THE FERMI–GBM THREE-YEAR X-RAY BURST CATALOG

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Received 2016 March 31; revised 2016 May 6; accepted 2016 May 11; published 2016 August 2

ABSTRACT

The Fermi Gamma-ray Burst Monitor (GBM) is an all-sky gamma-ray monitor well known in the gamma-ray burst (GRB) community. Although GBM excels in detecting the hard, bright extragalactic GRBs, its sensitivity above 8 keV and its all-sky view make it an excellent instrument for the detection of rare, short-lived Galactic transients. In 2010 March, we initiated a systematic search for transients using GBM data. We conclude this phase of the search by presenting a three-year catalog of 1084 X-ray bursts. Using spectral analysis, location, and spatial distributions we classified the 1084 events into 752 thermonuclear X-ray bursts, 267 transient events from accretion flares and X-ray pulses, and 65 untriggered gamma-ray bursts. All thermonuclear bursts have peak blackbody temperatures broadly consistent with photospheric radius expansion (PRE) bursts. We find an average rate of 1.4 PRE bursts per day, integrated over all Galactic bursters within about 10 kpc. These include 33 and 10 bursts from the ultra-compact X-ray binaries 4U 0614+09 and 2S 0918-549, respectively. We discuss these recurrence times and estimate the total mass ejected by PRE bursts in our Galaxy.

Key words: stars: neutron – X-rays: bursts

Supporting material: figure sets, machine-readable tables

1. INTRODUCTION

Rare, unpredictable, and transient astronomical phenomena are difficult to observe due to their very own nature, yet they often lead to exciting astrophysical discoveries. At any wavelength, the most efficient way of detecting rare transients is to maximize the observed field of view (FOV). The high-energy (X-ray and gamma-ray) sky can vary rapidly, on timescales much shorter than hours. If we are interested in short-lived rare transient phenomena (seconds to minutes long), the most relevant observational capability is the instantaneous FOV. Even though serendipitous detections occur, neither pointed narrow FOV instruments nor all-sky monitors based on scanning techniques are well suited to catch such short and rare events.

The Gamma-ray Burst Monitor (GBM) onboard the Fermi observatory has an instantaneous FOV of about 75% of the sky (Meegan et al. 2009) and is sensitive to photon energies down to 8 keV. Even though it was designed to detect and characterize gamma-ray bursts (GRBs), these characteristics make GBM a unique instrument to detect rare, short, and bright X-ray bursts (XRBs). In 2010 March, we initiated a systematic search for XRBs using Fermi–GBM data (Section 2). In the first three years, this search has yielded 752 thermonuclear X-ray bursts (tXRBs; Sections 1.1 and 3.1), 267 transient events from accretion flares and X-ray pulses (uFXPs), as well as 65 untriggered long gamma-ray bursts (uGRBs). We present here the Fermi–GBM Three-year X-ray Burst Catalog and summarize its main results with an emphasis on tXRBs.

1.1. The Rare and Most Energetic Thermonuclear Bursts

The accreted matter in neutron-star low-mass X-ray binaries (NS-LMXBs) piles up on the surface of the neutron star, reaching regions of increased density and becoming fuel for thermonuclear reactions. When ignition conditions are met at the bottom of the accreted shell, unstable reactions trigger a thermonuclear runaway that quickly burns the pile of fuel, generally a mix of hydrogen (H), helium (He), and heavier elements (“metals”). This cyclic phenomenon has been observed for four decades in what are known as thermonuclear (type I X-ray) bursts (Belian et al. 1976; Grindlay et al. 1976). The main parameter that sets the frequency or recurrence time of tXRBs is the mass accretion rate per unit area, $\dot{m}$ (Fujimoto et al. 1981; Bildsten 1998). The main reason is simple: $\dot{m}$ sets the rate at which fuel is replenished between tXRBs. However, other factors play an important role in the recurrence time of tXRBs, including composition and the thermal state of the NS envelope. In particular, at the lowest $\dot{m}$ (near or below 1% of the Eddington limit) the heat flux from the NS crust can critically influence the ignition conditions for tXRBs. Thus we can potentially use low-$\dot{m}$ tXRBs to constrain the internal properties of NSs (Cumming et al. 2006). However, because recurrence times of low-$\dot{m}$ tXRBs are of the order of weeks to months, they are extremely difficult to measure with pointed or scanning X-ray detectors. GBM has opened a new window to these events, and it is yielding the first accurate measurements of their recurrence times (Linares et al. 2012).
2. THE FERMI–GBM X-RAY BURST MONITOR

GBM is an all-sky monitor whose primary objective is to extend the energy range over which gamma-ray bursts are observed in the Large Area Telescope on Fermi (Meegan et al. 2009). GBM consists of 12 NaI detectors with a diameter of 12.7 cm and a thickness of 1.27 cm and two bismuth germanate (BGO) detectors with a diameter and thickness of 12.7 cm. The NaI detectors have an energy range from 8 keV to 1 MeV while the BGOs extend the energy range to 40 MeV. The GBM flight software was designed so that GBM can trigger on-board in response to impulsive events, when the count rates recorded in two or more NaI detectors significantly exceed the background count rate on at least one timescale from 16 ms to 4.096 s in at least one of four energy ranges above 25 keV. The lower energy and longer timescales are inaccessible to the on-board triggering algorithms owing to strong variations in background rates that are incompatible with a simple background modeling needed for automated operation on a spacecraft. Between 25 and 50 keV, only the shortest timescales (under 128 ms) are probed on-board. We report here on our search of GBM continuous data for impulsive events that are too long and too spectrally soft to trigger on-board.

GBM has three continuous data types: CTIME data with nominal 0.256 s time resolution and 8-channel spectral resolution used for event detection and localization, CSPEC data with nominal 4.096 s time resolution and 128-channel spectral resolution, which are used for spectral modeling, and CTTE (continuous-time tagged event) data with time stamps (2 μs precision) on individual events at full 128-channel spectral resolution, which were made available in 2012 November. The NaI CTIME and CSPEC data from 8 to 50 keV are used in the following analysis.

2.1. Data Selection

The Fermi–GBM X-ray Burst Monitor relies on daily inspection of CTIME channel 1 (12–25 keV) data and began operations on 2010 March 12. The CTIME data are rebinned to a minimum of 0.25 s time bins to adjust intervals of high-resolution data initiated by instrument triggers. NaI detector rates, from all 12 detectors and channels 0–2 (8–50 keV), are automatically filtered to remove phosphorescence events, times of high total rates, times near the South Atlantic Anomaly (SAA), and intervals of rapid spacecraft slews. An empirical background model is fit to the detector rates in each channel (0–2) and each detector. The background model has terms to account for bright sources and their Earth occultations plus a quadratic spline model to account for the low-frequency trends of the remaining background (below ~1 mHz). The background model is visually compared to the rates in the energy band between 12 and 25 keV with a time resolution of ~8.2 s. Transient events that rise above the background model are saved by manually selecting the corresponding time intervals. Source rates and background rates for the first three energy bands (8–50 keV) along with mid-times of these manually selected time intervals are recorded. Between 2010 March and 2013 March, the search resulted in 5093 selected events.

Type I X-ray bursts, the softest population of events likely to be detected, are expected to have a blackbody spectrum with a temperature between about 0.5 and 3 keV. Due to the gradual rollover in the expected photon spectrum between 12 and 25 keV and the steep drop in effective area in data from CTIME channel 0 (~8–12 keV) (Meegan et al. 2009), channel 1 (12–25 keV) is the channel most sensitive to these XRBs. The choice of 8.2 s timing resolution for channel 1 data is a compromise between the desire to maximize our sensitivity to these events and the time demands of this labor-intensive process, and limits the minimal detectable burst duration to around 10 s. Variations in background count rate over the Fermi orbit, caused both by changes in geomagnetic latitude and by varying spacecraft attitude, prevent visual identification of very long bursts. Our search is thus sensitive to bursts and flares with durations in the range 10–1000 s.

