The *Swift* and MAXI Galactic Transient Collaboration

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Abstract

NASA's *Swift* and JAXA's MAXI X-ray telescopes have, for the past 7 years, collaborated on the science and discovery of X-ray Binary Transients in our Galaxy and in the nearby Small and Large Magellanic Clouds. MAXI's near all-sky coverage every 90 minute ISS orbit, in the 0.5-20 keV energy range, allows for the rapid detection of bright ($>$ 40 mCrab) X-ray transients, and through the MAXI Nova Alert system, rapidly reports these new transients to the community. *Swift*'s capability of rapid slewing and autonomous TOO follow-up, combined with the well matched field of view of the *Swift*/XRT allows for accurate localization and follow-up of MAXI discovered transient sources. Here we discuss in detail how MAXI and *Swift* work together to localize X-ray transients, and the detail recent science results on SMC X-3 and the short lived transient sources MAXI J1957+032 and MAXI J0636+146.

Key words: workshop: 7 Years of MAXI

1. Introduction

The *"Monitor of All-sky X-ray Image"* (MAXI; Matsuoka et al. 2009) is a near all-sky imaging X-ray telescope installed on the Japanese Experiment Module - Exposed Facility (JEM-EF) on board the International Space Station (ISS). It consists of two X-ray detectors, the the Gas Slit Camera (GSC) and the Solid-state Slit Camera (SSC). The GSC consists 6 one dimensional position sensitive proportional camera, and provides sensitivity in the 2-30 keV energy range, with a FOV of 1.5 deg x 160 deg. The SSC is Charge Couple Device (CCD) based X-ray detector, operating in the energy range 0.5 - 12 keV, consisting of 32 CCDs with a 1.5 deg x 90 deg FOV. These cameras are fixed with respect to the ISS, and scan the sky as the ISS completes its 90 minute orbit, building up an almost complete image of the X-ray sky.

MAXI 's ability to collect an X-ray image of the sky in the 0.5-20 keV energy band, with sensitivities as low as 60 mCrab (5 sigma) in a single orbit and 15 mCrab in a day, makes it extremely capable at finding bright new transients in the local universe, in particular in this paper, we focus on X-ray binary sources discovered to be in outburst by MAXI in our Galaxy and in the nearby Small Magellanic Cloud (SMC).

The MAXI mission began when it was launched onboard the Space Shuttle and mounted on JEM-EF onboard the ISS on July 24th, 2009, and has been operating continuously since then.

NASA's *Swift* mission (Gehrels et al. 2004) was launched in November 2004 with the primary science goal of detecting and localizing Gamma-Ray Bursts (GRBs). *Swift* consists of three instruments, the hard X-ray (15-150 keV) Burst Alert Telescope (BAT; Barthelmy et al. 2005), a coded mask large area monitor capable of imaging 1/6th of the sky, the X-ray Telescope (XRT; Burrows et al. 2005), a Wolter Type-I X-ray (0.3 - 10 keV) telescope with CCD camera, with a $\sim$ 24 arcminute diameter FOV, and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005), a Ritchey-Chrétien optical telescope based upon the XMM-Newton Optical Monitor, with a 17 arc-minute square FOV, 6 filter (3 optical, 3 UV) imaging, and optical and UV grisms for spectroscopy.

The combination of these three instruments, along with a robotic spacecraft platform that allows for very

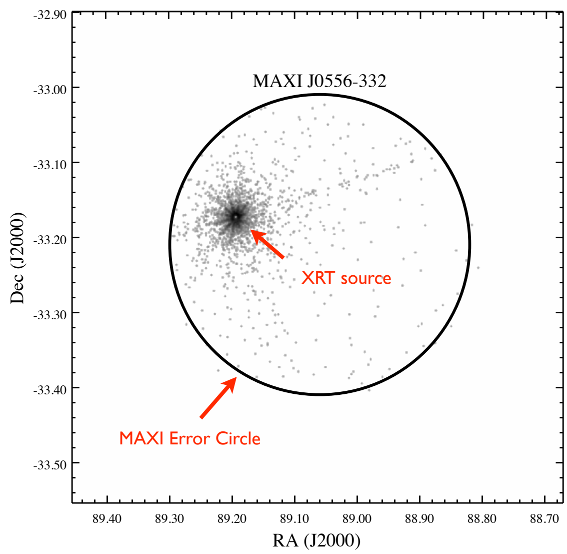

Fig. 1. Example of XRT localization of MAXI J0556−332 with *Swift*. MAXI error circle is shown over XRT Photon Counting mode data, clearly showing a bright transient source inside the MAXI error circle.

