A targeted search for repeating fast radio bursts associated with gamma-ray bursts

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ABSTRACT

The origin of fast radio bursts (FRBs) still remains a mystery, even with the increased number of discoveries in the last three years. Growing evidence suggests that some FRBs may originate from magnetars. Large, single-dish telescopes such as Arecibo Observatory (AO) and Green Bank Telescope (GBT) have the sensitivity to detect FRB 121102-like bursts at gigaparsec distances. Here we present searches using AO and GBT that aimed to find potential radio bursts at 11 sites of past γ-ray bursts that show evidence for the birth of a magnetar. We also performed a search towards GW170817, which has a merger remnant whose nature remains uncertain. We place $10\sigma$ fluence upper limits of $\approx 0.036$ Jy ms at 1.4 GHz and $\approx 0.063$ Jy ms at 4.5 GHz for AO data and fluence upper limits of $\approx 0.085$ Jy ms at 1.4 GHz and $\approx 0.098$ Jy ms at 1.9 GHz for GBT data, for a maximum pulse width of $\approx 42$ ms. The AO observations had sufficient sensitivity to detect any FRB of similar luminosity to the one recently detected from the Galactic magnetar SGR 1935+2154. Assuming a Schechter function for the luminosity function of FRBs, we find that our non-detections favor a steep power–law index ($\alpha \lesssim -1.0$) and a large cut–off luminosity ($L_0 \gtrsim 10^{42}$ erg/s).

Key words: gamma-ray burst: general – radio continuum: transients

1 INTRODUCTION

Fast radio bursts (FRBs; Lorimer et al. 2007; Thornton et al. 2013) are millisecond-duration radio pulses with large dispersion measures, generally known to be of cosmological origin (for recent reviews, see Petroff et al. 2019; Cordes & Chatterjee 2019), with the exception of FRBs from the Galactic magnetar SGR1935+2154 (The CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020). Measurements to date imply total isotropic energies of the order of $10^{38} – 10^{40}$ erg (Law et al. 2017; Zhang 2018; Dolag et al. 2015), and high brightness temperatures that point to coherent emission processes. So far, there are over 100 known FRBs (Petroff et al. 2016) with $\approx 20$ repeating (Spitler et al. 2016; CHIME/FRB Collaboration et al. 2019a,b; Fonseca et al. 2020). Over 50 were found within the last three years by The Australian Square Kilometre Array Pathfinder (ASKAP; Shannon et al. 2018) and The Canadian Hydrogen Intensity Mapping Experiment (CHIME; CHIME/FRB Collaboration et al. 2018). Despite this rapid growth in observational results, the origin of FRBs is still uncertain. Theories proposed to explain the origin of FRBs include giant flares from magnetars (Pshirkov & Postnov 2010; Kulkarni et al. 2014; Metzger et al. 2017), giant pulses powered by spin-down from extragalactic neutron stars (NS; Cordes & Wasserman 2016),

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produced from infalling asteroids to the pulsar’s magnetosphere (Dai et al. 2016), collapse of massive NSs (Falcke & Rezzolla 2014) or compact binary mergers. While there may be multiple classes of FRBs (Palaniswamy et al. 2018), the repeaters rule out catastrophic progenitors, at least for those particular objects. The localization of the repeating FRB 121102 (Spitler et al. 2016) to a low-metallicity dwarf galaxy (Tendulkar et al. 2017; Chatterjee et al. 2017), started pointing to a NS origin for FRBs. The more recent discovery of FRBs from the Galactic source SGR 1935+2154 (The CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020) further confirms this. The idea of a millisecond magnetar, a NS with millisecond birth period and a large magnetic field (> 10^{15} G), being responsible for the FRBs has been put forward since the discovery of FRBs (Pshirkov & Postnov 2010) and recently invoked to explain FRB121102 (Metzger et al. 2017). Connections have also been made previously between FRBs and Soft Gamma Repeaters (SGRs), where the sudden release in magnetic energy that the SGR may also produce an FRB (Katz 2016; The CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020). In SGRs, magnetic reconnection produces a strong magnetic pulse that propagates outwards and interacts with the surrounding gas, which could power a millisecond-duration burst in the radio band (Lyubarsky 2014).