2.2. Localization

Localization of our events of interest utilizes the angular response of the NaI detectors to reconstruct the most likely arrival direction based on the differences in background-subtracted count rates recorded in 12 NaI detectors that have different sky orientations. The method is adapted from the method used for GBM localization of GRBs (Connaughton et al. 2015), with a cruder background fitting method. We use data between 12 and 50 keV and the model rates more suitable for sources with softer energy spectra: galactic transients (power law with index = −2), solar flares (power law with index = −3), and type I XRBs (blackbody with temperature = 4 keV). This process yields a localization and a radius of 68% statistical uncertainty (assuming a circular uncertainty region), σ. We also determine a goodness-of-fit parameter, $\chi^2$, of the localization. Other parameters of interest include a rough event duration, a list of detectors with an angle between source and detector normal less than 60°, the net count rates in these detectors, and hardness ratios derived from count rates in different energy channels. If the event localizes to within $10^5$ of the centroid of the solar disk or is less than 3σ from the Sun’s position then the event is rejected, as are events with localizations clearly (beyond the statistical uncertainty) beneath the Earth’s horizon.

If the net count rates of the two brightest detectors are inconsistent with a single source direction then the event is rejected. Such events may occur during a particle shower within or near the spacecraft and are not associated with an astronomical source. An additional check is performed to eliminate particle events that originate in the spacecraft. These events appear to have a hard spectrum and thus might be initially classified as uGRBs, but unlike GRBs their light curves in the range 50–300 keV are very similar for all 12 NaI detectors. This produces a poor $\chi^2$ in the localization fit and we use a cut-off in $\chi^2$ of 1000 to reject these particle events, more tolerant than reported in Connaughton et al. (2015) because the quality of the background fits over the low-energy channel data analyzed here is more variable, and even real astrophysical events may produce localizations with large $\chi^2$ values. All other events are considered to be XRB candidates. Once the events are localized, they are searched for temporal and spatial coincidence with GBM- and Swift-triggered GRBs. If the XRB candidate event is located within 3σ of a triggered GRB and the mid-time of the XRB candidate event occurs within 150% of the T-90 duration of the GRB trigger time then the XRB event is considered to be a triggered GRB and rejected. After these filtering steps there are 2253 events remaining of the original manually selected sample of 5093. The vast majority of rejected events were identified as solar flares.
2.3. Spectral Analysis

Response matrices for each XRB candidate event are created from a response model constructed from simulations incorporating the Fermi spacecraft mass model into GEANT4 (Agostinelli et al. 2003). CSPEC data are used for spectral analysis in RMFIT, forward-folding spectral analysis software often used in GBM gamma-ray burst studies.11 Through localization and visual inspection (see Section 3.2) many of the events were identified with Sco X-1 and Vela X-1 (aFXPs) and spectral analysis was not necessary for identification. We did, however, perform spectral analysis on a few of these in order to aid in the association of those events in which identification was not apparent. Blackbody and power-law models are fit to all of the remaining data, the former because it is physically motivated for tXRBs and the latter because it is a simple model that can be used to fit a variety of events, and may be useful to classify their spectral hardness even if the model does not fully describe the data.

In the course of our spectral analysis, we identified fits for which the residuals of the unfolded spectrum for different detectors were inconsistent with each other. This is evidence for a bad localization, which we attributed to poor background fits in one or more detectors. We selected background time intervals before and after the source time interval, as is done for GRB localization by the GBM team. We fit the selections with a polynomial (usually a quadratic but occasionally a higher-order polynomial is necessary to fit the data) for each detector and for each channel between 0 and 2 (8–50 keV). The event is selected and the fitted backgrounds subtracted. A new localization is performed and the event is labeled as before. Subsequent localizations almost invariably provided an improved localization χ² and smaller error. This was most often because the previous background fit included the source and reduced the residual rates in each detector in a non-uniform manner, thus producing an erroneous localization and resulting in poor detector responses.

Weak events (85) in which spectral analysis was not possible were rejected. With these rejected events and events that were reclassified as solar due to the new localization, there remained 1084 XRB candidates. Figure 1 shows the results of the spectral modeling of these XRB candidates. The top panel is a histogram of the resulting temperatures from blackbody spectral modeling of these XRB candidates. The top panel is a histogram of the indices from power-law fits to the XRB event spectra. In each panel, diamonds are the data points, the solid line is the total model, and the dashed and dotted lines are the Gaussian components of the total model.

We checked whether scattering off the Earth’s limb was a possible contributor to the systematic error in the spectral analysis by checking the proximity of the events to the Earth’s limb. There were only 23 events that were within 100 s of the Earth’s limb and only two less than 20 s. These last two events had blackbody spectrum with a temperature of 3.0 keV is used to simulate the data. The simulated data are fit to a blackbody spectrum, resulting in the best-fit spectral temperature centered on 3.0 ± 0.16 keV for the brightest interval and 3.0 ± 0.3 keV for the weak interval, assuming that the temperatures are normally distributed. The resulting temperature distributions and fits to a Gaussian function are shown in Figure 2. These results indicate that any systematic error in the spectral analysis is not dominated by the lack of spectral sensitivity in GBM at these energies and fluxes.

We checked whether scattering off the Earth’s limb was a possible contributor to the systematic error in the spectral analysis by checking the proximity of the events to the Earth’s limb. There were only 23 events that were within 100 s of the Earth’s limb and only two less than 20 s. These last two events had blackbody temperatures of 3.3 ± 0.2 keV and 2.9 ± 0.2 keV and were within 10° of the Galactic center. We do not expect such limb events to be a source of systematic error in our catalog.

2.4. Temporal Analysis

Temporal analysis of XRB events includes the calculation of event duration, rise times, and decay times and was performed

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11 https://gamma-wiki.mpe.mpg.de/GBM/RMFITPublicReleasePage
after classification (see Section 3) was finished. Due to the nature of the aFXPs (see Section 3.2), these events were excluded from the temporal analysis. Durations for these events are taken from the time interval of the original event selection. Since this analysis requires detailed visual inspection of the light curve, these events underwent additional scrutiny to ensure that aFXPs did not contaminate the remaining categories.

For each event where durations are calculated, light curves for all detectors are visually inspected in the energy band 12–25 keV and background regions are selected. The background is fit to a polynomial (usually a quadratic but occasionally a higher-order polynomial is necessary to fit the data). The background fit is then subtracted from the light curve. The detectors, in which a signal is evident, are selected and the first three energy channels (8–50 keV) are added together and displayed as a single light curve. The peak intensity of the light curve ($t_{\text{peak}}$) is selected. The times at 25% of peak during the rise ($t_{25}$), 90% of peak during the rise ($t_{90}$), and 10% of the peak along the decay ($t_{10}$) are calculated. As in Galloway et al. (2008), the rise time $t_{\text{rise}}$ is the time for the intensity to rise from 25% to 90% of its peak value, the duration of the event is defined as $t_{90} - t_{25}$ and the decay time ($t_{\text{decay}}$) is defined as $t_{90} - t_{\text{peak}}$.

3. X-RAY BURST CATALOG

The three-year XRB catalog contains 1084 events occurring between MJD 55267 and 56347 (2010 March 12–2013 February 24), which are classified into three categories: the tXRBs, the aFXPs, and the uGRBs. Clear distinctions between the three categories are not possible; therefore, we make the following quantitative effort. First, the aFXPs are categorized based on location, visual inspection of the light curve, and spectral analysis (see Section 3.2). Second, the tXRBs are categorized using spectral analysis alone, and then the uGRB events are categorized based on spectral analysis and location.

