A possible polar origin for the FRB associated with a Galactic magnetar

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Fast Radio Bursts (FRBs) are millisecond-long radio pulses of extragalactic origin with peak luminosities far exceeding any Milky Way sources\(^1,2\). The prevalent invocation for the FRB origin\(^3\) involves magnetars: young, magnetically powered neutron stars with the strongest magnetic fields in the Universe\(^4,5\). A magnetar-defining signature is the emission of bright, hard X-ray bursts of sub-second duration. These occur in isolation or during a burst storm, when several hundred are observed within minutes to hours\(^6\). On April 27\(^{th}\) 2020, the Galactic magnetar SGR J1935+2154 entered an active period, emitting hundreds of X-ray bursts in a few hours\(^7,8\). Remarkably, only one of these\(^9-12\) temporally coincided with an FRB-like radio burst\(^13,14\). Here we report on the spectral and temporal analyses of 24 X-ray bursts emitted 13 hours prior to the FRB and seen simultaneously with NASA’s NICER and Fermi/GBM missions in their combined energy range. We demonstrate that the FRB-associated X-ray burst is very similar temporally, albeit strikingly different spectrally, from the 24 NICER/GBM bursts. If the FRB-associated burst were drawn from this magnetar burst population, its occurrence rate would be at most around 1 in 7000. This rarity combined with the unusual X-ray burst spectrum is perhaps indicative of an uncommon locale for the origin of the FRB-associated burst. We suggest that this unique event originated in quasi-polar open or closed magnetic field lines extending to high altitudes where radio emission can be generated, possibly from a collimated plasma flow.

SGR J1935+2154 was discovered in 2014, when it emitted a few short, hard X-ray, magnetar-like bursts. Follow-up X-ray observations revealed the source spin period (\(P=3.24\) s) and period derivative (\(dP/dt=1.43\times10^{-11}\) s/s), implying a large surface dipole magnetic field, \(B=2.2\times10^{14}\) G, and a spin down age, \(\tau=3.6\) kyr, thus confirming its magnetar nature\(^15\). The source became active again in May 2015, May and June 2016\(^16\), and December 2019. The source’s activity steadily increased with time, emitting larger numbers of bursts, brighter on average than the ones detected during the preceding activation\(^17\). On April 27\(^{th}\) 2020, SGR J1935+2154 entered yet another active period, the most prolific so far. It comprised a long-lasting burst storm, with at least a few hundred bursts observed within a few hours\(^3,4\).

We observed SGR J1935+2154 with the NICER X-ray Timing Instrument\(^18\) (0.2-12 keV) onboard the International Space Station on April 28, from 00:40:57 UTC until 00:59:36 UTC (\(-19\) minutes), covering just the tail end of the storm. This NICER observation revealed \(\sim 200\) bursts emitted by SGR J1935+2154, which was also visible by the Fermi Gamma-ray Burst Monitor (GBM). We identified a subset of 24 bursts simultaneously detected with NICER and GBM; due to the high background of the latter instrument, these are the brightest among the 200 detected with NICER. Thirteen hours after the NICER observation, concurrent with a magnetar burst\(^9-11\), a Fast Radio Burst (FRB) was also detected with the CHIME\(^13\) and STARE2\(^14\) radio telescopes; this FRB-contemporaneous X-ray burst was detected by the INTEGRAL\(^9\), KONUS-WIND\(^10\), and HXMT\(^11\) missions. NICER and GBM were not observing the source during the FRB time.

We used the NICER data for a temporal analysis of the 24 X-ray bursts, as it offers a very low background compared to GBM, and hence captures the full length of each burst. The T90 duration\(^19\) (interval during which 90% of the burst fluence is detected) of these bursts ranged from 230 ms to about 2 seconds, with a mean of 620 ms. The burst light curves display a variety of shapes, with some exhibiting a slow rise and decay bracketing a spiky top. Regarding its duration and temporal profile, the FRB-associated X-ray burst does not stand out, compared to the 24 bursts.
We next performed a broadband (1-300 keV) time-integrated spectral analysis of the bursts using the combined data of NICER and GBM, which allows similar energy coverage to HXMT (1-300 keV). This enabled a direct spectral comparison of the 24 bursts to the spectrum of the FRB-associated burst, as reported in the literature\(^\text{11}\). Further, the broadband combination of NICER+GBM and of HXMT captures an extended energy range for constraining the spectral curvature of the bursts.