rapid slewing, and automated follow-up of on-board detected GRBs as well as and ground command Target-of-Opportunity (TOO) observations make *Swift* the ideal mission not only for detecting GRBs, but also for detecting, localizing and following up a wide range of transient phenomenon.

For X-ray binaries, *Swift*/BAT is able to localize and detect the rising brightness of hard X-ray sources, making it especially capable of detecting black hole candidate (BHC) low mass X-ray Binaries (LMXBs), but less capable of detecting LMXBs containing neutron star (NS) compact objects, as these often have spectra that cut off above 10 keV. MAXI's lower energy response makes it much more sensitive to these transients, and therefore acts as a great compliment to the capabilities of BAT.

In this paper we discuss how utilizing *Swift* is utilized to localize and provide long-term monitoring of MAXI transients, and discuss recent science results as a result of this collaboration.

2. *Swift* response to MAXI transients

2.1. Target of Opportunity observations

NASA's *Swift* observatory has several unique features that make it an ideal observatory for following X-ray transients. For transients discovered on-board by the BAT instrument, *Swift* will automatically slew to the arc-minute accuracy BAT position, and perform automated observations of the source, reporting rapidly via the Tracking and Data Relay Satellite System (TDRSS) the position, spectrum and light-curve of the object, in hard X-ray, X-ray and optical/UV. XRT can localize a point source to an accuracy of 3.5 arc-second radius (all localization accuracies in this paper quoted at 90% confidence). Furthermore utilizing UVOT images of the field to correct for the systematic errors in the star tracker's pointing solution, this error can be reduced to as good as 1.5 arc-second radius (90% confidence). In many cases where transients have low absorption, UVOT may also detect an optical/UV counterpart to the X-ray transient, allowing for a sub-arc-second localization of the source, and a broad-band spectral energy distribution (SED) to be created utilizing data from optical, UV, X-ray and hard X-ray.

Swift is a robotic telescope and has an automated TOO feature that allows for ground commanded TOO observations, that override observations in the daily pre-planned science timeline. These TOO commands can be performed rapidly, either through TDRSS (with a 30 minute latency) or through ground station passes that occur regularly throughout the day. Results of such TOO observations are typically available within hours of observation, depending on the timing of ground station contacts after the upload. Streamlining and automation work by the *Swift* Science Operations Team means that setting up *Swift* TOO observations is a simple task, utilizing a web interface for submission of TOO requests, and a simple question and answer based command line tools for setting up TOO uploads, than can be performed over any secure Internet connection.

Swift TOO requests can be requested a variety of priorities: Priority 1 ("Highest Urgency") TOOs require rapid follow-up within 4 hours if possible, and will if necessary wake up the on call observatory duty scientist (ODS) to alert them that an observation needs to be performed; Priority 2 ("High Urgency") requires observations within a 24 hour period, and pages the ODS if it is within working hours (0800 - 1700 Eastern time); Priority 3 ("Medium Urgency") if observations are needed within days to a week; Priority 4 ("Low Urgency") for longer term observations (weeks to months).

Swift TOO requests are open to the entire community and in make up a large fraction of the observations that *Swift* performs. In 2016 there were 1300 approved TOO requests for *Swift*, at varying levels of priorities, and in many ways *Swift* has evolved to become an observatory where observations of transient phenomena of all kinds through TOOs has become the primary science.

