Multi-Messenger Astronomy with Swift

T. Sakamoto (AGU)
Swift

Review: GW 170817

GW 170817-like event in the BAT triggered samples?

O3 run: Swift observation status

Swift neutrino search: Azadeh talk this afternoon
Burst Alert Telescope (BAT)

- Aperture: 15-150 keV (15-350 keV)
- Det: CdZnTe (4 x 4 x 2 mm³)
- # of detectors: 32,768 (256 x 128)
- FOV: 120 deg x 90 deg
- Pos: 1'-3'

UV/Optical Telescope (UVOT)

- Aperture: 0.3-10 keV
- Focal Length: 3.5m
- Det: X-ray CCD (XMM MOS)
- FOV: 23' x 23'

X-Ray Telescope (XRT)

- Aperture: 128 CZT
- Focal Length: 3.5m
- Det: X-ray CCD (XMM MOS)
- FOV: 23' x 23'
## Characteristics of Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Field of View</th>
<th>Typical Sensitivity</th>
<th>Follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAT</td>
<td>![BAT Image]</td>
<td>$\sim10^{-9}$ erg cm$^{-2}$ s$^{-1}$ (15-150 keV)</td>
<td>Prompt data around $T_0$</td>
</tr>
<tr>
<td>XRT</td>
<td>![XRT Image]</td>
<td>$5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (0.3-10 keV; 1 ksec)</td>
<td>Follow-up</td>
</tr>
<tr>
<td>UVOT</td>
<td>![UVOT Image]</td>
<td>$\sim20$ mag ($v$; 200 s)</td>
<td>Follow-up</td>
</tr>
</tbody>
</table>
Automatic Tiling Observation

- Automatic tiling observation capability

Tiling patterns (figures from J. Kennea)

4-tiling
7-tiling
19-tiling
37-tiling

Required tiling pattern to cover 1° diameter
Required tiling pattern to cover 2° diameter

- Multiple pointing in one ToO upload (PPTOO)
**Rate trigger**

- 674 trigger criteria
- Each trigger criterion has a different trigger threshold
- ~80 triggers per day

- Event data (~10 s) capture (low priority)
- Subthreshold triggers (available through GCN; require regular data downlink)

**Image trigger**

- Every 64 s
- 15-50 keV band only
- All the images are downloaded (high priority)
- Used in the BAT transient monitor (Krimm et al.)

Image significance $\geq 6.5$

**Successful triggers:**
- Real time alert
- Autonomous SC slew
- Event data capture: $T_0-250s$ – $T_0+1000s$ (high priority)

Image significance $\geq 7.0$
GW 170817

Gravitational-wave event from BNS merger!
Association of GW 170817 and GRB 170817A

GW 170817/GRB 170817A (Abbott et al. 2017) GRB 170817A (Goldstein et al. 2017)

$T_0(GW) + 1.7\text{ s}$

$T_{90} = 2.0 \pm 0.5\text{ s}$

Probability of S-GRB class: 72%
- GW 170817 error region was occulted by the Earth
- Nothing in the BAT light curve at $T_0(GW)$
Swift Follow-up Observations

1. $T_0+1$ hr: 37 tiling at the center of the Fermi-GBM position
2. $T_0+4.6$ hr: (LIGO single sky map + GWGC) & Fermi-GBM location
3. $T_0+7.4$ hr: LIGO/Virgo three detector sky map + GWGC
4. $T_0+14.4$ hr: Follow-up on EM 170817
   - UVOT detections in all filters, but no XRT detection

(Evans et al. 2017)
UVOT Detection of the Counterpart!
(Evans et al. 2017)

Rapidly fading UV emissions were detected by UVOT

Clear detection of kilonova in UV
No XRT Detection at Early Phase

- 2017/8/18 – 2017/9/1
- 2017/9/12
- 2017/12/1 – 2018/1/4

Total exposure: 305 ks

Swift GRB X-ray afterglow light curves

- Typical X-ray afterglow flux @ $T_0+14$ hr:
  $10^{-11} - 10^{-13}$ erg/cm$^2$/s
- XRT should be able to detect X-rays in a few ks exposure
Off-axis Relativistic Jet Emission

Rise and fall radio/X-ray light curve (e.g., Mooley et al. 2018, Troja et al. 2018)

Radio

VLBI Superluminal Motion (Mooley et al. 2018)

\[ \beta_{\text{app}} = 4.1 \pm 0.5 \]

\[ t_0 + 230 \text{ d} \quad t_0 + 75 \text{ d} \]

Relativistic jet (GRB) is playing a major rule on late time radio and X-ray emission.
EM counterpart of GW 170817

- S-GRB like prompt gamma-ray emission ($T_{90} + 2s$) at $T_0(GW) + 1.7$ s
- Bright UV/optical emission (kilonova)
- No X-ray emission at the early phase
- Rise and fall radio and X-ray emission (off-axis GRB jet emission)
GW 170817-like event in the BAT triggered samples?

