Detection of two bright FRB-like radio bursts from magnetar SGR 1935+2154 during a multi-frequency monitoring campaign

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ABSTRACT

The recent CHIME/FRB and STARE2 detection of an extremely bright (fluence ∼ MJy ms) radio burst from the Galactic magnetar SGR 1935+2154 supports the hypothesis that (some) fast radio bursts (FRBs) are emitted by magnetars at cosmological distances. With the aim of detecting more bursts from SGR 1935+2154, we performed monitoring observations of the source using (up to) four small radio telescopes observing simultaneously at complementary radio frequencies, spanning the range from 327 MHz to 8.6 GHz. In close to four weeks of almost daily monitoring (265 hrs on source) we detected two bright radio bursts that are separated in time by only 1.4 seconds, i.e. separated by 43% of the 3.25-s rotational period of this neutron star. The bursts have fluences of 112 ± 22 Jy ms and 24 ± 5 Jy ms, respectively, and we measure a scattering time scale of 313 ± 31 μs at 1.32 GHz. Given the proximity of the bursts in time, we estimate the shape parameter k and rate parameter r of an assumed Weibull distribution and find k significantly less than one. This suggests a non-Poissonian, clustered emission process and is consistent with what has been measured for FRB 121102. Together with the CHIME/FRB and STARE2 burst, as well as a faint (fluence 60 mJy ms) burst reported by FAST, these observations demonstrate that SGR 1935+2154 can produce bursts with apparent energies spanning roughly 7 orders of magnitude. This raises the question whether they all arise from similar physical processes and whether the FRB population distribution extends to very low energies (∼ 10^{30} erg, isotropic equivalent).

Keywords: Fast Radio Bursts, Magnetars, SGR 1935+2154

1. INTRODUCTION

Fast radio bursts (FRBs) are bright (fluence ∼0.1 – ∼100 Jy ms), short-duration (∼10 μs – ∼10 ms), coherent radio signals of an unknown, extragalactic origin. Some have been seen to repeat from the same sky position and inferred distance (Spitler et al. 2016), while others have, as yet, not. In the case of repeating signals the term FRB is also used to refer to the source of the signals itself.

Many different progenitor and emission models have been proposed to explain the FRB phenomenon (see Platts et al. 2019, for a catalogue of FRB models), with one popular class of theories invoking neutron stars with exceptionally strong (10^{14} – 10^{16} G) magnetic fields, commonly known as magnetars. Until now, the absence of multi-wavelength detections of prompt emission (Scholz et al. 2017) as well as the large distances to FRBs (FRB 180916.J0158+65 is the closest known, at ∼ 150 Mpc, Marcote et al. 2020) have made it hard to study their broadband emission mechanism and local environments. This limits the avenues to differentiate between competing models. The localization of very nearby (tens of Mpc) FRBs could help, as would the discovery of an FRB source, at kpc distances, in the Milky Way.

On 28 April 2020 a breakthrough was made when The CHIME/FRB Collaboration et al. (2020a) and Bochenek et al. (2020c) independently detected an extremely bright radio burst from Galactic magnetar SGR 1935+2154, using the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst Project (CHIME/FRB; CHIME/FRB Collaboration et al. 2018) and the Survey for Transient Astronomical Radio Emission 2 (STARE2; Bochenek et al. 2020b), respectively. The reported burst fluence was 1.5 MJy ms at 1.4 GHz (Bochenek et al. 2020c), and the equivalent isotropic energy of the burst was approximately three orders of magnitude greater than any previously observed magnetar radio burst. If placed at the distance of FRB 180916.J0158+65, the burst would...
still have been detectable using a large single-dish telescope like Arecibo or the Five-hundred-meter Aperture Spherical radio Telescope (FAST; Nan et al. 2011). These detections strongly suggest that at least some FRBs are produced by magnetars. For this reason, this burst has been referred to as FRB 200428 in the literature. While it is not conclusively established that this burst comes from the same physical process(es) as extragalactic FRBs, we will nonetheless use this nomenclature for the rest of this paper.

