Galactic Transients with Swift
(with an emphasis on BHBs and Swift/MAXI coordination)

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Swift is an NASA Medium Explorer class mission

- **Primary objective:**
  - Rapid detection and follow-up of Gamma Ray Bursts (GRBs) ~100 per year.
- Satellite in LEO, 96 min orbital period
- Launched November 2004 (just celebrated 7\textsuperscript{th} birthday)
- Mission managed out of NASA GSFC.
- Mission Operations Center at The Pennsylvania State University.

- **My role at Swift:**
  - Head of the Swift Science Operations Team
    - In charge of the daily science operations (observations, planning, etc of Swift).
  - Instrument scientist for the Swift X-ray Telescope
Swift’s instruments

- 3 instruments
  - Burst Alert Telescope (BAT)
    - Coded mask telescope, 15-150 keV energy range, 1/6 sky field of view.
    - Detects and localizes GRBs and other transient events.
    - Monitors daily brightness of galactic transients.
  - X-ray Telescope
    - 0.3-10 keV energy range. 23.6 arc-min FOV
    - Localizes point sources to up to 1.5 arc-sec error radius (90% conf.)
  - UV/Optical Telescope (UVOT)
    - UV/Optical photometry in 7 filters: u, v, b, 3 UV filters, and “white”. Also UV and Optical Grisms.
    - 17 arcmin FOV.
Swift as a Galactic Transient Mission

Swift is an ideal as a tool to follow-up and localize new X-ray transients:

★ Broad band observing: 650nm to 150keV (UVOT/XRT/BAT)
★ BAT covers almost whole sky on average day:
  ✴ Able to discover new bright hard transients
★ Accurate localization:
  ✴ XRT ~3.5 arc-sec radius, with UVOT correction can reduce to ~1.5 arc-sec radius (90% confidence). Sub arc-second with UVOT counterpart.
★ Low overhead observations.
  ✴ Rapid slewing means that 1ks observations can be made easily and often -> regular monitoring.
★ Capability to command Swift to autonomously observe TOOs.
  ✴ Swift can be on target within minutes of a transient notice being distributed (more typical is 30 mins to a day once decision to observe is made).
Swift’s Role in Galactic Transients

➡ Discovery
★ BAT triggers and BAT Transient Monitor
★ Localization
★ Accurately localize based on error circles from BAT, MAXI, INTEGRAL, Fermi, RXTE etc.

➡ Identification of source type
★ Determination of type through X-ray spectroscopy, and UV/Optical and timing analysis.
★ Localization leads to identification from by other observatories.

➡ Monitoring
★ Obtaining short ~1ks observations every 1 day to 1 week.
★ Soon we will be in a post RXTE world. Swift will be the only satellite capable of performing long term monitoring.
A large variety of objects

- “Galactic Transients” cover a large range of different objects:
  - Supergiant Fast X-ray Transients
  - Be/X-ray Binaries
  - Millisecond Pulsars
  - NS LMXB, e.g. Z-track, Atoll sources
  - “Very Faint X-ray Binaries”
  - Black Hole Candidate Binaries (BHBs)
  - X-ray Bursts
  - etc....

- Today I’m going to focus on what I’ve been studying - follow-up of BHBs discovered by MAXI and followed up with Swift.
"Monitor of the All Sky X-ray Image" (MAXI)

- Japanese scanning slit X-ray telescope mounted on the ISS.
- Scans large proportion of the sky every ISS orbit (~96 mins)
- Energy range 2-20 keV
- Excellent at detecting new bright transients!
Goals:
- To more accurately localize new Galactic Transients detected by MAXI.
- Aide the search for new black hole candidates discovered by MAXI.

0.2 degree diameter XRT FOV is well matched to the typical error circles for well-localized MAXI detected point sources (i.e. not “short” transients where error boxes are large, where tiling is necessary).

Trigger criteria:
- Previously unknown, “within the Galaxy”.
- Has a MAXI error circle ~0.2 degrees radius.
- Expanded sometimes to include checking up on possible known sources.

Approved program for 1ks localization and one extra 1ks follow-up for spectroscopy if bright.
- Follow-up monitoring programs are frequently approved if the initial observations are a success, through Swift TOO program.