The XRB events are from a wide variety of sources and their spectra are expected to be just as varied. The tXRBs are expected to have a blackbody spectrum (0.5–3 keV) while many of the aFXPs and uGRBs are expected to have nonthermal spectra, which may be modeled, in part, by a power law. Although the power-law spectral model is generally not a good choice for all three categories of events, it serves well as an indicator of spectral properties for which all categories may be compared. We used spectral results from 32 events that we confidently associate with 4U 0614+09 from this work and Linares et al. (2012) to compare the spectral fit results from a blackbody and power-law model (see Figure 4). There is a tight correlation between the blackbody temperature and the index from a power-law fit, justifying our sole use of the power law in spectral comparisons. This correlation, when considering all events, is tight up to 4 keV (index $=-2.5$), after which there is considerable scatter in the blackbody temperature.

We choose to be inclusive with our category of tXRBs and use a cut-off in spectral index of $-2.5$ (4 keV). Any event that is not an aFPX and has a spectral index that is consistent (1σ) with being softer than $-2.5$ (<4 keV) is categorized as a tXRB (see the red distribution in the right panel of Figure 5). This exceeds, by a good margin, the theoretical maximum temperature for type I bursts (Boutloukos et al. 2010). The left panel of Figure 5 shows the distribution of power-law indices for all
XRB events. The softer distribution has a centroid of $-3.2 \pm 0.25$ and, being the softer distribution, is expected to contain the tXRBs. The spectral index cut-off of $-2.5$ represents a $3\sigma$ departure from the centroid, thus validating our choice.

The uGRBs are expected to be isotropically distributed across the sky while the tXRBs are mostly at the Galactic center. If we assume GBM uniform exposure, the power-law index cut-off that maximizes the isotropy of the source distribution can also be used to distinguish these two categories. Using the Rayleigh test, the maximum isotropy ($\chi^2 = 1.8/3$) occurs for those events whose power-law index is consistent ($1\sigma$) with being greater than $-2.43$, thus again validating our choice of $-2.5$ as a spectral index discriminator between the uGRBs and the tXRBs. Three uGRB events had a spectral index between $-2.43$ and $-2.5$ and could arguably be placed in the tXRB classification: they were 10101041428, 11100350666, and 12062078172.

Figure 6 shows the location of all the events in Galactic coordinates with the categories distinguished by color and symbol. The purple diamonds are the tXRBs and there are a large number distributed around the Galactic center, which is consistent with the distribution of the known type I XRBs. There is a smaller cluster of events consistent with the location of 4U 0614+09. The aFXPs are shown as blue circles and are largely in three clusters centered around A 0535+26, Vela X-1, and Sco X-1. The green squares are the uGRBs, which are distinguished by their isotropic distribution. The classification scheme is summarized in Table 1. Details for each category are given in Tables 3–5 and light curves for the bright detectors for each event are shown in Appendices A–C. The background shown in the light curves is an automated background used for initial localization and is not representative of the background used for spectral, final location, and temporal analysis.

3.1. Thermonuclear X-Ray Bursts (tXRBs)

The largest category of events in our catalog contains soft events, and their spectra are well fit using a simple blackbody model with temperature in the range $\sim 2–5$ keV, largely consistent with the spectral properties of thermonuclear bursts from accreting neutron stars (e.g., Swank et al. 1977). They also show a spatial distribution consistent with the $\sim 100$ known thermonuclear burst sources (“bursters”; see Figure 7), strongly concentrated toward the Galactic bulge region. For the bursts that are bright enough, time-resolved spectroscopy reveals cooling along the tail of the burst, the unequivocal signature of tXRBs. All of our tXRBs associated with 4U 0614+09 are bright enough for verification via time-resolved spectroscopy, including those reported by Linares et al. (2012). In the most energetic bursts from 2S 0918-549 we also detect cooling along the decay (Section 4.1.2).

We detect in total 752 tXRB candidates, with 375 bright enough for time-resolved spectral analysis. Their average blackbody temperature is $3.2 \pm 0.3$ keV. This value is consistent with the highest temperature measured during photospheric radius expansion (PRE) bursts, when the photosphere is thought to reach the surface of the neutron star at the end of the Eddington-limited phase (the so-called “touchdown”; Lewin et al. 1993; in’t Zand 2005; Kuulkers et al. 2010). The properties of the full sample of tXRBs are presented in Table 5, including morphology and spectral parameters. Light curves for these events are given in Appendix C, labeled by burst ID.

GBM location errors are typically larger than a few degrees and occasionally tens of degrees (Connaughton et al. 2015). Since the majority of known bursters are within $\lesssim 20^\circ$ of the Galactic center, individual identification of tXRBs is limited to those located sufficiently far from the Galactic bulge. Due to this limitation intrinsic to the GBM location accuracy, we make no attempt to associate events within this central distribution. Instead, we focus on those sources that are more than $30^\circ$ from Sag A*. Out of 103 known bursters, this leaves 26 systems that we attempt to associate with our tXRB events. Furthermore, we use MAXI 2–20 keV weekly light curves (Matsuoka et al. 2009) in an attempt to determine whether a given burster was active at the time of the tXRB (see below). We place the 26 bursters far from the Galactic bulge into one of the following four categories.

1. If the source is close enough to be detected in MAXI but has not flared within our catalog time period, the source is considered to be always off and we remove it from consideration. Only Cen X-4 is in this category.

2. There are six bursters that are below the $10\sigma$ detection threshold in MAXI but have always shown persistent emission whenever they have been observed with pointed X-ray detectors. All but one (4U 1323-62, with an orbital period of 2.9 hr) are confirmed or candidate ultra-compact X-ray binaries (UCXBs: orbital periods shorter than 1 hr; see in’t Zand et al. 2007): 4U 0513-40 (in the globular cluster NGC 1851), 4U 1246-58, 4U 1915-05 (dipper), 4U 2129+12 (M15-X-2 in the globular cluster M15), and 2S 0918-549 (discussed in detail in Section 4.1.2). They are assumed to be persistently accreting at a low rate, and considered to be candidates for association with all events. Their mass accretion rates are below 5% of the Eddington limit (in’t Zand et al. 2007), which explains the low persistent flux detected by MAXI together with their distances $\gtrsim 5$ kpc.

3. There are eight sources whose transient or persistent activity can be monitored with MAXI: when actively accreting they are detected above the $10\sigma$ threshold. We only consider these sources as possible associations to our events if the source exceeds the $10\sigma$ threshold in the week of the event. These sources are 4U 0614+09

![Figure 4. Distribution of blackbody temperatures for the XRB candidates associated by location and spectral shape with 4U 0614+09 shows a close correlation with the index of the power-law distribution.](image-url)
Figure 5. Distribution of the spectral index from power-law fits to the XRB candidate spectra. Left: diamonds are the data points for all the XRB events. The solid line is a model fit to the data, and the dashed and dotted lines are the two Gaussian components of the total model. Right: separation of indices by class of event. The red curve is the index distribution for the tXRBs, the blue curve is that for the aFXPs, and the green curve is that for the uGRBs. Contributions from Sco X-1 and Vela X-1 (both aFXPs) are marked.

Figure 6. Centroids of the localization of all events in Galactic coordinates. The purple diamonds are the locations of the tXRBs, the blue circles are the locations of the aFXPs, and the green squares are the uGRBs. The error circles are marked.

4. The remaining category contains 11 sources with no available MAXI weekly light curves. This category includes some of the so-called “burst-only sources” (Cornelisse et al. 2002a) as well as faint transients in which there is only one known outburst with which the source was discovered. Swift-BAT daily light curves for these sources, when available, do not provide a clear distinction between quiescent and active periods. These sources are: MAXI J1421-613 (outburst in 2014 January, i.e., after catalog), UW CrB (peculiar, persistently faint “accretion disk corona” source, known since 1990, (persistent atoll and UCXB candidate; discussed in detail in Section 4.1.1), EXO 0748-676 (quasi-persistent transient, in quiescence since 2008), GS 0836-429 (transient, outburst in 2012 July), 4U 1254-69 (persistent atoll dipper), Cir X-1 (peculiar atoll/Z), Ser X-1 (persistent), Aql X-1 (canonical atoll transient with typically one or two outbursts per year), and Cyg X-2 (persistent Z source) (see, e.g., Galloway et al. 2008 and references therein). EXO 0748-676 has not shown activity in MAXI during our search period, thus in practice this burster is treated as off.

