Swift Follow-up Observations of MAXI Discovered Galactic Transients

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Abstract

We describe the results of the first year of a program to localize new Galactic Transient sources discovered by MAXI with NASA's *Swift* mission. *Swift* is ideally suited for follow-up of MAXI discovered transients as its X-ray Telescope (XRT) field of view (~ 0.2 degrees radius) is closely matched to the typical MAXI error circle. The XRT is capable of localizing new sources to an accuracy of up to 1.5 arc-seconds radius (90% confidence), and the *Swift* Optical/UV Telescope also provides optical imaging of any optical counterpart of the X-ray source. If no optical counterpart is found with *Swift* (usually due to absorption), the XRT position is good enough to allow for ground based IR telescopes to positively identify the optical counterpart. Although localization and identification of MAXI transients is the main aim of the program, these are often followed up by long term monitoring of the source. We present here results from 2 of these monitoring programs: the black-hole candidate MAXI J1659−152, and the Be/X-ray binary candidate MAXI J1409−619.

Key words: X-rays: individual: LS V+44 17, HD 347929/1RXS J180724.2+194217, SAX J1452.8−5949, MAXI J1659−152, MAXI J1409−619, 4U 1137−65/GT Mus

1. Introduction

The process of accretion that drives most X-ray astrophysical phenomena can often be dramatic and short lived, with increases in accretion rates causing X-ray flux increases of up to 6 orders of magnitude from quiescent levels. In many cases these events lead to the discovery of previously unknown systems, or systems that were previously considered uninteresting. The flare-up of a Galactic X-ray transient typically heralds a rapid increase in the rate of accretion onto a compact object (white dwarf, neutron star or black hole), and provides an ideal laboratory for studying astrophysics in a relativistic regime. Even though transients have been studied for many years, our understanding of the processes behind extreme accretion events remains relatively poor. X-ray transients also cover a wide range of different system phenomenology, including Black Hole binaries systems (e.g. Remillard & McClintock 2006), Low Mass X-ray Binaries, High Mass X-ray Binaries (HMXB), millisecond pulsars (e.g. Campana et al. 2008), Cataclysmic Variables, Novae and Supergiant Fast X-ray Transients (e.g. Romano et al. 2010).

These transient events are rare, and often short lived, making detection and detailed study difficult. To obtain a good rate of detection of transient outbursts, X-ray instruments that cover very large areas of the sky are required. However, these wide field instruments typically lack the spatial resolution required to provide accurate localizations necessary for further optical and IR observations, and often do not have enough spectral sensitivity for a detailed analysis of the characteristics of the outburst. Therefore follow-up observations with complementary observatories, such as *Swift*, are required to provide more accurate positions and simultaneously observe the broadband (Optical to Gamma-ray) spectral behavior.

"Monitor of All-sky X-ray Image" (MAXI, e.g. Ueno et al. 2009), part of the Japanese Experiment Module on the International Space Station, provides a powerful tool for discovery of new X-ray transients. MAXI's ability to perform a near all-sky 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 more capable of finding transients than other instruments like *Swift*'s Burst Alert Telescope (BAT; Barthelmy et al. 2004) which has too hard an energy band, or RXTE PCA Galactic Bulge scans (limited spatial and temporal coverage).9 MAXI's capability of finding transient X-ray phenomena has been proven in the first year of operations by the detection of outbursts of known sources, GRBs, and most recently the discovery of a new Galactic transients: MAXI J1659−152 and MAXI J1409−619.

We report here on the results of a program to localize MAXI discovered X-ray Galactic X–ray transients utilizing NASA's *Swift* Gamma-Ray Burst Explorer Mission (e.g. Gehrels et al. 2004). *Swift* has proven capabilities in the follow-up of transient sources: fast slewing, flexible scheduling, and the ability to perform rapid TOO observations of targets through spacecraft commanding as quickly as within 1 hour of the announcement of a target's location. Recent developments of the *Swift* planning infrastructure have been driven towards making these observations both quicker and less burdensome on the small *Swift* mission operations team. *Swift*'s X-ray Telescope (XRT; Burrows et al. 2004) has a field of view of approximately 23.6′ diameter, well matched to the typical 0.2 degree error circle from MAXI. The *Swift* UV/Optical Telescope (UVOT; Roming et al. 2005) here also provides two valuable services in support of these observations: broad band optical/UV observations of the optical counterpart of the new transient (if visible); and astrometric correction of XRT data that allows X-ray localization errors to be reduced to as little as 1.5 arcseconds radius (90% confidence).