We fit the broad-band spectra of all 24 bursts with, either a fully thermal model consisting of two blackbody (2BB) components, or a non-thermal model consisting of a power-law (PL) with a high-energy exponential cutoff (CPL), both modified by absorption from the interstellar medium along the line of sight to the source. We find that most of our bursts are adequately fit with both models, but also note that the 2BB model comprises one extra free parameter compared to CPL. Overall the CPL spectral model fits 23 of the 24 bursts consistently well, being superior to the 2BB model for 3 of these bursts (see methods). However, for the brightest burst, the statistically preferred fit was a non-purely thermal model (BB+CPL).

We present in Figure 1 the broadband spectrum of a burst with similar time-averaged flux to the FRB-associated burst; its spectrum is typical for 23 of the 24 bursts. For comparison we overlay in dashed lines a NICER+GBM simulated spectrum based on the HXMT FRB-associated burst. The two spectra differ markedly, with the latter exhibiting a much higher cutoff energy and a softer power law component. This difference is intrinsic to the bursts: our simulations confirm that we would have easily detected and recovered to the few percent level the spectral parameters of a burst similar to the FRB-associated one.

Figure 2 demonstrates this difference with the distribution of the photon indices of the CPL model (left panel). Assuming that the HXMT burst is drawn from our sample of 24 bursts, we measure a joint cumulative distribution function between the Kernel density function of our population of bursts and the probability density function (PDF) of the HXMT burst of about 1.42x10\(^{-4}\), or at most 1 in 7000. A similar analysis for the high-energy cutoff, \(E_{\text{cut}}\) (Figure 2, right panel) implies that the probability of a burst with \(E_{\text{cut}}= 84\) keV to be drawn from our \(E_{\text{cut}}\) population is negligible (1.0x10\(^{-16}\)).

Finally, for all bursts we find a strong correlation between their cutoff energy and flux (Figure 3), with brighter bursts exhibiting higher energy cutoffs\(^\text{10}\). The FRB-associated burst clearly stands out as an outlier in the sample.

The uniqueness of the FRB-associated burst compared to the rest of the SGR J1935+2154 bursts extends beyond this recent activation. The GBM bursts from previous activations had average cutoff energies (CPL fits) of 16 keV, with a standard deviation of 3 keV, and photon indices of 0.1, with a standard deviation of 0.5\(^\text{17}\); the index suffers from large systematic uncertainties when measured in the GBM 8-200 keV energy range only, as is the case for the previous activations. The earlier events are, therefore, consistent with our sample of 24 bursts within 1\(\sigma\) uncertainty, and further highlight the spectral dissimilitude of the FRB-associated burst.
How can this special FRB-associated burst exhibit such drastically distinct spectral properties? The answer may lie in its locale. The 0.2-2 sec durations of the 24 bursts constitute many regional transit timescales, implying that closed field lines are needed\textsuperscript{20,21} to trap the plasma. If these field lines possess a fairly restricted range of altitudes, the high opacity plasma\textsuperscript{21} powering the emission will likely possess only a modest range of effective temperatures\textsuperscript{22,23}. Smaller, hotter regions reside nearer the field line footpoints on the surface, and altitudinal temperature gradients broaden the spectrum somewhat\textsuperscript{23}. For a representative burst X-ray luminosity of $L_{\gamma}\sim 10^{40}$ erg/sec, the Stefan-Boltzmann law $L_{\gamma} = \sigma T^4 R^2$ yields a temperature of $T\sim 10^8$ K for $R\sim 10^6$ cm, commensurate with a value of $E_{\text{cut}}\sim 10-15$ keV, while at $R\sim 10^7$ cm altitudes, $T\sim 3\times 10^7$ K. Accordingly, an altitude range spanning a decade yields a spectral extent compatible with the NICER-Fermi/GBM observations. This geometry could be provided by quasi-equatorial dipolar magnetic flux tubes, quadrupolar field morphologies or even toroidal structures associated with field line twists\textsuperscript{24,25}, all of which would possess large emission solid angles $\Omega\sim 2\pi$.

