Discovery of 17 X-ray Transients with MAXI/GSC and Their Nature

Hitoshi Negoro, and MAXI team

Department of Physics, Nihon University
1-8 Kanda-Surugadai, Chiyoda-ku, Tokyo, Japan
E-mail(HN): negoro.hitoshi@nihon-u.ac.jp

Abstract

MAXI newly discovered 15 uncatalogued, and two unidentified X-ray transients for seven years. From the MAXI and followup observations, especially thanks to rapid Swift/XRT followup observations, those transients were found to be six black hole candidates, six neutron stars including one pulsar, and one white dwarf. The possible nature of the remaining four sources, especially MAXI J1957+032 and MAXI J1501−026 recently discovered, are discussed. Characteristics and statistics of these X-ray transients are reviewed focusing on the discovery rate of the black hole candidates and the spatial distribution of these transients in our Galaxy. The peak fluxes of the MAXI transients except for two black hole candidates, MAXI J1659−152 and MAXI J1910−057, are relatively low and about 100 mCrab or less. This implies that MAXI has observed distant areas in our Galaxy as was expected before the launch. On the other hand, a high discovery rate of transients at high galactic latitudes suggests the presence of a large number of low mass X-ray binaries wandering in the halo.

Key words: X-rays: transients, X-ray novae — binaries: black holes, neutron stars, white dwarfs

1. Introduction

One of the characteristic features of X-ray binaries is transient behavior. They show various time variations, e.g., X-ray bursts, outbursts, and state transitions. The number of the observed outbursts is a fundamental key to test stellar and binary evolution theories. In our Galaxy, for instance, 0.1–1 billion stellar black holes are expected to be present theoretically, but only about 60 black hole X-ray binaries (here after BHCs)[1] have been discovered (e.g., Corral-Santana et al. 2016). And, more than 90% of BHCs are transients, showing outbursts typically last more than 100 days (McClintock & Remillard 2006).

Thus, searching transient BHCs and neutron star binaries is important not only to study physical properties of those objects, but also to confirm the evolution theories. MAXI, Monitor of All-sky X-ray Image (Matsuoka et al. 2009), with two very wide fields of view ($\sim 150^\circ \times 3^\circ$ each) is a mission focusing on the discovery of such transients rather than short-term rapid variability such as X-ray bursts and gamma-ray bursts.

Of course, MAXI also detected a number of bursts and flares from various objects as was originally expected (Negoro et al. 2016a, hereafter NKS). Here, I summarize the nature of 17 new X-ray transients (mostly novae) discovered with GSC (Mihara et al. 2011; Sugizaki et al. 2011) for 7 years, and discuss the MAXI capability to discover such transients and the spatial distribution of the MAXI transients in our Galaxy.

2. 17 X-ray Transients Discovered with MAXI/GSC

MAXI/GSC solely or independently discovered 17 X-ray transients in terms of the MAXI/GSC Nova-Alert System (NKS). The locations of these transients on galactic coordinates are shown in figure 1. Observational properties of the 15 X-ray novae discovered in the first 68 months are described in NKS. After that, MAXI newly discovered a short X-ray transient MAXI J1957+032 on 2015 May 11 (Negoro et al. 2015a), and a short and soft X-ray transient MAXI J1501−026 on 2015 August 26 (Nakahira et al. 2015).

2.1. Definition of MAXI transient sources

First of all, I decribe the definition of "new MAXI transients" used here. The MAXI objects should be uncatalogued objects. Not only gamma-ray bursts (GRBs) but also quiescent or faint known objects are not included even if an outburst from the source is observed for the first time. For instance, MAXI J0911−655/Swift

*1 These black holes include dynamically mass-determined black holes and black hole candidates showing very similar observational properties. Here, those black hole binaries are simply denoted as black hole candidates (BHCs) because no direct evidence has not been obtained, yet, from both types of objects.

