MAXI 7 Years Highlights

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ABSTRACT

Since MAXI started observation on August 15, 2009, MAXI is monitoring the X-ray sky for more than 7 years. The light curves of about 350 sources are updated in every 4 hours or 1 day and open through MAXI homepage (http://maxi.riken.jp). Alerts from MAXI on new X-ray transients are sent to subscribers in the MAXI alert mailing lists at 12 seconds after the emerge as the earliest case. Many of them were followed up by the Swift/XRT and the nature of the source were revealed. Seventeen new sources were found by MAXI. Six of them were new black holes (BH). Soft X-ray flash at an ignition of a nova was detected for the first time in 2011 November 11. Tidal disruption events have formed a new category of transients after the discovery of Swift J1644+57. MAXI was useful that it had motnitored the source activity before the event.

MAXI catalogs of both GSC and SSC were issued listing new members of X-ray emitters in the 21st century. Fluxes of X-ray binaries are monitored continuously recording histories of activities of the neutron stars (NS) and BH. Monitoring data is used for detailed observations with Suzaku, Chandra and XMM-Newton. Data with uniform quality are used for power-spectrum-density analysis in AGNs and study of accretion disk instabilities in NS-LMXB and BH binaries. Normal and giant outbursts of Be X-ray binaries are monitored enabling a detailed discussion on the Be stellar disk together with optical emission-line profiles. MAXI detected large flares from blazars as well as those from active stars, and one-hour lasting superbursts from NS-LMXB. Gamma-ray bursts have been detected steadily, whose number reached 85. Still, we had 7 MAXI unidentified short soft transients (MUSST).

In 2015 LIGO started operation and found the gravitational wave sources. NICER, a new X-ray telescope on the ISS, will be mounted in early 2017. Together with these new instruments, MAXI will open new windows to understand the universe further.

KEY WORDS: MAXI, All-sky monitor, Transients, Time-domain astronomy

1. MAXI instruments

On 2009 July 16, MAXI was launched by the space shuttle Endevour (Matsuoka et al. 2009). A Japanese astronaut Koichi Wakata moved the robotic arm to mount MAXI to JEM-EF port #1 (Figure 1). MAXI/GSC (Mihara et al. 2011, Sugizaki et al. 2011) has two field of views (FOV), Horizontal and Zenithal, each with $160^{\circ} \times 3^{\circ}$ FOV. Since the operation of GSC is limitted to the low background region around the equator, the fraction of the working time is ~0.4 (Sugizaki et al. 2017). Even though, MAXI/GSC can scan almost the whole (90%) sky in one orbit (92 minutes) thanks to the two FOVs. Dwell time of one MAXI scan is ~60 s, and the 5σ sensitivities are ~130 mCrab / 1 scan, ~20 mCrab / 1 day, ~4 mCrab / 1 month, and ~1 mCrab / 1 year (Negoro et al. 2016).

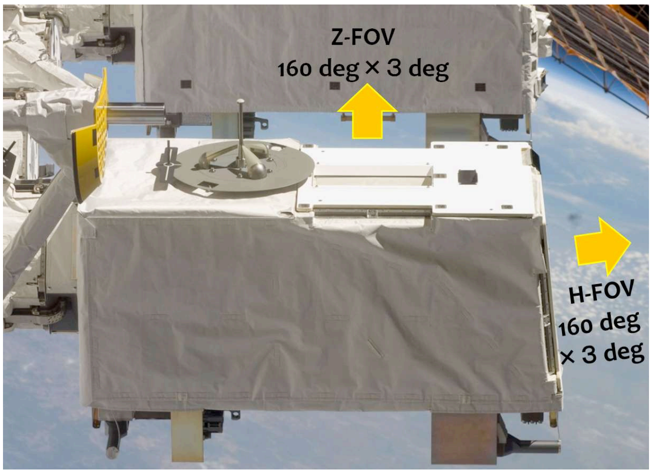

Figure 1. Real MAXI on ISS. Photo taken from the docked space shuttle (©NASA). Right-hand side is the moving direction of ISS. MAXI has two FOVs.

