X-ray bursts and superbursts - recent developments

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Abstract

The past decade and a half has seen many interesting new developments in X-ray burst research, both observationally and theoretically. New phenomena were discovered, such as burst oscillations and superbursts, and new regimes of thermonuclear burning identified. An important driver of the research with present and future instrumentation in the coming years is the pursuit of fundamental neutron star parameters. However, several other more direct questions are also in dire need of an answer. For instance, how are superbursts ignited and why do burst oscillations exist in burst tails? We briefly review recent developments and discuss the role that MAXI can play. Thanks to MAXI's large visibility window and large duty cycle, it is particularly well suited to investigate the recurrence of rare long duration bursts such as superbursts. An exploratory study of MAXI data is briefly presented.

Key words: X-rays: bursts — X-rays: binaries — Stars: neutron

1. Introduction

The first X-ray burst was detected in 1969 (Belian et al. 1972; see also Kuulkers et al. 2009a), with the same instrumentation that revealed gamma-ray bursts (Klebesadel et al. 1973) - the Vela 5 and 6 satellite series. Curiously, that first X-ray burst is still the brightest ever recorded, with a peak flux close to 50 times the Crab source. It is the brightest simply because it came from the nearest-known X-ray burster: Cen X-4 at 1 kpc.

The real kick-off for X-ray burst research was in 1975, when the first long-duration observations were performed with the first 3-axis stabilized Dutch astronomy satellite ANS. Hunting for a black hole in the globular cluster NGC 6624 (Heise 2010), Grindlay & Heise (1975) stumbled over X-ray bursts. Just 10 months before, the first theoretical paper about thermonuclear burning on neutron stars (NSs) was published by Hansen & van Horn (1975). As the observations showed, the theory needed fine tuning and the first link between bursts and thermonuclear flashes on NSs was established by Woosley & Taam (1976) and Maraschi & Cavaliere (1977).

From the mid seventies on, X-ray bursts were detected in large numbers, culminating in a present day count of about 11 thousand, mostly thanks to recent observations with BeppoSAX WFC (e.g., Cornelisse et al. 2003), RXTE (Galloway et al. 2008a), HETE II (e.g., Suzuki et al. 2007) and INTEGRAL (e.g., Chenevez et al. 2011).

Actually, the full name of the bursts that we discuss here is Type I X-ray bursts, to distinguish them from Type II X-ray bursts that are thought to result from spasmodic accretion in 2-3 sources (e.g., Lewin et al. 1993), but for brevity we ignore this longer name.

We here briefly review recent developments in X-ray burst research and discuss expectations for the *Monitor of All-sky X-ray Image* (MAXI). For comprehensive reviews, the reader is referred to Lewin et al. (1993), Bildsten (1998) and Strohmayer & Bildsten (2006).

2. The nature of X-ray bursts

An X-ray burst is the radiative cooling after a thermonuclear shell flash occurring just $\sim$1 m beneath the surface of a NS. During such a shell flash, the accreted mixture of hydrogen and/or helium is ignited due to a quick pressure build-up at the bottom of the accreted pile in the very large gravitational field strength on the NS. The nuclear heating rate increases quicker with temperature than does the radiative cooling (T^4) and a runaway ensues which only dies when all or most fuel is burnt. This lasts a fraction of a second, but the subsequent radiative cooling of the burnt layer lasts longer - of order 1 min. While the burning layer heats up to $\sim$ 2 GK (e.g., Woosley et al. 2004), the photospheric temperature is limited to a peak of about $\sim$ 0.03 GK or $\sim$ 3 keV, right in the classical X-ray regime (e.g., Galloway et al. 2008a).

The nuclear chain reaction can become very complex, particularly if the hydrogen abundance is high at the point of ignition. In that case rapid proton capture becomes important. It involves hundreds of isotopes whose decay rates have rarely been measured experimentally in particle accelerators on earth (e.g., Schatz et al. 2001). Thus, X-ray bursts are very relevant for nuclear physics (e.g., Davids et al. 2003; Cyburt et al. 2010).

The range of observational phenomena in X-ray bursts is predominantly determined by 3 parameters: composition, accretion rate (e.g., Fujimoto et al. 1981) and NS spin . This particularly introduces different X-ray bursting behavior between hydrogen-deficient ultracompact X-ray binaries (with $P_{\rm orb} < 1$ hr) and hydrogen-rich long-period systems (e.g., in 't Zand et al. 2007) and large changes during accretion outburst of transients (for a nice recent example, see Chenevez et al. 2010).