Approved Swift Cycle 6 and 7 GI program, re-submitted for Cycle 8.
MAXI/Swift Localization Example

Error radii:
MAXI = 0.2 deg
XRT = 3.5 arcsec
XRT/UVOT = 1.7 arcsec
UVOT = 0.26 arcsec
Black Hole Candidate Binaries

- LMXB systems with “stellar mass” BHs, ∼3-20 solar masses.
- BHBs are usually fit by a model consisting of thermal disk emission and Comptonized/jet emission.
  ★ Line emission also present, but not often detected by Swift.
- BHBs emission classified into states based on:
  ★ Spectral Hardness/Power-law slope
  ★ Presence of QPOs
  ★ Ratio of emission components (“disk fraction”)
  ★ States have been defined by RXTE observations/energy range (2-20 keV).
BHC State Definitions

➡ State definitions are different depending on who you ask, but typically:

★ Hard state - typically when low flux, power-law dominates with photon index <1.7.
★ Soft/Thermal state - disk dominates > 80% of the 2-20 keV flux.
★ Intermediate states between these two.
★ Quiescence
Swift/MAXI BHB discoveries

- 3 new BHBs detected by Swift and MAXI as part of this program
- I’ll discuss 2 today:
  - ★MAXI J1659-152
    - Shortest period BHB yet discovered
  - ★MAXI J1836-564
    - “Cool disk” BHB
- Not covered by these slides:
  - ★MAXI J1543-564
    - relatively “normal” BHB, tracked from discovery to quiescence by Swift/XRT
MAXI J1659-152

- Triggered BAT at 08:05 UT on Sept 25, 2010, but was mis-identified as a GRB (Mangano GCN #11296). Followed up by XRT/UVOT 31 mins later.

- MAXI reported detection at 02:30UT (Negoro ATEL #2873), confirming this was a new Galactic Transient.
MAXI J1659-152: Swift Monitoring

- MAXI J1659 was monitored by Swift XRT/UVOT over 27 days until it entered a Sun constraint.
- Excellent coverage of early part of light curve due to GRB-style follow-up.
- Brightness and spectral changes seen across all wavelengths detected by Swift.
MAXI J1659-152: QPOs

- Evolving QPOs seen in WT data
- QPO frequency correlated with $\Gamma$ in initial stages, as seen in other BHBs (e.g. 4U 1543-47, Kalemci et al. 2005.) As well as increasing frequency, QPOs evolves to higher energies.
- QPO behavior consistent with other black-hole binaries.
MAXI J1659-152 "Dips"
MAXI J1659-152: Periodicity

- Swift/XRT sees “frequent dips” in the light curve.
- RXTE and XMM-Newton’s measurements find 2.4 hour periodicity in these dips (not eclipses).
- Lomb-Scargle analysis of Swift/XRT WT data finds period of 2.42 +/- 0.09 hours present in Swift data.

- Assuming this period is orbital in nature, this makes MAXI J1659-152 the shortest orbital period black-hole candidate binary yet known.

★ Previous confirmed is Swift J1753.5-0127 at 3.2 hours (Zurita et al. 2008).
MAXI J1659-152: Spectral Evolution

- BAT + XRT spectra modeled with standard absorbed disk blackbody + power-law model.
  - Other more complex models available, but diskbb+po well fits data.
- See canonical state changes associated with Black Hole Binaries:
  - Spectrum initially dominated by PL with $\Gamma=1.5$ (Low/Hard State)
  - Quickly evolves to $\Gamma=2.5$ (“Steep Power-Law State”)
  - Thermal disk component rises from $kT_{\text{in}}=0.2$ to 0.8-1 keV, and disk fraction slowly rises peaking at around 50% (evolution to “Thermal State” AKA “High/Soft State”, but never gets there).

Note: Rapid rise of $N_H$ during initial outburst.
Inner disk radius evolution.

\[ kT_{in} \propto R_{in}^{-3/4} \quad \text{(Cabanac et al. 2009).} \]

