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X-ray Binary Transients in the Magellanic Clouds and the Milky Way

Workshop 6

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Abstract. The X-ray sky is dominated by luminous galactic sources, variable on time-scales from milliseconds to years. Their eruptive behaviour is now under continuous monitoring by *MAXI, Swift, INTEGRAL* and other high-energy missions, and representing a superb exemplar of time-domain astronomy. Understanding the astrophysics of such variability requires multi-wavelength follow-up studies from a suite of ground- and space-based facilities. As SALT is a 100% Q-scheduled telescope, one of its key scientific capabilities is related to Target-of-Opportunity (ToO) programmes, and there has been a dedicated SALT Large Programme on Transients in place since 2016, a significant fraction of which has been devoted to the follow-up of X-ray binary transients. This Workshop addressed questions of how such programmes should evolve once the era of *MeerKAT* and *MeerLICHT* begins in ∼2018-9 (as well as other huge surveys at optical wavelengths), identifying the range of facilities that would be needed, and the key science topics. There is a clear and growing need for responses to transients to be faster (within minutes if possible), and to be multi-wavelength (particularly in radio and X-ray). Furthermore, extended ongoing coverage of such events (days to weeks for the next 'V404 Cyg'-type outburst) will be needed for maximum astrophysical return. That would require careful management and coordination of a wide range of ground- and space-based facilities, and optimising coverage against logistical constraints that are often conflicting.

Keywords. Accretion, accretion disks, stars: novae, cataclysmic variables, X-rays: general

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1. Background

The Southern African Large Telescope (SALT), the largest single-dish telescope in the southern hemisphere, has operating constraints that require it to be 100% Q-scheduled (see Buckley, p. 176), a mode that makes it ideal for responding rapidly to unpredictable and transient phenomena. Furthermore, SALT's operating elevation angle was chosen so as to provide access to all of both Magellanic Clouds, which are home to a surprisingly large population of X-ray binary transients (all are high-mass, Be X-ray binary systems, or BeXs), most of which are only revealed at the times of their unpredictable transient outbursts (see Buckley, p. 176, Charles, p. 127). Such transients in the Clouds and the Milky Way all have accreting compact objects which are white dwarfs, neutron stars and black holes, providing excellent opportunities to study these rare and exotic end-points of stellar evolution. This work has advanced significantly over the last 20 years as a result of the almost continuous all-sky X-ray monitoring (ASM) that has been provided since 1996,

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first by *RXTE*, then by *Swift* and *MAXI*, and now by *ASTROSAT*, yielding several new transients per year over that time and providing a rich resource for studies in high-energy astrophysics. It is through those transients that all accurate BH-mass measurements have been made, enabling radial-velocity studies of the donors once the X-rays have returned to quiescence. The BeX transients in the SMC are all X-ray pulsars, and include a recent example of an ultra-luminous X-ray outburst (ULX), defined as substantially exceeding the compact object's Eddington Luminosity (see Charles, p. 127).

Detailed study of these transients requires coordinated ground- (and space-)based follow-up observations, especially optical spectroscopy; since 2016 there has therefore been a SALT Large Project (using about 8% of the total time available) dedicated to transient alerts, including the X-ray transients (XRTs) discussed here.

The Workshop began with the recognition that, by mid-2018, MeerKAT would be operational in the Northern Cape. Furthermore, it will be combined with MeerLICHT (currently in commissioning), the wide-field optical telescope at Sutherland that is slaved to the MeerKAT pointing position, thus guaranteeing simultaneous optical coverage of any transient phenomena seen in the radio. Given the existence of this new data stream (including sensitivity to radio transients), what should we be doing differently regarding studies of XRTs?

MeerKAT would undoubtedly provide a powerful transient response facility in its own right, and already has the ThunderKAT programme in place, which includes follow-up observations of XRTs. However, without X-ray coverage, recognising XRTs as transients at other wavelengths is not straightforward. Currently it is hard to identify XRTs in Gaia data, as the Gaia cadence means that they appear similar to Cataclysmic Variables (CVs), and there is a class of fainter X-ray transients (accreting millisecond X-ray pulsars) that will look like CVs even with faster sampling ...