3. Recent developments

RXTE and BeppoSAX, launched in 1995/6, provided an enormous enrichment in the knowledge of the X-ray burst phenomenon. This pertains to interesting details, such as long tails in normal X-ray bursts (in 't Zand et al. 2009), peculiar profiles (e.g., Bhattacharyya & Strohmayer 2007; Zhang et al. 2009), and the return of X-ray bursts in Cir X-1 after 30 years of accretion (Linares et al. 2010), but foremost in a broader sense as discussed in Sects. 3.1-3.4 below. As a result, theory improved, on issues such as flame spreading (Spitkovsky et al. 2002), rotational mixing (Piro & Bildsten 2008; Keek et al. 2009), nuclear reaction chains (e.g., Fisker et al. 2008), convection (e.g., Weinberg et al. 2006), sedimentation (Peng et al. 2007) and multi-zone 1D simulations of series of bursts (Woosley et al. 2004).

3.1. Burst oscillations

NS spin frequencies were notably lacking for low-mass X-ray binaries during 30 years of measurements, until Strohmayer et al. (1996) detected a transient 363 Hz oscillation in 6 X-ray bursts from GX 354-0/4U 1728-34. The strict reproducibility of the (asymptotic value of the) frequency supported an identification with the NS spin. Many more sources with such oscillations were quickly found with RXTE, but it was not until 6 years later (Chakrabarty et al. 2003) that final proof came for it being due to NS spin, with the simultaneous detection of a burst oscillation and a millisecond pulsar in SAX J1808.4-3658. To date, one quarter of all bursters exhibited burst oscillations, with frequencies between 245 and 620 Hz. The phenomenon is not completely understood though. Most burst oscillations are detected in the tails of X-ray bursts, when the NS is presumed to radiate uniformly. How can the radiation be confined? One explanation is r-mode oscillations (Heyl 2004; Piro & Bildsten 2005; Lee & Strohmayer 2005; Narayan & Cooper 2007; Cooper 2008) and another one is Coriolis force containment (Spitkovsky et al. 2002). A third obvious idea is that the fuel is magnetically confined. However, the magnetic dipole field strengths in low-mass X-ray binaries ($\sim 10^8$ G) are considered to be insufficient for that.

An interesting discovery was made recently of a peculiar X-ray burster showing burst oscillations and a pulsar at only 11 Hz (Bordas et al. 2010; Chenevez et al. 2010; Strohmayer & Markwardt 2010; Altamirano et al. 2010) that has very fast series of faint X-ray bursts, with wait times between bursts down to 5 min (Motta et al. 2011). The value for α (defined as the fluence in the accretion flux between bursts divided by the fluence in bursts; see, e.g., Lewin et al. 1993) is normal, strongly suggesting the X-ray bursts to be thermonuclear in origin despite the small wait times and fluences (e.g., Chakraborty et al. 2011; Linares et al. 2011). Fuel confinement again appears to be a straightforward explanation for this behavior. Instead of being spread over the entire neutron star, the accreted matter is confined to a spot (ergo, a pulsar signal) and it takes less matter, and thus less time, to reach a thick-enough pile for ignition of a (less energetic) flash. Cavecchi et al. (2011) were able to exclude r-mode oscillations and Coriolis force containment as viable explanations for such a slow NS spin, leaving only magnetic confinement. A magnetic field strength of $B > 10^9$ G could be sufficient for that, and would be consistent with the observed channeled accretion. The necessarily larger magnetic field strength could be related to the small spin frequency, because the Alfvén radius would stretch to slower regions of the accretion disk. Still, Cavecchi et al. note that this is not a natural explanation for burst oscillations in many other sources, because there B is unlikely to be that high. Perhaps the magnetic field is then boosted up during the burst, an idea put forward by Boutloukos et al. (2010).

3.2. Long X-ray bursts

If the ignition is deeper, more mass needs to cool down and the cooling time is longer. This may range from 10-30 min for so-called intermediate duration bursts to 1 d for superbursts. Since the amount of fuel contained in such thick piles is appropriately larger, the wait times between bursts is longer - from days to years, depending on the accretion rate and composition.