Millisecond magnetars may be born in the core collapse of massive stars and/or in the merger of binary NSs (e.g., Usov 1992; Dai & Lu 1998). The rotational energy of a NS is given by,

\[ E_{\text{rot}} \approx 2 \times 10^{52} \text{erg} \left( \frac{M}{1.4 M_\odot} \right) \left( \frac{R}{10 \text{ km}} \right)^2 \left( \frac{P}{1 \text{ ms}} \right)^{-1}. \]

(1)

Rapid rotation (periods of milliseconds) gives sufficient rotational energy to power a \( \gamma \)-ray burst (Metzger et al. 2011). Therefore, GRBs with intrinsic energy \( < 10^{52} \text{ erg} \) which is the maximum rotational energy may be powered by magnetars. Energy injection from a rapidly rotating magnetar is often invoked to explain the energy in GRBs with a supernova (SN) connection (hereafter called GRB-SNe, Mazzali et al. 2014). By comparing the kinetic energy of the associated SN and the \( \gamma \)-ray energy, Mazzali et al. (2014) shows that a magnetar central engine likely powers all GRB–SNe. In this scenario, the spin-down energy of a highly magnetized NS is deposited in the ejecta.

A merger that produces a stable NS that is rotationally supported may also quite possibly be a source of repetitive FRBs (Yamasaki et al. 2017). The general picture concerning binary neutron star (BNS) mergers is that the merger produces either a BH or a long-lived NS depending on the EOS and the maximum allowable mass for a NS, \( M_{\text{max}} \), which could be more than 2.1 \( M_\odot \) (Cromartie et al. 2020). For BNS total mass of \( \approx 1.3 - 1.6 M_{\odot} \) (Cromartie et al. 2020). For BNS total mass of \( \approx 1.3 - 1.6 M_{\odot} \), prompt collapse to a BH occurs, for masses \( \lesssim 1.2 M_{\odot} \), a hypermassive NS is formed as an intermediate product, which then loses angular momentum and collapses to a BH (Margalit & Metzger 2017), and for low-mass BNS, an indefinitely long-lived NS may be formed (Margalit & Metzger 2017).

The FRB–GRB connection has also been discussed previously, with FRBs resulting from the collapse of a supra-massive NS to a BH (Zhang 2014). Palaniswamy et al. (2014) searched for prompt radio emission coincident with GRBs, but these searches could have suffered from low sensitivity (SEFD > 800 Jy), whereas a typical FRB would have a flux density \( \approx 0.5 \text{ Jy} \). Furthermore, DeLaunay et al. (2016) identified a \( \gamma \)-ray transient in connection with an FRB, whose high isotropic \( \gamma \)-ray energy may be attributed to a magnetar origin, and Bannister et al. (2012) detected candidate single pulses from GRBs. Adding to these, the presence of an SN remnant is one explanation for the large RM and the highly magnetized environment of the FRB121102 (Michilli et al. 2018). Intriguingly, Nicholl et al. (2017) found that FRBs arising predominantly from repetitive sources, i.e. originating from magnetars, occur at a rate of \( 10^4 \text{ Gpc}^{-3} \), consistent with the rates derived from observations. It is also worthwhile pointing out that the birth rate of non-repeating FRBs (\( \sim 2700 \text{ yr}^{-1} \text{ Gpc}^{-3} \)) is consistent with the high end of the BNS merger rate (Nicholl et al. 2017; Yamasaki et al. 2017).

Motivated by these ideas, we targeted several relatively nearby GRB sites and the BNS merger GW170817 in search of possible FRB signals. A sensitive telescope like Arecibo should be able to detect FRB121102-like bursts of flux density 1.8 mJy (Palaniswamy et al. 2014) to a distance of up to \( \approx 4.8 \text{ Gpc} \). The details of our FRB search observations are presented in Section 2, data analysis in Section 3, present results and place constraints on FRB progenitors in Section 4, and we offer our conclusions in Section 5.