Furthermore, ZTF (the successor to PTF and iPTF) has already seen First Light and is due to commence operations early in 2018. More significantly, in the early 2020s, LSST will begin operating, and thereby increase the rate of transient discoveries by at least another order of magnitude and probably more. With such an increase in the number of transient alerts over all wavelengths compared to the handful that are dealt with now, we must prepare adequate responses to what will become a deluge of new sources. Alerts currently arrive in a variety of ways – GCNs, ATels, Gaia alerts and VOEvent alerts; the latter are considered to be the most efficient method, and are hence likely to be used in future. From the alerts, 'brokers' will compile the useful information that will make it easier to choose appropriate and potentially interesting follow-up targets. (It was pointed out that LSST is unlikely to use VOEvents because there will simply be too many of them, so a new system must be developed).

For the XRT community, the 2015 outburst of the BHXRT V404 Cyg was the most luminous event for several decades. Combined with extraordinary variability across all wavelengths, it demonstrated the power of arranging for simultaneous multi-wavelength observations of such events (see Middleton *et al.* 2017) However, that outburst surprised us all by turning off after only 2 weeks. In retrospect it was clear that the follow-up would have been far more effective if a programme of the necessary coordinated observations had been prepared and put in place *before* such an event, as the data actually obtained were often haphazard and short in duration (as expected at such short notice). Examination by Bernardini *et al.* (2017) of V404 Cyg's historical optical light-curve leading up to the outburst showed that there was some indication of an impending major outburst, so that kind of information should be exploited wherever possible in order to offer sufficient advanced warning of an outburst so that appropriate follow-up observations can be triggered before it actually happens. The question then is whether we know well enough what XRTs look like on the rise to outburst to be able to do this.

The Workshop was comprised of a 1.5-hr open discussion around these issues, without formal presentations. This report is a summary of the comments that were recorded.

2. Science Topics

The high-energy phenomena directly accessible through the X- and γ-ray regime have facilitated enormous gains in our understanding of compact objects and accretion physics in recent decades. Obvious examples of the benefits of rapid multi-wavelength transient follow-up are GRBs and gravitational-wave events, which are discussed elsewhere in these Proceedings. However, the giant surveys underway already, or soon to begin, will open up science opportunities in the following areas:

• Much improved distance estimates will eventually become available from Gaia for known sources. However, most XRTs will not be accessible to Gaia. Some distances (e.g. to V404 Cyg) have been measured with VLBI, but those are rare (although SKA will eventually have the spatial resolution for radio parallax work).

• Opportunities to investigate the reliability of the *Eddington Luminosity*, now that several of the brightest ULXs have been shown to be pulsars, and hence neutron stars. Could all ULXs in fact be neutron stars?

• Why have no BeXs with BHs been found in the SMC? So far, all are X-ray pulsars. Do such systems exist, and if so, how do we find them? This is important for studies of the evolution of binaries.

• Better knowledge of source extinction through galactic plane surveys, such as IPHAS, will be very important for planning follow-up observations.

• Intermediate and superbursts can be studied, i.e., thermonuclear bursts, X-ray sources that last a few hours (which is much longer than the normal time-scales of minutes for X-ray bursts). These are important for understanding the surface-layer properties of neutron stars, but are rare and unpredictable, and are hence very difficult to catch; they are concentrated in the Galactic Bulge. This science will probably only become feasible with the launch of the *Einstein Probe*.

3. Future Facilities and Monitoring Programs

3.1. *X- and γ-ray missions*

It is clearly essential to have ongoing access to high-energy (X-ray/γ-ray) ASM coverage which has a rapid localisation and identification capability. The existing suite of *MAXI/Swift/INTEGRAL* has been extremely effective, but the missions are ageing (now a decade or older), although they are expected to continue operating into the early 2020s. ASTROSAT also has an ASM (called the Scanning Sky Monitor, see https://webapps.issdc.gov.in/SSM_Web/index.jsp) which is now operational.

The most sensitive pointed follow-ups are currently provided by *Chandra* and *XMM-Newton*, the largest X-ray telescopes ever built, and although both missions are now approaching 20 years of operation, it is expected that they too will continue into the 2020s, although their successor, *Athena*, will not appear until 2028. More recent X-ray imagers include *NuSTAR, HXMT and NICER*, and will be enhanced considerably by *eROSITA* (part of *Spectrum-Roentgen-Gamma*) when it is launched in 2018, performing the first deep medium-energy all-sky survey (taking 4 years) as well as reaching 30$\times$ fainter than *ROSAT*.

Ideally, a fully-ASM instrument that is more sensitive by an order of magnitude is needed as well, but it could not then be a small, piggy-back instrument, as has been the case for all previous ASMs. However, such a dedicated mission planned for launch in the early 2020s is China's *Einstein Probe*. Nevertheless, no hard X-ray/γ-ray successor to *INTEGRAL* is currently planned for accessing energies >10keV, even though *NuSTAR*

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has demonstrated the importance of the 10–70keV region and there is clear community support for maintaining access to that spectral range.