The high $E_{\text{cut}}\sim 84$ keV and spectral breadth for the FRB-associated burst suggest a much larger range of altitudes $R$, perhaps a factor 100 or more. This signals a locale for the activated field lines (open or closed) near the magnetic pole. Magnetic trapping would then have less of an altitudinal “iso-thermalization” imprint and more of a collimating one with $\Omega<4\pi$. The super-Eddington luminosity\textsuperscript{20,21} would drive a mildly-relativistic flow upward from the stellar surface\textsuperscript{21}. As this wind cools adiabatically before becoming transparent to electron scattering, the X-ray spectrum would soften, with the time-integrated convolution generating similar $\sigma T^4 R^2 \Omega/4\pi$ effective luminosities over a broader range of photon energies. The Comptonized spectrum would be comparatively steep due to lower average scattering opacities, like that observed for the FRB burst; its shape would depend on lateral expansion, plasma density decline and the flow dynamics. The high $E_{\text{cut}}\sim 84$ keV suggests $T\sim 10^9$ K at the $R\sim 10^6$ cm base, implying $\Omega/4\pi\sim 10^{-4}-10^{-3}$, i.e., an opening angle of $\sim 1.3^\circ$. At higher altitudes, the plasma would be unencumbered by magnetic Thomson scattering opacity and free to engage in coherent radio emission mechanisms.

This quasi-polar/non-polar dichotomy for the FRB-associated and “orphan” X-ray bursts is consistent with the rarity of the FRB one. Uniform distribution of the activation locales on the surface for hundreds of SGR J1935+2154 bursts constitute an average angular separation of their flux tube footpoint centroids of around $4-5^\circ$. The polar colatitude of the last open field line for this magnetar is $\theta_{\text{c}}\sim (2\pi R_{\text{SS}}/P_c)^{1/2} \sim 0.46^\circ$. Accordingly, if the FRB-burst is generated proximate to the open field line zone, it is essentially unique\textsuperscript{26} in the archival burst assemblage. It is notable that the two peaks of the FRB are separated by 29 ms\textsuperscript{13,14}, corresponding to a stellar rotation through angle $3.3^\circ$. Such temporal morphology of the radio signal is unlikely to come from highly-curved field lines. Yet it is a natural outcome of a highly-collimated emission region within a slightly flared flux tube near the pole. The angular extent of this zone must exceed around $\Delta \theta_c\sim 3-4^\circ$ for the two radio peaks to be observed. Given the polar field line flaring relation $R/R_{\text{SS}}\sim (\Delta \theta_c/\theta_c)^2$, this implies an FRB emission locale at more than $\sim 50-100$ stellar radii $R_{\text{SS}}$, high enough to enable transparency to Thomson scattering. Detecting the FRB then requires the observer to approximately sample the magnetic pole, tilted relative to the spin axis, once during the rotation period. Thus emerges a paradigm of a high-altitude, quasi-polar locale for this FRB that is similar to the perceived site\textsuperscript{27,28} for persistent radio emission in normal pulsars.
Figure 1. Left panels: Light curves of one of the 24 bursts analyzed in this Article as seen with Fermi/GBM (upper-panel) and NICER (Lower-panel). No signal distinguishable from the background was observed above \( \sim 100 \) keV by GBM. The X-axis is time in seconds from a fiducial burst start time. Right-panels: NICER+GBM spectrum of this burst in photon flux space, \( F_E \) (upper-panel). The dots represent the data, binned for clarity, color-coded by instrument (NaI 6, NaI 7 are the two GBM detectors used for this burst). In all panels, the error bars are presented at the 1\( \sigma \) level. The solid curves define the best-fit CPL model. The dashed lines constitute the best fit CPL model to a simulated spectrum based on the spectral properties of the FRB-associated burst as seen with HXMT. Residuals of the best-fit model to our NICER+GBM spectrum are shown in the lower-panel in standard deviation units \( \sigma \).
Figure 2. Grey-solid lines represent the probability density function (PDF) of the CPL index (left panel) and high-energy cutoff $E_{\text{cut}}$ (right panel) for our sample of 24 bursts. In both panels, the black-solid lines are the PDF of a Gaussian kernel for the corresponding 24 PDFs. The blue dot-dashed lines are the PDFs of the index (left) and the high-energy cutoff (right) as measured in the FRB-associated burst. The probability of the FRB-associated burst to have an index drawn from our population of bursts is $1.4 \times 10^{-4}$, while the probability of $E_{\text{cut}}$ to be drawn from our sample is $1.0 \times 10^{-16}$, highlighting the unique properties of the FRB-associated burst compared to the rest of the burst population.
Figure 3. Cutoff energy, $E_{\text{cut}}$, versus flux in the 1-250 keV range for the 24 bursts in our sample (black-squares). A 20% systematic uncertainty was added to all flux values (see methods). The grey-shaded area is the 3σ best fit linear model to 10000 simulated sets of data points drawn from a bivariate Gaussian distribution with mean and standard deviation as measured in the actual data points. A positive correlation is clearly seen in our sample. The FRB-associated burst is shown as a blue-diamond. While possessing a typical flux, the $E_{\text{cut}}$ of the FRB-associated burst is >15σ away from this correlation. We do not detect any other statistically significant correlation between any other pairs of spectral parameters in our sample.
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Methods