### 2 OBSERVATIONS

Our target list contains 11 GRBs visible in the Arecibo Observatory (AO) declination range and the BNS merger GW 170817, which was observed with the Green Bank Telescope (GBT). Out of the 11 GRBs, there are six long GRBs (lGRB) with SN associations, and five GRBs (one IGRB and four short GRBs; sGRBs) that exhibit plateaus in the X-ray light curve. The target list and their properties are given in Table 1. All GRBs have been localized to a region < 2.5 arcsec by high energy observations, which allows single-dish telescopes with a field-of-view (FoV) of a few arcminutes to cover the entire localization error region at full sensitivity.

Full Stokes (or polarization self-and cross-products), 8-bit, high time resolution spectra were recorded at both telescopes. A known pulsar was observed at the start of each observation session to verify the status of instruments. Table 2 lists information about the observation setup for AO and GBT. The dates since the GRB trigger, on which the observations were conducted, are shown in Figure 1.

Arecibo observations were carried out between 2017 December 12:50 UTC and 2018 December 19:55 UTC. Arecibo targets were observed for \( \sim 0.6 \) hours on each epoch. A total of 114 hours of observations were obtained on all GRBs, with 1–21 hours on each target at each frequency depending on the LST availability. We note that all of the sources are away from the Galactic plane. Data were recorded using the Puerto Rico Ultimate Pulsar Processing Instrument

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**Table 1.** All GRBs have been localized to a region < 2.5 arcsec by high energy observations, which allows single-dish telescopes with a field-of-view (FoV) of a few arcminutes to cover the entire localization error region at full sensitivity.

**Table 2.** Overall FRB search observations are presented in Section 2, data analysis in Section 3, present results and place constraints on FRB progenitors in Section 4, and we offer our conclusions in Section 5.
Figure 1. The timescale of our radio observations for the sources that are listed in Table 1 since the GRB trigger. All observations were made within a time span of 412 days, between the dates of November 2, 2017 and December 19, 2018. Our targets are arbitrarily offset along the y-axis for clarity. Black, blue and green diamonds represent 1.4 GHz, 4.5 GHz and 2 GHz observations, respectively. GRB 130702A was monitored ∼ once a month in order to verify the origin of an excess dispersion measure seen on the first observation.

(PUPPI) at center frequencies of 1380 MHz and 4.5 GHz with a bandwidth of ≈ 600 MHz with 512 frequency channels and sampled at 40.96 µs.

GBT observations were carried out between 2017 November 02:41 UTC and 2018, July 31:02 UTC on 10 epochs. GW 170817 was observed for ∼ 1 hour at each frequency during each observation. Since low-frequency emission may be self-absorbed by the post-GRB ejecta at early epochs, observations were conducted at 1.4 and 1.9 GHz on the first two epochs and afterwards only at 1.4 GHz on the following epochs. GBT data were recorded on the GUPPI spectrometer with a sampling time of 10.24 µs. To minimize any intrachannel dispersive smearing to that caused by the difference between the true and estimated

DM, data were semi-coherently dedispersed at a DM of 80 cm⁻³ pc. This DM is an estimate corresponding to DM = DM_{MW} + DM_{IGM} + DM_{H}, where DM_{MW} = 35 cm⁻³ pc is the contribution from the Milky Way (Yao et al. 2017), DM_{IGM} = 7 cm⁻³ pc, is the intergalactic medium (Ioka 2003), and DM_{H} = 35 cm⁻³ pc is the host galaxy (assuming a host like the MW). We use DM_{H} = 35 cm⁻³ pc, which is the approximate DM contribution from the Milky Way for a line of sight out of the plane.