2. Observation Planning and Analysis

Observations of new transients by *Swift* are triggered from results of the MAXI Nova Alert System (Negoro et al. 2009), which reports on outbursts from targets on both single orbit timescales and longer. Decision to trigger *Swift* observations is made based on the following criteria: Is the source not obviously identified with a already known X-ray transient? Is the MAXI error circle small enough to be covered adequately by the XRT field of view? Is the new transient Galactic in origin? Is the new transient sufficiently bright and long-lived to still be visible by *Swift*?

Triggers that meet this criterion are submitted to the *Swift* Mission Operations Center (MOC) as a high priority Target of Opportunity (TOO) request for observations within 24 hours. *Swift* observations typically occur within 24 hours of the MAXI trigger, but can be as quick as within an hour of the TOO request being submitted.

Swift's low background means that a credible detection and localization can be made for sources in 1ks with just 10 counts. XRT's sensitivity corresponds to a count rate of approximately 0.7 c s^{-1} $mCrab^{-1}$. Given that MAXI transients typically have brightness of 40 mCrab and above this makes it trivial to detect such transients with *Swift*, unless they have rapidly faded. UVOT obtains exposures in B, V and White filters, which provide the best chance of being able to utilize UVOT data to perform astrometric corrections. XRT is forced into Photon Counting mode to ensure imaging mode data is taken.

Analysis of *Swift* data is performed utilizing the methods presented in Evans et al. (2009), via an automated process. The XRT point source is localized using PSF fitting, and then astrometric correction to reduce systematic errors. In the case of heavy pile-up, PSFs with modelled pile-up are used to fit the position and the core of the PSF is excluded to remove the effect of pile-up from the extracted light-curves and spectra of the point source. The results of this analysis are published rapidly via The Astronomers Telegram[1], typically within 24 hours of the observation.

3. Results

In this section we summarize the results of the observations performed as part of this program covering the time period of April 2010 to the end of December 2010. We provide localizations, identifications, source types and details of any *Swift* monitoring of the objects where applicable. During 2010 the program was triggered on 6 occasions. Results are presented in chronological order of discovery.

3.1. LS V +44 17

On March 31st, 2010 at 02:10 UT, MAXI detected a transient outburst (Morii et al. 2010), which was reported to be consistent with the location of LS V +44 17, a Be/X-ray binary system. A *Swift* TOO was submitted to follow-up and confirm the identification of this transient. However before a TOO could be uploaded at 18:34 UT on April 1st, 2010 BAT triggered on LS V +44 17 and *Swift* observed this source with the XRT and UVOT autonomously. An XRT localization confirmed that the X-ray transient was indeed an outburst of LS V +44 17 (Stratta et al. 2010).

3.2. HD 347929/1RXS J180724.2+194217

On June 27th, 2010 at 08:27 UT MAXI detected an X-ray transient. Usui et al. (2010) reported that the source was likely an outburst of the RS CVn system HD 347929 (also named 1RXS J180724.2+194217). A *Swift* follow-up TOO was performed to confirm the identification at