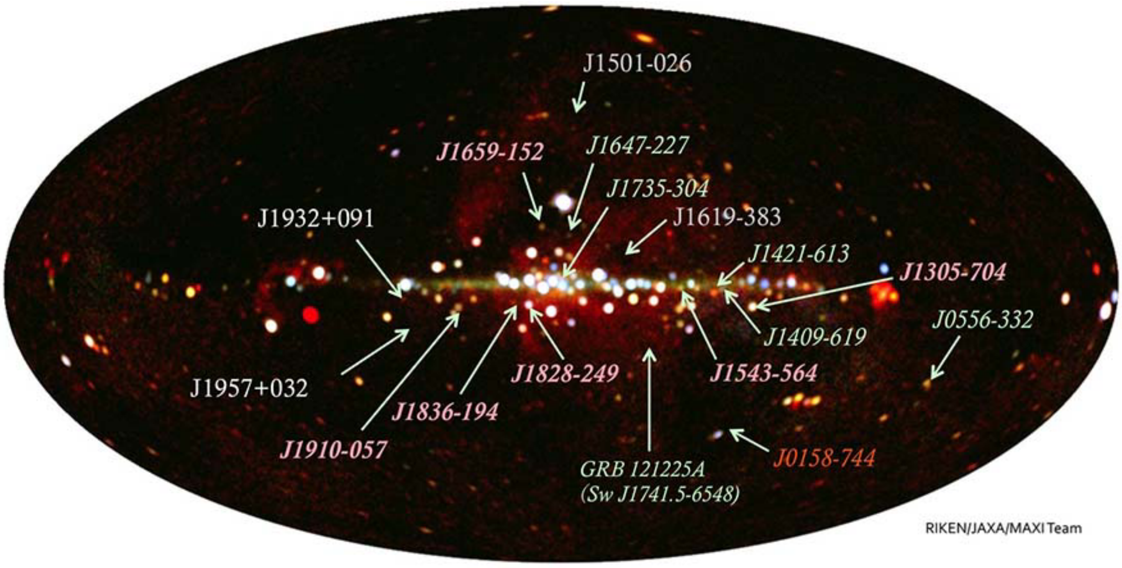

Fig. 1. 17 X-ray transients MAXI discovered. Six black hole candidates shown in bold italic (pink), six neutron star binaries in italic (green), one white dwarf binary in italic (red), and four unknowns. The background image was obtained by five years GSC observations and three years SSC observations. Therefore, the new sources are not always visible in this map.

J0911.9−6452, of which an outburst was recognized for the first time in 2016 February, is a member of the globular cluster NGC 2808 (Serino et al. 2016). The source has been identified as Chandra source No. 15 (Homan et al. 2016, also see Servillat et al. 2008). Thus, the source was a known catalogued source, and not included in the MAXI sources, here.

The identification by other observatories is, therefore, very important. Of the 17 new transients, MAXI J1619−383 (Serino et al. 2014) and MAXI J1501−026 have not been identified by other observatories, yet. Sun constraints did now allow other observatories to observe MAXI J1619−383 in outburst (NKS). In that case, radio observations are likely a powerful tool to localize the position and to know the nature of the source from, for instance, the radio and X-ray luminosity diagram (Corbel et al. 2013; Corbel 2017). From the X-ray spectrum, MAXI J1619−383 is likely to be a low-mass X-ray binary hosting a neutron star (NKS). For MAXI J1501−026, see §2.3.

On the other hand, the following transients are excluded in the list even if Swift/XRT successfully caught the (uncatalogued) sources: short hard transients, which might be associated with GRBs, and short (soft) transients detected only at a single (or a few) scan transit(s), having not enough statistics or information to restrict the nature of the source. A former example is MAXI J0636+146. MAXI J0636+146 was detected significantly at, at least, two scan transits (Negoro et al. 2016b). Swift/XRT successfully observed the source, but the nature of the source is still unclear (Kennea et al. 2016b; Kennea 2017). While, the latter soft transients includes MAXI Unidentified Short Soft Transients (MUSSUT) discussed by Mihara (2017).

