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Supplementary information

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Multiwavelength constraints on the origin of a nearby repeating fast radio burst source in a globular cluster

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Supplementary Information

Gamma-ray Bursts (GRBs) from Extragalactic Magnetar Giant Flares

Over 8,000 GRBs have been detected so far using a variety of high-energy instruments (e.g., see the online GRBweb catalogue[126]). Several of these GRBs (GRB 970110[108], GRB 051103[109,110], GRB 070201[111], GRB 070222[112], and GRB 200415A[113]) have been localized to host galaxies in the local Universe, and they are believed to be associated with giant flares from extragalactic magnetars based on their temporal characteristics, energetics, and spectral properties. The absorbed X-ray pseudo-fluences of GRB 970110, GRB 051103, GRB 070201, and GRB 200415A (Fig. 5) are all several orders of magnitude larger than our 3σ X-ray fluence limits from FRB 20200120E, measured using NICER and XMM-Newton at the times of bursts B4 and B9 (Table 1). Based on this, we conclude that a soft X-ray burst, with similar properties to these extragalactic magnetar flares, was not produced near the times of these radio bursts from FRB 20200120E. We are unable to place strong constraints on the possibility of a GRB 070222-like flare being emitted from FRB 20200120E, since the absorbed X-ray pseudo-fluence of GRB 070222 is slightly (a factor of $\sim$2) below our 3σ X-ray fluence limits.

Additionally, we note that the position of GRB 051103 was triangulated to the M81/M82 galaxy group using the Interplanetary Network (IPN)[127]. The position of GRB 051103 is significantly offset from the VLBI position of FRB 20200120E by $\sim$0.6°. Based on the reported localization regions, we conclude that GRB 051103 and FRB 20200120E are not associated (at a confidence level greater than 418σ).

X-ray Pseudo-Fluence Distribution of FRB-Emitting Magnetars

Ordinary magnetars, with similar energetics and activity levels as SGR 1935+2154, are believed to be unable to account for the repetition rates observed from the cosmological repeating FRB population[128]. If repeating FRB sources are powered by magnetars, then they must be younger than typical 1–10-kyr-old magnetars found in the Milky Way, possess larger magnetic fields, and have larger energy reservoirs[43,128]. An FRB-emitting magnetar may therefore be capable of powering more energetic high-energy bursts than ordinary Galactic magnetars[128]. In this case, the distribution of magnetar burst X-ray pseudo-fluences shown in Fig. 5 would be shifted towards larger values for such FRB-emitting magnetars by an amount proportional to the square of its magnetic field. Our prompt X-ray fluence limits would then reside in the bulk of the resulting X-ray pseudo-fluence distribution, indicating that it would be possible to detect many short bursts from these highly energetic, FRB-emitting magnetars in the soft X-ray band with NICER, XMM-Newton, and possibly other X-ray detectors. Although the repetition rate of FRB 20200120E is comparable to that of other active repeating FRBs[66], the energies of radio bursts detected from FRB 20200120E (Table 3) are several orders of magnitude lower than those from most active repeating FRBs[21,22], such as FRB 20121102A and FRB 20180916B. This suggests that, if FRB 20200120E is a magnetar, it could be powered by a source with a lower energy reservoir than other repeating FRBs.

X-ray Emission from Giant Radio Pulse-Emitting Pulsars

Enhanced X-ray emission has been detected during giant radio pulses from some Galactic pulsars, such as PSR B1937+21 and the Crab pulsar. X-ray observations of PSR B1937+21 have revealed that its X-ray pulse profile peak is closely aligned with its radio giant pulses, rather than the peak of its normal radio pulse profile[129]. This provides strong support for a common origin between giant pulses from radio MSPs and their pulsed X-ray emission. Our X-ray observations were not sensitive to detecting pulsed X-ray emission from a PSR B1937+21-like object at the distance of FRB 20200120E. The 3σ persistent X-ray flux upper limit from our deepest Chandra observation of FRB 20200120E (Extended Data Table 2) was $\sim10^3$ times larger than the expected pulsed X-ray flux of PSR B1937+21 ($F^{\mathrm{B1937+21}}_{\mathrm{X,\,3.63\,Mpc}} = 4\times10^{-18}\ \mathrm{erg\ s^{-1}\ cm^{-2}}$)[130], if it were placed at the distance of FRB 20200120E. An X-ray enhancement of $3.8\pm0.7\%$ has also been observed in the Crab pulsar's time-averaged pulsed X-ray emission, coinciding with giant radio pulses[131], but we cannot rule out a similar X-ray enhancement from FRB 20200120E due to limited sensitivity during our X-ray observations.