### Table 1. The list of targets.

| Name                      | Redshift | Distance | RA (deg) | DEC (deg) | gl (deg) | gb (deg) | Expected DM (cm⁻³ pc) | Duration (sec) | $L_{\text{min}}$ (erg/s) |
|---------------------------|----------|----------|----------|-----------|----------|----------|------------------------|----------------|------------------------|
| GRB030329/SN2003dh        | 0.169    | 812      | 10:44:50:03 | 21:31:18:15 | 216.98 | 60.69 | 264.32 | 25 | 4.0 × 10⁴⁰ |
| GRB060218/SN2006aj        | 0.033    | 145      | 03:21:39:69 | 16:52:01:6 | 166.92 | -32.88 | 173.08 | 2100 | 1.28 × 10⁴⁰ |
| GRB120422A/SN2012bz       | 0.280    | 1434     | 09:07:36:42 | 14:01:06:0 | 215.22 | 36.43 | 413.64 | 5.35 | 1.25 × 10⁴¹ |
| GRB130427A/SN2013cq       | 0.340    | 1795     | 11:32:32:63 | 27:41:51:7 | 206.51 | 72.50 | 472.37 | 162.83 | 1.75 × 10⁴¹ |
| GRB130702A/SN2013dx       | 0.145    | 687      | 14:29:14:78 | 15:46:26:1 | 11.35 | 64.64 | 241.17 | 59 | 2.88 × 10⁴⁰ |
| GRB130215A/SN2013ez       | 0.597    | 3508     | 02:53:56:6 | 13:23:13:2 | 163.07 | -39.76 | 991.80 | 65.7 | 7.52 × 10⁴¹ |
| GRB130603B                | 0.356    | 1894     | 11:28:48:15 | 17:04:16:9 | 236.42 | 68.42 | 498.47 | 0.18 | 2.19 × 10⁴¹ |
| GRB140903A                | 0.351    | 1863     | 15:52:03:27 | 27:36:09:4 | 44.39 | 50.12 | 241.17 | 59 | 2.12 × 10⁴¹ |
| GRB051221                 | 0.547    | 2868     | 21:54:48:71 | 16:53:28:2 | 73.54 | -28.58 | 786.02 | 1.4 | 5.03 × 10⁴¹ |
| GRB100816A                | 0.803    | 4529     | 23:26:57:62 | 26:34:43:9 | 100.44 | 32.57 | 1396.40 | 2.9 | 1.25 × 10⁴² |
| GRB130831A                | 0.479    | 2459     | 23:54:29:91 | 29:25:47:6 | 88.33 | -31.82 | 663.84 | 32.5 | 3.69 × 10⁴¹ |
| GW170817                  | 0.0098   | 42       | 13:09:48:089 | -23:22:53:35 | 308.37 | 39.29 | 77.27 | 2.0 | 2.49 × 10⁴⁸ |

References: Stanek et al. (2003), Cano et al. (2014), Mazzali et al. (2014), D’Elia et al. (2015), Abbott, et al. (2017) and https://swift.gsfc.nasa.gov/archive/GBTpg.

### Table 2. Summary of observational setup.

| Name       | Telescope | $f_p$ (MHz) | $T_{\text{sys}}$ K | Gain (K/Jy) | BW (MHz) | $N_{\text{chan}}$ | $t_{\text{samp}}$ µs | FoV deg² |
|------------|-----------|-------------|-------------------|-------------|----------|-------------------|---------------------|----------|
| AO         | 1.4       | ≈30         | 8                 | 600         | 512      | 40.96             | 9.5 × 10⁻³       |
| AO         | 5.0       | ≈30         | 4                 | 800         | 512      | 40.96             | 7.8 × 10⁻³       |
| GBT        | 1.4       | ≈20         | 2.9               | 800         | 512      | 10.24             | 1.8 × 10⁻³       |
| GBT        | 1.9       | ≈22         | 1.9               | 800         | 512      | 10.24             | 8.7 × 10⁻³       |

$T_{\text{sys}}$, Gain and FoV values for AO and GBT are obtained from http://www.naic.edu/~astro/Kstatus/rcvrtabz.shtml and https://science.nrao.edu/facilities/gbt/proposing/GBTpg.pdf respectively.

### 3 DATA ANALYSIS

Data from both telescopes were processed with the GPU accelerated pipeline Heimdall² and the PRESTO analysis package (Ransom 2001).