In this sense, the definition is somewhat ambiguous. Some may be excluded or included in future.

2.2. Category of the new transients

Currently, the 17 new transients are categorized into six BHCs, six neutron star binaries, one white dwarf binary, and four unknowns (figure 1). MAXI discovered the most BHCs, six, of 14 BHCs found after the MAXI launch, though none of their mass is not dynamically determined. The observed properties of the six BHCs are summarized in Negoro & MAXI team (2014) and NKS. Six sources were found to be neutron star binaries from regular pulses or X-ray bursts (NKS). MAXI J1932+091 with a probable Be companion (Itoh et al. 2014) is a candidate of a super-giant fast X-ray transient (NKS; Sakamaki & Negoro 2017), and spectral properties of MAXI J1619−383 are consistent with that of neutron star LMXBs (NKS). MAXI J0158+744 is a quite rare, rapidly fading super-soft-source on the outskirts of the Small Magellanic Cloud (SMC) (Morii et al. 2013).

2.3. Nature of MAXI J1957+032 and MAXI J1501−026

What is the nature of the new transients of MAXI J1957+032 and MAXI J1501−026? MAXI J1957+032 was discovered with MAXI/GSC on 2015 May 11 (Negoro et al. 2015a). INTEGRAL also independently discovered the source (Cherepashchuk et al. 2015). Thus, it is known as IGR J19566+0326. As shown in figure 2, MAXI J1957+032 exhibited short X-ray outbursts

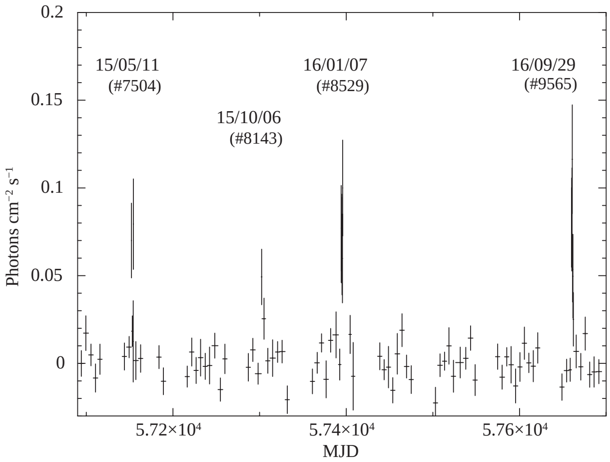

Fig. 2. MAXI/GSC 2-20 keV light curve of MAXI J1957+032. The numbers below the dates (YY/MM/DD) are reference numbers of The Astronomer's Telegram. 6 hr-bin data are used, and rebinned up to 5 days as the detection significance should be more than 3 sigma level.

four times (2nd: Sugimoto et al. 2015; Kennea et al. 2015, 3rd: Tanaka et al. 2015, and 4th: Negoro et al. 2016c; Kennea et al. 2016a).

X-ray fluxes of MAXI J1957+032 rapidly decreased to below the detection limit of MAXI/GSC typically in less than one day. As a result, the nature of the source had been long in mystery. Extensive Swift/XRT followup observations for the 4th outburst (Kennea et al. 2016a), however, revealed a clear correlation between the flux and the power-law photon index, strongly suggesting that the source is a neutron star LMXB (Kennea 2017).

On the other hand, MAXI J0501−026 is a quite mysterious object. The source was detected at 440 mCrab only at a single scan transit on 2015 August 26, and its spectrum was extremely soft, e.g., $kT_{\rm BB} = 0.53 \pm 0.07$ keV for a blackbody fit (Nakahira et al. 2015). These properties are reminiscent of the SSS source MAXI J0158+744. However, no X-ray (Swift/XRT; J. Kennea private comm.) and optical (KWFC; Morokuma et al. 2015) counterpart was found.