Hakala et al. (2005), IGR J17062-6143 (persistently faint at <1% of the Eddington luminosity since its discovery in 2006, Degenaar et al. 2013 and references therein), SAX J1818.7+1424, SAX J1324.5-6313, and SAX J2224.9+5421 (Cornelisse et al. 2002a), Swift J185003.2-005627 (faint transient active in 2011 May–June), MXB 1906+00, XB 1940-04, XTE J1223-058, and 4U 2129+47. They are considered for association with the tXRBs, even though their activity and history of mass accretion rate are often ill constrained.

An association list is generated for each tXRB using the following criteria. If the event location is within 2σ of a burster in the association list above, then that event is associated with the source. If more than three sources are associated with an event, then the event has a large location error, and all associations are rejected as spurious. All associations are listed in the table in ascending order of distance (in σ given in parenthesis) from the source. If only one source is located within 2σ of an event then it is listed in bold type, and we consider this a robust association. Out of the total of 752 tXRBs, 685 have no associations and 29 have non-unique associations. We find unique associations for 54 tXRBs, with eight known bursters. For this reduced sample we can assess the origin of the bursts, and their properties are summarized in Table 2.

3.2. Accretion Flares and X-Ray Pulses

Accretion-powered events such as those originating from Sco X-1, A 0535+26, and Vela X-1 are identified once their location and spectra are known (see Figure 8). Sco X-1 events have soft emission (PL index <−3) and are generally well localized to Sco X-1’s position. These events are usually part of a longer flaring episode that is distinctive in data from GBM channel 1 (12–25 keV). Events from Vela X-1 and A 0535+26 are typically part of a chain of pulsations that are identified in the CTIME data due to the dominant harmonic of their characteristic spin periods of 103.3 s and 283.5 s respectively as well as their harder spectra with a typical power-law index in excess of −2.5. The events in Table 3 associated with A 0535
Table 1
Summary of Source Classification

| Category | Number of Events | Selection Process | Properties |
|----------|------------------|-------------------|------------|
| aFXPs    | 267              | Location, visual inspection spectral (Sco X-1, $\Gamma < -3$) | Periodic, continuous flares |
| tXRBs    | 752              | Spectral ($\Gamma < -2.5$) | Galactic; $\mathcal{E} = 3.2 \pm 0.3$ keV |
| uGRBs    | 65               | Spectral ($\Gamma > -2.5$); isotropic | Hard; extragalactic |

Figure 7. Purple diamonds are the locations of the tXRBs. The black filled circles are the locations of the known type I bursters. Those that we have multiple associations for are labeled in black. A few of the aFXP sources are labeled in blue for comparison. The location errors on the events are typically larger than the symbols and it is easy to see that it would be impossible to attempt to associate those events near the Galactic center without a coincident detection with another instrument.

+26 coincide with a giant flare from A 0535+26 that occurred in 2011 February (Camero-Arranz et al. 2011).

The aFXPs are summarized in Table 3. The columns are as follows: ID is the time of the midpoint, in UTC, of the event selection identified by YYYYMMDDTTTTT where YY indicates the last two digits of the year, MM the month, DD the day, and TTTTT is the time in seconds from the start of the day. Peak is the time (UTC) of the peak count rate for the event measured in seconds since MJD 55267. R.A. and decl. indicate the GBM location and Error is the statistical error on the location. Association is the source that is associated with the event. The light curves for these events are in Appendix A and identified by ID.

3.3. Untriggered GRBs

The uGRBs are hard events that are selected due to their isotropic distribution on the sky, which implies an extragalactic origin (see Figure 9). In principle, extragalactic bursts could arise from sources other than GRBs, but given the broad range of spectral and temporal behavior exhibited by GRBs, we use the term uGRB to denote our whole extragalactic population of bursters. Their spectra are well fit with a Band function (Band et al. 1993) or power law with an exponential cut-off function that is typical of GRBs. Parameters from the spectral fits using the Band function were typically not well constrained and are not reported. The spectral results for the power law and power law with exponential cut-off are summarized in Table 4. The first four columns are the same as for the aFXPs. Columns 6–8 are the results of spectral fitting using a power law with an exponential cut-off parameterized as $E_{\text{peak}}$. A “-” in these columns denotes that the spectral parameters could not be constrained and these results are left out of the table. The sixth column is $E_{\text{peak}}$ in keV, the seventh column (Comp Flux) is the energy flux [erg cm$^{-2}$s$^{-1}$] from 10 to 10000 keV, and the eighth column (Comp Flnc) is the energy fluence [erg cm$^{-2}$] from 10 to 1000 keV. The last four columns are results from the temporal analysis discussed in detail in Section 2.4 and include the rise time, fall time, duration, and a column labeled Structure describing the temporal structure of the event. The Structure column contains an “S” if the light curve is single-peaked or an “M” if it is multi-peaked. If an event is multi-peaked, the rise time and fall time that are calculated may no longer represent a true rise or fall time for the event since the peak of the event could occur on any of the multiple peaks. The light curves for these events are in Appendix B and identified by ID.

4. DISCUSSION

We have uncovered a large catalog of untriggered bursts in the GBM data that reflect the power of GBM as an all-sky monitor of diverse astrophysical phenomena in the hard X-ray energy band. Despite the difficulties inherent in uncovering these bursts in the background-limited GBM detectors, and the limitations imposed by GBM’s coarse source localization, we identified at least three distinct classes of events: untriggered GRBs, accretion-powered flares and X-ray pulsations from known sources, and thermonuclear type I X-ray bursts.

Our source classification relied strongly on spectral modeling and, particularly for the aFXPs, location. Classification from spectral analysis was complicated by the overlapping distributions of spectral parameters among the different classes. We used the spatial distribution of source locations on the sky to verify our choice for the cut-off in spectral hardness for the events assigned to the uGRB sample by verifying that this cut-off maximized the isotropy of the spatial distribution.

The tXRBs are the primary science driver for this catalog and we discuss them in depth in Section 4.1. The distribution of temperatures from the blackbody spectral fits of the tXRBs is shown in Figure 10. The temperature distribution has a hard tail that extends beyond 6 keV, prompting speculation that there was a fourth, unknown category of XRBs. Monte Carlo analysis performed in Section 2.3 indicates that GBM has sufficient spectral sensitivity to accurately measure the spectral temperature down to 3 keV, yet there are 62 tXRBs whose spectral temperature exceeds 4.0 keV and none is associated with a known type I source. Furthermore, these events are distributed along the Galactic plane and concentrated at the Galactic center. A few are weak and may be explained by poor
background subtraction, while a few may be soft GRBs with chance location along the Galactic plane. We find no evidence of a bimodal distribution in spectral temperature or fluence, thus we conclude that a fourth, "unknown" category is unwarranted with the current data set. We will revisit this when more data have been analyzed.

The aFXPs were a byproduct of our XRB search since we have dedicated programs to study them (The GBM Pulsar Project12 and The Earth Occultation Project13). Nevertheless; the aFXPs in the catalog provide a unique opportunity to observe these sources in rare, bright states that would normally require a targeted observation.

The brightest (other than the Sun) recurring source that GBM observes from 8 to 50 keV is Sco X-1, and we intentionally attempted to avoid this source since our focus was on tXRBs; nevertheless, Sco X-1 dominates the aFXP category due to its numerous flares. Its persistent nature makes background subtraction difficult and this occasionally leads to poor localization. Luckily, its soft spectrum (index $\sim$–3.5) makes this source relatively easy to identify. The other aFXPs are neutron stars powered by magnetically dominated accretion with a harder spectrum (index $\sim$–2).