Low-mass X-ray Binaries (LMXBs)

X-ray observations have revealed large numbers of LMXBs in the globular clusters of nearby galaxies[132]. Many LMXBs likely also reside in FRB 20200120E's globular cluster. The distribution of persistent X-ray luminosities from Galactic LMXBs shown in Fig. 4b indicates that our X-ray observations would have been sensitive to detecting persistent or transient X-ray emission from up to $\sim$30% of the brightest, Milky Way-like LMXBs[102] from FRB 20200120E's location. Based on our deepest X-ray observation with Chandra, we rule out an association between FRB 20200120E and LMXBs with persistent X-ray luminosities larger than $L_{\mathrm{X}} > 9.8\times10^{36}\ \mathrm{erg\ s^{-1}}$.

There are two types of X-ray bursts produced by LMXBs: type I and type II X-ray bursts. Type I X-ray bursts are thermonuclear explosions that are triggered by unstable ignition of accreted hydrogen and/or helium on neutron stars (NSs) in LMXBs[133]. The typical durations of type I X-ray bursts range from seconds to minutes, and very bright type I X-ray bursts can reach Eddington luminosities at the NS surface. The absorbed X-ray pseudo-fluence distribution of type I X-ray bursts (Fig. 5) shows that a small fraction (0.1–0.2%) of type I X-ray bursts have X-ray pseudo-fluences that are above our 3σ X-ray fluence limits, derived from NICER and XMM-Newton observations of FRB 20200120E at the times of bursts B4 and B9 (Table 1). Thus, type I X-ray bursts with similar or larger X-ray pseudo-fluences than our X-ray fluence limits would have been detectable from FRB 20200120E near the times of these radio bursts.

Type II X-ray bursts are caused by accretion instabilities during mass transfer onto NSs in binary systems, and they are thought to originate from the sudden release of gravitational potential energy during the accretion process. Type II X-ray bursts have been detected from only a few LMXB sources[114,115]. We find that the most energetic type II X-ray bursts from MXB 1730–335 have absorbed X-ray pseudo-fluences that are slightly above our best 3σ X-ray fluence limit, derived at the time of burst B4 from NICER observations of FRB 20200120E (Fig. 5 and Table 1). Thus, X-ray bursts similar to these bright type II X-ray bursts would have been detectable from FRB 20200120E during our NICER observations. However, the absorbed X-ray pseudo-fluences of type II X-ray bursts from other LMXB sources, such as GRO J1744–28, were below the NICER and XMM-Newton X-ray fluence detection thresholds. Therefore, an LMXB capable of producing type I or type II X-ray bursts cannot be entirely excluded as a possible source type for FRB 20200120E.

High-mass X-ray Binaries (HMXBs)

Although FRB models involving HMXBs[134,135] have been invoked to explain the 16 day periodic radio activity[136] observed from the repeating FRB 20180916B and its positional offset from the nearest region of active star formation in its host galaxy[137], it is unlikely that FRB 20200120E is powered by an active HMXB. The massive stellar OB companions of HMXBs have lifespans less than $\sim$1–10 Myr, which is significantly shorter than the age ($\sim$10 Gyr) of FRB 20200120E's globular cluster[17]. Approximately 5% of Galactic HMXBs have measured X-ray luminosities above $10^{37}\ \mathrm{erg\ s^{-1}}$ in the soft X-ray band[103]. Only a few of our deepest X-ray observations would have been sensitive to detecting persistent or transient X-ray emission from a bright, Milky Way-like HMXB at the high-end of the Galactic luminosity distribution (Fig. 4b and Extended Data Table 2), if placed at the distance of FRB 20200120E.

Relativistic Shock Models

There are two popular classes of models involving NSs that are commonly invoked to explain the coherent radio emission observed from FRB sources: magnetospheric (pulsar-like) models[138,139] and relativistic shock (GRB-like) models[26,27,140,141]. In the relativistic shock model described in refs. 26 and 27, the emission from FRBs is thought to be produced by synchrotron maser emission from ultrarelativistic, magnetized shocks that are generated from the collision of flare ejecta (produced by a central engine) and an upstream medium at large distances. Here, we examine the theoretical predictions for multiwavelength emission from the relativistic shock model[26,27] (Methods) and compare these predictions to our results from simultaneous X-ray and radio observations of FRB 20200120E.