Intermediate duration bursts (in 't Zand et al. 2005; Cumming et al. 2006, Falanga et al. 2008) are thought to be helium flashes on cold NSs. The larger pressure of the thicker pile (roughly up to 10 m/10^{10} g cm^{-2}) is thought to compensate for a lower temperature at ignition. The lower temperature may be the result of either a low accretion rate, which will decrease crustal heating through pycnonuclear reactions and electron capture processes, or the absence of hydrogen in the accreted material, preventing heating by the CNO cycle, or both. The combination of circumstances seems likely in many ultracompact X-ray binaries. in 't Zand et al. (2007) propose from accretion disk theory that persistent low accretion rates can only occur in ultracompact systems and, thus, identify six new candidate ultracompact systems from a list of persistent bursters. However, this diagnostic appears to be not full proof, based on the detection of hydrogen in the optical spectrum of one such candidate (Degenaar et al. 2010).

Superbursts, discovered by Cornelisse et al. (2000), have been detected 17 times, from 10 sources that also exhibit ordinary X-ray bursts (e.g., Keek & in 't Zand 2008b; Kuulkers 2009b). They have ignition depths of order 10^2 m/10^{12} g cm^{-2}. No helium or hydrogen is thought to survive at those depths. This led Cumming & Bildsten (2001) and Strohmayer & Brown (2002) to suggest carbon as fuel - a shell-flash analog to core-flash type Ia supernovae. The carbon is either within the accreted material or produced through helium/hydrogen burning. In the latter case there must be an intricate balance with the destruction of carbon through normal X-ray bursts. It is not clear yet how this balance is reached. The ignition is fairly close to the presumed NS crust. Thus, superbursts may be good probes of those crusts (Cumming et al. 2006). Current theories about crusts are at odds with understanding superburst recurrence times: they are measured to be too short as compared with theory (e.g., Keek et al. 2008a).

3.3. Short wait times

At least $y = 10^8$ g cm^{-2} of fuel needs to be accreted before the density threshold for ignition may be reached at the bottom of the accreted layer. For a NS radius of $10R_{10}$ km, a mass accretion rate of $10^{-9}\dot{M}_{-9}$ M$_\odot$ yr^{-1} and a pile column thickness of $10^8 y_8$ g cm^{-2}, it takes $t_{\rm wait} = 5.5R_{10}^2 y_8/\dot{M}_{-9}$ hr before that happens[1] for accretion onto the complete NS (c.f., Sect. 3.1). Therefore, if $t_{\rm wait}$ is less than roughly half an hour, fuel must have been left from the previous burst. In recent years this has been observed often. Boirin et al. (2007) observed the systematic occurrence of *triple* bursts in long ($\sim$ 24 hr) uninterrupted observations of EXO 0748-676. The initial burst in these was always found to have longer tails, indicating that secondary bursts are always hydrogen-poorer. Keek et al. (2010) confirmed this result in a larger source sample, after a systematic search for *multiple* bursts in BeppoSAX and RXTE data based on the MINBAR database (Galloway et al. 2008b). Keek et al. found multiple bursts in 15 bursters. It is, therefore, a rather common phenomenon. However, no such bursts were seen from (candidate) ultracompact X-ray binaries, with a significance of 10^{-3}, indicating that hydrogen is a necessary ingredient. Other features are a shortest wait time of 3.8 min and a *quadruple* burst in 4U 1636-536 with the 4 bursts occurring within a 53 min time span[2].

*1 We ignore general relativistic corrections which amount to several tens of percents at most.

*2 4U 1636-53 appears to be a rosetta stone of peculiar thermonuclear burning features besides multiple bursts: multiple superbursts (Wijnands 2001), mHz oscillatory burning (Revnivstev et al. 2001; Heger et al. 2007; Altamirano et al. 2008) and odd burst shapes (van Paradijs et al. 1986; Zhang et al. 2009).

Multiple bursts are not understood yet. It could be related to rotational mixing in these fast rotators.