We search the data at the recorded frequency and time resolution using a GPU accelerated pipeline Heimdall. The data were dedispersed at 1–7000 cm⁻³ pc and were searched for pulse widths of 40.96 µs–41.93 ms with the increments in the power of two. This generated 17,672 candidates above $S/N = 10$. These candidates were then fed to convolutional

² https://sourceforge.net/projects/heimdall-astro/
neural network FETCH\(^3\) to classify candidates between radio frequency interference (RFI) and potential FRB candidates (Agarwal et al. 2020). We use model \(\Lambda\) with a probability threshold of 0.5 for the candidate classification. FETCH labelled 425 candidates as positives. These were inspected manually, 68 candidates were single pulses from the above mentioned test pulsars. The rest of the candidates were false positives due to a nearby airport radar. Figure 2 shows an example candidate appearing at a non–zero DM, due to chirped RFI from radar at 4.5 GHz. The appearance of the signal within a narrow band of 4250–4350 MHz confirms the non–astrophysical nature of the signal.

Within PRESTO, RFI excision was done using the tool rfifind, which creates a mask in which the affected frequency channels and time chunks are replaced by median values. The data were referenced to the Solar System barycentre and de-dispersed at 1000 trial DMs ranging from 0 to 1000 cm\(^{-3}\) pc. For GRB130215A and GRB100816A, since the expected DM is > 1000 cm\(^{-3}\) pc (as listed in Table 1), we search 333 trial DMs ranging from 1000 to 2000 cm\(^{-3}\) pc. The dispersion smearing within a channel of \(\Delta \nu = 800/512\) MHz at the lowest frequency of 0.98 GHz from this step size is 8.3 \(\mu\) s DM \(\Delta \nu^{-3}\) \(\approx\) 13.7 \(\mu\) s, which is negligible. Significant peaks (> 10 \(\sigma\)) were searched for, in the de-dispersed time series using the single–pulse pipeline in PRESTO. Each DM vs time plot was visually inspected for real bursts, and those that peaked at a DM of zero were considered as RFI. Candidates that appeared at non–zero DM were reprocessed with dspsr (van Straten & Bailes 2011) using the DM and time output by the single–pulse search pipeline in PRESTO, and plotted using PSRCHIVE plotting routines (Hotan et al. 2004). Candidate bursts detected in the single–pulse search were classified as RFI upon further examination.

4 DISCUSSION

In this section, we discuss the timescales for radiation to escape the GRB ejecta, the possibility of detecting FRBs from magnetars based on the expected flux and the constraints placed on the luminosity function based on non–detections.

4.1 Detectability of a repeating FRB

The environment of the burst/merger site is an important consideration when determining the timescales for radio emission to escape. The free–free optical depth for the (Oxygen dominated) ejecta would reach \(\tau_{\text{eff}} = 1\), on a timescale

\[
t = 10 \times \left(93 f_{\text{ion}}^2 \nu_{\text{GHz}}^{-2} \tau_{\text{ion}}^{-3/2} M_{10}^2 t_{10}^{1/2} \nu_{\text{GHz}}^{-5}\right)^5 \text{ yr},
\]

after the explosion (Metzger et al. 2017), where \(f_{\text{ion}}\) is the ionized fraction of the ejecta, \(\nu_{\text{GHz}}\) is the observing frequency, \(M_{10}\) is the ejecta mass in units of \(10^{10}\) \(M_{\odot}\) and \(T_{\text{ion}}\) is the ejecta temperature in units of \(10^4\) K. Assuming ejecta masses of \(\sim 10^{10}\) \(M_{\odot}\), \(f_{\text{ion}} = 0.4\), ejecta velocities \(\sim 10^4\) km s\(^{-1}\), \(T_{\text{ion}} = 1\) radio emission may escape after 6 and 3 yr after the explosion at frequencies 1 GHz and 4.5 GHz respectively. With relatively smaller ejecta masses in mergers (than in SNe), ejecta will be transparent to \(\sim 1\) GHz emission on a timescale of several months (Metzger et al. 2017). This could be as soon as \(\sim\)three months for ejecta mass of \(\sim 0.001 M_{\odot}\). Our search observations were carried out \(\approx\) 3 months–15 yr after the explosion.

