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Multi-wavelength Studies of High-Latitude Black-Hole X-ray Transients

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Over the last 25 years ~75% of the low-mass X-ray binary X-ray transients have been shown to contain black-hole compact objects, based on optical spectroscopy of their kinematics when in quiescence. Because many of these systems are extremely faint in quiescence and unobservable, we have utilised the method of studying them when in X-ray outburst that exploits the fluorescence features produced by X-ray irradiation of the donor's inner face, thereby allowing us to track the motion of the donor. Such outbursts are unpredictable and hence these studies must necessarily be through Target-of-Opportunity programs, and hence are ideal for SALT for accessible targets. Here we report on our SALT ToO studies of two transients, both believed to contain black holes and both at high galactic latitude.

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1. Introduction

X-ray transient (XRT) behaviour has been known since the earliest days of X-ray astronomy, and is displayed by both high-mass and low-mass X-ray binaries (HMXBs and LMXBs respectively) [1]. However, the HMXB transients are mostly BeX systems, consisting virtually entirely of neutron stars accreting from high mass donors in long period eccentric orbits, where transient outbursts normally occur during periastron passage (although there are a handful of O supergiants amongst the INTEGRAL-discovered class of heavily obscured supergiant fast X-ray transients, see [2]). The great majority of these are in the SMC. Consequently these prove challenging for the determination of their system parameters, unless extensive orbital phase coverage of their X-ray pulsations is possible (see [3] for further details). LMXBs on the other hand are the dominant form of galactic XRTs (and Cen X-2 was the first to be discovered, based only on rocket observations in 1967), with typically two such sources being found every year. These consist of low-mass ($\leq$0.5M$_\odot$) quasi-normal donors transferring matter via Roche-lobe overflow onto a compact object, which can be either a neutron star (NS) or black hole (BH), and with a short (hours to $\sim$1d) orbital period.

LMXB XRTs exhibit very bright, rare X-ray outbursts (see [4] for sample X-ray light-curves) that normally decay exponentially within a few weeks or months, and have a very long recurrence time of decades or more (only a handful are known to have recurred within the $\sim$50 year lifetime of X-ray astronomy). They are associated with optical counterparts that exhibit a very large ΔV$\leq$8 [1] together with radio emission that signifies the presence of relativistic jets (the brightest sources are revealed as *microquasars*, such as GRO J1655-40 and GRS 1915+105 [5], although these are unusual XRTs with their longer orbital periods and very different outburst behaviour). In outburst the accretion disc completely dominates the optical flux that is observed, making it impossible to study the intrinsic emission from the mass-losing donor. It is therefore necessary to wait until the system returns to quiescence, when the disc is much fainter, and the donor becomes the dominant optical light source. Optical spectroscopy and photometry of the donor can then reveal the orbital period and radial velocity (RV) curve of the system, from which the system parameters can be inferred. There have been two basic methods used for such studies:

1.1 Dynamical study of donor in X-ray quiescence

The most straightforward (and best) approach is to measure the RV curve of absorption features (of amplitude K_2 km s^{-1}) in the quiescent donor over the full orbital period, P, so as to determine the system's mass function, $f(M)(= PK_2^3/2\pi G = M_X^3 \sin^3 i/(M_X+M_2)^2)$, and M_X, M_2 are the compact object and donor masses, respectively. It is clear that, by definition, $M_X > f(M)$, and so in sufficiently high inclination BH systems (such as V404 Cyg, where $f(M)$=6.1M$_\odot$ [6]) that alone provides highly significant constraints, because M_2 is so low compared to M_X. (This is in stark contrast to the situation in HMXBs, where $M_2 >> M_X$ and so it is then crucial to know M_2 well in order to provide any sensible constraints on M_X.)

Further knowledge of an LMXB's system parameters can come if the optical spectroscopy of the donor is of sufficient quality and resolution to be able to determine the star's rotational broadening, $v_{rot} \sin i = 2\pi R_2/P \sin i = K_2 \times 0.46(1+q)^{2/3}/q$, where q is the mass ratio (M_X/M_2) and R_2 is the donor's radius [7]. That is because we know the donor must be filling its Roche lobe in order for mass-transfer to be ongoing, and so $R_2/a = 0.46(1+q)^{-1/3}$ where a is the binary separation [8]. Hence if we have measured K_2 and $v_{rot}\sin i$, then we can determine q. (Note that q is often defined as the inverse of that used here.)

Finally, it is possible to infer the binary inclination, i, from the photometric light-curve in quiescence, as the donor is distorted in a well-defined way when filling its Roche lobe, and this leads to a double-humped modulation (the so-called *ellipsoidal* modulation) on the orbital period. The amplitude of this modulation is a function of i, providing there is no significant contribution to the light-curve from the residual accretion disc [9], and hence it is then possible to obtain a complete solution to the system parameters. Out of the more than 50 XRTs discovered so far, measurement of system properties in quiescence has now been achieved using these techniques for 17 of them [10].