Our best prompt 3σ X-ray fluence limit with NICER at the time of burst B4 constrains the relativistic flare energy from FRB 20200120E to be $E_{\rm flare} < 3 \times 10^{40}$ erg in the 0.5–10 keV energy band. This limit is lower than the range of flare energies (10^{41}–10^{48} erg) predicted in ref. 27 for other repeating and non-repeating FRBs, based on the properties of their radio bursts. Larger flare energies are predicted for other FRB sources, using the relativistic shock model[26,27], because their radio bursts are typically longer in duration and have larger energies than those observed from FRB 20200120E (equation (10)).

From equation (10), we find that a relativistic flare energy of $E_{\rm flare} \approx 5.3 \times 10^{37}$ erg is predicted near the time of burst B4. At the distance of FRB 20200120E, the corresponding X-ray fluence for this flare would be approximately 3.4×10^{-14} erg cm^{-2}, which is below our 3σ X-ray fluence limits (Fig. 5 and Table 1). Using equation (11) and our best 3σ X-ray fluence limit for burst B4 in Table 1, we place the following constraint on the ratio of the relativistic flare energy to radio burst energy for FRB 20200120E in the 0.5–10 keV energy band: $(\eta_{\rm shock} \approx 1.9 \times 10^4) < (1.1 \times 10^7 = \eta_{\rm lim}^{\rm B4})$, where $\eta_{\rm lim}^{\rm B4}$ is our most constraining upper limit on the X-ray-to-radio fluence ratio of FRB 20200120E from simultaneous X-ray and radio measurements at the time of burst B4. The predicted X-ray flare to radio burst fluence ratio ($\eta_{\rm shock} \approx 1.9 \times 10^4$) obtained for FRB 20200120E from the relativistic shock model is 2–3 times smaller than the X-ray-to-radio fluence ratio ($\eta_{\rm SGR\ 1935+2154} \approx 4.6 \times 10^4$) derived from the FRB-like burst detected from SGR 1935+2154 on 28 April 2020, based on the reported X-ray and radio fluences from Insight-HXMT[12], STARE2[9], and CHIME/FRB[8]. To probe the fluence ratio predicted by equation (11) for a relativistic shock from FRB 20200120E, using NICER in the 0.5–10 keV energy band, a more energetic radio burst ($E_{\rm R} \gtrsim 580 \times E_{\rm R}^{\rm B4}$) would be required for radio bursts with widths comparable to B4.

However, the ultra-short-timescale variability ($\delta t \lesssim 100$ ns) previously reported in some radio bursts detected between 1.2 and 2.3 GHz from FRB 20200120E[21,22] disfavours models that require the FRB emission to be produced by relativistic shocks located at large distances ($\gtrsim 10^{10}$ cm) from a compact object[142,143] and instead suggests that the emission may be produced within the magnetosphere of a NS.

Comparisons between FRB 20200120E and Other Repeating FRBs

There are remarkable differences between the observed properties of FRB 20200120E and other repeating FRBs. The isotropic-equivalent luminosities of radio bursts detected from FRB 20200120E are, on average, several orders of magnitude fainter than the luminosities of radio bursts from other repeating FRBs[21,22]. Some repeating FRB sources, such as FRB 20121102A[144–146] and FRB 20180916B[137,147], have been localized to star-forming galaxies and spatially associated with nearby knots of star formation within their host galaxies. This is consistent with expectations from FRB models involving young pulsars or magnetars formed through core-collapse supernovae[5,46,148]. On the other hand, it is unlikely that a massive star has recently undergone a core-collapse supernova in the ~10-Gyr-old globular cluster associated with FRB 20200120E, which provides strong evidence for an alternative, delayed formation channel for FRB 20200120E. Together, this suggests that FRB 20200120E may be an atypical source among the repeating FRB population.