Measured fluxes of bursts from the repeating FRB 121102 were scaled to the distance of each GRB to estimate the expected flux if a repeater–like source resided in the GRB site. Assuming radiometer noise limitations for each burst, the signal-to-noise ratio

\[
S/N = \frac{F \cdot S}{\beta T_{\text{sys}} \sqrt{\nu}} \approx \frac{F \cdot S}{\beta T_{\text{sys}} \sqrt{\nu}}, \quad (3)
\]

where \(F\) is the expected fluence given by \(F_{\text{min}} = S w\) where \(S\) is the flux, \(w = 1.0\) ms is the pulse width, \(T_{\text{sys}}\) is the system temperature, \(G\) is the telescope gain (the numbers given in Section 2), \(\Delta \nu\) is the bandwidth, \(\beta = 1.07\) accounts for digitization loss factors, and \(N_p = 2\) is the number of polarizations (Rane et al. 2016). From the radiometer equation, the minimum flux corresponding to \(S/N = 10\) for the AO setup is \(S_{\text{min}} \approx 36\) mJy at 1.4 GHz and \(S_{\text{min}} \approx 63\) mJy at 4.5 GHz. The minimum flux for GBT is \(S_{\text{min}} \approx 84\) mJy at 1.4 GHz and \(S_{\text{min}} \approx 98\) mJy at 1.9 GHz. Figure 3 shows the luminosity distribution and the \(S/N\) of 224 bursts at 1.4 GHz and 4 – 6 GHz from FRB 121102 (Palaniswamy et al. 2014; Hardy et al. 2017; Spiteri, et al. 2018; Zhang et al. 2018; Michilli et al. 2018; MAGIC Collaboration et al. 2018; Gourdji, et al. 2019; Hessels et al. 2019). The \(S/N\)

| Table 3. GRB name, frequency, total time on the source, the number of epochs observed and the average time duration of each observation. |
|-----------------|-----------------|-----------------|-----------------|
| Name            | Frequency (MHz) | Total Time (hours) | Number of Epochs | Average Time (hours) |
| GRB030329       | 1380            | 4.5              | 7               | 0.65               |
|                 | 4500            | 1.7              | 4               | 0.42               |
| GRB051221       | 1380            | 14.7             | 15              | 0.98               |
|                 | 4500            | 2.5              | 5               | 0.51               |
| GRB060218       | 1380            | 8.7              | 16              | 0.55               |
|                 | 4500            | 6.9              | 13              | 0.53               |
| GRB120422A      | 1380            | 3.5              | 4               | 0.88               |
|                 | 4500            | 1.2              | 2               | 0.60               |
| GRB130427A      | 1380            | 2.7              | 4               | 0.67               |
|                 | 4500            | 1.0              | 2               | 0.51               |
| GRB130702A      | 1380            | 13.7             | 21              | 0.65               |
|                 | 4500            | 6.9              | 15              | 0.46               |
| GRB130215A      | 1380            | 12.1             | 19              | 0.64               |
|                 | 4500            | 7.5              | 12              | 0.63               |
| GRB130603B      | 1380            | 2.3              | 3               | 0.76               |
|                 | 4500            | 1.0              | 2               | 0.50               |
| GRB140903A      | 1380            | 4.1              | 6               | 0.68               |
|                 | 4500            | 3.1              | 6               | 0.51               |
| GRB051221       | 1380            | 14.7             | 15              | 0.98               |
|                 | 4500            | 2.5              | 5               | 0.51               |
| GRB100816A      | 1380            | 5.4              | 8               | 0.67               |
|                 | 4500            | 1.3              | 3               | 0.44               |
| GW170817        | 1399            | 8.7              | 10              | 0.86               |
|                 | 1999            | 1.8              | 2               | 0.91               |

\(^3\) https://github.com/devanshkv/fetch
A search for FRBs

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Figure 2. Candidate burst (chirped RFI) from the single-pulse search pipeline in FETCH from GRB051221 with the brightest signal at DM = 486.4 pc cm$^{-3}$. The signal is shown as flux vs time (top), frequency vs time (middle) and DM vs time (bottom).

histograms for bursts when scaled to the distances of two example GRBs from our sample are also shown at 1.4 GHz and 4.5 GHz. The S/N histograms are created by scaling flux density of FRB 121102 bursts to the distances of the GRBs and calculating the ratio between the expected flux density and minimum flux density $S_{\text{min}}$. If magnetars emit FRB121102-like bursts, Arecibo should be able to detect the brightest bursts of luminosity $\approx 9 \times 10^{42}$ erg/s (flux density of 1.8 Jy at 4.5 GHz) at GRB distances up to 4.8 Gpc.