3.4. Superexpansion - nova-like shells

Already in the 1970s X-ray bursts were noted with precursors, preceding the burst by and lasting for a few seconds (Hoffman et al. 1978). It was realized (e.g., Hanawa & Sugimoto 1982) that super-Eddington luminosities may occur during X-ray bursts, resulting in photospheric radius expansion. This may be so extreme that the peak of the black body spectrum moves to lower temperatures, in tandem with the expansion, and out of the X-ray band introducing the appearance of a gap in the burst profile (e.g., Tawara et al. 1984). The radial expansion of the photosphere is by at least a factor of 100. Therefore, this is called *superexpansion*, in contrast to the moderate expansion that is seen in most Eddington-limited bursts. in 't Zand & Weinberg (2010) performed a systematic search of precursors in BeppoSAX, RXTE and published data and found 32 cases from 8 sources. Interestingly, all sources are (candidate) ultracompact X-ray binaries. This is a consistent picture: superexpansion implies the quickest energy release which is typical for He burning and not for H burning.

The hypothesis about superexpansion is that the luminosity generated by the nuclear burning is so high that even below the surface of the NS the Eddington-limit is surpassed and a thick layer is blown away. For intermediate duration bursts the column thickness may be $\sim 10^8$ g cm^{-2} for an ignition column depth of $\sim 10^{10}$ g cm^{-2}. This shell is optically thick until, through the expansion, it is diluted so that it becomes optically thin. The NS then becomes visible through the shell and the main burst becomes visible. The rate of expansion can be estimated through simple black body modeling of the precursor. Velocities have been measured of up to 10% of the speed of light. In 3 or 4 cases (Strohmayer & Brown 2002; in 't Zand et al. 2011) signatures of accretion disk disruption by this shell have been detected.

4. Why are X-ray bursts so fascinating?

One of the questions in fundamental physics is the behavior of matter at extreme densities. On the one hand this regime can be probed at high temperatures with particle accelerators on earth. On the other hand, for cool temperatures, with NSs (e.g., Paerels et al. 2009). This is, arguably, the primary driver for X-ray burst research.

NSs harbor the densest bulk matter in the visible universe, with densities that are higher than that in atomic nuclei, approaching that of nucleons. The behavior of matter at these densities is described by quantum chromodynamics (QCD). Currently this theory is incomplete at high bulk densities due to the uncertain many-body behavior. There is a dire need of experimental data, ide-

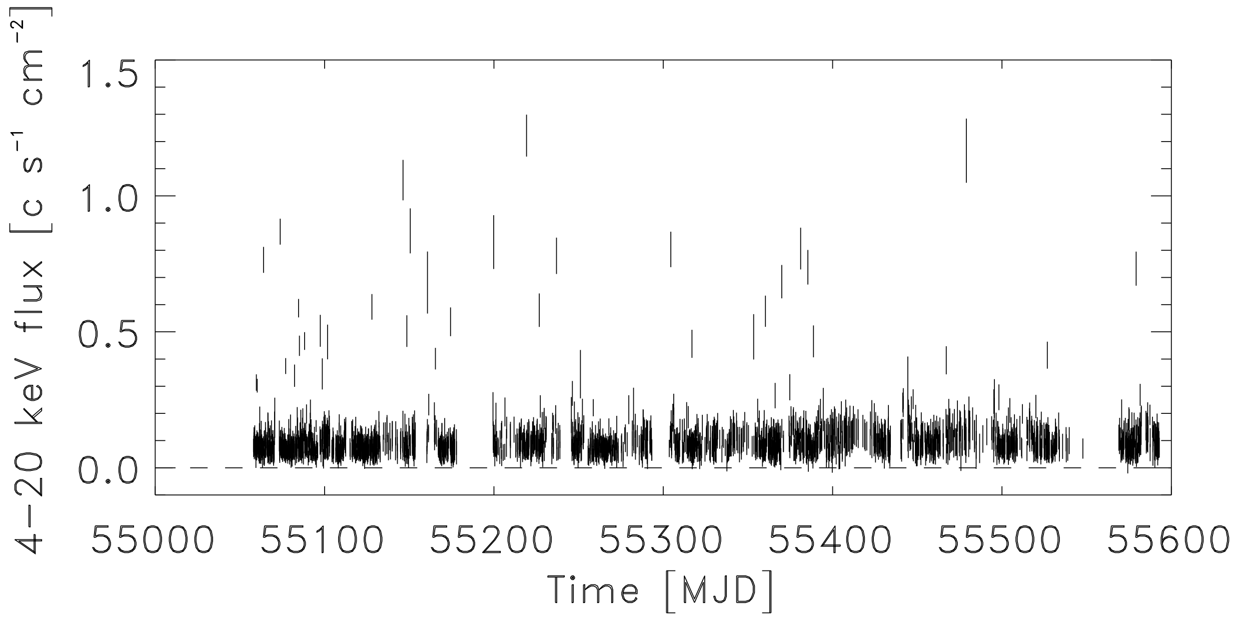

Fig. 1. MAXI/GSC orbital light curve of GS 1826-24 until Feb 1, 2011. The fluctuations upwards are indicative of X-ray bursts. See Sect. 5.1..