NICER observations and data processing. NICER\textsuperscript{5,6} is a non-imaging instrument onboard the International Space Station, with a restricted field of view covering about 30 arcminutes\textsuperscript{2}. It consists of 56 coaligned X-ray concentrating optics, each with an associated Focal Plane Module (FPM) detector, 52 of which are currently operating. NICER is sensitive to photon energies in the range of 0.2-12 keV, and currently provides the largest collecting area in this energy band peaking at \( \sim 1900 \text{ cm}^2 \) at 1.5 keV. The FPMs are split into groups of 8, which are simultaneously controlled by a set of electronics called a Measurement Power Unit (MPU). Each MPU operates independently of the others. For data reduction and processing, we use NICER Data Analysis Software (NICERDAS) version 7, as part of HEASoft 6.27.2, and Xselect version 2.4.

NICER observed SGR J1935+2154 on April 28\textsuperscript{th} 2020 with several uninterrupted snapshots. The first covers the period from 00:40:57 UTC until 00:59:36 UTC, or approximately 19 minutes. Over 200 bursts were observed with NICER during this period. Our main focus in this Article is the analysis of the bursts that are simultaneously observed with GBM. Given the high background in GBM, the subset of 24 bursts employed in this analysis were the brightest bursts observed with NICER, and for some of these instrumental deadtime is non-negligible. Deadtime in NICER starts becoming significant for sources with count rates larger than 20000 counts s\textsuperscript{-1}, hence for integrations of tens of milliseconds, i.e., during the peak of the bursts, deadtime correction is required. We applied our deadtime correction by following the method described in Wilson-Hodge et al.\textsuperscript{7}; here we give a summary of the steps. We start our analysis with the unfiltered event files for each MPU separately, applying standard filtering criteria to create corresponding filtered event files. We account for two types of deadtime, (1) the time during which each FPM of each MPU is “dead” while processing an event and (2) data packets lost due to saturation in each MPU slice. The first type of deadtime is recorded as a column in the event files, and we used the unfiltered event files to track it during the burst times (given that all events, not only the good ones, contribute to this type of deadtime). The second type of deadtime is recorded in the Good Time Intervals (GTIs) of the filtered event files and packet number in the housekeeping files for each MPU. This loss of events is apparent in the tails of the two brightest bursts (bursts 3 and 8 in Table 1); however, it does not affect any of the other 22 bursts we analyze here.

For our spectral analysis, a deadtime-corrected exposure for each burst is derived after correcting for the fraction of exposure that is lost due to the two types of deadtime mentioned above. We find that deadtime is most significant for the two brightest bursts with the lost GTIs, and we estimated a deadtime fraction of about 30\% and 20\%, respectively. For the remaining 22 bursts, the deadtime fraction ranged from 10 to about 2 percent.