Table 2
GBM Bursts with Associated Bursters

| Burster          | Number of Bursts | $D$ (kpc) | $L$ ($10^{38}$ erg s$^{-1}$) | $E$ (10$^{51}$ erg) | Duration (s) | Rise (s) | $(kT)$ (keV) | Category$^a$ |
|------------------|------------------|-----------|-------------------------------|--------------------|--------------|----------|------------|--------------|
| 4U 0614+09       | 33               | 3.2$^b$   | 0.3–1.7                       | 0.4–6.1            | 6.0–51.3     | 1.2–8.6  | 3.2        | 3            |
| 2S 0918-549      | 10               | 5.0$^c$   | 0.7–1.7                       | 1.0–17.0           | 9.7–75.6     | 2.5–38.9 | 3.1        | 2            |
| SAX J1818.7+1424 | 4                | 9.4$^d$   | 2.2–4.3                       | 8.8–25.7           | 20.1–90.9    | 13.5–62.0| 3.5        | 4            |
| UW CrB           | 2                | 5$^e$     | 1.0–1.0                       | 1.4–1.8            | 10.6–13.7    | 2.4–4.9  | 3.2        | 4            |
| IGR J17062-6143  | 2                | 5$^f$     | 0.9–1.0                       | 2.0–2.6            | 16.0–22.0    | 6.9–10.2 | 3.6        | 4            |
| XB 1940-04       | 1                | 8$^g$     | 4.4–4.4                       | 28.9–28.9          | 50.1–50.1    | 11.8–11.8| 3.9        | 4            |
| Ser X-1          | 1                | 8.4$^h$   | 2.8–2.8                       | 19.4–19.4          | 52.6–52.6    | 39.9–39.9| 3.1        | 3            |
| MAXI J1421-613   | 1                | 7$^i$     | 2.0–2.0                       | 13.8–13.8          | 53.9–53.9    | 2.3–2.3  | 4.8        | 4            |

Notes.
$^a$ Detection category from Section 3.1.
$^b$ Kuulkers et al. (2010).
$^c$ in’t Zand (2005), 4.0–5.3 kpc.
$^d$ Cornelisse et al. (2002a), <9.4 kpc.
$^e$ Hakala et al. (2005), >5–7 kpc.
$^f$ Degenaar et al. (2013).
$^g$ Murakami et al. (1983), unknown distance.
$^h$ Cornelisse et al. (2002b), 7.7–10.0 kpc.
$i$ Serino et al. (2015), <7 kpc.

Table 3
GBM Accretion-powered Events

| ID               | Peak (s) | R.A. (deg) | decl. (deg) | Error (deg) | Association |
|------------------|----------|------------|-------------|-------------|-------------|
| 10033115145      | 01656753 | 237.6      | –19.0       | 6.6         | Sco X-1     |
| 10033122117      | 01663724 | 253.6      | –10.7       | 6.4         | Sco X-1     |
| 10041602529      | 03026531 | 239.0      | –19.0       | 1.1         | Sco X-1     |
| 10041602579      | 03026532 | 240.2      | –12.1       | 1.6         | Sco X-1     |
| 10041602801      | 03026803 | 250.2      | –21.8       | 2.1         | Sco X-1     |

The aFXPs were a byproduct of our XRB search since we have dedicated programs to study them (The GBM Pulsar Project12 and The Earth Occultation Project13). Nevertheless; the aFXPs in the catalog provide a unique opportunity to observe these sources in rare, bright states that would normally require a targeted observation.

The brightest (other than the Sun) recurring source that GBM observes from 8 to 50 keV is Sco X-1, and we intentionally attempted to avoid this source since our focus was on tXRBs; nevertheless, Sco X-1 dominates the aFXP category due to its numerous flares. Its persistent nature makes background subtraction difficult and this occasionally leads to poor localization. Luckily, its soft spectrum (index $\sim$–3.5) makes this source relatively easy to identify. The other aFXPs are neutron stars powered by magnetically dominated accretion with a harder spectrum (index $\sim$–2). Again, none of the

12 http://gamma-ray.msfc.nasa.gov/gbm/science/pulsars.html
13 http://heastro.phys.lsu.edu/gbm
| ID          | Peak (s) | R.A.  | decl. | Error (deg) | Epeak (keV) | Comp Flux (10^{-8} erg cm^{-2} s^{-1}) | PL Index | PL Flux (10^{-7} erg cm^{-2} s^{-1}) | Comp Flnc (10^{-17} erg cm^{-2} s) | Rise (s) | Fall (s) | Duration (s) | Structure |
|----------------|---------|-------|-------|-------------|-------------|----------------------------------------|----------|--------------------------------------|------------------------------------|----------|----------|-------------|-----------|
| 100312066566   | 00006572| 94.6  | 71.7  | 6.7         | …           | 7.17 ± 0.90                            |          | 20.5 ± 2.5                          | -1.675 ± 0.064                    | 7.82 ± 0.85 | 22.3 ± 2.4 | 9.38 ± 1.0 | 10.67 ± 2.3 | S         |
| 100403645457   | 01965350| 67.2  | -13.4 | 9.8         | 63.8 ± 10.0 | 5.09 ± 0.56                            |          | 14.5 ± 1.6                          | -1.577 ± 0.099                    | 13.3 ± 2.6 | 38.2 ± 7.5 | 3.48 ± 1.6  | 21.87 ± 2.7 | S         |
| 100415282537   | 02965835| 261.6 | 47.8  | 2.1         | 24.2 ± 2.0  | 2.28 ± 0.23                            |          | 17.7 ± 1.8                          | -2.17 ± 0.15                      | 4.28 ± 0.96 | 33.2 ± 7.4 | 28.38 ± 9.49 | 125.40 ± 9.3 | S         |
| 10041565751    | 03003352| 272.7 | -19.1 | 4.9         | 92.0 ± 12.0 | 7.99 ± 0.72                            |          | 22.8 ± 2.0                          | -1.595 ± 0.057                    | 15.3 ± 1.4  | 43.8 ± 4.2 | 7.65 ± 0.9  | 19.38 ± 0.7 | S         |
| 10062847601    | 09378789| 358.8 | 69.1  | 1.0         | 125.6 ± 7.0 | 15.91 ± 0.62                           |          | 136.3 ± 5.3                         | -1.492 ± 0.020                    | 28.55 ± 0.96 | 244.6 ± 8.4 | 24.75 ± 6.9 | 101.82 ± 6.9 | S         |
| 10071023190    | 10391193| 299.8 | -45.0 | 12.5        | 69.9 ± 8.5  | 5.14 ± 0.47                            |          | 10.50 ± 0.97                        | -1.725 ± 0.070                    | 9.4 ± 1.0   | 19.3 ± 2.1 | 9.29 ± 3.3  | 15.33 ± 3.3 | M         |
| 10071069939    | 10437939| 89.9  | -84.0 | 5.4         | 62.6 ± 11.0 | 3.94 ± 0.44                            |          | 9.6 ± 1.0                           | -1.799 ± 0.075                    | 6.94 ± 0.89 | 16.9 ± 2.1 | 5.52 ± 8.7  | 14.66 ± 8.7 | M         |
| 10071369978    | 10697195| 290.2 | 68.3  | 15.9        | 46.5 ± 15.0 | 3.46 ± 0.63                            |          | 7.0 ± 1.3                           | -1.99 ± 0.12                      | 5.18 ± 0.99 | 10.5 ± 2.0 | 14.30 ± 7.9 | 23.36 ± 7.9 | M         |
| 10072541217    | 11705212| 313.8 | 76.8  | 1.2         | 112.7 ± 18.0| 13.3 ± 1.0                            |          | 65.4 ± 3.3                          | -1.664 ± 0.033                    | 21.6 ± 1.2  | 105.9 ± 6.1 | 17.89 ± 2.3 | 42.92 ± 2.3 | M         |
| 10081624089    | 13588900| 164.0 | 37.1  | 3.7         | 50.0 ± 4.9  | 6.12 ± 0.37                            |          | 22.5 ± 1.3                          | -1.910 ± 0.042                    | 10.11 ± 0.71 | 37.1 ± 2.6 | 25.64 ± 2.7 | 50.41 ± 2.7 | M         |

(This table is available in its entirety in machine-readable form.)
aFXPs was intentionally targeted by our efforts but bright pulsations from these sources occasionally mimic XRBs in the 12–25 keV band, and only careful follow-up review of these events reveals the train of pulses that help to identify these sources.