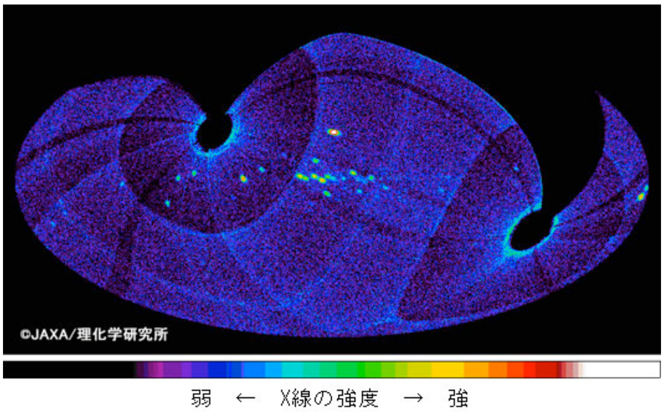

Figure 2. First light of MAXI/GSC on 2009 August 15. This image was press-released by JAXA and Riken. Two scan poles with 10° radius move on $\delta = \pm 23°$ lines with a presession period of the ISS orbit (70 days).

2. Press releases, papers and awards

There are 13 press-releases from MAXI starting with the first light of MAXI/GSC (Figure 2). The first X-ray nova for MAXI, XTE J1752-223, was press-released from the Astronomical Society of Japan in 2010 September as "slow-eating BH" (Nakahira et al. 2010). Press-releases of scientific results followed as a BH nova MAXI J1659-152 (Yamaoka et al. 2012), a slow X-ray pulsar MAXI J1409-619 (Yamaoka et al. 2011), a tidal disruption event Swift J1644+57 (Burrows et al. 2011), Cygnus super bubble (Kimura et al. 2013), a massive nova ignition MAXI J0158-744 (Morii et al. 2013), a nearby monster GRB 130427A (Maseli et al. 2014), and a optical quick (~2 minutes) followup of V404 Cyg (Kimura et al. 2016).

Refereed papers using MAXI data reached 192 (as of 2017 February). Those by MAXI team are 62. Praising ~100 citations, the PASJ Excellent Paper Award 2013 was given to Matsuoka et al. (2009) by Astronomical Society of Japan (Figure 3). We had three MAXI conferences in 2008, 2010, and 2016. Admiring the MAXI leading of the current time-domain astronomy and multi-messenger astronomy, ISS R&D Conference 2016 Innovation Award in Earth and Space Science was given to the MAXI by CASIS (Center for the Advancement of Science In Space), American Astronautical Society, and NASA.


CERTIFICATE

The PASJ Excellent Paper Award 2013
Publications of the Astronomical Society of Japan
The Astronomical Society of Japan

Dr. Masaru Matsuoka

"The MAXI Mission on the ISS:
Science and Instruments for
Monitoring All-Sky X-Ray Images"

by Masaru Matsuoka, Kazuyoshi Kawasaki, Shiro Ueno, Hiroshi Tomida, Mitsuhiro Kohama, Motoko Suzuki, Yasuki Adachi, Masaki Ishikawa, Tatehiro Mihara, Mutsumi Sugizaki, Naoki Isobe, Yujin Nakagawa, Hiroshi Tsunemi, Emi Miyata, Nobuyuki Kawai, Jun Kataoka, Mikio Morii, Atsumasa Yoshida, Hitoshi Negoro, Motoki Nakajima, Yoshihiro Ueda, Hirotaka Chujo, Kazutaka Yamaoka, Osamu Yamazaki, Satoshi Nakahira, Tetsuya You, Ryoji Ishiwata, Sho Miyoshi, Satoshi Eguchi, Kazuo Hiroi, Haruyoshi Katayama, and Ken Ebisawa

The above paper, published in PASJ, Vol.61, 999-1010 (2009), has been selected as the most outstanding paper in the recent publications of PASJ. You, as a coauthor, are awarded the 18th PASJ Excellent paper award.

March 20, 2014

The Astronomical Society of Japan
President Takashi Sakurai

Figure 3. PASJ Excellent Paper Award 2013 to the MAXI misison paper, Matsuoka et al. (2009).

3. Scientific results

3.1. MAXI all-sky map and catalog

The GSC all-sky map was presented in Mihara (2014). The SSC all-sky map was published by Kimura et al. (2013). The 37 months MAXI/GSC catalog in high galactic region was by Hiroi et al. (2013). In there, 500 sources were detected with a higher significance than 7σ. The detection limit was ~0.4 mCrab. The log N - log S relation is consis- tent with HEAO-1's result in fluxes $>10^{-11}$ erg cm^{-2} s^{-1}. However, the 40% of object members had changed since 1970's. Thus MAXI has created a catalog in the early 21st century.