If the object really emitted a blackbody spectrum, from the normalization of the spectral fit, we can estimate the source distance to be ~ 1 kpc for a neutron star with a radius of 11 km, or ~ 640 kpc for a white dwarf with a radius of 7,000 km. Thus, the nature of the source is quite puzzling. I exclude this source in the following discussion though it is a quite high galactic source.

In summary, the nature of the 17 new X-ray transients are very likely six BHCs, nine neutron star binaries, one white dwarf binary, and one (quite) unknown.

3. Discovery Rate of Black Hole Candidates

3.1. Expected and observed rates

Before the MAXI launch, in 2008, I optimistically estimated the discovery rate of BHCs with MAXI/GSC to be 7.5–15 BHCs/yr, which was 5–10 times higher than before (1.5 yr^{-1}), taking into account the extension of observable regions, the star distribution in our Galaxy, and frequent scanning of the galactic center region (Negoro 2009).

The expected rate is unexpectedly higher than the current rate of 2.0 yr^{-1} not only by MAXI but also by Swift and INTEGRAL (figure 3). One reason of the discrepancy is that unfortunately no bright (> 1 Crab) novae have appeared for more than ten years, which decreases the rate by 1–2. Furthermore, no observatories have found even faint (< 0.1 Crab) BHCs since the discovery of IGR J17454-2919 at the end of September, 2014 (Chenevez et al. 2014). This also reduces the rate by ~ 1. Another reason is that the past discovery rate, which was estimated from 29 novae[2] from 1987 to 2007, was already increased by, for instance, deep observations of the galactic plane with RXTE/PCA (not ASM), INTEGRAL, and Swift.

Furthermore, more importantly, new outbursts from a similar number of known BHCs to new ones were also detected (see Table 2 in NKS for MAXI detections until 2015 March). For instance, XTE J1856+053 (Suzuki et al. 2015), XTE J1908+094 (Krimm et al. 2013; Negoro et al. 2013), GS 1354−645 (Miller et al. 2015) and GS 2023+338/V404 Cygni (Barthelmy, et al. 2015; Negoro et al. 2015b; also see Rodriguez et al. 2015) showed renewed activity for the first time in 8, 10, 18, and 26 years, respectively. This potentially reduces the chance of discovery for later missions. A recurrence rate of outbursts reduced from such detections is, however, very important to estimate the numbers of BH binaries and BHs in our Galaxy.

Certainly, it is difficult for MAXI to discover outbursts close to bright sources due to moderate spatial resolution as an all-sky monitor. INTEGRAL and Swift, however, detected such sources, for instance, Swift J174510.8−262411 (Cummings et al. 2012) near GX 3+1 and IGR J17454−2919 (Chenevez et al. 2014) near the galactic center. Thus, this is unlikely to help the large difference so much.

From the above discussion, the observed rate may increase to ~ 5 if the X-ray sky is just like before and if we look for faint sources on longer time scales (see §5).

*2 Later, some were found to be BHCs, and the current number of BHCs newly discovered in this period is 34, which yields the rate of 1.7 yr^{-1}