Slope = -3/4
MAXI J1659-152: Derived numbers

- Companion star $M_2 \sim 0.19\pm0.05M_\odot$ (derived from mass/period relationship of Smith & Dhillon, 1998).
  - Likely that companion is M5 dwarf ($M_V \sim 12-15$) - similar to Swift J1753.5-0127
  - Companion $V>21$ based on USNO-B non-detection in quiescence $>1$ kpc distance.
- Dips rather than eclipses implies inclination is 60-75 degrees.
- $V_{\text{peak}} = 16.5$
- From XRT $d>6.1$ kpc based on:
  - $L_{\text{peak}} > 0.1L_{\text{edd}}$ ($M_{\text{BH}} > 3.2M_\odot$)
- High galactic latitude ($b^{\perp} = 16$). Likely MAXI J1659-152 is in the Galactic Halo (cf. Swift J1753.5-0127, XTE J1118+480).
**MAXI J1659: BH Mass Estimates?**

- *Naive* mass estimates from minimum measured value of $R_{in}$ from diskbb fits (assuming min value = accretion inner edge at ISCO)?
  - If we assume $R_{in} = 6.0R_g$ (non-spinning) then $M_{BH}=2-3.1M_\odot @ 6kpc$ (too low)
  - If we assume $R_{in} = 1.0R_g$ (maximally spinning), then $M_{BH}=13-18M_\odot @ 6kpc$
- However - diskbb fit does not give a physical value for inner disk radius, more complex modeling required to obtain good estimate of BH mass.
  - $M_{BH} = 3.6-8 M_\odot$ ($d=5.3-8.6$ kpc) based on better spectral fits based on RXTE and Swift combined data (Yamaoka et al., 2011).
  - Shaposhnikov et al. (2011) estimated the black hole mass to be $20\pm3 M_\odot$ based on method using QPOs, photon index and fit with Bulk Motion Componization (bmc) model from RXTE data.
  - Optical measurements surely incoming? vsini?
- All evidence points to it being very likely that MAXI J1659-152 contains a **black hole** compact object.
MAXI J1659-152: Conclusion

- Transient shows many signatures of black hole binaries, and demonstrates Swift’s ability to measure them:
  - QPOs and PDS variability
  - Characteristic spectral model and light-curve shape
  - Canonical state changes (but no full evolution to “Thermal State”)
  - Optical counterpart brightness changes.
- Evidence of rapidly increasing $N_H$ during the initial day of the detection
  - Is this real? We’ll have to catch more of these with Swift in the future to investigate!
- X-ray detected period of 2.4 hours is shortest yet known for a black hole binary.
MAXI J1836-564: ATELs→BHB

- Detected August 30, 2011 by MAXI and Swift/BAT (Negoro et al., ATEL #3611).
- TOO observations triggered the same day by Swift (Kennea et al., ATEL #3613):
  - XRT localizes to 1.8” accuracy.
  - UVOT finds an V=16.2 optical counterpart.
  - No catalogued object at this position, so >5 magnitude rise in brightness of optical counterpart (cf. MAXI J1659).
- RXTE QPOs and spectra suggests this is a BHB (Strohmeyer and Smith, ATEL #3618).
- BHB nature backed up by EVLA detection (Miller-Jones et al., ATEL #3628).
- GROND (Rau et al., ATEL #3619) and VLT (Pakull and Motch, ATEL #3640) suggest optical/IR emission due to jet.
MAXI J1836-564 flux evolution.

- BAT light curve shows clear fading trend when XRT peaks:
  - ★ spectral softening.
- XRT HR roughly anti-correlated to X-ray brightness.
- V-band brightness appears to drop during peak (analogous to drop seen usually in transition to soft state).
- Source now fading (100 c/s to 10c/s in XRT), but optical counterpart getting brighter!
MAXI J1836 - A cool disk

**diskbb**

Below RXTE energy range

**power**
The typical state transitions seen in BHBs have been largely defined by observations with RXTE. RXTE’s lower energy range (2 keV) means that it is not sensitive to cooler disks (0.2-0.5 keV). MAXI J1836 appears to show a dip in optical similar to that typically seen when the source is in the “soft/thermal state” due to quenching of jet, but as far as the standard state definitions say, the source was never in that state. Reality: MAXI J1836 has a cooler disk than most BHBs, 0.2-0.4 keV, and optical dip coincides with the peak of the disk temperature. ★Study of the evolution of this disk is unique Swift science!
Correlation of v-band to Photon Index

![Correlation of v-band to Photon Index](image)
Atypical “cool disk” BHB, temperature maxes out at 0.4 keV.

Study of this system in detail unique Swift science.

Correlation between optical brightness of counterpart to fitted photon index.

Need to perform broad band SED spectral fitting to understand system.