*[1] http://www.astronomerstelegram.org

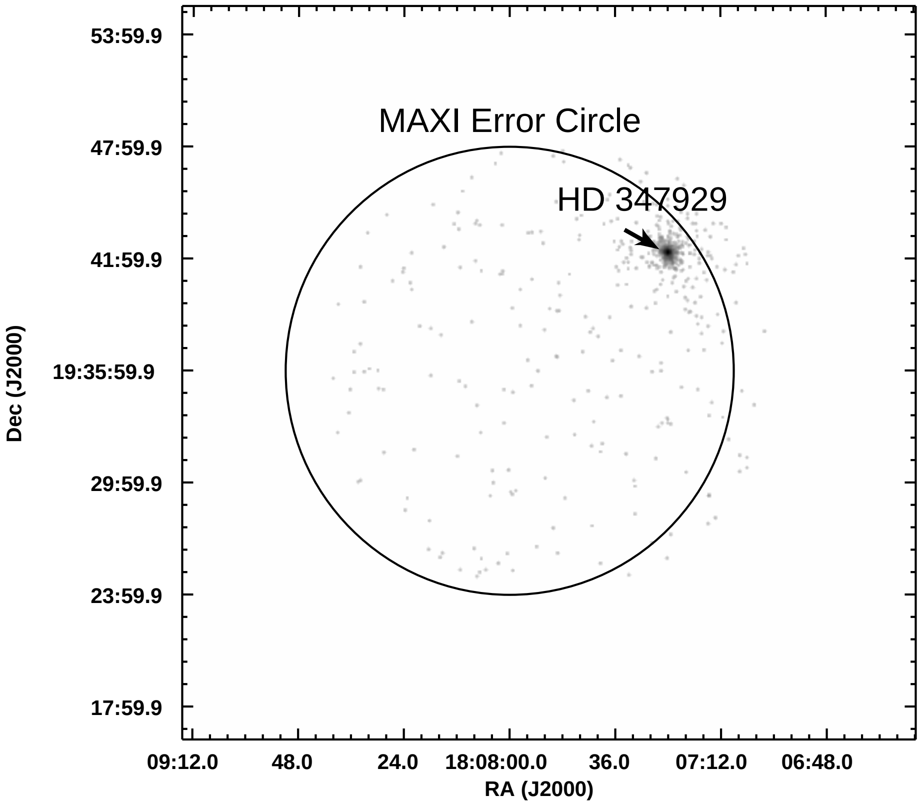

Fig. 1. The XRT field of view of HD 347929, with MAXI transient error circle marked. This observation is typical of what is seen in this program for other follow-ups.

00:10 UT on June 29th, 2010. *Swift*/XRT detected a bright X-ray source that was consistent with the coordinates for HD 347929, confirming that the MAXI transient was indeed an outburst of the RS CVn system (Kennea et al. 2010a). Figure 1 shows the *Swift*/XRT field on HD 347929, and the MAXI error box, as an example of a typical follow-up of a 0.2 degree MAXI transient error circle.

3.3. SAX J1452.8-5949

A MAXI discovered X-ray transient consistent with the location of SAX J1452.8−5949 was reported (Kawai, private communication) on August 17th, 2010. MAXI detected the source to be approximately 100 times brighter than seen in an archival XMM-Newton observation of the source.

Two *Swift* observations were performed, one centered on the MAXI error circle, and one centered on SAX J1452.8−5949. The observations show a weak detected source at the position of SAX J1452.8−5949, but no evidence of enhanced emission.

3.4. MAXI J1659−152

MAXI J1659−152 was first reported when it triggered the *Swift*/BAT at 08:05 UT on September 25th, 2010 (Mangano et al. 2010), but was misidentified as a Gamma-Ray Burst and named GRB 101225A. Follow-up observations by the *Swift*/XRT and UVOT occurred 31 mins after the BAT detection and localized the bright transient, finding it to be a new uncatalogued X-ray source. Negoro et al. (2010) reported that MAXI had detected the source at 02:30 UT, approximately 5.5 hours before the BAT detection, confirming that this was not a GRB, but in fact a previously unknown X-ray transient.

The XRT enhanced localization of the source found the following coordinates: RA, Dec = $16^h59^m01^s.56$, $-15°15'30''.5$ (J2000, $1.7''$ error radius, 90% confidence). A UVOT counterpart close to the XRT error circle was found at the following coordinates: RA, Dec = $16^h59^m01^s.679$, $-15°15'28''.54$ (J2000; $0.70''$ error radius, 90% confidence). This UVOT error circle was consistent with a later EVLA radio detection of the transient