Given NICER’s comparatively small field of view, the background for the bursts’ spectra was assumed to be the underlying burst-free persistent emission, most probably originating on the stellar surface. This component varies throughout the observation, and hence, was measured in segments of 100 seconds, constituting around 31 stellar rotation periods. This background constituted less than 1\% of the fluxes for all 24 bursts. Finally, we use the NICER response files provided in the HEASoft calibration database, version 20200202.
Fermi-GBM observations and data reduction. The Gamma-ray Burst Monitor (GBM) onboard the Fermi Gamma-ray Space Telescope consists of 12 Sodium-Iodide (NaI) detectors sensitive to photons in the energy range 8-1000 keV and 2 Bismuth Germanate (BGO) detectors sensitive to photons in the 0.2-40 MeV range. The detectors are spread over a cubic configuration which covers the full Earth un-occulted sky. SGR J1935+2154 was in the field of view of GBM during the entire length of the first NICER snapshot. Few detectors had good viewing angles towards the source (<50 degrees) without any blockage from the spacecraft itself. We use these detectors for our spectral and temporal analyses. GBM automatically triggered on only one occasion during the NICER observation, hence, we relied on the continuous time-tagged events (CTTE), with a time resolution of 2 microseconds, to search for other bursts that were detected with NICER in the same time span. We extracted burst and background spectra using the GBM Data Tools version 1.0.3 and created response files for each burst using the GBM Response Generator version 2.0, which uses GBM calibration files version 10.

Burst search. We performed a burst search in both NICER and GBM in a similar manner. The search consisted of estimating the Poisson probability of a time-bin (with a certain resolution, $tbin$) to be a random fluctuation around an average mean within a certain time-interval ($dt$). Any $tbin$ with counts that show $>5$ sigma deviation from the mean is saved as a possible burst. The procedure is repeated after excluding all bins that were flagged as bursts, until no further bins are found to deviate sufficiently from the mean. We experimented with multiple time-intervals $dt$, namely between 20 and 200 seconds in steps of 20 seconds and found that they all gave consistent results. Our final results are for $dt=100$ seconds. We performed the search using multiple time resolutions (4 ms, 32 ms, 128 ms, and 512 ms) so that we do not miss any possible weak precursors or faint tails to the bursts. For NICER, we performed the search on all 52 FPMs combined. For GBM, we performed the search on each of the NaI detectors separately. In both NICER and GBM, two bursts were considered separate if the count rate between them remains at the background level for 0.5 seconds or longer. This corresponds to less than 15% of the magnetar spin rotation period. Using this method, we find over 200 bursts in NICER and 24 bursts in GBM. All GBM bursts were also found in NICER. This subset of 24 is the focus of this Article.

Temporal analysis. We measured the T90 duration for each burst, i.e., the interval of time during which 5% to 95% of the total burst fluence is accumulated. Given the very low count background of NICER compared to GBM, we relied on the former data to estimate T90s, since the latter would underestimate the T90. We performed this analysis in count space. We built light curves at 4-millisecond resolution and corrected the number of counts in each 4 millisecond bin for the loss of exposure due to deadtime. We then combined these light curves to form one high signal-to-noise light curve. We estimated the background in intervals of 0.5 to a few seconds just before and after the start and end times of the bursts, respectively. We created a background-corrected cumulative counts plot and assumed that the burst T100 (or 100 percent of the burst fluence) resides 3$\sigma$ above and below the background before the start and after the end of the burst, respectively. Then, we estimated the T90 from this background-corrected interval. The distribution of T90s for the 24 NICER+GBM bursts is shown in Figure 1 (supplement). The distribution is broad with a mean of about 620 ms. Hence, the T90 duration of the FRB-associated burst as measured with HXMT, which is about 530 ms, is well within the population of bursts as observed with NICER. Note that the instruments on board HXMT are low background instruments and hence more appropriately compared to NICER rather than GBM. We also note that the bursts’
temporal shapes as observed with NICER are considerably varied, with a few closely resembling the FRB-associated one\textsuperscript{11}: a slow rise and a slow decay, separated by a spiky structure.

**Spectral analysis.** We performed our spectral analysis using the X-ray Spectral Fitting Package Xspec version 12.11.0k\textsuperscript{12}. For each burst, we simultaneously fit the NICER spectrum and the spectra from all GBM detectors that satisfied the criteria as described above. For each burst, we fit for the time interval T90 as measured with Fermi to maximize the signal to noise ratio at high energies. This corresponds to an average of \(\sim 70\%\) of the full length of the NICER bursts. We verified that performing our spectral analysis using the NICER T90 does not alter any of our conclusions. For all spectral models described below, we add an absorption component due to the interstellar medium between Earth and SGR J1935+2154. For this purpose, we used the \textit{tbabs} model in Xspec. We assumed the abundances of Wilms et al.\textsuperscript{13} and the photo-electric cross-sections of Verner et al\textsuperscript{14}. Moreover, we add a multiplicative constant to all the models to take into account any calibration uncertainties between all the instruments. We find this constant normalization to be at most 10\% between the GBM detectors. As for the difference between NICER and GBM, we find this calibration uncertainty to be between 10 and 50 \%, with the highest deviations (also with the largest uncertainties) corresponding to the weakest bursts. The average of this calibration uncertainty among our population of 24 bursts is \(21\pm 15\%\).