A few days after the announcement of FRB 200428, Zhang et al. (2020a) used FAST to detect a much fainter (fluence 60 mJy ms), highly linearly polarized burst from SGR 1935+2154. Its polarization properties are very similar to FRB 121102 (Michilli et al. 2018) and FRB 180916.J0158+65 (CHIME/FRB Collaboration et al. 2019).

In addition to the CHIME/FRB and STARE2 radio burst detection of FRB 200428, a bright, hard X-ray burst was detected independently by the Konus-Wind (Ridnaia et al. 2020), INTEGRAL (Mereghetti et al. 2020), AGILE (Tavani et al. 2020), and Insight-HXMT (Li et al. 2020a) satellites. This hard X-ray burst is temporally coincident with the radio pulse after accounting for dispersive delay. SGR 1935+2154 has been known to undergo periods of X-ray outbursts in 2014, 2015, and 2016, but simultaneous radio observations at these times did not produce any significant detections (Younes et al. 2017). The radio bursts from this most recent outburst are thus the first to be detected from this source, and the simultaneous radio/X-ray detection is a first for any Galactic magnetar (or FRB source) in general.

FRB models that invoke a magnetar origin come in a variety of flavors (Platts et al. 2019). Given the short-durations and high brightness temperatures of FRBs, highly magnetised neutron stars have always been a natural ingredient for models, but debate remains about whether the emission region of the radio burst is close to the neutron star (i.e. within or just outside its magnetosphere; e.g., Kumar et al. 2017), or whether they originate much further out in a relativistic shock (e.g., Metzger et al. 2019, via a synchrotron maser mechanism). Whether the magnetar is a lone actor, or is externally influenced is also an important open question. Magnetospheric radio emission could be triggered (or obscured) by an external plasma stream – e.g., the relativistic jet of a nearby accreting black hole (Zhang 2018), or the wind of a massive binary stellar companion (Lyutikov & Popov 2020).

The identification of periodic activity in at least one repeating FRB (The CHIME/FRB Collaboration et al. 2020b) is suggestive of such interaction, within a binary system, but stands in contrast with the fact that SGR 1935+2154 is an isolated source.

The detection of more radio bursts from SGR 1935+2154, and a more detailed characterisation of its activity levels, can help understand whether it is genuinely an FRB source, with similar physical nature to the sources of (repeating) extragalactic FRBs. Given the great brightness of FRB 200428, a coordinated campaign of small radio telescopes (25-m diameter) with large on-sky time (hundreds of hours) can complement deeper, but shorter campaigns using larger radio telescopes. Furthermore, the relatively narrow-band emission seen from some FRBs (Hessels et al. 2019; Gourdji et al. 2019; Majid et al. 2020) motivates a coordinated, multi-telescope campaign that spans a wide range of radio frequencies simultaneously.

In this article, we discuss such a coordinated multi-frequency observing campaign of SGR 1935+2154 that lasted for about four weeks since FRB 200428 was announced by Scholz & CHIME/FRB Collaboration (2020) and Bochenek et al. (2020a). Fortunately, in the final observation of the campaign described here, we detected two bright bursts that were separated in time by only 1.4 seconds. These bursts are about four orders of magnitude fainter than FRB 200428 but also three orders of magnitude brighter than the subsequent burst reported by FAST. In §2 we discuss our observations; in §3 we describe our data analysis and reduction pipeline; in §4 we present our results; and in §5 we discuss the implications of our results in terms of similarities to observed properties of FRBs. Finally, we offer concluding remarks in §6.