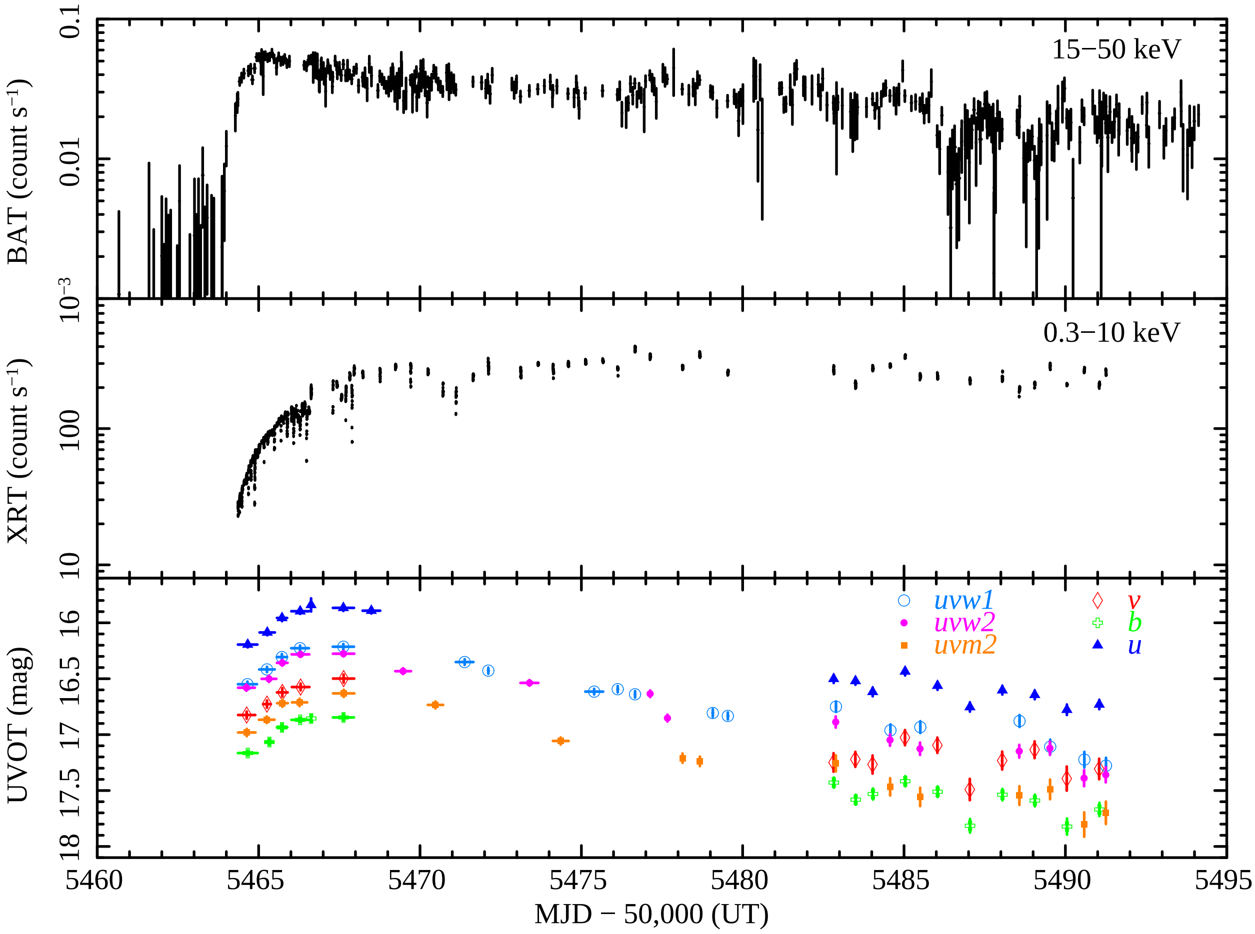

Fig. 2. The *Swift* light-curves of MAXI J1659−152 during its visibility period of 27 days starting September 25th, 2010. Presented here are results from the BAT Transient Monitor, the XRT count rate, and the UVOT light-curve in multiple filters (as labeled).

(Paragi et al. 2010), and therefore is considered the best *Swift* localization of the transient. Observed correlated variability of the UVOT counterpart also unambiguously confirms its association with MAXI J1659−162.