ally the mass and radius of one NS (e.g., Lattimer & Prakash 2007; Paerels et al. 2009).

Many X-ray bursts reach luminosities equal to the Eddington limit, $(2-4)\times 10^{38}$ erg s^{-1}. Therefore, they show NS surfaces at maximum brightness. In principle this makes X-ray bursts ideal tools to diagnose NSs, particularly to measure their radius which is not possible in radio pulsars since that radiation arrives from the magnetosphere instead of the NS itself.

Due to the large compactness of NSs (M/R $\approx$ 0.1 M$_\odot$/km), just short of that at the Schwarzschild radius (M/R$\approx$0.3 M$_\odot$/km), space-time is strongly curved around them. General relativity predicts a gravitational redshift that for nominal NS parameters (M=1.4 M$_\odot$, R=10 km) amounts to 30%. If discrete spectral features were found and identified, this would be a straightforward measurement. A tentative measurement by Cottam et al. (2002) spurred many observations with Chandra and XMM-Newton, including on the same source, but failed to repeat the measurement (Thompson et al. 2005; Kong et al. 2007; Cottam et al. 2008; Misanovic et al. 2010). Nevertheless, this has not been given up yet. in 't Zand & Weinberg found evidence of absorption edges in low-resolution measurements of two superexpansion bursts with RXTE. Such bursts have not been detected with Chandra or XMM-Newton yet. This is difficult, because these bursts are so rare.

In the mean time, efforts stepped up to derive NS radii from continuum burst spectra. In principle the method is straightforward (e.g., van Paradijs 1979): if the emission is black body radiation, the law of Stefan-Boltzmann applies: $F = (R_{\rm NS}/d)^2\sigma T^4$ where σ is the Stefan-Boltzmann constant, d the distance and F the bolometric flux. F and T are measured during bursts, and d can be determined independently, for instance if the source is one of the 13 or 14 bursters in a globular cluster. d may also be canceled out if a burst of the same source is seen to reach the Eddington limit through photospheric radius expansion (see above). Then $F\ d^2 = L_{\rm Edd}/4\pi$ with $L_{\rm Edd} = 4\pi cGM/0.2(1+X)$ and X the hydrogen abundance. However, as straightforward as this seems, as difficult it is to infer good constraints on $R_{\rm NS}$. The emission is not exactly black body due to scattering against hot electrons in the atmosphere; distances are seldom better determined than 15% (for instance, because X is difficult to determine; e.g., Kuulkers et al. 2003); and the emission may not be isotropic. Effort is underway to eliminate these systematic uncertainties. The reader is referred to Özel et al. (2006), Güver et al. (2010), Suleimanov et al. (2010) and Steiner et al. (2010).

5. What can MAXI do?

MAXI (Matsuoka et al. 2009; Sugizaki et al. 2011) scans 95% of the 2-30 keV X-ray sky each day at a sensitivity of about 15 mCrab. Each sky position is transited in 40-150 s exposures every 92 min. The capability is similar to the All-Sky Monitor on RXTE (Levine et al. 1996), except for a broader energy range (up to 30 instead of 12 keV) and a higher resolution of the photon energy information on the ground. The sensitivity towards X-

Table 1. Burst counts of MAXI data until Feb 2, 2011. Exposure time (4th column) is simply the number of orbits (3rd column) times 45 s. The last column provides accumulated times when there are at least 2 orbital measurements within 2 hr.