2.2. *Swift*'s response to MAXI transients

MAXI's GSC, high sensitivity and low background is the main instrument that is utilized for detection of X-ray transients. SSC suffers from background issues, making it difficult to use for transient searches. X-ray transients in MAXI data are detected by the "Nova-Alert System", as detailed by (Negoro et al. 2016). Detec-

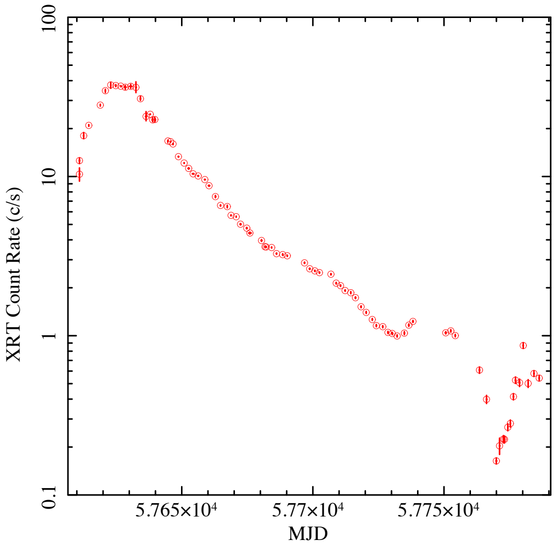

Fig. 2. *Swift*/XRT X-ray light-curve of SMC X-3 during its outburst in 2016-2017.

tions are disseminated via email alerts to the X-ray transient community, and later via Astronomers Telegram (ATEL). The typical error region for a slowly varying X-ray transient detected by MAXI is $\sim$ 0.2 degrees radius, although fainter transients, or transients that are undergoing rapid variability on the timescale of a MAXI transit will have larger error regions. This 0.2 deg error region is well matched with the *Swift*/XRT FOV, which is also approximately 0.2 degrees radius, meaning that most bright MAXI transients can be localized with a single pointing of the *Swift* XRT. An example of this type of localization is given in Figure 1.

For fainter transients, where the source is varying over the transient time of MAXI, or in crowded regions of the sky (e.g. the Galactic Center region) the error regions are typically larger than can be covered by a single XRT pointing. For these cases *Swift* is able to perform automated tiling observations of approximately circular regions. These tiling observations consist of 4, 7, 19 or 37 tiles. Although the larger number of observations means that each tile must be exposed for a shorter exposure time, the brightness of MAXI detected transients ($>$ 5 mCrab) equates to XRT count rates of $>$ 3 count/s, which given the very low background in the XRT, are easily detectable in observations as short as 60s.

The *Swift*/MAXI transient group have had a program, approved through the *Swift* Guest Investigator program, for high priority rapid follow-up of MAXI detection X-ray transient sources in the Milky Way and nearby galaxies (i.e. the SMC and LMC). This program has been approved for *Swift* Cycles 6, 7, 8, 9, 11, 12 and 13, covering the period of April 1st, 2010 to March 31st, 2018. Although the program was not approved for *Swift* Cycle 10 (April 1st, 2014 to March 31st 2015), observations during this time were performed as part of the regular TOO program.

This program has the goal of providing localizations and identifications of MAXI transients, and the program team comprised both members of the *Swift* and MAXI teams. As part of this program, the *Swift*/MAXI transient team has submitted 55 TOO requests for MAXI follow-ups, and reported results in at time of writing, 56 ATELs. In addition, many papers have been published by the *Swift*/MAXI transient group and others as a result of the discoveries made by MAXI and this program, and utilizing the follow-up observations triggered via the *Swift* TOO program, including the discoveries of 6 new BH candidates by MAXI: MAXI J1659−152 (Kennea et al. 2011), MAXI J1836-194 (Ferrigno et al. 2012), MAXI J1543−564 (Stiele et al. 2012), MAXI J1828−249 (Filippova et al. 2014), MAXI J1910−057 (Degenaar et al. 2014) and MAXI J1305−704 (Shidatsu et al. 2013).

Beyond this initial localization, the *Swift* TOO program has been utilized in order to perform monitoring observations of many of the MAXI sources.