Swift performed follow-up monitoring observations of MAXI J1659−152 for approximately 27 days following its initial detection, after which the source was no longer visible due to a Sun constraint. In Figure 2 we show the BAT, XRT and UVOT light-curves of the transient, along with the XRT hardness ratio. The transient shows considerable broadband spectral evolution. The 15–150 keV BAT flux shows a standard fast rise/exponential decay shape, similar to many X-ray transients. The XRT rise was slower to peak, and slower to decay. The UVOT data showed similar rise to peak, followed by a long decay.

The XRT+BAT combined spectrum of MAXI J1659−152 is well fit by a model that consists of an absorbed power-law + disk blackbody spectrum, which is typical for blackhole binary systems. MAXI J1659−152 also goes through several canonical state changes (for an explanation see Remillard and McClintock, 2006), which are typically seen in blackhole binary systems. In observations taken during the initial detection the spectrum can be well described by a hard power-law ($\Gamma \simeq 1.6$), typical of a blackhole binary system in the Hard State. The source rapidly softens to the Steep Power-Law State ($\Gamma \simeq 2.5$) around September 27th, 2010. Following this the spectrum becomes increasingly dominated by a $kT \simeq 1$ keV disk blackbody component, signifying the evolution of the source into the Thermal State, although this state transition never occurred by the end of the *Swift* observation period.

QPOs were observed in the source by both *Swift* and RXTE (Kalamar et al. 2010), a further signature that MAXI J1659−152 is a blackhole candidate. Furthermore the *Swift*/XRT light-curve shows significant and variable dips in the X-ray light-curve, suggestive of eclipsing and/or dipping due to absorption by the accretion disk itself. Analysis of the XRT light-curve using a Lomb-