4.2 Luminosity function

In this section, we attempt to place an upper limit on the FRB rate and constrain the FRB luminosity function parameters based on the non-detection of FRBs in our data. The rate of FRBs above a minimum luminosity $L_{\text{min},i}$ may be expressed by the Schechter function (Schechter 1976) which gives the event rate density

$$\phi = \phi^* \left( \frac{L_{\text{min},i}}{L_0} \right)^{\alpha} e^{-L_{\text{min},i}/L_0},$$

where $\phi^*$ is a reference event rate density, $\alpha$ is the power law exponent, and $L_0$ is the cut-off luminosity. Here, $L_{\text{min},i}$ is minimum detectable luminosity calculated as $L_{\text{min},i} = 4\pi S_{\text{min},i}D_L^2$, at the $i^{\text{th}}$ GRB, for a burst detected with the minimum detectable flux $S_{\text{min}}$, calculated from the radiometer equation. The minimum flux corresponding to S/N = 10 for AO and GBT are given in Section 3. Table 1 lists $L_{\text{min}}$ values for each GRB at 1.4 GHz. The minimum luminosity of the AO sources at 4.5 GHz is 6.18 times larger than at 1.4 GHz. The minimum luminosity for GW 170817 at 1.9 GHz is $2.88 \times 10^{38}$ ergs$^{-1}$.

Following Luo et al. (2020), the burst rate is then given by,

$$R(> L_{\text{min}}) = \int_{L_{\text{min}}/L_0}^{\infty} \phi^* \left( \frac{L}{L_0} \right)^{-\alpha} e \left( \frac{L_{\text{min},i}}{L_0} \right) d \left( \frac{L}{L_0} \right) = R_0 \Gamma \left( \alpha + 1, \frac{L_{\text{min}}}{L_0} \right),$$

where $R_0$ is the all-sky event rate in sky$^{-1}$ day$^{-1}$, $\Gamma$ is the incomplete gamma function. Here we have replaced the volumetric rate by the all-sky rate. If the $i^{\text{th}}$ GRB site was searched for $T_i$ days, the expected number of pulses for that GRB is,

$$n_i = \left( \frac{RT_i \Omega}{41253 \text{deg}^2} \right).$$

Here, $\Omega$ is the FoV of the telescope (listed in Table 2) and $T_i$ is the observation time on the $i^{\text{th}}$ source. Therefore, assuming a Poisson distribution of pulses, the probability of observing zero pulses in the $i^{\text{th}}$ GRB is, $p_i = e^{-n_i}$.

The likelihood of not detecting any GRBs in the entire sample, $L$, is the product of all the probabilities, i.e.

$$L = \prod_{i=1}^{N} p_i.$$

By summing individual logarithms, we see that

$$\log(L) = -R_0 \sum_{i=1}^{N} \left( \alpha + 1, \frac{L_{\text{min},i}}{L_0} \right) T_i \frac{\Omega}{41253 \text{deg}^2}. $$

Figure 3. Luminosity distribution of FRB 121102 bursts (top), S/N histograms of GRB060218 (middle) and GRB051221 (bottom). The S/N histograms show the S/N at which FRB 121102-like bursts would be detected at given GRB distances. The black dotted vertical line corresponds to $\text{S/N} = 10$. The red and black S/N histograms represent bursts at 1.4 GHz and 4.5 GHz respectively.
For a given non-detection probability, we can place an upper limit on the all-sky rate and place constraints on the parameters of the luminosity function using Equation 8. Figure 4 shows $R_0$ vs $\alpha$ and $L_0$ values. We have combined all data from both AO and GBT.