3.2. MAXI transients

MAXI discovered 17 new sources in addition to 85 gamma-ray bursts (Negoro et al. 2017). The breakdown is 1 white dwarf binary, 6 NS, 6 BH, and 1 unknown. The completely new kind of phenomenon was massive nova ignition MAXI J0158-744 (Morii et al. 2013). On 2011 November 11, a bright (~ 1 Crab) but soft (< 5 keV) X-ray transient appeared near SMC. Fortunately both H and Z-SSC detected it. It was not detected in the next GSC scan (Figure 4). About 11 hours later Swift/XRT detected a vary faint (10^{-3} of MAXI's flux) source. It was identified to a Be star (B1-2 IIIe) at SMC distance (= 60 kpc). Then the flux was 10^{40} erg s^{-1}, which exceeds the Eddington limit for 1 *M*o by a factor of 100. The GSC spectrum can be fitted by any of power law, black body (BB), and thermal brems. If BB was applied, the temperature was 450 eV and the radius was 10^3 km. The Swift spectra can be fitted by BB with 60 → 110 eV and area of 10^4 → 10^2 km. From the SSC-Z observation, an ionized Ne line was detected. Theoretical explanation followed (Ohtani et al. 2014). The size and temperature are typical to a white dwarf (WD) and the light curve was similar to that of a classical nova. The difference was the faster time-scale and the higher temperarure. The MAXI part was interpreted as an ignition phase of a nova, which was observed for the first time in the history of nova. Also, it was soft X-ray against the expectation of UV emission. The Swift part corresponds to the super soft source (SSS) phase. The fast time-scale and high temperature can be explained by a very massive (nearly Chandra- sekhar limit of) WD. Thus the system would be a vary rare one composed of a massive O-Ne WD and a Be star.

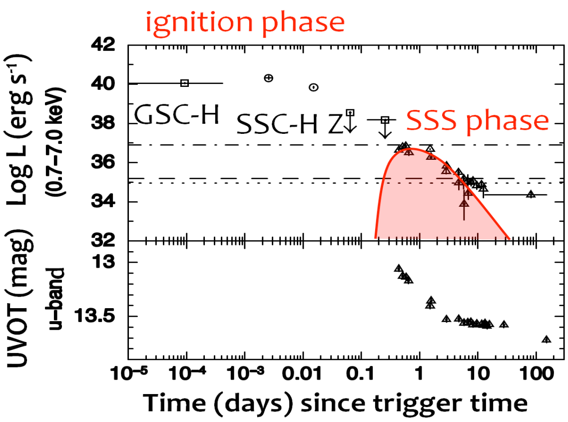

Figure 4. X-ray light curve of MAXI J0158-744. After trigger by GSC-H, SSC-H and SSC-Z detected successively (Morii et al. 2013).

3.3. Huge stellar flares

MAXI detected huge stellar flares unbiasly. Those are from nearby (~100pc) active stars: dMe stars and RS CVn (and Algol) binaries. The peak luminosities are 10^{34}-10^{36} erg s^{-1} and 10^{36}-10^{39} erg s^{-1}, respectively. These are 10^3-10^7 times larger than the largest solar flares, and even 1-10^4 times larger than the super flares of G-type stars (Tsuboi et al. 2016, Tsuboi et al. 2017).

3.4. Monitoring X-ray binaries (XRB)

Activities of NS- or BH- XRB are monitored once in 92 minutes and made public at MAXI HP[1] every 4 hours or every day. Periodical and non-periodical outbursts from BeXRB were presented by e.g. Mihara et al. (2014) and Nakajima et al. (2017). The MAXI data are compiled in BeXRB activity web page[2] by ESA/ESAC.

The non-periodic outbursts of NS low-mass X-ray binaries (LMXB) are studied by Asai et al. (2012), where repetition of outbursts in several hundred days were clearly shown. Sudden decrease in the last part of an outburst was related to the propeller effect, from which magnetic fields of the NS was estimated (Asai et al. 2013). A small outburst without spectral state transition was named “mini outburst” in Asai et al. (2015). It was an observational evidence of purr-type disk instability predicted theoretically. Outbursts of BH are also watched by seveal researchers (Figure 5).

A long-term monitoring of an XRB is also useful for detailed observations. Chandra observation by Heinz et al. (2015) showed giant X-ray light echoes around Cir X-1. This “Lord of the Rings” was understood using the light curves of MAXI in hundreds of days.