We use the \textit{pgstat} statistics in Xspec to estimate the best-fit model parameters and their associated uncertainties. This statistic is usually used for Poisson distributed data with Gaussian distributed background: the case of our spectra. To test the goodness-of-fit for each model, we relied on the Anderson-Darling\textsuperscript{15} (AD) test statistic, which compares the empirical distribution functions of the data and model (details on these statistics can be found in [https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSappendixStatistics.html](https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSappendixStatistics.html)). We utilize the goodness command in Xspec to simulate 1000 spectra based on a given model and compare their AD test statistic to that of the data. If the data are drawn from this model, then around 50\% or less of the simulated spectra should have test statistic less than that of the data.

We first attempted to fit the spectra with a simple model consisting of either a blackbody (BB) or a power-law (PL). Individually, these two simple models failed to give a statistically good fit to any of our 24 bursts. We then attempted to fit the data with the two principal models that are usually invoked to explain the spectral curvature of magnetar short bursts. These are the two blackbodies (2BB) and a cutoff PL (CPL), the latter possessing one less free parameter. According to the simulations as described above, the CPL model gave consistently good fits to 23 bursts, barring the brightest one in our sample. On the other hand, the 2BB model resulted in either similar goodness-of-fit results compared to the CPL model or slightly worse (e.g., bursts 1, 8, and 14). The brightest burst (flagged in Table 1 supplementary material with an asterisk) cannot be adequately explained with either of the above two models, although the CPL results in better statistics compared to the 2BB one. For that burst, we find that the combination of a BB+CPL model is required to give a good fit. We conclude that, given the smaller number of parameters for the CPL model compared to the 2BB and its moderately better performance across flux levels, the CPL model is adequate to describe 23 of the 24 bursts that we analyze in this Article. An extra BB component with temperature \(T=8.6\pm 0.3\) keV is required for the brightest one. The spectral parameters for all these bursts are summarized in Table 1. The fluxes are given in the 1-250 keV band for direct comparison with the flux of the FRB-associated burst\textsuperscript{11}. Therein, we only quote the
results of the CPL parameters, although we give the results of our simulations to gauge the goodness of fits from both the CPL and the 2BB model for ease of comparison (last two columns).

We recognize that selection biases may affect these conclusions to a certain extent: our choice to examine here only GBM-detected bursts as a comparison set preferentially skews the distribution of power-law indices to lower, more negative values (harder spectra), heightening the distinction from the FRB-associated burst. On the other hand, it also tends to prefer higher cutoff-energy values, partially muting that distinction. In examining the spectra of bursts detected only with NICER, we find that they are generally fainter and, consistent with the correlation demonstrated in Figure 3, possess lower cutoff energies. However, the smaller number of counts and the relatively narrow energy band result in poorly constrained fit parameters.

Table 1. Burst durations and spectral parameters. Time is from 2020 April 28, 00h. The burst with an asterisk is the one burst where a BB+CPL model is required to provide a statistically good fit to the data. A 2BB model cannot provide a good fit as is evident from the last column. The burst highlighted in bold-face is the one presented in Figure 1 of the main text. Numbers in parentheses represent the 1σ uncertainty on the corresponding last digit.