3. Recent Science Results

In this section we will highlight results of science results that have been enabled by the *Swift*/MAXI collaboration. Due to the large number of results as a result of this program it would be impossible to list all the science results from this collaboration during the entire MAXI mission in this paper, so instead we highlight a few results obtained in the last 12 months of this collaboration. We also do this in order to highlight that the collaboration between *Swift* and MAXI remains highly productive one, even given the relative old ages of the two missions.

3.1. SMC X-3

SMC X-3 is a Be/X-ray binary in the SMC, with an optically measured orbital period of 44.86 day (Cowley and Schmidtke 2004). In addition it has a measured pulsar period of 7.78s (Edge et al. 2004a). It has demonstrated large Type II outbursts (outbursts not linked to the orbital period) on several occasions since it was first discovered by the SAS 3 X-ray observatory in 1977 (Clark et al. 1978).

On 13:17UT on August 8th, 2016, MAXI detected a bright X-ray transient in the SMC. As the SMC is a dense source of X-ray transients, several of which were in outburst at the time, it was not possible to positively identify at the time which source was in outburst, so this outburst was named MAXI J0058-721 (Negoro et al. 2016b).

Observations performed on August 10th, 2017 by *Swift* XRT found a bright point source at a position consis-

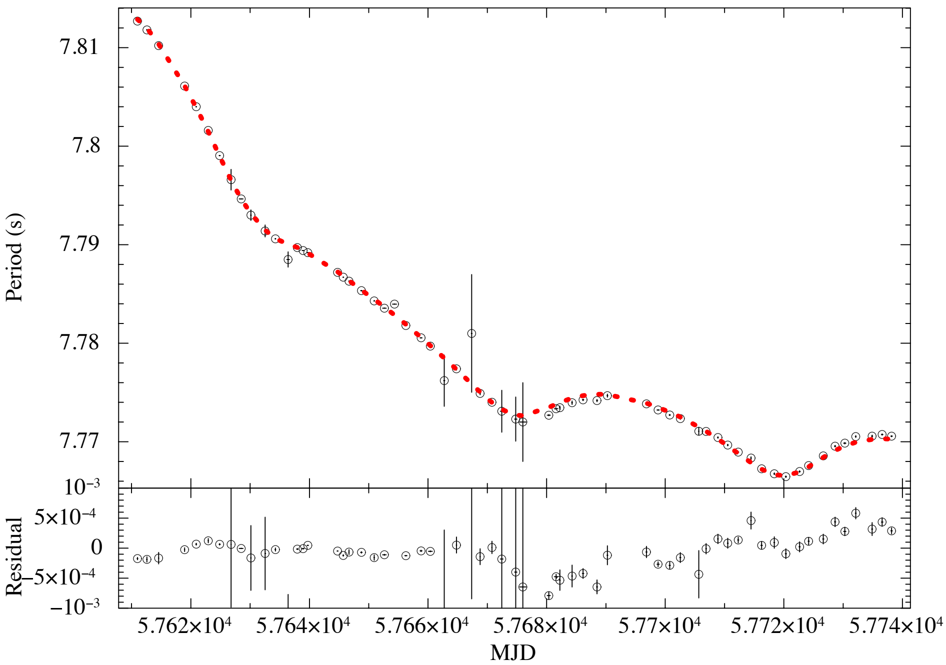

Fig. 3. Pulsar period of SMC X-3 over time, with a model for both spin-down based on the equations of Ghosh and Lamb (1979), and orbital modulation due to the Doppler effect.

tent with SMC X-3, and inside the error circle for MAXI J0058−721 (Kennea et al. 2016a). The XRT position is consistent with the Chandra position of SMC X-3 reported by (Edge et al. 2004b). Given the appearance of SMC X-3 in such a bright state, the brightest it has been seen since its previous outburst in 2003, it was concluded that that MAXI J0058−721 was indeed the reappearance of SMC X-3.