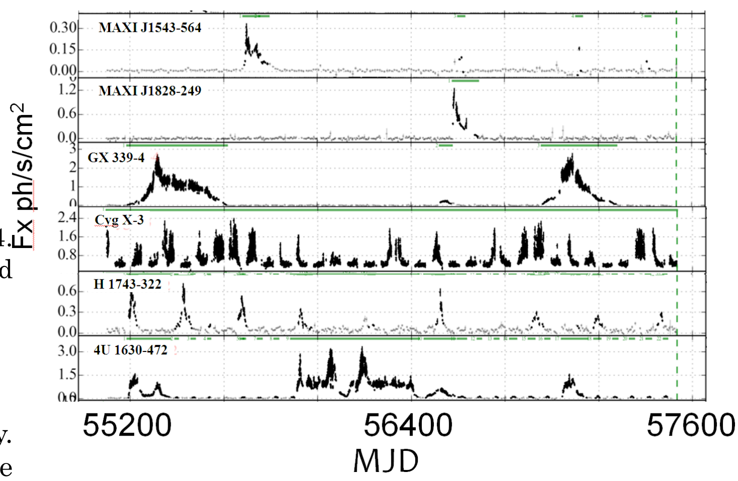

Figure 5. X-ray light curves of BH binaries. Taken from MAXI HP[3]. Hardness curves, intensity-hardness plots and spectra are also available.

1 http://maxi.riken.jp/
2 http://integral.esac.esa.int/bexrbmonitor/
3 http://maxi.riken.jp/mxondem/outburst/BH/

The pulsation was mointored with MAXI from some X-ray binary pulsars. The 7.67s pulsation of 4U 1626-67 is detected in each 60-day. Since 7.67s is short enough compared to the ~60 s scan time, we can get rid of uncertainty by variable background and source-flux in the folding process. For the intensity of 30 mCrab, we need 60-day integration to detect a pulsation. In the 7 years of MAXI observation, 4U 1626-67 increased the luminosity by 20%. The spin up rate is related to a flux. In the historical view, 4U 1626-67 repeats spin-up and down. Together with historical results, the P-dot and flux relation is well explained by the Ghosh and Lamb (1979) theory (Figure 6). Their $n(\omega)$ function with the fastness parameter ω can handle both spin-up and down. The surface magnetic filed is known from the cyclotron feature. Then we can determine the mass and radius of the NS if we know the distance accurately enough (Takagi et al. 2016).

Superburst is a long X-ray burst in NS-LMXB lasting ~3000s. Normal X-ray burst is a H and He burning, while the superburst contains a C burning in addition to H and He. Since the intensity and duration match MAXI scanning,

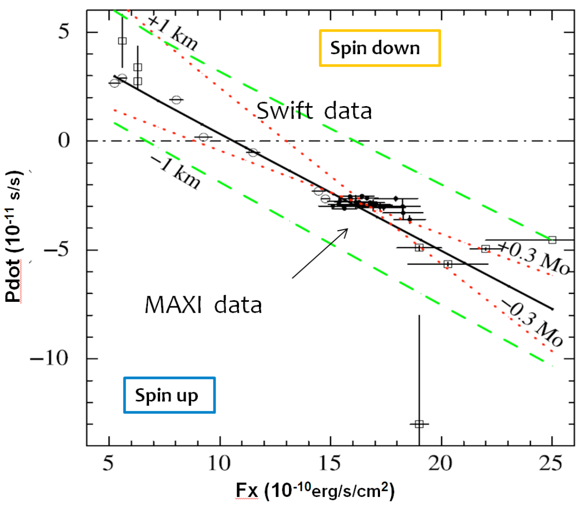

Figure 6. Flux and pulse period derivative of 4U 1626-67 with MAXI and previous results. The best-fit model is by Ghosh and Lamb (1979). In this plot we added a flux uncertainty of $\pm$5.5% so as the $\chi_\nu{}^2$ to be 1.0. If we assume the dis- tance D=10 kpc, we can obtain the mass M = 1.74$\pm$0.05 Mo, and radius R = 13.5$\pm$0.1 km of the NS very accurately. The dashed and the dotted lines correspond to changes of the radius by 1 km and the mass by 0.3 Mo, respectively. (Takagi et al. 2016).

MAXI detected 12 superbursts including intermediate bursts, among 28 ever detected (Serino et al. 2016).

Taking the advantage of MAXI's continuous sampling, a long term power spectrum density (PSD) was studied. In Cyg X-1, long-term PSD down to 10^{-7} Hz was obtained by Sugimoto et al (2016) for both soft state and hard state. Two-layered accretion disk was discussed based on it. They needed to correct observational gaps and aliases arising from the sparse-sampling by snap-shot observations. Premitive PSDs of many sources without corrections are publicly available from MAXI HP[4].