Object	# bursts	Orbits	SB expos. (yr)
GS 1826-24	24	4291	0.64
4U 1636-53	14	4850	0.72
Aql X-1[1]	7	5044	0.77
4U 1608-52[1]	3	4535	0.66
4U 1735-44	4	3691	0.54
4U 1746-37	3	4280	0.64
HETE J1900.1-2455	3	4255	0.63
4U 1724-30	2	4212	0.63
4U 0513-40	2	3522	0.51
SLX 1735-269	2	4477	0.65

[1]Transient with 2 outbursts in MAXI data

ray bursts is, therefore, similar to RXTE-ASM.

5.1. An exploratory look at MAXI data

A good illustration of MAXI's capability on X-ray bursts is provided by measurements of GS 1826-24. The bursting behavior of this source is convenient because it exhibits bursts every 3 to 6 hr that are long with respect to the transit time of the source through MAXI's 3^o (full-width at zero response) field of view (c.f., Galloway et al. 2004). Figure 1 shows the orbital light curve. About 35 spikes can be discerned in this lightcurve. 24 are far from data gaps and are possibly X-ray bursts.

We have reviewed the orbital data for a few known frequent X-ray bursters and counted the numbers of possible bursts, see Table 1. Many bursts are expected to be shorter than the transit time. Therefore, the burst signal in 1-orbit accumulations may be smeared out and the orbital data is not optimum for finding ordinary X-ray bursts. A typical decay time scale of 10 s implies that the 1-orbit-averaged signal will be at most 1/4 of the peak flux. The data needs to be reviewed at a higher time resolution to search for the typical fast-rise exponential-decay burst profile. Such a resolution is not available publicly, because it is non-trivial for analysis: the data are strongly modulated by the triangular-shaped transit responses of multiple sources in the FOV. The data also needs to be reviewed at higher spectral resolution, to search for a cooling signature that may not be visible in the 3 bands that are at the moment publicly available.

5.2. MAXI on superbursts

The orbital data are ideally suited to search for superbursts since the burst duration is much longer than one transit and a burst would be covered by a number of consecutive transits. The capability is similar to the RXTE ASM which revealed 8 superbursts in 15 years (Wijnands 2001; Kuulkers et al. 2002, Remillard & Morgan 2005; Kuulkers 2005, 2009b). If one combines all times when two orbital data points are within 2 hr from each other, for all 10 known superbursters, the total exposure time is close to 6 yr (see Table 1). The average superburst recurrence time is $2^{+2}_{-0.7}$ yr (in 't Zand et al. 2003), implying that MAXI data is expected to contain about 3 superbursts. Up to February 2011, no superburst has been identified yet in MAXI data (Serino, priv. comm.). The chance probability for detecting none is 5%.

6. Future

There are unexplored niches in X-ray burst research that can be probed with presently available instrumentation. Chandra and XMM-Newton, with their spectrographs LETGS, HETGS and RGS, have not yet measured superexpansion bursts and superbursts, while these are the types of bursts which have the highest probability for revealing discrete spectral features, as predicted by theory and suggested by low-resolution data. RXTE will be operative for at least one more year and will be able to continue searching for burst oscillations. Just very recently this brought the surprise of the 11 Hz oscillator. There is hope that it will break the high-speed record NS spin frequency of 716 Hz (Hessels et al. 2006). Spin frequencies of 1 kHz or higher are measurable by RXTE and would rule out some theories for the NS internal constitution (Lattimer & Prakash 2007).

The key to significant advancement in future instrumentation is collecting area, so that burst oscillations can be studied in greater detail and at lower amplitude, and spectra can be measured more accurately. A number of proposed future missions with square-meter collecting area would meet that challenge: IXO, LOFT, AXTAR and GRAVITAS. With regards to measuring recurrence times of rare X-ray bursts, it would be worthwhile to have an all-sky monitor with a duty cycle that is significantly higher than the few percent duty cycles delivered by for instance MAXI and ASM and with at least moderate sensitivity, such as proposed on AXTAR (Ray et al. 2010) or MIRAX (Braga & Mejia 2006). The already-flying GBM on Fermi has a high duty cycle and delivers interesting X-ray burst results (Linares et al., these proceedings), but has a non-optimum bandpass starting at 8 keV.

Acknowledgments. I am grateful to the SOC and LOC for inviting me to this very well organized, interesting and enjoyable workshop. Nobuyuki Kawai and Motoko Serino are thanked for advice on MAXI data and Anna Watts for useful discussions on burst oscillations. This research has made use of the MAXI data provided by RIKEN, JAXA and the MAXI team.

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