The sky rate for non-repeating FRBs, $R_0$ is $1140$–$7000$ sky$^{-1}$ day$^{-1}$ (Agarwal et al. 2020; Champion et al. 2016). To estimate the all-sky rate of repeating FRBs, we assume the volume density of repeaters to be $100$–$10000$ Gpc$^{-3}$, and adopt a typical lifetime of $30$–$300$ yrs (Nicholl et al. 2017). For example, this can be converted to an all sky-rate of $15.2 < R_0 < 1.52 \times 10^5$ sky$^{-1}$ day$^{-1}$ for repeaters at $1.4$ GHz. To convert the volumetric rate to an all-sky rate we assume that the current AO setup can detect an FRB of $0.19$ mJy at $1.4$ GHz (mean flux of FRB121102; Palaniswamy et al. 2014) up to a distance of $\approx 2.2$ Gpc with $S/N = 10$). These rates are marked in Figure 4. To be consistent with the expected rates, $L_0$ should be higher for smaller $\alpha$ (blue and aqua green regions). In general $\alpha \lesssim -1.0$ and $L_0 \gtrsim 10^{42}$ erg s$^{-1}$.

Luo et al. (2020) finds from real FRBs luminosity function parameters $L_0 = 2.9 \times 10^{44}$ ergs$^{-1}$, $\alpha = 1.79$ and a volumetric rate of $\phi^\star = 339$ Gpc$^{-3}$ yr$^{-1}$. This corresponds to an all-sky rate of $R_0 \approx 42.4$ sky$^{-1}$ day$^{-1}$ at $1.4$ GHz. From Figure 4, and Equation 8 we find that for $L_0 = 2.9^{+1.9}_{-1.7} \times 10^{44}$ ergs$^{-1}$ and $\alpha = 1.8^{+0.2}_{-0.3}$ gives $R_0 = 128$ sky$^{-1}$ day$^{-1}$ for 95% non-detection probability. This upper limit $R_0$ is $\approx 3$ greater than found by Luo et al. (2020). We further note that the all-sky FRB rate for repeaters will be a fraction of this rate.

The all-sky rate may be expressed as

$$R(S) = R_0 \left( \frac{S}{S^\star} \right)^\alpha,$$

where $S$ is the minimum flux density, $R_0$ is the reference rate and $\alpha$ is the source count index from the log N-log S relation (Lawrence et al. 2017). For $\alpha = -0.83$ and $S = 0.036$ Jy (Agarwal et al. 2020), we place an upper limit of $R_0 \approx 4200$ sky$^{-1}$ day$^{-1}$ for a likelihood of 95%. This is a factor of $\approx 3.6$ higher than the all-sky rate estimate $R_0 = 1140$ sky$^{-1}$ day$^{-1}$ (Agarwal et al. 2020).

5 CONCLUSION

We conducted a single-pulse search for FRBs from 12 well-localized targets that show evidence for magnetar formation. The target list includes six GRB-SNe, four sGRBs, one IGRB without a SN association, and GW170817, for which the merger remnant is undetermined. These searches were conducted $\sim 1$–$15$ years after the explosion. We show that large single-dish telescopes are well suited to detect FRBs from such extragalactic targets at Gpc distances. Our searches resulted in candidates that were confirmed to be either RFI or single pulses from the known test pulsars. Our constraints on the FRB luminosity function parameters, based on non-detection, are consistent with published values. We further place an upper limit on the all-sky rate that is $\approx \times3$ larger than what is reported in Luo et al. (2020).

The detection of a late-time FRB signal from a GRB site would undoubtedly be the smoking gun signature of magnetar birth which would have a tremendous scientific impact with vast implications for fundamental physics and cosmology for this decade (Law et al. 2019). New wide-field radio telescopes have more than doubled the number of FRBs over the last two years. However, even with the increased number of bursts in the last two years, mechanisms that produce FRBs remain a mystery. Determining the observing cadence remains one of the main challenges in targeted searches. If FRBs are indeed related to explosive events, a better understanding of the emission process and the environment of the explosion will help determine factors such as time for radiation to escape and thereby an observing cadence for future targeted searches. Novel techniques to catch possible radio bursts from gravitational wave counterparts are emerging (Clancy et al. 2019). Better algorithms that reduce the number of candidates and distinguish between RFI and real transients are also in place. Furthermore, even though radio telescopes with large fields-of-view is dominating FRB searches, sensitive single-dish telescopes will continue to play a crucial role in follow-up searches at targeted locations.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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