3.5. AGN variability

Some AGN show rapid variability. The most variable one is the BL Lac objects. Figure 7 shows 3-day flares of Mrk 421. X-ray flux changed by more than one-order-of-magnitude in several days. Long-term PSD of Mrk 421 has a break at 10^{-5} Hz. In lower frequency than that, the PSD extended in a power-law down to 10^{-8} Hz (Isobe et al. 2014).

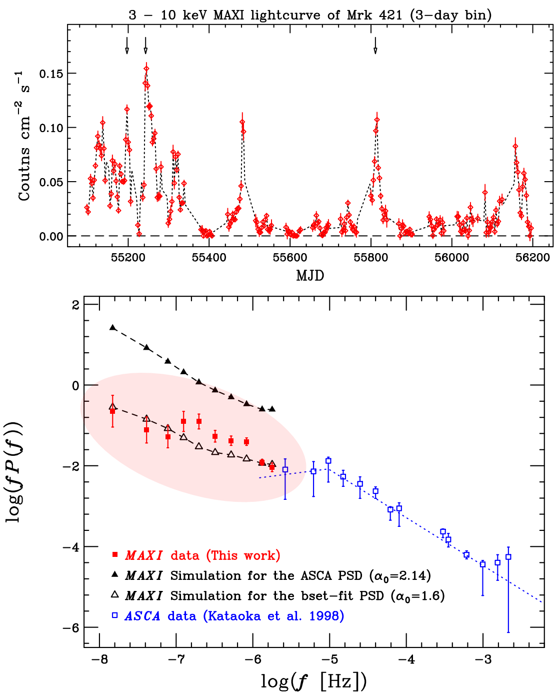

Figure 7. *top*：MAXI light curve of Mrk 421. *bottom*：long-term PSD of Mrk 421 (Isobe et al. 2014)

[4] http://maxi.riken.jp/PSD

3.6. Gravitational wave & unknown transients

Last year the histrical detection of the first gravitational wave (GW) was reported. GW 150914 occurred at 2015 September 14 9:50:45 UT. Unbiased survey of MAXI is suitable for watching an X-ray counter part of a GW. Unfortunately MAXI was not operating at the time of the GW detection because it was in a high background region. In 4 minutes later, MAXI resumed the operation and 3 σ upper limit (2-20 keV) was obtained as 0.1 $c\,s^{-1}cm^{-2}$ ~ 30 mCrab ~ 10^{-9} $erg\,s^{-1}$ cm^{-2} (Kawai et al. 2017). MAXI also put upper limits in flux just before, long before and long after the event. For the second one GW 151226 MAXI was operating at the occurrence, but just an upper limit was obtained (Serino et al. 2017).

In the seven years of unbiased operation, MAXI has accumulated unknown soft short transients. In spite of the Swift/XRT followups, no counter part was detected for the seven sour- ces (Table 1). We named it MAXI unidentified short soft transient (MUSST). In Figure 8 MAXI J1501-026 was shown as an example. It is soft : detected only with MAXI in the soft X-ray band (2-10 keV) and not detected by Swift/BAT nor GRB detectors. It is a short transient not detected in the next scan of MAXI, and unidentified because of undetection by the Swift/XRT follow-up.

Table 1. Seven MUSST sources

Name MAXI / GRB	Date	Flux (Crab)	Atel/GCN
M J1501-026	2015-8-26	0.44	A #7954
G 150428C	2015-4-28	0.16	G#17772
M J1540-158	2015-3-11	0.1	G#17568
G 140814A	2014-8-14	0.23	G#16686
M J0545+043	2014-4-12	0.2	A #6066
G 130407A	2013-4-07	0.17	G#14359
M J1631-639	2011-4-29	0.12	A #3316

We reported some sources with GRB names. But they would not be GRB because they were soft and did not accompany X-ray afterglows.

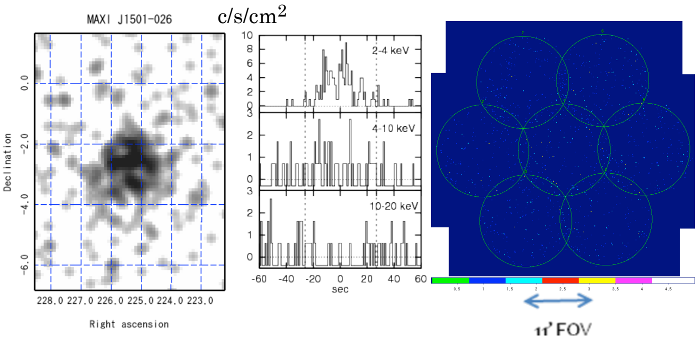

Figure 8. MAXI J1501-026 as an example of MUSST. *left* : MAXI image at detection. It is very bright. *middle*: light curves of MAXI scan in three energy bands. There was no flux in the hard band (10-20 keV). *right* : X-ray image of Swift/XRT followup. No source was detected in the MAXI error region.