Nevertheless, these quiescent XRT studies have provided the most precise mass constraints on stellar-mass BHs, and indicated that ∼75% of XRTs harbour BHs. And it is of profound importance in fundamental physics to determine the boundary between NS and BH masses (in order to constrain the NS equation-of-state, but as yet we have too few accurately determined masses with which to unambiguously investigate the distribution of compact object masses [11, 12] and decide whether it is continuous from NSs to BHs, contains a gap, or has a maximum mass.

1.2 X-ray fluorescence of donor during XRT outburst phase

The reason that so few XRTs have well-determined system parameters is because the majority of them are much too faint in quiescence (R>23, due to either distance, or extinction, or both) to be observable with even the largest telescopes currently available. An alternative approach has been developed over the last 15 years that attempts to obtain dynamical information on the donor during the X-ray active phase of an XRT outburst. While the intrinsic donor light is indeed swamped by that from the X-ray irradiated disc, the X-rays must also irradiate the inner face of the donor causing fluorescence emission which is observed as the Bowen blend of CIII/NIII at $\lambda\lambda$4640-50. Such emission also arises from the accretion disc, which is very broad (due to the high velocities in the disc), but if sufficiently high spectral resolution is employed then the sharply defined emission from the donor can be separated. Applied to the continuously X-ray bright system, Sco X-1, this allowed the donor to be seen and dynamically studied for the very first time [13], and has now been successfully used on a number of "steady" X-ray sources [14]. More importantly it was used on the recurrent XRT GX339-4, allowing the mass function to be determined for the first time, confirming that it is a BH system [15] and providing a vivid demonstration of this powerful new avenue for investigating XRTs in the active phase.

Such XRT outbursts are completely unpredictable, and hence obtaining optical spectroscopy during outburst requires ToO programs to be in place. Since it is 100% Q-scheduled, SALT is ideal for such work, although the observations require careful scheduling due to the nightly sky access restrictions that are inevitable with SALT. We describe here the initial results from SALT ToO observations of two XRTs during their outbursts. This is part of a larger ToO program that includes VLT and GTC. Large telescope apertures are essential for such studies, as although XRTs in outburst can reach V∼15–16, it is necessary to use medium to high spectral resolution in order to adequately resolve the donor's sharp Bowen emission features from the underlying broad disc emission.

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2. Two New High Latitude Transients Observed with SALT

Over the last 10 years, X-ray all-sky monitoring, which had been almost the sole preserve of RXTE, has been augmented by the INTEGRAL, Swift and MAXI missions. During this time they have revealed four new XRTs (MAXI J1305-704, Swift J1357.2-093313, MAXI J1659-152, Swift J1753.5-0127), which, together with the already known XRTs GRO J0422+32 and XTE J1118+480, are all short-period ($\leq$5h) systems at high galactic latitude. This means that they all have low interstellar extinction, making them important objects for studying the spectral energy distributions of XRT out to UV wavelengths [16, 17], and the similarity of their properties suggest that they may form a new sub-class of XRTs [18]. Two of these have been the subject of SALT ToO observations, using the Robert Stobie Spectrograph (RSS)[19, 20] on SALT [21, 22] at SAAO, Sutherland.

2.1 MAXIJ1305-704

This new XRT was discovered in April 2012 and exhibited typical properties of a BH LMXB outburst, with a high, soft X-ray state that decayed exponentially, moving into a low, hard state [4]. More importantly, X-ray dips were noted in the light-curve from Swift observations [23] which indicated that it was a high inclination system, and periods of a few hours were suggested. Consequently, $\sim$2hrs/night of SALT ToO spectra were obtained with the Robert Stobie Spectrograph (RSS) and the G2300 grating on April 15 and 16, giving a resolution of 105 km s^{-1} (FWHM). Our averaged spectrum is shown in Figure 1, revealing very strong, double-peaked HeII λ4686 and Balmer emission as well as a very broad Bowen blend. The breadth of these features strongly supports the proposed high inclination, as does the large ($\sim$0.2 mag) variability seen in our SAAO optical photometry. For full details, see [24].

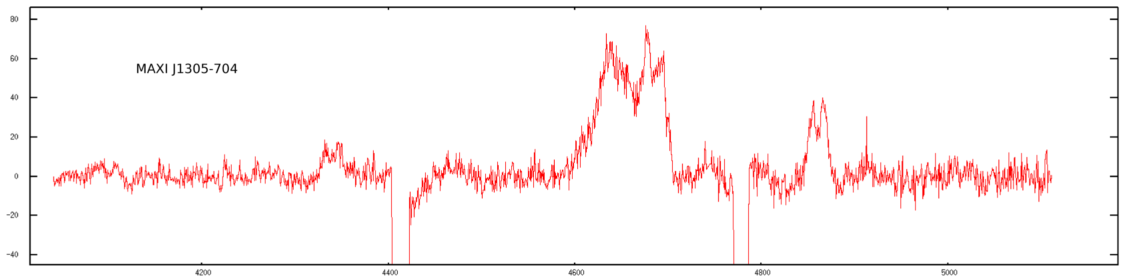

Figure 1: Average SALT spectrum of MAXI J1305-704 obtained during its Apr 2012 outburst.