Triggered by the MAXI detection of SMC X-3, *Swift* began a series of monitoring observations to track the outburst of SMC X-3. As SMC X-3 was bright, and had a known pulsar period, XRT data was taken in Windowed Timing mode (WT) in order to avoid pile-up and to allow us to obtain an accurate measure of the pulsar period, which would provide another confirmation that this source is indeed SMC X-3. These timing observations did indeed confirm this, with observations taken on August 10th, 2016 showing a period of 7.812749 ± 0.000012 s (Kennea et al. 2016b). These observations also showed that the source was hard, well fit by a power-law model with a photon index of 1.10 ± 0.02, and when corrected for a standard SMC distance of 61 kpc, the X-ray luminosity was 3.7×10^{38} erg/s/cm^2 (0.5-10 keV), a value which is $> 2L_{\rm Edd}$, without correcting the lumiinosity to bolometric. SMC X-3 was undergoing super Eddington accretion.

Table 1. The orbital parameters of SMC X-3 as derived by fitting the evolution of the pulsar period throughout the 2016–2017 outburst to a combined model of spin-up model of Ghosh and Lamb (1979) and a model of Doppler shifted orbital modulation of the pulsar period. For details of this orbital determination please see Townsend et al. (2017)

Parameter	Value
Orbital Period	45.383 ± 0.421 days
Eccentricity	0.22 ± 0.01
Omega	208.77 ± 2.86 degrees
$a_x(sin)(i)$	196.2 ± 3.7 light-s
$T_{\rm periastron}$	MJD 57676.90 ± 0.56

Over the next few months, *Swift* monitored both the flux and pulsar period evolution of SMC X-3. After a short period spent rising to a it reached a peak X-ray luminosity of $\sim 10^{39}$ erg/s/cm^2, after which followed a slow decline of flux. At the time of writing SMC X-

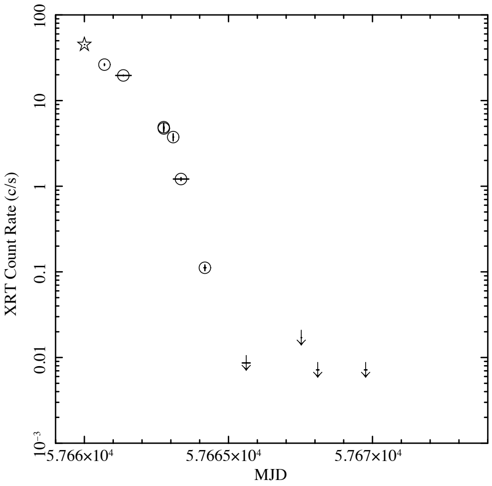

Fig. 4. X-ray light curve of MAXI J1957+032 as seen by MAXI (star) and *Swift* (circles).

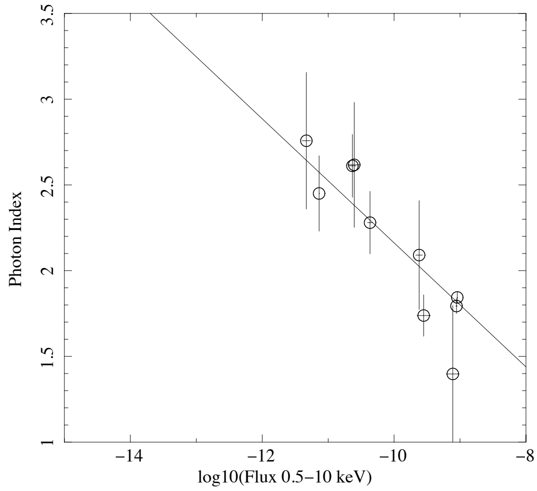

Fig. 5. Spectral evolution of MAXI J1957+032 with flux, as seen from all *Swift*/XRT data taken from the three observed outbursts.

3 is still in outburst, but at brightness approximately 2 orders of magnitude below its peak. The count rate evolution of SMC X-3 can be seen in Figure 2.