The uGRBs are either GBM sub-threshold trigger events or events that occur when triggering is disabled (a rare occurrence). The sub-threshold events are an interesting population of GRBs that might include intrinsically weak, distant, or off-axis GRBs whose detection has consequences for population synthesis studies and future gravitational wave experiments optimized to detect rotating collapsars (Ott et al. 2011) and will be explored in future work. Figure 11 shows the spectral index distribution (in red) of the GBM-triggered GRBs during the XRB catalog period whose duration (T_{90}) is greater than 4 s. Overlaid (in blue) on the triggered distribution is the spectral index distribution of uGRBs. It is reasonable from the figure to claim that most of the uGRBs are a sub-threshold continuation of the triggered GRB population.

4.1. GBM’s View on Thermonuclear Bursts

With an instantaneous FOV covering 75% of the sky, GBM offers unprecedented coverage of most Galactic bursters. Due to its sensitivity at energies above ~8 keV, GBM detects only the hottest phases of the hottest type I X-ray bursts: the touchdown phase of PRE bursts (as shown quantitatively in the simulations presented in Linares et al. 2012). Thus our GBM X-ray burst monitor is a “PRE burst monitor” with an excellent observing duty cycle (50%, interrupted only by Earth occultations and SAA passages).

Figure 12 shows a histogram of energy flux (10–100 keV) for the tXRBs from the blackbody spectral fits. The flux distribution was fit (χ² = 101/81 dof) with a Gaussian with the centroid at 3.1 × 10^{-8} erg cm^{-2} s^{-1} and a standard deviation of 1.2 × 10^{-8} erg cm^{-2} s^{-1}. The faintest tXRB in the catalog has a flux of (3.4 ± 1.0) × 10^{-9} erg cm^{-2} s^{-1}, which gives an estimate of the absolute flux limit in our catalog. Due to the strongly variable X-ray background at 8–50 keV, however, the minimum detectable flux can vary strongly.

PRE bursts reach the Eddington limit, which for a 1.4 M_{⊙} neutron star is in the range [1.6–3.8] × 10^{38} erg s^{-1} (depending of the radius and composition of the photosphere; see, e.g., Lewin et al. 1993; Kuulkers et al. 2003). In order to test whether the flux distribution is consistent with thermonuclear bursts from the Galactic bulge, we adopt a fiducial Eddington luminosity of L_{Edd} = 2.5 × 10^{38} erg s^{-1}, and show in Figure 12 the 10–100 keV fluxes corresponding to L_{Edd} at distances of 8 and 10 kpc (horizontal lines labelled L_{Edd,8} and L_{Edd,10}). At least three factors contribute to the observed flux scatter: (i) bursters have a range of distances, (ii) different systems can have different L_{Edd} (due to differences in mass, radius, or photospheric composition of the neutron star), and (iii) even in a given burster the peak luminosity of PRE bursts shows significant scatter (Galloway et al. 2008).

We thus conclude, from the flux distribution shown in Figure 12, that our tXRB sample is consistent with a population of Eddington-limited PRE bursts coming from a mix of bursters around the Galactic bulge region. Moreover, because only a handful of tXRBs have fluxes lower than that corresponding to an Eddington-limited burst at 10 kpc (yet several known bursters are more distant than that), we estimate that our catalog is limited to PRE bursts occurring within ~10 kpc. The fluence distribution, on the other hand, shows that for an assumed distance of 8 kpc, most bursts have energies between 10^{39} and 10^{40} erg (see horizontal lines labelled E39 and E40 in Figure 12), although the range of fluences is wide, covering about two orders of magnitude. The duration of the tXRBs in the GBM band also spans a wide range, between ~5 and ~500 s. The observed distributions of fluence and duration are not bimodal, either in the full tXRB sample or in the two low-m bursters presented in Sections 4.1.1 and 4.1.2. This indicates that the longest and most energetic thermonuclear bursts, sometimes referred to as “intermediate/long bursts,” are an extreme case of normal burst ignition.

We use hereafter a bolometric correction factor of f_{bol} = 1.9 to convert from 10–100 keV to bolometric burst flux and fluence, which we derive using a typical $kT_{sh} = 3$ keV spectrum. Moreover, due to the high background rate and lack of sensitivity below 8 keV, GBM only detects the peak of tXRBs, where the temperature is highest. To take this into account (i.e., to include an estimate of the energy radiated during the burst tail), we use a “band correction factor” of $f_{band} = 1.3$ to convert from GBM fluences (8–50 keV) to a more standard (2–50 keV) energy band. This band correction...
was calculated by Linares et al. (2012) using simulated GBM light curves of bursts observed with the RXTE-PCA.

4.1.1. 4U 0614+09

The burster and UCXB candidate 4U 0614+09 has been studied extensively by most X-ray missions, and is known to accrete persistently at a rate close to 1% of the Eddington limit. Due to its location far from other bursters and its proximity (Kuulkers et al. 2010 measured a distance of $d = 3.2 \, \text{kpc}$, which we adopt in this work), it is an ideal source in which to study thermonuclear bursts at low accretion rates. During the first year of the Fermi–GBM X-ray burst monitor we detected 15 bursts from 4U 0614+09 (Linares et al. 2012).

Our three-year catalog includes 33 tXRBs from 4U 0614+09 detected by GBM between 2010 March and 2013 March. This is the same number of bursts detected from 4U 0614+09 with nine different instruments over the course of 15 years (1992–2007, Kuulkers et al. 2010), which shows the drastic improvement in detection efficiency gained by GBM. Given GBM’s 50% observing duty cycle, we measure a burst recurrence time of $t_{\text{rec}} = 17 \pm 2 \, \text{day}$ (1σ Poissonian uncertainty), 5 day longer than, but consistent with, the results of Linares et al. (2012). The closest burst pair we find is only 1.4 day apart, on 2012 June 18/20, the shortest wait time between thermonuclear bursts measured from this source to date. The bolometric and band-corrected burst energies from 4U 0614+09 span more than an order of magnitude, between $[0.4 – 6.1] \times 10^{39} \, \text{erg}$, and show no evidence of bimodality, as shown in Table 2 and Figure 13.

4.1.2. 2S 0918-549

Before our GBM campaign, seven thermonuclear bursts had been reported from the UCXB candidate 2S 0918-549, between 1996 and 2004 (in’t Zand 2005; we use the same distance of $d = 5 \, \text{kpc}$ throughout this work). This burster is analogous to 4U 0614+09 in many ways: both are candidate UCXBs persistently accreting at a very low rate, and without detected hydrogen or helium lines in the optical spectrum (Nelemans et al. 2004). The inferred mass accretion rate in 2S 0918-549 is about a factor of two lower, $\sim 0.5\%$ of the Eddington limit (see Figure 13). In three years, we detect 10 tXRBs from 2S 0918-549, yielding a recurrence time of $t_{\text{rec}} = 56 \pm 12 \, \text{day}$. The closest pair of bursts was detected in 2011 August, only $\sim 16 \, \text{day}$ apart.