However, in order to search for sharp features from the donor within the Bowen blend, it is necessary to know the orbital period. Values of 1.5, 2.7 and 9.74h [23] have been proposed, but none of these reveal any sharp components when subjected to Doppler tomography analysis [24], nor is there a clear periodicity in our SAAO photometry (which has many peaks between 2 and 8 hours, largely a result of the observational sampling). We have reanalysed the long *Suzaku* observation of MAXI J1305-704 [24], and find that the X-ray dipping behaviour is better fit with a period of 4.98h, and that this is also consistent with our optical photometry. We are now in the process of using this revised period to more carefully search our SALT spectra for features that can be associated with the irradiated donor.

2.2 Swift J1753.5-0127

This remarkable XRT went into X-ray outburst in 2005, and while it then began a typical exponential decay, this halted after a few months at a level of ~20mCrab, and the source has remained X-ray active to the present day [18]. Such extended intervals of X-ray activity are rare, and invokes comparison with EXO 0748-676 (a NS XRT) which remained "on" for ~24y before returning to quiescence. Furthermore, Swift J1753.5-0127 displayed extraordinary fast variability properties, with optical variations leading the X-rays during simultaneous optical/RXTE observations [25]. The physical cause of such behaviour is still a subject of much speculation.

The optical spectrum of Swift J1753.5-0127 during the original outburst was extremely smooth and featureless [26], apart from the very peak of outburst when double-peaked HeIIλ4686 and Hα was reported, again suggesting a high inclination. However, ongoing monitoring of this XRT (in optical and X-rays) revealed a ~420d modulation in the light-curves at all wavelengths [18] which, if interpreted as a superorbital modulation in a high mass-ratio binary, would require an extremely high q ~500, and hence a very low mass (~0.02$M_\odot$) donor, essentially a brown dwarf. Interestingly, this is actually similar to the donor in the AMXP SAX J1808.4-3658, and it is expected that short-period LMXBs will have very low-mass donors.

While Swift J1753.5-0127 has still not returned to X-ray quiescence, the detection of features associated with the donor have already been claimed [27]. Remarkably these are in emission and absorption, but are not at identifiable wavelengths that relate to the (likely) late-type companion. Accordingly their claimed velocities and inferred masses require confirmation.

2.2.1 A low-L_X soft state

Then in Jan 2015, the hard X-ray flux from this source dropped significantly, while Swift reported a large increase in low energy flux, indicating that the spectrum had become extremely soft. In the normal hardness/intensity diagrams for XRTs, Swift J1753.5-0127 was in (for this source) a new X-ray state, and detailed X-ray spectroscopy with XMM and NuSTAR was undertaken (details of which can be found in [28]). This was also similar to X-ray states in which the X-ray irradiation of the donor can lead to enhanced fluorescence emission, and so we arranged for a SALT ToO spectrum to be obtained in Mar 2015 (using RSS and the same setup as for MAXI J1305-704), which is shown in Figure 2.

Again this spectrum revealed extremely broad Bowen blend and HeIIλ4686 emission, indeed they merge into each other completely, providing support for a high binary inclination. Unfortunately, even though we know the orbital period (3.2h [29]) there are no sharp features present which might be associated with the irradiated donor, so this is a case where we must wait until it enters true quiescence in order to study the donor directly. However, if our mass ratio estimates are correct for this system, then the donor will be extremely faint and hence will almost certainly require TMT or e-ELT to undertake such a study.

3. Conclusions

The current suite of X-ray monitoring missions (just augmented with the successful launch of ASTROSAT) provides a very wide energy range, which appears to be key to unearthing new

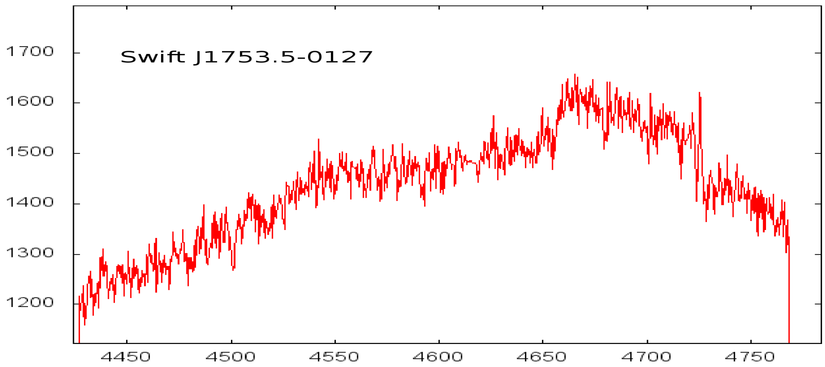

Figure 2: Average SALT spectrum of Swift J1753.5-0127 obtained during Mar 2015 at the time of its transition into the unusual soft state.

populations of XRTs. The work described here shows why immediate ground-based follow-up is crucial to understanding their properties, as many are unobservable at other times, and demonstrates the capabilities of SALT for such programs. It is clear that spectroscopic follow-up will become of increasing importance now that GAIA is operating, and a huge increase in large-telescope, rapid follow-up spectroscopic capacity will be essential to fully exploit LSST when it begins operations in the early 2020s.

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