2. OBSERVATIONS

2.1. Radio observations

Since the announcement of FRB 200428 by Scholz & CHIME/FRB Collaboration (2020) and Bochenek et al. (2020a), we observed SGR 1935+2154 daily for up to almost 12 hours, starting on April 29 22:45 UT (MJD 58968.94791) and finishing on May 25 09:00 UT (MJD 58994.375). The telescopes involved were the 25-m single dish RT1 at Westerbork in the Netherlands (Wb, P- and L-band), the 25-m and 20-m telescopes at Onsala Space Observatory in Sweden (O8, O6; L- and X-band) and the 32-m dish in Toruń, Poland (Tr, C-band). All stations operated independently as single dishes, recording 2-bit baseband data (circular polarisations) in VLBI Data Interchange Format (VDIF, Whitney et al. 2010) with the local digital base band converters (DBBC2 or DBBC3 systems).

Westerbork RT1: We observed in two different frequency ranges, covering 313.49 – 377.49 MHz (P-band) split into eight 8 MHz-wide subbands during part of each run. The other part of a run covered 1259 – 1387 MHz (L-band) split at first into four 32-MHz-wide bands (29 April - 19 May) which was later changed to eight 16-MHz-wide bands (20 – 25 May) for easier processing. We recorded 3-minute
scans with a 1-minute gap in between scans during the first seven runs (29 April – 06 May); for the remaining 11 observations this was changed to 10-minute recordings and 20-second gaps. At the beginning of both the P-band observations and the L-band observations we observed either pulsar PSR J1921+2153 or the pulsar PSR J1935+1616 as test sources to verify the system.

**Onsala:** The Onsala 25-m dish (O8) observed at L-band with varying frequency ranges and bandwidths over 14 nights. We recorded the entire available bandwidth of 512 MHz between 1222 – 1739 MHz during the first three observations (29 April - 02 May). Owing to the large fraction of radio frequency interference (RFI, ∼ 50%) in the band we subsequently tested setups with 256 MHz of continuous bandwidth placed within the above range (02-09 May). Eventually, we settled for a 128 MHz-wide band split into eight 16-MHz-wide bands between 1360 – 1488 MHz (09-15 May, Table A1). We observed either PSR J0358+5413 or PSR J1935+1616 as test sources towards the beginning of the observations. For two runs (06–08 May) the Onsala 20-m telescope (O6) joined the observations covering the frequency range 8080 – 8592 MHz (X-band), split into sixteen 32-MHz-wide subbands. Both stations O8 and O6 observed for five to twelve hours during each run, recording 15-minute scans with a 12-second gap in between scans.

**Toruń:** The 32-m dish at Toruń (Tr) observed at C-band for about 8 hours during a total of 19 nights. We recorded the entire 256 MHz of bandwidth covering the frequency range of 4550 – 4806 MHz, split into eight 32 MHz wide subbands. We performed 5-minute scans on the tests pulsars at the beginning and the end of each observing run. During the first six nights (29 April – 5 May) we scheduled a main 15 min observing loop that consisted of 880 seconds of recording on SGR 1935+2154 and 20-second gaps dedicated to gain correction. For these first runs we observed PSR J1935+1616 and PSR J2022+2854 as the test sources. Thereafter we increased the gaps by 10 seconds but the length of the observing loop was left unchanged. Also, from 5 May onwards only PSR J2022+2854 was observed for the system performance checking. We also observed during the night of 3 May 2020 for which Li et al. (2020c) reported a bright X-ray burst but due to a wrong setup the antenna was off source, hence all data were discarded.

2.2. **Simultaneous X-ray observations**

In order to investigate the presence of X-ray bursts from SGR 1935+2154, we searched the HEASARC\(^1\) archive for X-ray observations performed simultaneously with our radio observations. Publically available pointed observations were taken by the Neutron star Interior Composition Explorer (NICER; Gendreau et al. 2016) and the Neil Gehrels’s Swift Observatory (Swift; Gehrels et al. 2004), observing SGR 1935+2154 two (ObsIDs 3020560107/8) and nine (ObsIDs 00033349049/50/56/58/60-63/66) times during the radio campaign, respectively. In addition, the target was in the field of view of the monitoring instruments aboard Swift (the Burst Alert Telescope or BAT) and Fermi (the Gamma-ray Burst Monitor or GBM; Atwood et al. 2009) the majority of the time. Swift/BAT only records data in time-tagged event (TTE) mode high time resolution (∼ 0.2 ms) around automatic burst triggers, but did not report any burst triggers during the radio observations. Fermi/GBM instead always records in TTE mode with a 2 µs time resolution. Therefore, we focused on the Fermi/GBM data at times of particular interest in the radio campaign. Finally, we considered the observing schedule\(^2\) and burst list\(^3\) from the Hard X-ray Modulation Telescope (HXMT; Zhang et al. 2020b) as reported by Li et al. (2020b).