A. Sudo, T. Sakamoto, M. Serino (AGU)
EM Counterpart of GW 170817

- Weak prompt gamma-ray emission
- No X-ray emission detectable by XRT
- UV emission detection by UVOT

Swift GRB observations

- Detection of a prompt gamma-ray emission by BAT
- X-ray detection by XRT: ~80% (including no immediate slew)
- Detection of UV/IR emission by UVOT: ~30%
Simulation setup
- Light curve shape of GRB 170817A is modeled by fitting.
- Best fit spectral models (Goldstein et al. 2018) are used for the 1st peak and the 2nd peak.
- Using the background data of GRB 170516A.
- 30 degree off-axis energy response is used.
- Simulated the counts in the BAT standard 80 channels every 100 ms.

**Simulated light curves of GRB 170817A**

**BAT will detect GRB 170817A in 23 sigma (15-150 keV)**

**BAT will trigger GRB 170817A if it happens in the FoV**
Search for Non-GRB Triggers

GW 170817-like event could be treated as “non GRB” since no X-ray detection is very rare for GRBs.

1024 Non-GRB triggers
1221 GRB triggers

Instrumental noise event: 2%
Long duration event (>64 s): 7%
Match to the INTEGRAL catalog: 6%
BAT significance <7 σ: 8%
Known sources or attitude error: 77%

No candidate
Search for GRB Triggers

GW 170817-like event has bright UV/optical detection, but no or weak X-ray detection

2245 on-board triggers (14 years)

1024 Non-GRB triggers

1221 GRB triggers

No UV/optical detection: 2%

Long duration event (>64 s): 2%

No prompt XRT observation (T₀ < 200 s): 12%

X-ray detection: 84%

3 candidate events!
Three Candidate Events

<table>
<thead>
<tr>
<th>GRB 051105A</th>
<th>GRB 070209</th>
<th>GRB 090305A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detection:</strong></td>
<td><strong>Detection:</strong></td>
<td><strong>Detection:</strong></td>
</tr>
<tr>
<td>20.12 mag (UVW2)</td>
<td>18.14 mag (V)</td>
<td>19.48 mag (V)</td>
</tr>
<tr>
<td>$T_0 + 87$</td>
<td>$T_0 + 71$</td>
<td>$T_0 + 62$</td>
</tr>
<tr>
<td>Note: reported on the UVOT GRB catalog</td>
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</tr>
</tbody>
</table>

$T_{90} = 56$ ms

$T_{90} = 68$ ms

$T_{90} = 540$ ms

No detection

No detection

No detection
Three candidate events similar characteristics to EM of GW170817 are found in 14 years of Swift operation. The fraction of such events is 0.24%, and they are very rare.

At the distance of GW170817, the estimated event rate of NS merger is 0.4-14 events in 14 years (Abbott et al. 2018). Therefore, our number of three candidates are consistent with the rate.
Swift

O3 Observation Status
Swift Follow-up Strategy of O3 run

- CBC triggers with a modest (>0.25) probability of containing a NS
  - 800 fields or 90% of galaxy-convolved prob. for 80 s each
  - Re-observe 500 s per field (up to 4 days)
- CBC triggers with a low (<0.25) probability of containing a NS
  - No follow-up (unless FAR < 1/10 yr and the galaxy convolved probability region of >0.50 within 24 hours)
- CBC triggers with zero probability of containing a NS
  - No follow-up (unless FAR < 1/10 yr and LV error region < 10 deg²)

- Swift Gravitational Wave Galaxy Survey (PI: Tohuvavohu)
  - Pre-imaging 5000 of the brightest galaxies within 100 Mpc, to provide X-ray and UV templates for transient searches.
- XRT results: http://www.swift.ac.uk/LVC/
- BAT event data downlink by command
## Summary of O3 GW Events