Two of the bursts, shown in Figure 14, are consistent with the so-called “long bursts” (in’t Zand 2005; Cumming et al. 2006; Chenevez et al. 2008). These were detected on 2010 April 30 and 2011 April 4, with durations in the GBM band of $66 \, \text{s}$ and $76 \, \text{s}$, respectively. They have energies above $10^{40} \, \text{erg}$ and their duration in the full 2–50 keV band is likely more than ten times longer than that in the GBM band, i.e., several tens of minutes (the band-corrected duration is more...
uncertain than the total energy; see Linares et al. 2012 for an estimate). Both the burst durations and energies show a continuous distribution in the ranges [10–76] s and [0.1–1.7] × 10^{40} erg, respectively (energies are bolometric and band-corrected, see Section 3.1).

4.1.3. Other Bursters and the Integrated Galactic tXRB Sample

The remaining associations, 11 tXRBs detected from the direction of six other bursters, are presented in Table 2. Some of these events are faint and have large location errors (Table 5), which together with the low number of tXRBs per burster makes the association uncertain. These include: (i) four events from the direction of SAX J1818.7+1424 (detected on 2010 July 1, 2010 July 11, 2010 October 2, and 2011 January 28); (ii) two events from the direction of the burster UW CrB at high Galactic latitude (on 2011 November 3 and 2011 December 31) and two from the direction of IGR J17062-6143 (on 2010 July 19 and 2011 April 29); (iii) one event associated with XB 1940-04 (2010 October 20), one with Ser X-1 (2010 May 31), and one tXRB from the direction of MAXI J1421-613 (on 2011 October 16; note that this source was discovered in outburst in 2014 January).

It is also worth discussing which bursters are missing from the association list. Most notoriously, we do not detect any tXRB from 4U 1246-58 in our three-year catalog. In a study of this burster and UCXB candidate accreting persistently below 1% of the Eddington rate, in’t Zand et al. (2008) found seven PRE bursts, all but two with long durations, and a distance of 4.3 kpc. The corresponding burst recurrence time between 1996 and 2008 was 12 ± 6 days (in’t Zand et al. 2007). In contrast, our non-detection of GBM bursts from 4U 1246-58 between 2010 and 2013 implies a 95% lower limit on the recurrence time \( t_{\text{rec}} > 186 \) day, significantly longer than that measured by in’t Zand et al. (2007). Thus our results suggest that a drastic change in the burst properties of this burster took place between 2008 and 2010, which might be linked to the long-term decay of its persistent emission already noted in in’t Zand et al. (2008).

Two other UCXB bursters are probably too distant to be detected with the GBM X-ray burst monitor: 4U 0513-40 (8.2–11 kpc according to Galloway et al. 2008) and 4U 2129+12 (X-2 in M15, 10.4 kpc away according to Harris 1996). 4U 1915-05 is also close to our detection limit (6.8–8.9 kpc according to Galloway et al. 2008) and is a high-inclination “dipper” UCXB, which may explain why no bursts are detected by GBM in the present catalog. The remaining UCXBs and bursters with low mass accretion rates are too close to the extended Galactic bulge region to be resolved by GBM, but are included in the total Galactic rate measured and discussed below.

In addition to Figure 12, Figure 12 shows the distributions of blackbody temperature, fluence, and duration in the full sample of tXRBs. The vast majority of tXRBs come from the Galactic “extended bulge” region (489 located within 30° of Sag-A). Fluence and duration are clearly correlated, showing that the most energetic thermonuclear bursts are also the longest, as expected given the physical (Eddington) limit on the burst luminosity.

The total of 752 tXRBs detected in our three-year catalog, correcting for the 50% observing duty cycle, implies a total rate of 1.37 ± 0.04 thermonuclear bursts per day (1σ Poissonian uncertainty). This represents the average over three years of all bursters within the reach of the GBM X-ray burst monitor,
| ID           | Peak (s) | R.A. (deg) | decl. (deg) | Error (sigma) | Name (distance) | BB Temp (keV) | BB Flux (10^-8 erg cm^-2 s^-1) | BB Flnc (10^-7 erg cm^-2) | PL Index | PL Flux (10^-6 erg cm^-2 s^-1) | PL Flnc (10^-7 erg cm^-2) | Rise (s) | Fall (s) | Duration (s) | Structure |
|--------------|----------|------------|-------------|---------------|-----------------|---------------|-------------------------------|--------------------------|-----------|-----------------------------|------------------------|----------|----------|-------------|----------|
| 10032800979  | 1038378  | 98.4       | 4.6         | 3.4           | 4U_0614+09      | 3.09 ± 0.10   | 3.21 ± 0.12                  | 7.88 ± 0.31              | -3.198 ± 0.097 | 6.46 ± 0.35                  | 7.91 ± 0.43          | 2.73     | 11.98    | 16.71 S     | S        |
| 10032840831  | 1042340  | 18.2       | -26.4       | 9.1           |                 | 1.378 ± 0.065 | 0.710 ± 0.057                 | 6.96 ± 0.56              | -5.73 ± 0.26         | 0.782 ± 0.070                  | 7.66 ± 0.68          | 16.16    | 65.29    | 87.79 S     | S        |
| 10032872401  | 1045401  | 244.9      | -46.3       | 6.5           |                 | 3.36 ± 0.31   | 1.95 ± 0.22                  | 1.59 ± 0.17              | -2.76 ± 0.24         | 3.00 ± 0.61                   | 2.45 ± 0.50          | 1.10     | 5.87     | 7.25 S       | S        |
| 10033065596  | 1062075  | 246.1      | -22.8       | 2.9           |                 | 3.17 ± 0.12   | 3.47 ± 0.16                  | 32.6 ± 1.5               | -3.08 ± 0.12         | 4.22 ± 0.33                    | 39.6 ± 3.1           | 27.22    | 90.86    | 123.39 S    | S        |
| 10033165178  | 1070678  | 236.0      | -52.8       | 3.1           |                 | 3.43 ± 0.15   | 3.39 ± 0.18                  | 4.15 ± 0.22              | -2.90 ± 0.13         | 4.51 ± 0.43                    | 5.52 ± 0.53          | 1.52     | 7.46     | 11.39 S     | S        |
| 10040229862  | 10844268 | 236.3      | -54.0       | 5.0           |                 | 3.09 ± 0.18   | 2.15 ± 0.15                  | 3.52 ± 0.25              | -3.12 ± 0.18         | 2.78 ± 0.32                    | 4.54 ± 0.53          | 3.15     | 5.87     | 9.82 S       | S        |
| 10041030044  | 1053564  | 270.3      | -23.9       | 13.4          |                 | 4.39 ± 0.59   | 1.75 ± 0.27                  | 2.14 ± 0.33              | -2.40 ± 0.27         | 3.04 ± 0.94                    | 3.7 ± 1.1            | 2.52     | 7.26     | 10.29 S     | S        |
| 10041112629  | 10604627 | 274.2      | -17.0       | 16.5          |                 | 3.24 ± 0.14   | 3.48 ± 0.19                  | 5.98 ± 0.31              | -3.10 ± 0.14         | 4.35 ± 0.40                    | 7.11 ± 0.65          | 11.02    | 4.49     | 16.03 M     | M        |
| 10041333419  | 10798228 | 285.4      | -21.8       | 8.4           |                 | 3.15 ± 0.10   | 3.30 ± 0.13                  | 6.74 ± 0.27              | -3.09 ± 0.10         | 4.14 ± 0.28                    | 8.46 ± 0.58          | 2.34     | 14.02    | 16.86 M     | M        |
| 10041672571  | 103096580| 267.9      | -28.2       | 3.1           |                 | 2.79 ± 0.12   | 2.94 ± 0.15                  | 4.80 ± 0.25              | -3.34 ± 0.14         | 3.47 ± 0.28                    | 5.67 ± 0.47          | 13.21    | 6.34     | 21.69 M     | M        |

(This table is available in its entirety in machine-readable form.)
which we estimate below corresponds to distances $\lesssim$10 kpc (Section 4). Due to GBM’s broad sky coverage, this constitutes an unprecedented measurement of the total Galactic thermonuclear burst rate, which we discuss in Section 4.