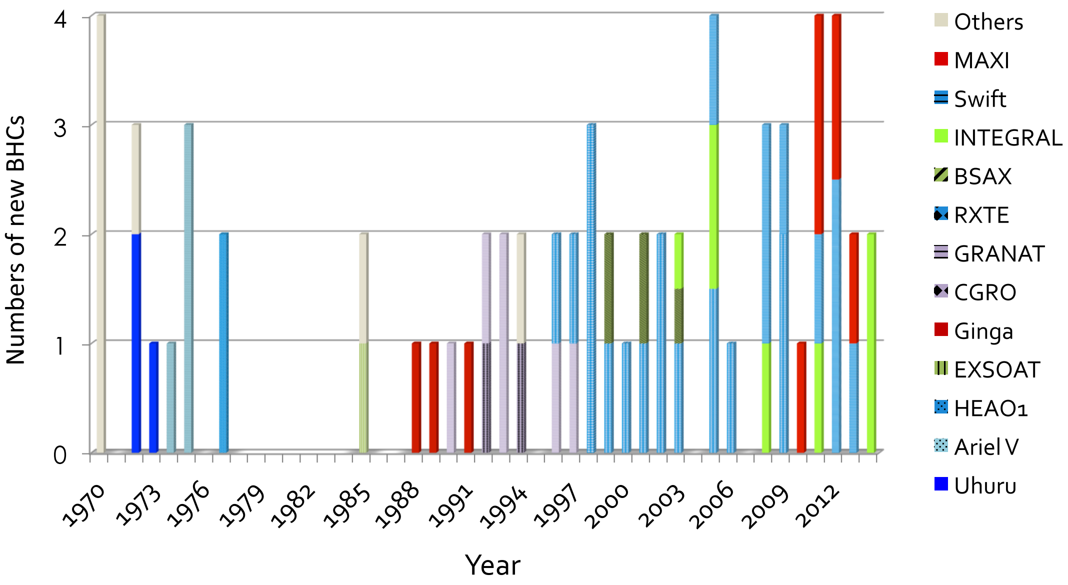

Fig. 3. Historical numbers of black hole candidates discovered by various missions. The numbers shown here are slightly different from those shown by Corral-Santana et al. (2016). This is due to the difference in the definition of BHCs.

3.2. Distant black hole candidates?

MAXI indeed detected faint X-ray novae as was expected. The peak fluxes of MAXI J1543−564, J1836−194, J1305−704, and J1828−249 were approximately 100 mCrab, which were much smaller than those of previous bright novae by two orders of magnitudes (NKS). The peak luminosities of BH novae are distributed around 10% of the Eddington luminosity, $L_{\rm Edd}$ (Chen et al. 1997; Dunn et al. 2010).

On the other hand, of the above four MAXI transients, MAXI J1543+564 (Kennea et al. 2011; Stile et al. 2012), J1305−704 (Morihana et al. 2013), and J1828−249 (Tomsick & Corbel 2014) also exhibited the soft-to-hard (or soft-to-intermediate) state transitions. The soft-to-hard state transitions are known to occur at about 1–4% $L_{\rm Edd}$ for nine sources including three NS binaries (Maccarone 2003) and in the range of 0.5–10% $L_{\rm Edd}$ with the peak at 2–3% $L_{\rm Edd}$ for 25 BHCs (Dunn et al. 2010, also see Masumitsu & Negoro 2017).

From these facts, these sources are thought to be relatively far from the solar system, ≥ 12 kpc, e.g., for MAXI J1543+564 (Stile et al. 2012).

Thus, it can be said that MAXI is actually observing distant parts of our Galaxy, and detecting distant galactic transients, though half GSCs have not been used.

4. Distribution of the MAXI Transients and Its Suggestion

4.1. High galactic latitudes sources

Let me go back to all the X-ray transients, but now excluding the quite unknown source MAXI 1501−026 and the SMC source MAXI J0158−744. One of the noticeable features of the MAXI transients is that some of them are located at relatively high galactic latitudes as shown in figure 1. One out of six BHCs, five or six of nine NS binaries are at galactic latitudes of more than 8 deg. This suggests the presence of a number of LMXBs in the galactic halo. Note that MAXI J1932+091 is the only high mass X-ray binary (candidate) in the MAXI transients. It is known that bright LMXBs are often in globular clusters (e.g., Predehl et al. 1991). But, we could not find any globular clusters in these source directions.

Figure 4 shows cumulative numbers of LMXBs counted from the high galactic latitude. These numbers are obtained from the 4th LMXB catalogue by Liu et al. (2007), which contains 187 LMXBs in our Galaxy, the LMC (Large Magellanic Cloud), and the SMC. In the histogram, globular cluster members, the nearby (~ 200 pc) LMXB 4U 1700+24, LMC and SMC members are all excluded for this specific purpose[3].