Paper work in progress
Identifying BHBs with Swift

How can we tell if an X-ray transient contains a Black-hole using Swift (and no RXTE)?

★ Accurate localization:
  ✴ Ground based follow-up in radio and IR/Optical can identify if source is likely BHB.

★ Daily to weekly monitoring observations
  ✴ Spectral fits. Track evolution of disk and jet components.
  ✴ Track Canonical State Transitions seen in BHBs.
  ✴ Characteristic track on hardness/intensity plot.
  ✴ Track $L_X/L_{\text{opt}}$ evolution (a good discriminator between BHBs and other NS LMXBs, e.g. Russell et al., 2006)
  ✴ Detailed Spectral modeling to place limits on the mass of the compact object.
  ✴ Monitoring for the presence of “obviously a NS” events like Type I X-ray bursts.

★ QPOs are a good discriminator and can be detected by Swift in brighter transients like MAXI J1659-152, but many too faint (need RXTE).

→ Conclusion: Monitoring is needed to make a good determination of transient source type with Swift.
- Detected by MAXI on Oct 17th, 2010 at 41mCrab, reported Oct 20th by Yamaoka et al (ATEL #2959)
- Swift observed at 15:14UT (4 hours after ATEL) for 1ks. Found a bright new transient (no catalog match other than 2MASS).
- This is the first “MAXI only” new Galactic Transient found. Didn’t trigger BAT during initial detection.
MAXI J1409-619: What is it?

- Initially thought to be a candidate SFXT.
  - Highly absorbed X-ray spectrum ($4 \times 10^{22} \text{ cm}^{-2}$)
  - 2MASS IR counterpart to source
  - 6.5+/-0.2 keV ~200eV Iron line reported from RXTE (Yamaoka et al., ATEL #2969), seen in Swift PC mode data at ~6.7 keV.

- Monitoring by Swift over 90 days.
  - Initially detected in October, ~1-2 c/s
  - Went into Sun constraint
  - Triggered BAT in Dec after coming out of Sun constraint, much brighter.
  - Slowly faded to quiescence by MJD 55580.
P = 503 +/- 10 s sinusoidal periodicity found in latest XRT data.

No evidence of this period in previous observations with Swift and RXTE.
MAXI J1409-619: period changes

The pulse shapes with different energy ranges are quasi-simultaneous observations were on December 14, 2010. The pulsed fraction was about 40%.

From Yamaoka et al. (2011, in prep)

Table 1. Best-fit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_0$</td>
<td>MJD 55534.00</td>
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<tr>
<td>$P$ (s)</td>
<td>$506.507^{+0.018}_{-0.018}$</td>
</tr>
<tr>
<td>$\dot{P}$ (s s$^{-1}$)</td>
<td>$-4.463930e-06^{+6.50823e-08}_{-6.77357e-08}$</td>
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<tr>
<td>$\ddot{P}$ (s s$^{-2}$)</td>
<td>$9.233550e-13^{+1.22724e-13}_{-1.13832e-13}$</td>
</tr>
<tr>
<td>$\frac{d^3P}{dt^3}$ (s s$^{-3}$)</td>
<td>$5.265600e-19^{+8.22769e-20}_{-8.99278e-20}$</td>
</tr>
</tbody>
</table>
Improvements

➡ Localization: Dealing with large error boxes
★ Swift auto-tiling:
   ✴ Automated Tiling of larger error has been developed by the Swift/BAT team which makes searching error boxes from Fermi/MAXI/INTEGRAL possible.
   ✴ Multiple tiles of large circular regions will be possible in one orbit, rather than taking hours to days.

➡ Faster and more accurate MAXI reporting has improved Swift follow-up time, e.g. MAXI J1836 Swift on target same day as detection by MAXI.

➡ BAT can trigger on transients, but right now we mostly cancel them in 1-2 orbits, and then follow up with relatively short observations.
Conclusion

Swift is uniquely well equipped to study Galactic Transients:
- Discovery (BAT)
- Accurate localization (XRT+UVOT)
- Determination of type (XRT/UVOT/BAT)
- Long term monitoring (XRT/UVOT/BAT)

Fulfills a unique monitoring role if/when RXTE goes away

Also much of what we know about these objects is defined by RXTE observations - Swift’s lower energy sensitivity gives a different perspective.

Can provide vital early outburst studies