4. MAXI future

MAXI's operation was adopted untill 2018 March. In terms of the Japanese contribution to ISS, JAXA continues to join the ISS program till 2024. They call it "op-3". We MAXI team will apply for a further 2-3 years of extension of MAXI operation. New science points in this extension will be a search for an X-ray counter part of GW and revealing the MUSST. In general words, search for the discovery space in the time-domain astronomy (Figure 9). Here cooperation with new instruments is a key. The JEM mission CALET is operating since 2015 (Nakahira et al. 2017). CALET/GBM observes GRB simultane- ously with MAXI. Advanced LIGO is operating since 2014 to detect a GW. Currently O2 is going on. But the most advance will be coorporation with NICER.

NICER is a new ISS instrument which will be launched in 2017 April. It will be attached to ELC3 truss in the NASA part. NICER is an array of pointing X-ray telescopes without imaging. Besides the main purpose of tracing the pulse light curve of a single NS, it will be capable of a quick follow-up of a new MAXI transient. We MAXI team and NICER team proposed the OHMAN (On-orbit Hookup of MAXI And NICER) project to connect the two on orbit for the real-time follow-ups. The point is "Watch the X-ray transient in X-ray while it is still bright".

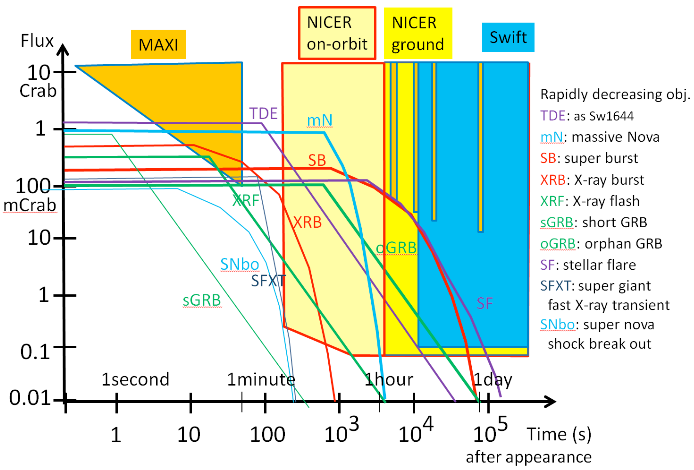

Figure 9. Rapidness of follow-up in X-ray and sensitivity. Discovery space in the time-domain astronomy is shown. Some kinds of quick decaying objects can be detected with the on-orbit MAXI – NICER connection. Here we assume
MAXI: When the explosion started in MAXI FOV,
NICER: MAXI alert on-orbit and via-ground,
Swift: MAXI alert through GCN. Exposure of 1ks.

Besides the cooperation with new instruments, continuing MAXI operation can make follows.

- Coordinated observation of transients in multi-wavelength in Japan and internationally.
  New black hole binaries : 1-2 / yr
  Huge stellar flares
  Low-mass X-ray binary and super bursts
  Gamma-ray bursts
  Tidal disruption events
  X-ray binary transients
- 3rd catalog in low galactic region (|b|<10°)
  Hori et al. (2017) and more sources.
  More X-ray photon statistics. Sensitivity reaches confusion limit (~0.5 mCrab). The number of sources reaches ~1000.
  With Light curves and variability index.
  i.e. information in time-dimension, too.
- Permanent MAXI archive at ISAS (Ebisawa 2017)

5. Summary

Continuous monitoring of MAXI on ISS has been providing basic information on variability of X-ray sources, which is distributed freely to the world. A real-time alert triggers many follow-up observations of ground observatories and satellites in orbit. New phenomena (as an ignition of a nova) and six black holes were discovered. MAXI has opened a new era of time-domain astronomy and of multi-messenger astronomy with the highly-sensitive X-ray all-sky monitor and the real-time alert. Together with new instruments such as gravitational wave detectors and the X-ray detector NICER on ISS, MAXI will be on the cutting edge of the X-ray astronomy.

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