3.2. *Optical and Radio Facilities*

Even from the small subset of science topics mentioned above, it is clear that we can expect a huge number of transient events to be revealed by *ZTF*, *MeerKAT* and other surveys. They will need rapid optical spectroscopic follow-up that is ideally immediate, but certainly within minutes. While smaller telescopes can contribute here, especially in the fastest responses (provided that the most variable transients are still bright enough), there will undoubtedly be enormous demand for 10m-class spectroscopic capabilities of the type personified by SALT. Indeed, even for brighter objects, the fast variability will require higher time-resolution in order to examine the astrophysics in detail, so again the need is for larger telescopes. That will mean having instruments dedicated to transient follow-ups, as we expect there soon to be more than enough events to keep them fully occupied. Facilities that could contribute to such a programme include:

• at SAAO/Sutherland:

– Increase the fraction of SALT time allocated to transient follow-ups. They are currently using 8% of SALT time, a commitment which continues until November 2018, but it will definitely need increasing once *MeerKAT*/*MeerLICHT* begin operations and new radio transients are identified. However, additional staff will be required for any enhanced programmes, both for SALT and for any radio transient follow-ups with *MeerKAT*.

– The 1-m and 1.9-m telescopes are already operable remotely from Cape Town, and SAAO is keen on switching to a fully automated (robotic) mode for transient follow-up work. There is support amongst the user community for this idea; an operational framework needs to be prepared.

– A 1.8-m WF NIR telescope (PRIME) is currently in the design phase; it is targetted to be operational in 2020, and will have a transient over-ride option in place.

– the Korean Microlensing Telescope network (KMT) is now operational at Sutherland, CTIO and Siding Spring, providing photometric monitoring and follow-ups of transients.

– when *MeerKAT* is not operating, *MeerLICHT* will survey or monitor the Magellanic Clouds and Galactic Centre.

• Gemini-South: OptiCAM (X-Shooter successor) is specifically designed for rapid-response transient follow-up.

• Tokyo University is completing a 6.5-m IR-optimised telescope near ALMA that is due to be operational in 2019. With a 2-colour NIR wide-field camera, mid-IR camera and multi-object spectroscopic capabilities, it will enable powerful transient follow-up studies.

• ZTF will have a Galactic Plane survey of sufficient depth and field of view to identify transients for X-ray/radio follow-up.

• ESO allows proposers to bid for ALMA ToOs that can be triggered in response to transients.

• AMI's rapid-response system enabled it to be the first radio telescope to respond to the *Swift* trigger of V404 Cyg, 2 hours post-burst. The success of the AMI rapid-response observing mode has motivated many other radio facilities to implement a similar system; they include the Australia Telescope Compact Array (ATCA), *LOFAR*, and the Murchision Widefield Array (MWA). Ensuring such capabilities are also installed on up-coming sensitive radio telescopes such as *MeerKAT*, and the SKA will ensure that there are dedicated radio facilities available which are primed to react instantly to XRTs.

3.3. *Dedicated Radio Follow-up Facility – KAT-7?*

One key area in transient follow-ups that was recognised is the need for a facility that can undertake extended observations of an unpredictable event. The paradigm here is that of the 'next V404 Cyg'-type event, where an object reaches unprecedented, extreme brightness levels across X-ray, optical and/or radio. The V404 Cyg 2015 event was observed extensively in the radio by the AMI array at Cambridge, for which large amounts of time had been pre-allocated for transient follow-ups. The AMI observations of V404 Cyg clearly demonstrated the power of rapid-response telescopes as something that should be employed for future outbursts of this magnitude. AMI was able to continue monitoring V404 Cyg for 8 hours a day over 3 weeks, covering the entire outburst, observing jet ejections, and following their subsequent evolution.

However, there is no equivalent facility in the southern hemisphere, and it was realised that *MeerKAT*/SKA itself would not be able to dedicate the (substantial) amounts of time needed for following an event of this nature. One suggestion (that was strongly supported by all the Workshop participants) was to refurbish and upgrade the original KAT-7 test array, as it would then have a similar size and sensitivity to AMI and thence be ideal for extended, dedicated transient follow-up work for *MeerKAT*. It might be funded through additional contributions from all the SKA partners, and ideally maintained as part of (normal) *MeerKAT* operations. The interest in such radio transients was found to be spread across all SKA partners, and international funding would clearly be the route to pursue.

4. Acknowledgements

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