at their early stages, the question "*Does the optical really rise before the X-ray?*" remains elusive due to the lack of early X-ray detections.

5 | INTRODUCING XB-NEWS

To alert the community to an optical brightening of an X-ray binary as soon as possible after it has been captured in an observation, an automated pipeline and alert system is required, thereby removing human actions and reaction times. As images are acquired, we have to manually download them, perform the photometric measurements, and then build the light curves. This process is labor-intensive and it depends on the availability of someone to do the work in a timely fashion.

We have recently been awarded a grant to fund the development of the automated data pipeline and alert system outlined above. We are currently developing the X-ray Binary New Early Warning System (XB-NEWS) to achieve this and to process our archive of monitoring observations in a systematic fashion. There are two essential components to such a system. The first component is a data pipeline that takes as input a raw image and associated calibration data, and outputs a calibrated photometric measurement of the required target. The second component is an alert pipeline that analyses the complete target light curve including the new data point and decides if anomalous behavior is occurring. The alert pipeline can then send an automated message to the XB-NEWS team.

The first component of the system is already relatively well developed as of August 2018. The system interrogates the LCO data archive (https://archive.lco.global/) at regular intervals (up to once every few minutes) for a predefined list of targets. Any new science data (raw and reduced) that are available in the archive for the required targets, including master calibration files (e.g., master flat frames), are downloaded and integrated into our local archive. A data quality control step is implemented locally. Work is currently being done on automatically identifying poor reductions due to low-quality master flat frames, and then redoing the flat fielding stage with a better quality master flat frame from close-in-time to the image to be calibrated. The target flux will be (re)measured and appended to the relevant light curve. All of the light curves for the targets will be visible online at a dedicated webpage.

One of the key aspects of the data pipeline is that it is designed to be highly robust and fully automatic. The delay between an image being made available in the LCO archive and the photometry being appended to the light curve will be of the order of 1–10 min, limited principally by the cadence at which the LCO archive is interrogated by the pipeline. Hence, the pipeline is in essence a near real-time pipeline. We will make the data pipeline publicly available via *GitHub* along with full documentation because it has a more general application to LCO data management and photometry. We also intend to rereduce all of our older data with XB-NEWS and integrate the results into our local archive.

The alert system is yet to be developed. However, it is envisioned that each time a new photometric data point arrives, the relevant light curve will be reanalyzed for anomalous behavior (e.g., gradual brightening, outburst, fading, and possibly color changes). If anomalous behavior is detected, then the system will alert the XB-NEWS team and we will write an alert in the form of an ATel if the behavior is worthy of multiwavelength attention. This will allow rapid multiwavelength follow-up observations of the target when appropriate. We intend to investigate and harness the power of machine-learning techniques for the anomaly detection where possible. We expect the first XB-NEWS announcements to be made in early 2019.

When we detect a new outburst, we will also trigger other facilities. For example, the sensitivity of *Swift*, triggered within 1–2 days of the initial optical brightening, will help shed light on the question of if the optical rises first, if outbursts are inside-out or outside-in, and how the inner disk is filled by matter during the initial rise. For additional X-ray coverage, we have informal agreements to alert *ASTROSAT* (Singh et al. 2014), *HXMT* (Hard X-ray Modulation Telescope; Zhang et al. 2014), *NICER* (Neutron star Interior Composition Explorer; Gendreau et al. 2012), and *INTEGRAL* (INTErnational Gamma-Ray Astrophysics Laboratory; Winkler et al. 2003) teams of new outbursts. We will also aim to gather radio, mm, and infrared rapid follow-up observations based on new detections, to catch the outburst rise over multiple wavelengths.

In addition to detecting the initial stages of new outbursts, the real-time monitoring of LMXBs (and potentially other variable sources) will allow us to detect unusual behavior. For example, in 2016 we discovered, by analyzing new data of the BH system Swift J1753.5–0127, that it had suddenly faded dramatically after an 11-year-long outburst (Al Qasim et al. 2016; Russell et al. 2016a; Zhang et al. 2019). This fade was not noticed at other wavelengths; it was too faint for X-ray all-sky monitors. In the past, we have detected state changes and strong variability in some LMXBs from our monitoring (e.g., Lewis et al. 2010a, 2010b; Russell et al. 2010b). We are also expanding our monitoring programs beyond LMXBs, to systems such as cataclysmic variables (e.g., G. Zhang et al. 2017).

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