The proximity of FRB 20180916B (luminosity distance of $d_{\rm L} = 149$ Mpc)[147], along with its 16 day radio activity period[136] and precise localization[147], has enabled targeted multiwavelength searches for emission outside of the radio band[14,18,19,149,150]. The prompt, high-energy upper limits from observations of FRB 20180916B have yielded constraints that challenge models invoking giant magnetar flares[14,18,19]. However, previous X-ray observations of FRB 20180916B have lacked the sensitivity to place constraints on the emission of magnetar-like intermediate flares or short X-ray bursts. On the other hand, deep optical limits at the time of an energetic radio burst from FRB 20180916B yielded an upper limit of ~10^2 on the optical-to-radio fluence ratio, ruling out strong optical emission from a blast wave in the wind of a hyperactive magnetar[151]. FRB models involving giant magnetar flares are also ruled out for FRB 20200120E, based on our simultaneous X-ray and radio observations, and GRB-like shocks are disfavored based on the temporal variability observed in previously reported radio bursts from FRB 20200120E[21,22,142,143].

Simultaneous X-ray and radio observations of more distant repeating FRB sources, such as FRB 20201124A[152] (luminosity distance of $d_{\rm L} = 453$ Mpc) and FRB 20121102A[23] (luminosity distance of $d_{\rm L} = 972$ Mpc), have provided upper limits that are consistent with a flaring magnetar origin. These upper limits also disfavor a link between extremely energetic GRB-like events, with X-ray energies larger than 10^{45}–10^{47} erg, and FRB 20201124A[152] or FRB 20121102A[23]. It has not yet been possible to rule out less energetic high-energy transients from these repeating FRB sources due to the limited sensitivity of currently operating telescopes. Since the origins of FRB 20200120E and other repeating FRBs may be different, the constraints derived from observations of other repeating FRBs[153] provide complementary insight into the nature of the sources comprising the repeating FRB population.

Future Searches for X-ray Emission from FRBs

We find that the prospects for detecting X-ray bursts from extragalactic FRB sources, located within 1–10 Mpc, are particularly promising in the soft X-ray band using both current and future X-ray telescopes. In Extended Data Fig. 5, we show how the predicted X-ray burst fluences in the soft (0.5–10 keV) and hard (10–250 keV) X-ray bands vary with distance for different emission models and sources that are known to or could produce observable high-energy emission and FRB-like radio emission from extragalactic distances. We also show nominal 3σ X-ray burst fluence detection thresholds for a selection of currently operating X-ray telescopes (AstroSat, Chandra, Fermi, INTEGRAL, NICER, NuSTAR, Swift, and XMM-Newton). These detection thresholds are conservative estimates, based on the in-orbit sensitivities of each instrument under nominal operating conditions, and are consistent with typical prompt high-energy results from FRB observations performed using these X-ray telescopes. The sensitivity at the time of observations may be affected by the instrument's background level, off-axis angle between the detector and the source, and possibly other factors.

Using currently operating X-ray telescopes, such as NICER, X-ray bursts similar to the X-ray burst that accompanied the FRB-like radio burst from SGR 1935+2154 on 28 April 2020[12] are detectable from extragalactic FRB sources located within $\sim$1 Mpc (Extended Data Fig. 5). More energetic X-ray bursts may be detectable from larger distances. Modest improvements in the sensitivity of currently operating high-energy X-ray detectors would facilitate deeper studies of the parameter space of magnetar-like bursts produced from nearby extragalactic FRB sources (Fig. 5).

Future X-ray telescopes with much larger effective areas, such as NewAthena[154] and Strobe-X[155], would be able to detect X-ray bursts with properties similar to the X-ray burst associated with FRB-like emission from SGR 1935+2154[12] from sources located as far as $\sim$5–10 Mpc in the soft X-ray band, if the bursts are not heavily absorbed. These same types of bursts may only be detectable from FRB sources located within $\sim$300 kpc in the hard X-ray band due to the sensitivity limitations of current and planned X-ray telescopes. Our predictions for HEX-P, NewAthena, and Strobe-X are based on the currently available sensitivity information for these X-ray telescopes[154–156].

In summary, we showed that current and future X-ray telescopes will have the greatest sensitivity to detecting X-ray bursts in the soft X-ray band from extragalactic FRB sources within 1–10 Mpc. Many models predict multiwavelength emission from FRBs. However, no electromagnetic radiation has yet been detected from any extragalactic FRB source at any wavelength outside of the radio band (between radio frequencies of roughly 100 MHz[157,158] and 8 GHz[159]). Additional multiwavelength observations of nearby FRBs with sensitive X-ray instruments in the future will provide further insights into the emission mechanisms of FRBs, opportunities for testing predictions from FRB models, and valuable information that will aid in illuminating the origins of the sources comprising the FRB population.

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