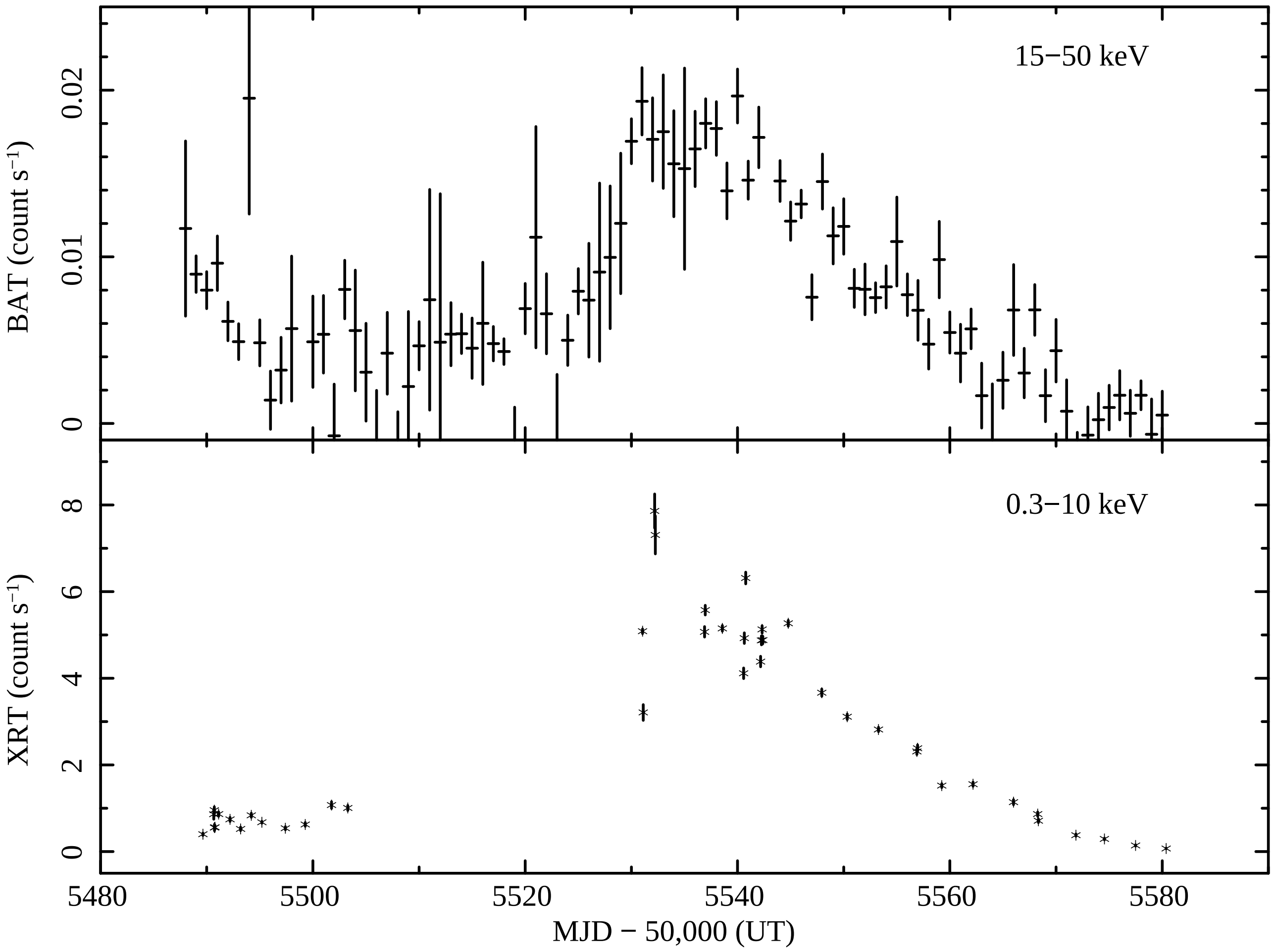

Fig. 3. The *Swift* light-curves of MAXI J1409−619 between October 20th, 2010 and January 19th, 2011. Shown here are the BAT transient monitor light-curves and the XRT 0.3–10 keV light-curve. Note that the gap in the XRT lightcurve between November 3rd, 2010 and November 30th, 2010 caused by MAXI J1409−619 being unobservable due to being too close to the Sun.

Scargle technique (Scargle et al. 1982) finds a period of 2.42±0.09 hours, which is presumed to be the orbit period. This periodicity was also observed by RXTE (Belloni et al. 2010) and XMM-Newton (Kuulkers et al. 2010) observations. If this periodicity is the orbital period, this would make MAXI J1659−152 the shortest period blackhole binary system yet discovered.

A detailed analysis of the *Swift* data from MAXI J1659−152 is given by Kennea et al. (2011).

3.5. MAXI J1409−619

On October 17th, 2010 MAXI reported the detection of MAXI J1409−619 at a level of 41 mCrab (Yamaoka et al. 2010). *Swift* observed the transient at 15:14 UT, on October 20th, 2010 and found a bright, uncatalogued point source at the following coordinates: RA, Dec = $14^h08^m02.56^s$, $-61°59'00''.3$ (J2000, 1.9″ error radius, 90% confidence), identifying the source as a previously unknown X-ray transient (Kennea et al. 2010b).

Swift monitored MAXI J1409−619 for 23 days until it went into a Sun constraint, during that period the source showed a variable light-curve (see Figure 3) ranging between 0.5–1 XRT count s^{-1}. The X-ray spectrum was well described by an absorbed power-law model, with a high absorption ($N_H = 4 \times 10^{22}$ cm^{-2}).

On November 30th, 2010 at 15:35 UT, after the source had come out of a *Swift* Sun constraint, BAT triggered on MAXI J1409−619 and found the source to be in a higher state, approximately 7 times brighter than seen in the previous observations. Furthermore, analysis of the XRT light-curve showed the presence of an ~ 500 second periodicity, which was not detected in the earlier data (Kennea et al. 2010c). This periodicity likely originates from the neutron star compact object in the system, and as such is the pulsar period of MAXI J1409−619. This period was confirmed by RXTE (Yamamoto et al. 2010) and Fermi/GBM (Camero-Arranz et al. 2010). The presence of the ~ 500 second periodicity strongly indicates that MAXI J1409−619 is HMXB source, with the transient nature making it likely to be a Be/X-ray binary system, although the source type has yet to be confirmed.

Monitoring observations of MAXI J1409−619 performed by XRT show that the source continued to brighten to peak around November 30th, 2010, followed by a decay into quiescence in late January, 2011 (Figure 3).