3. **DATA REDUCTION AND ANALYSIS**

3.1. **Radio observations**

The baseband data from each participating station was shipped via the internet to Onsala Space Observatory (OSO) where we searched the data with a pipeline that was developed to search for FRBs in baseband recordings. We performed the following steps on each scan:

1. Create separate (baseband) files for each subband;
2. Channelize and detect each subband;
3. Splice all subbands together into one filterbank;
4. Dedisperse the filterbanks and search for bursts;
5. Classify and inspect burst candidates;
6. Create coherently dedispersed filterbanks for the best candidates and verify.

In the current recording setup the data are sampled as 2-bit real numbers. Each scan is recorded in a single VDIF-file that contains both polarisations of all \(N\) subbands. The software package that we use to channelise the baseband data and create total intensities (digifil from DSPSR; van Straten & Bailes 2011) can currently only unpack VDIF files that contain two polarisations of one single subband. Therefore, prior to creating 8-bit filterbanks with digifil we use jive5ab\(^4\) to split each scan into \(N\) separate files that contain both circular polarisations. Each subband is channelised and detected

\(^{1}\) https://heasarc.gsfc.nasa.gov
\(^{2}\) http://enghxmt.ihep.ac.cn/dqjh/317.jhtml
\(^{3}\) http://enghxmt.ihep.ac.cn/bfy/331.jhtml
\(^{4}\) https://github.com/jive-vlbi/jive5ab
Table 1. Range of dates of the observations

| Station | Dates observed in 2020 | Band | Bandwidth [MHz]| SEFD [Jy]| Completeness [Jy ms] |
|---------|------------------------|------|---------------|---------|---------------------|
| Wb      | 29 April – 11 May      | P, L<sub>Wb</sub>| 40, 100       | 2100, 420| 78, 10              |
|         | 18 May – 25 May        | P, L<sub>Wb</sub>| 40, 100       |          |                     |
| O8      | 29 April – 15 May      | L<sub>O8</sub>| 100, 175, 250 | 350     | 8, 6, 5             |
| Tr      | 29 April – 05 May      | C    | 240           | 220     | 3                   |
| O6      | 05 May – 08 May        | X    | 500           | 785     | 8                   |

<sup>a</sup> Wb: Westerbork RT1, O8: Onsala 25m, Tr: Toruń, O6: Onsala 20m.

<sup>b</sup> P: 314 – 377 MHz; L<sub>Wb</sub>: 1260 – 1388 MHz; L<sub>O8</sub>: varying ranges between 1227 – 1739 MHz, see full details in Table A1; C: 4550 – 4806 MHz; X: 8080 – 8592 MHz.

<sup>c</sup> Effective bandwidth accounting for RFI and band edges.

<sup>d</sup> From http://old.evlbi.org/user_guide/EVNstatus.txt

<sup>e</sup> Assuming a 7σ detection threshold

Figure 1. Overview of the observations of SGR 1935+2154 during this campaign. Both panels show 15.5 days, with observations color-coded by observing frequency. Vertical lines indicate the times of reported bursts. Solid line: events found in our campaign; long-dashed: CHIME and STARE2 detections (Scholz & CHIME/FRB Collaboration 2020; Bochenek et al. 2020a); dotted: detection by FAST (Zhang et al. 2020a); dash-dotted: X-ray bursts as reported by a) Ursi et al. (2020), b) Hurley et al. (2020) and Verrecchia et al. (2020), c) a Fermi/GBM trigger on May 20, 2020 at 21:47:07.548 UT. During X-ray events b) and c) no radio counterparts were found in any of our data which allows us to put upper limits on the fluences as listed in Table 1. Unfortunately we can draw no conclusions from our data coincident with event a) because Wb was in a recording gap and O8 was affected by strong RFI.