On average, the GBM bursts in 2S 0918-549 ($t_{\text{rec}} = 56 \pm 12$ day; $\langle E \rangle = 6 \times 10^{49}$ erg) are more energetic and less frequent than those from 4U 0614+09 ($t_{\text{rec}} = 17 \pm 2$ day; $\langle E \rangle = 2 \times 10^{59}$ erg). This is qualitatively explained by ignition models, given that 2S 0918-549 accretes at a rate about half that of 4U 0614+09 (Cumming et al. 2006). Lower $\dot{m}$ implies a colder neutron star envelope, a longer fuel accumulation time, and a greater ignition depth. However, ignition models still have problems in reproducing these recurrence times and burst energies quantitatively (Kuulkers et al. 2010; Linares et al. 2012). Assuming solar metallicity, the pure helium ignition models from Cumming & Bildsten (2000) require large amounts of deep crustal heating to reproduce the recurrence times that we measure in 2S 0918-549 and 4U 0614+09: more than 3 MeV per accreted nucleon (see Figure 7 and further discussion in Linares et al. 2012). Having two low-$\dot{m}$ bursts with robust GBM measurements of recurrence times, we can place the first meaningful constraints on the $t_{\text{rec}}$–$\dot{m}$ relation at $\dot{m}/\dot{m}_{\text{Edd}} \sim 1\%$. The measured $t_{\text{rec}}$ and $\dot{m}$ in 2S 0918-549 and 4U 0614+09 are not consistent with a linear relation, and suggest a steeper relation $t_{\text{rec}} \propto \dot{m}^{1.7 \pm 0.8}$.

We find a total Galactic rate of 1.4 PRE bursts per day, out to about 10 kpc from the Sun and averaged over the three years of our catalog (Section 4.1.3). During PRE bursts the atmosphere of the neutron star can be pushed by radiation forces up to hundreds or thousands of kilometers above the surface, and small but significant amounts of nuclear burning ashes may be ejected (Weinberg et al. 2006). To conclude, we roughly estimate the total mass ejected by the PRE bursts uncovered by GBM, by adding their bolometric- and band-corrected fluences and assuming they are all at 8 kpc (see Section 3.1 and discussion above). This yields a total radiated energy of $8 \times 10^{42}$ erg, or $1.6 \times 10^{43}$ erg after correcting for the 50% observing duty cycle. For a nuclear energy release of 1.6–4.4 MeV per nucleon, this translates into $[4–11] \times 10^{24}$ g of burned fuel. For a fraction of ejected mass of $10^{-4}–10^{-2}$ (Weinberg et al. 2006), this implies a total of $[4 \times 10^{20}–10^{23}]$ g ejected during three years. With the above assumptions, we are able to place direct observational constraints on the amount of mass ejected into the interstellar medium by PRE bursts in our Galaxy (within 10 kpc of the Sun): $10^{-13}$–$10^{-11} M_\odot \text{ yr}^{-1}$.
Whether or not this contributes significantly to the Galactic abundances of any elements (proton-rich isotopes have received particular attention in the context of thermonuclear bursts; see Weinberg et al. 2006 and references therein) remains a subject for future studies.

M.L. was supported by the Spanish Ministry of Economy and Competitiveness under the grant AYA2013-42627. This work was also supported by NASA Fermi-GI grant nr. NNX11AO19G (PI: Linares). This research has made use of the MAXI data provided by RIKEN, JAXA, and the MAXI team.

APPENDIX A
LIGHT CURVES OF aFXPs

Figure 15 contains a sample of the light curves for one aFXPs. The four brightest detectors are shown for the 12–25 keV band. The source angle to the detector bore sight is given by $\alpha$. A complete set of light curves for all aFXPs is available in the online version.

APPENDIX B
LIGHT CURVES OF uGRBs

Figure 16 contains a sample of the light curves for one uGRBs. The four brightest detectors are shown for the 12–25 keV band. The source angle to the detector bore sight is given by $\alpha$. A complete set of light curves for all uGRBs is available in the online version.

APPENDIX C
LIGHT CURVES OF tXRBs

Figure 17 contains a sample of the light curves for one tXRBs. The four brightest detectors are shown for the 12–25 keV band. The source angle to the detector bore sight is given by $\alpha$. A complete set of light curves for all tXRBs is available in the online version.

REFERENCES

Agostinelli, S., Allison, J., Amako, K., et al. 2003, NIMPA, 506, 250
Band, D., Matteson, J., Ford, L., et al. 1993, ApJ, 413, 281
Belian, R. D., Conner, J. P., & Evans, W. D. 1976, ApJL, 206, L135
Bildsten, L. 1998, in NATO ASIC Proc. 515, The Many Faces of Neutron Stars, ed. R. Buccheri, J. van Paradijs, & A. Alpar (Dordrecht: Kluwer), 419
Boutloukos, S., Miller, M. C., & Lamb, F. K. 2010, ApJL, 720, L15
Camero-Arranz, A., Finger, M. H., Wilson-Hodge, C., et al. 2011, ATel, 3166
Chenevez, J., Falanga, M., Kuulkers, E., et al. 2008, in Proc. 7th INTEGRAL Workshop, 33, online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=67
Connnaughton, V., Briggs, M. S., Goldstein, A., et al. 2015, ApJS, 216, 32
Cornelisse, R., Verbunt, F., in’t Zand, J. J. M., et al. 2002a, A&A, 392, 885
Cornelisse, R., Verbunt, F., in’t Zand, J. J. M., Kuulkers, E., & Heise, J. 2002b, A&A, 392, 931
Cumming, A., & Bildsten, L. 2000, ApJ, 544, 453
Cumming, A., Macbeth, J., in’t Zand, J. J. M., & Page, D. 2006, ApJ, 646, 429
Degenaar, N., Miller, J. M., Wijnands, R., Altamirano, D., & Fabian, A. C. 2008, ApJ, 719, 360
Fujimoto, M. Y., Hanawa, T., & Miyaji, S. 1981, ApJ, 247, 267
Galloway, D. K., Muno, M. P., Hartman, J. M., Psaltis, D., & Chakrabarty, D. 2008, ApJS, 179, 360
Grindlay, J., Gursky, H., Schnopper, H., et al. 1977, ApJL, 212, L17
Hakala, P., Ramsay, G., Muhli, P., et al. 2005, MNRAS, 365, 1133
Harris, W. E. 1996, AJ, 112, 1487
in’t Zand, J. J. M. 2005, A&A, 441, L1
in’t Zand, J. J. M., Bassa, C. G., Jonker, P. G., & Markwardt, C. B. 2007, A&A, 465, 953
Kuulkers, E., den Hartog, P. R., in’t Zand, J. J. M., et al. 2003, A&A, 399, 663
Kuulkers, E., in’t Zand, J. J. M., Atteia, J.-L., et al. 2010, A&A, 514, A65
Lewin, W. H. G., van Paradijs, J., & Taam, R. E. 1993, SSRv, 62, 223
Linares, M., Connaughton, V., Jenke, P., et al. 2012, ApJ, 760, 133
Matsuoka, M., Kawasaki, K., Ueno, S., et al. 2003, A&A, 61, 999
Meegan, C., Lichti, G., Bhat, P. N., et al. 2009, ApJ, 702, 791
Murakami, T., Inoue, H., Koyama, K., et al. 1983, PASJ, 35, 531
Nellemans, G., Jonker, P. G., Marsh, T. R., & van der Klis, M. 2004, MNRAS, 348, L7
Ott, C. D., Reisswig, C., Schnetter, E., et al. 2011, PhRvL, 106, 161103
Serino, M., Shibata, M., Ueda, Y., et al. 2015, ApJ, 797, 30
Swank, J. H., Becker, R. H., Boldt, E. A., et al. 1977, ApJL, 212, L73
Weinberg, N. B., Bildsten, L., & Schatz, H. 2006, ApJ, 639, 1018