Only 6% (10 of 175) known LMXBs are located at galactic latitudes $|b| > 15.8$ deg, but 20% (3 of 15) MAXI transients were found at the high latitudes. The significance of the large discrepancy between these ratios is low. But the significance becomes more significant if lower latitude sources are included; 9% (15/175) vs. 33% (5/15) at $|b| > 12.4$ deg, and 18% (31/175) vs. 40% (6/15) at $|b| > 7.6$ deg. Thus, MAXI detected high galactic latitude sources 2–3 times larger than expected from the distribution of known LMXBs, though the significance is not enough, yet.

*3 For 4U 1543−47, the galactic latitude of +5.4 deg is used, not +54. deg in the catalogue.

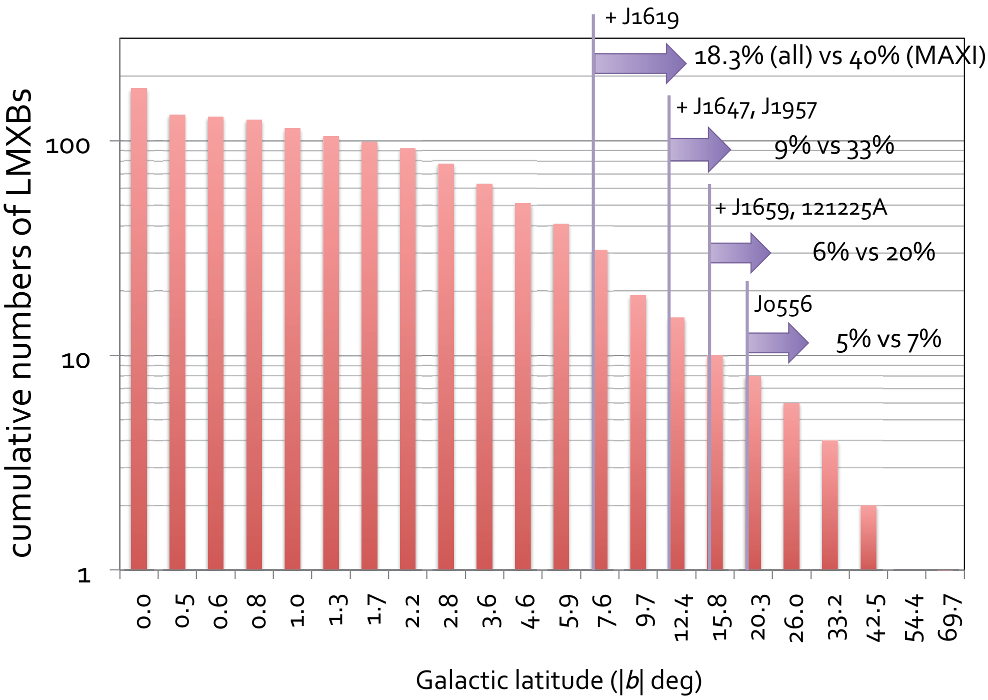

Fig. 4. Logarithmically binned cumulative numbers of galactic LMXBs counted from the high galactic latitude from the LMXB catalogue by Liu et al. (2007) and MAXI transients. The left side bin shows the number of $|b| < 0.5$ deg, exceptionally.

This suggests the presence of a large number of unknown/sleeping LMXBs at high galactic latitudes unless MAXI happened to find many transients at high latitudes. In that case, this also implies that MAXI failed to detect a much larger number of transient LMXBs (about 30 LMXBs) on or near the galactic plain because of the poor spatial resolution of the MAXI cameras. If so, INTEGRAL or Swift (and RXTE) should detect a large fraction of such sources during their galactic scan survey. But, the discovery rate of such sources is not so high. This might indicate that the transient LMXBs have a different galactic distribution from the known LMXBs.