<table>
<thead>
<tr>
<th>GW</th>
<th>(T_0) (GW) UTC</th>
<th>Event Type</th>
<th>FAR [yr]</th>
<th>(L_d) [Mpc]</th>
<th>BAT Sum Prob [%]</th>
<th>Swift NFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>S190408an</td>
<td>2019-04-08 18:18:02.288</td>
<td>BBH</td>
<td>&lt;1/100</td>
<td>1473 ± 358</td>
<td>0.02</td>
<td>No</td>
</tr>
<tr>
<td>S190412m</td>
<td>2019-04-12 05:30:44.166</td>
<td>BBH</td>
<td>&lt;1/100</td>
<td>812 ± 194</td>
<td>0.28</td>
<td>No</td>
</tr>
<tr>
<td>S190421ar</td>
<td>2019-04-21 21:38:56.251</td>
<td>Terrestrial</td>
<td>1/2</td>
<td>2281 ± 697</td>
<td>23.09</td>
<td>No</td>
</tr>
<tr>
<td>S190425z</td>
<td>2019-04-25 08:18:05.017</td>
<td>BNS</td>
<td>1/(7 x 10^4)</td>
<td>155 ± 45</td>
<td>11.78</td>
<td>Yes</td>
</tr>
<tr>
<td>S190426c</td>
<td>2019-04-26 15:21:55.337</td>
<td>NSBH</td>
<td>1/1.6</td>
<td>375 ± 108</td>
<td>4.51</td>
<td>Yes</td>
</tr>
<tr>
<td>S190503bf</td>
<td>2019-05-03 18:54:04.294</td>
<td>BBH</td>
<td>1/19</td>
<td>421 ± 105</td>
<td>99.75</td>
<td>No</td>
</tr>
<tr>
<td>S190510g</td>
<td>2019-05-10 02:59:39.292</td>
<td>BNS</td>
<td>1/37</td>
<td>269 ± 108</td>
<td>0.95</td>
<td>Yes</td>
</tr>
<tr>
<td>S190512at</td>
<td>2019-05-12 18:07:14.422</td>
<td>BBH</td>
<td>1/16</td>
<td>1331 ± 341</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>S190513bm</td>
<td>2019-05-13 20:54:28.747</td>
<td>BBH</td>
<td>1/(1 x 10^5)</td>
<td>1987 ± 501</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>S190517h</td>
<td>2019-05-17 05:51:01.831</td>
<td>BBH</td>
<td>1/13</td>
<td>2950 ± 1038</td>
<td>5.34</td>
<td>No</td>
</tr>
</tbody>
</table>
Swift XRT observed fields

(Green: observed XRT fields, Red: planned but not observed)

• No prompt $\gamma$-ray detection
• Possible UVOT source (GCN circ. 24296)
  • No X-ray emission
  • No X-ray/UV emission at Oct 21/22 UT, 2018
• Not confirmed by other ground telescopes (note: there is a M2-dwarf star near UVOT position)
BAT FoV at $T_0$(GW)
Summed LV probability within the BAT FoV: **4.51%**

Swift XRT observed fields
(****Green**: observed XRT fields, **Red**: planned but not observed)

- **894** observed fields (18% LV prob.)
- No prompt $\gamma$-ray detection
- 114 X-ray sources detected (probably none of them are the EM candidate)
Swift XRT observed fields

Summed LV probability within the BAT FoV: 0.95%

Earth LV probability map

BAT FoV

997 observed fields (59% LV prob.)

- No prompt $\gamma$-ray detection
- 33 X-ray sources detected
  (probably none of them are the EM candidate)
- $3 \sigma$ UL: $3 \times 10^{-12}$ erg/cm$^2$/s
  (0.3-10 keV)
- Swift/BAT is powerful all sky hard X-ray monitor to search for the prompt gamma-ray emission associated with GW.
- Swift will do ~1000 pointing observations for the LV triggers with the NS containing probability of >0.25.
- Three GW events (S190425z, S190426c, S190510g) were followed up by Swift. So far, no obvious EM counterpart.
Yamada Conference LXXI:
Gamma-ray Bursts in the Gravitational Wave Era 2019

Date: October 28 – November 1, 2019
Venue: Red Brick Warehouse, Yokohama, Japan
URL: http://yokohamagrb2019.wikidot.com/

• Registration and abstract submission are opened!
  (due June 15)
• Book your hotel ASAP!!

Confirmed invited speakers:
- M. Branchesi (Gran Sasso Sci. Inst.)
- J. Burgess (Max-Planck-Inst.)
- E. Burns (NASA/GSFC/USRA)
- P. D’Avanzo (INAF)
- H. van Eerten (U. of Bath)
- A. van der Horst (George Washigton U.)
- K. Kajita (ICRR/U. of Tokyo)
- K. Kiuchi (Kyoto U.)
- M. Kole (U. of Geneva)
- R.-Y. Liu (DESY)
- D. Perley (Liverpool J. Moores U.)
- J. Selsing (U. of Copenhagen)
- P. Shawhan (U. of Maryland)
- D. Siegel (Columbia U.)
- K. Toma (Tohoku U.)
- T. Totani (U. of Tokyo)
- E. Troja (NASA/GSFC/UMCP)
- K. Wiersema (U. of Warwick)
- B. Zhang (U. of Nevada)


LOC: S. Kisaka, T. Sakamoto (Chair), M. Serino, S. Sugita