| Burst # | TIME UTC (ms) | T90 | N_H | _ | E_cut | F_1–250keV | Constant pgstat/dof | Goodness | Goodness (2BB) |
|---------|-------------|-----|-----|-----|-------|-----------|---------------------|----------|----------------|
| 1       | 41:32:143   | 408(4) | 3.1(1) | -0.45(3) | 14(1) | 38.0(8) | 1.2(1) | 906/938 | 38.4 90.2 |
| 2       | 43:25:184   | 776(7) | 3.9(2) | -0.34(6) | 9.7(4) | 16.5(4) | 1.1(1) | 316/303 | 58.6 56.3 |
| 3*      | 44:08:212   | 445(5) | 2.8(1) | -0.25(8) | 20(1) | 186.7(4) | 0.82(4) | 280/318 | 16.9 100 |
| 4       | 44:09:286   | 276(10) | 4.0(3) | -0.5(1) | 11.5(5) | 35(1) | 1.2(1) | 203/188 | 50.4 39.8 |
| 5       | 45:31:099   | 352(9) | 3.0(5) | -0.5(2) | 10(1) | 8.7(7) | 1.3(3) | 465/584 | 61.5 43.8 |
| 6       | 46:00:035   | 1160(20) | 3.8(2) | -0.30(7) | 9.7(6) | 7.2(3) | 1.3(2) | 278/273 | 21.5 65.5 |
| 7       | 46:06:427   | 231(7) | 3.9(7) | -0.27(4) | 11(2) | 13(1) | 1.4(3) | 317/419 | 45.6 48.4 |
| 8       | 46:20:170   | 654(8) | 3.1(1) | -0.38(4) | 16.3(3) | 112(1) | 0.87(4) | 460/374 | 70.9 100 |
| 9       | 46:23:456   | 1190(20) | 3.8(3) | -0.2(1) | 7.3(6) | 3.0(1) | 0.8(1) | 774/792 | 85.3 86.6 |
| 10      | 46:43:088   | 672(8) | 3.3(4) | -0.34(1) | 9.9(5) | 6.5(2) | 1.2(2) | 226/225 | 30.4 32.5 |
| 11      | 47:24:977   | 875(5) | 4.5(5) | -0.45(11) | 8(1) | 2.7(3) | 1.4(5) | 507/672 | 31.8 82.8 |
| 12      | 47:57:532   | 741(7) | 4.0(5) | -0.2(1) | 9(1) | 8.3(3) | 1.2(3) | 758/736 | 59.7 10.7 |
| 13      | 48:44:836   | 652(8) | 3.7(2) | -0.2(1) | 8(1) | 4.4(2) | 1.4(2) | 812/836 | 91.3 48.3 |
| 14      | 48:49:270   | 985(22) | 3.9(3) | -0.25(6) | 14.3 | 24.3(7) | 1.3(1) | 854/933 | 75.3 100 |
| 15      | 49:00:275   | 2090(40) | 4.2(2) | 0.0(1) | 7(1) | 4.1(2) | 0.8(2) | 814/841 | 57.3 51.3 |
| 16      | 49:06:474   | 517(10) | 4.2(2) | -0.3(2) | 7(2) | 5.1(7) | 1.4(3) | 357/501 | 3.2 37.3 |
| 17      | 49:16:610   | 877(11) | 3.8(2) | -0.52(8) | 8.1(4) | 14.7(4) | 1.3(1) | 848/873 | 12.2 84.3 |
| 18      | 49:22:393   | 304(8) | 3.1(4) | -0.8(2) | 6(1) | 8.6(6) | 1.2(3) | 532/627 | 31.1 78.2 |
| 19      | 49:27:323   | 401(6) | 3.3(8) | -0.4(2) | 10(3) | 8.8(2) | 1.5(5) | 260/349 | 40.2 24.5 |
| 20      | 49:46:678   | 290(10) | 4.3(5) | -0.5(1) | 6.9(5) | 10.1(5) | 1.3(2) | 737/809 | 56.6 31.4 |
| 21      | 50:01:031   | 817(7) | 3.6(2) | -0.3(1) | 8.2(4) | 8.4(3) | 1.4(3) | 810/876 | 64.2 62.9 |
| 22      | 51:35:913   | 522(8) | 4.0(5) | -0.6(2) | 7(1) | 12.0(8) | 1.3(2) | 548/605 | 19.1 44.5 |
| 23      | 51:55:453   | 763(5) | 4.5(6) | -0.3(4) | 7.8(2) | 7.6(7) | 1.2(4) | 488/567 | 17.0 29.7 |
| 24      | 54:57:475   | 315(8) | 3.6(2) | -0.54(8) | 9.3(4) | 30(1) | 1.2(2) | 816/859 | 88.5 40.4 |
Extended Data Figure 1. T90 distribution of the 24 bursts in our sample. The blue bar represents the T90 of the FRB-associated burst as measured with HXMT.\textsuperscript{11}
References Extended Data.

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