3.6. 4U 1137-65/GT Mus

MAXI reported an outburst of a transient whose localization is consistent with the RS CVn star GT Mus, a.k.a. 4U 1137−65 (Nakajima et al. 2010) on November 10th, 2010 at 6:17 UT. *Swift* performed a target of opportunity observation of the MAXI error circle at 23:13 UT for 1ks. *Swift* detected a bright X-ray source whose localization is consistent with that of GT Mus, confirming that the MAXI detection was indeed an outburst of this known source (Kennea et al. 2010d).

4. Conclusions

We have presented the results of a *Swift* program to rapidly follow-up and localize MAXI discovered X-ray transients. Typically, the MAXI localization of a source (~ 0.2 degrees) is well matched to the XRT field of view, making XRT the ideal instrument to attempt to more accurately localize the transient. *Swift*'s unique observing flexibility also allows us to rapidly follow-up and report on the detection of these transients, usually within 24 hours of being notified of the transient by the MAXI team. *Swift* is capable of localizing transients to an accuracy of up to 1.5 arc-seconds radius (90% confidence), or even more accurate if a UVOT counterpart is found.

We have reported on 6 triggers of the *Swift*/MAXI transient follow-up program. Two of those triggers localized and confirmed the present of a previously unknown transient source, one (MAXI J1659−152) is a new blackhole binary system. In both cases *Swift* follow-up and monitoring observations of these targets was triggered, giving valuable insight into the nature of these transients. For the other 3 triggers *Swift* was able to positively identify the source of the MAXI trigger. In only 1 case was the result of MAXI follow-up inconclusive (SAX J1542.8−5949).

The unique complementary capabilities of *Swift* and MAXI has proven to be well matched in the search for and localization of new Galactic transients sources. The all-sky monitoring of MAXI, combined with *Swift*'s rapid response TOO capability and the convenient similarity of the XRT's field of view with the typical MAXI error circle, has proved to be very successful in accurately localizing new transient sources, which provides an important service to the community.

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References

Barthelmy, S. D., et al. 2005, Space Sci. Rev., 120, 143

Belloni, T. M., Motta, S., Munõz-Darias, T. 2010, The Astronomer's Telegram, 2926

Burrows, D. N., et al. 2005, Space Sci. Rev., 120, 165

Camero-Arranz, A., Finger, M. H., Jenke, P., 2010, The Astronomer's Telegram, 3069

Campana, Stella and Kennea, "*Swift* Observations of SAX J1808.4−3658: Monitoring the Return to Quiescence", 2008, ApJ, 684, 99

Evans, P. A., et al. 2009, MNRAS, 397, 1177

Gehrels, N., et al. 2004, ApJ, 611, 1005

Kalamar, M., et al. 2010, The Astronomer's Telegram, 2881

Kennea, J. A., et al. 2010a, The Astronomer's Telegram, 2701

Kennea, J. A., et al. 2010b, The Astronomer's Telegram, 2962

Kennea, J. A., et al. 2010c, The Astronomer's Telegram, 3060

Kennea, J. A., et al, 2010d, The Astronomer's Telegram, 3025

Kennea, J. A., et al, 2011, ApJ, *In press*

Kuulkers, E., et al. 2010, The Astronomer's Telegram, 2912

Mangano, V., et al. 2010, GCN, 11296

Nakajima, M., et al. 2010, The Astronomer's Telegram, 3021

Negoro, H. 2009, Astrophysics with All-Sky X-Ray Observations, 60

Paragi, J. A., et al, 2010, The Astronomer's Telegram, 2906

Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49

Romano, La Parola, et al. "Two years of monitoring Supergiant Fast X-ray Transients with *Swift*", 2011, MNRAS, 410, 1825

Roming, P. W. A., et al. 2005, Space Sci. Rev., 120, 95

Scargle, J. D. 1982, ApJ, 263, 835

Stratta, G., et al. 2010, GCN, 10561

Ueno et al. "The MAXI Mission Overview and Schedule", Astrophysics with All-Sky X-ray Observations, Proceedings of the RIKEN symposium, p. 8.

Usui et al. 2010, The Astronomer's Telegram, 2700