4.2. LMXBs wandering in the halo?

Figure 5 shows an edge-on view of our Galaxy and locations of the MAXI transient sources projected onto an x-z plane, where the x–axis is taken to be alone the direction from the Solar system to the galactic center. Some distances to the sources are taken from literatures. Some are estimated from luminosities at the state transitions for BHCs as described in §3.2, and for MAXI J0556−332 (Sugizaki et al. 2013). Some NS binaries can be also estimated from the peak fluxes of X-ray bursts (NKS) as reference to Kuulkers et al. (2003). The distances to MAXI J1619−383, J1932+091, and J1957+032 are unknown, and assumed to be 4 kpc without any strong reasons except for J1957+032 (see Kennea 2017).

It can be found from the figure that more than half MAXI transients are not close to the solar system, but far and above the galactic disk. Thus, it is possible that MAXI observed runaway LMXBs on the analogy of runaway radio pulsars. To estimate the number of such LMXBs, we need more samples and more quantitative discussion for the detection or non detection for galactic plane transient sources. Measurement of the proper motion of the transients is, of course, very important as was the case of XTE J1118+480 (Mirabel et al. 2001).

5. Discussion and Future Works

Finally, a strategy to find fainter X-ray novae is described. Currently, the longest time bin to find transient events in the nova-alert system is 4 d bin, and the detection limit with the bin is about 8 mCrab (NKS). But, if we use 16 or 32 d bin, then the detection limit can be decreased to 5 mCrab or less. I have already confirmed using archival data that previously undetectable faint X-ray novae, e.g., IGR J17177−3656 and Swift J1357.2−0933, and some tidal disruption events triggered the nova-alert system!

Furthermore, reanalyzing all the data for more than seven years is also in preparation by K. Tanaka at Nihon university to obtain the complete sample of X-ray transients.

The detection of the high galactic latitude sources are entirely due to high sensitive, and long-term all-sky-survey with MAXI/GSC. Such detection may reveal the nature of a possible large number of previously unknown

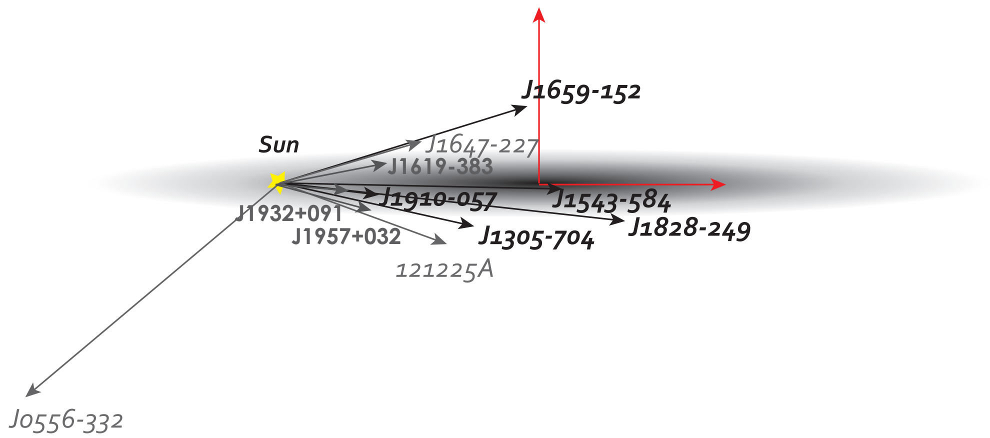

Fig. 5. An edge-on view of our Galaxy, and projected distances of the MAXI transients on the plane. The sources in bold black font and gray font are BHCs and NS binaries, respectively. The sources to which the distances have been estimated are shown in italic font. The distances to the other sources are assumed to be 4 kpc.

LMXBs wandering in the halo. More quantitative estimation and discussion will be reported elsewhere. In this sense, too, further continuous observations by MAXI in future and the detection of transient events must be very important not only for the stellar and binary evolution/formation theories, but also for previously unknown LMXBs wandering in the halo.

This work was supported by JSPS KAKENHI Grant Numbers 24540239 and 16K05301.

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