The pulsar period evolution of SMC X-3 (also see Figure 3), appears complex. Overall the pulsar is as expected spinning up during the accretion, but the rate is complex and there appears to be some modulation. Given that the SMC X-3 has a measured 45 day period, we attempted to fit this light-curve with a model of spin-up and orbital period induced changes in the pulsar period due to the Doppler effect. However, this model provided a poor fit. In an attempt to better model this change, and given the extreme nature of the accretion onto SMC X-3, we decided to model the spin-up using the model of Ghosh and Lamb (1979), following from the work of Takagi et al. (2016), where spin-up ($\dot{P}$) is modeled based on the X-ray luminosity of the source. The fitted orbital parameters of SMC X-3 are given in Table 1. As can be seen the orbital period measured from this method matches withing errors that measured in onoptical by Cowley and Schmidtke (2004), and in addition, we for the first time have a measure of the orbital eccentricity of SMC X-3. The full results of this modeling are and further analysis of the 2016–2017 outburst of SMC X-3 are reported by Townsend et al. (2017).

3.2. MAXI J1957+032

MAXI J1957+032 is a faint X-ray transient first detected on May 11th, 2015 by MAXI/GSC (Negoro et al. 2015). It was also detected by INTEGRAL (Cherepashchuk et al. 2015) and seen to decay quickly(Molkov et al. 2015). Further repeated outbursts occurred on October 6th, 2015 (Sugimoto et al. 2015), January 7th, 2016 (Sugimoto et al. 2015) and on September 29th, 2016 (Negoro et al. 2016a). *Swift* performed rapid follow-up observations of three out of four of these triggers.

MAXI and *Swift* observations show similar outburst profiles for all three observed triggers, that of a rapid decay within a period of 6 years from detection. We show in Figure 4 the outburst light curve of the most recently observed outburst off September 29th, 2016. The outburst light curve can be well described by a period of slow decay lasting ~ 2 days, followed by a rapid decline to non-detection over the next 3–4 days. The rapid decline is somewhat similar to what is seen from X-ray pulsars rapidly decay due to the propeller effect (e.g. Tsygankov et al. 2016), although other explanations cannot be ruled out as to the rapid decline. Also there is no evidence of X-ray pulsations is found in MAXI J1957+032 XRT data.

During these outbursts the source also shows considerable spectral variability. Shown in Figure 5, we plot the fitted photon index for all the *Swift* observations of MAXI J1957+032, plotted against flux, and find that they are anti-correlated, with $r = -0.91$. This softening of spectrum has been reported to be seen in NS X-ray binaries by Wijnands et al. (2015), and the evolution of the photon index with flux is very similar to that shown in Figure 1 of that paper for NS sources. Assuming this is the case, this points to a NS origin for MAXI J1957+032, and scaling the fluxes to the luminosities from that figure, allows us to estimate the distance to MAXI J1957+032 as being between 2-4 kpc. We plan to follow future outbursts of this source with longer exposures in order to search for signatures of a pulsar and to better determine the shape of the outburst light-curve.

3.3. MAXI J0636+146

On November 4th, 2016 at 02:20UT MAXI detected a new X-ray transient, named MAXI J0747+146. This source was seen at a level of 51 ± 13 mCrab for two orbits, and then was no longer detected, proving it to be short lived (Negoro et al. 2016c). *Swift* observations rapidly followed at 06:12UT, less than 4 hours after the MAXI detection. *Swift* localized the transient and determined that it was not a previously known point source. UVOT observations showed no detection of the object (Kennea et al. 2016c). *Swift* monitoring observations were triggered, until the source was no longer detected by *Swift* 5 days later. The rapid decline of MAXI J0636+146 prompts speculation that it may be similar source type to MAXI J1956+032. However, several important differences are apparently, firstly the spectrum of the source is very soft, best fit with a black-body model with $kT = 0.6 \pm 0.1$ keV, furthermore there is not strong evidence for spectral evolution throughout the outburst, although time resolved spectral fits are consistent with cooling, they are also consistent with a constant level temperature, so better quality spectra would be needed to make any strong conclusion on this. Given the lack of optical counterpart, especially as the fitted X-ray absorption is essentially negligible, the origin of this outburst remains a mystery.

4. Conclusion

Swift and MAXI have proven to be a highly successful combination for the rapid detection, localization and follow-up of X-ray transients in the local Universe. Both have unique capabilities, MAXI with its near all-sky coverage in soft X-rays, and *Swift* with its sensitive focused instruments and ability to rapidly get on-target, and also perform long term follow-up observations.

5. Acknowledgements

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