separately (but simultaneously) and the resulting filterbank files are combined in one single file that contains the entire observed frequency range with the utility splice from SIGPROC (Lorimer 2011). The time resolution of the filterbanks at L-, C-, and X-band is 64 µs while the frequency resolution is 125 kHz, 250 kHz and 2 MHz, respectively. Given the dispersion measure (DM) of SGR 1935+2154 (DM<sub>SGR</sub> = 332.7206 ± 0.0009 pc cm<sup>−3</sup>; The CHIME/FRB Collaboration et al. 2020a), this implies a maximal intra-channel time smearing of < 190 µs in our lowest channel at L-band (1227 MHz). The filterbanks created from the P-band data have a much finer channelisation (7.8 kHz) to limit residual intra-channel time smearing to ~ 700 µs at the lower end of the band. Time resolution is accordingly lower (1 ms) than in the other bands.

We manually inspect subsections of the data from each station to identify frequency ranges that are continuously affected by radio frequency interference (RFI). Based on this analysis we create channel masks for flagging that are passed on to all subsequent steps of the burst search pipeline.

We search the filterbanks for bursts with Heimdall<sup>5</sup> as the dedispersion and burst finder engine. Since the dedispersion is known <i>a priori</i> we do not perform a full search

<sup>5</sup> https://sourceforge.net/projects/heimdall-astro/
Figure 2. Band-averaged profiles (top) and dynamic spectra (bottom) of B1 (left panels) and B2 (right panels) as detected by Westerbork RT1. To the right of each dynamic spectrum we show the time-scrunched, bandpass-corrected spectra. The bursts are plotted with a time and frequency resolution of 32 µs and 500 kHz, respectively, and are coherently de-dispersed using a DM of 332.7 pc cm$^{-3}$. The dark cyan bars represent the full-width at half-maximum (FWHM; Table 2) of the burst profile as determined with a Lorentzian fit to the autocorrelation function of the bursts in the time direction. The light cyan bars are 2 and 1.5 times the FWHM of B1 and B2, respectively. The cyan bars are placed such that they maximize the derived fluence. The spectra of the bursts are the summation of the dynamic spectrum under the light cyan bar. The total intensity burst profile is shown in black, the red and blue profiles represent the Faraday-corrected linear and circular polarisation, respectively. The white bands marked with red ticks in the dynamic spectra indicate frequency channels that have been masked due to subband edges. For visual purposes the limits of the color map have been set to the 1st and 99th percentile of the dynamic spectrum. The dark bands in the 1.325–1.335 GHz region are due to persistent RFI, which is seen throughout the entire observation.
in DM-space but instead limit the search range to DM$_{\text{sgr}} \pm 50$ pc cm$^{-3}$. The candidates found by Heimdall above a signal-to-noise (S/N) threshold of seven are then classified either as RFI or potential candidates by FETCH (Agarwal et al. 2019). We inspect the candidates by eye and, as a final step, we use the software correlator SFXC (Keimpema et al. 2015) to create coherently dedispersed filterbanks around the times of the most convincing candidates, for final verification.

As mentioned above, we observed well-known pulsars in each observing run to verify the integrity of our data and the reliability of our processing pipeline. To that end, we perform the steps described above also on the pulsar scans. In addition, we fold the filterbank files that contain a scan of a pulsar with DSPSR’s dspsr and inspect the folded profiles. The respective pulsars were detected each time with the exception of PSR J1921+2153 observed with Wb at L-band. At this frequency the pulsar was detected only about half the time, which we attribute to diffraction scintillation. The test pulsar PSR J1935+1616 is bright enough to detect several individual pulses with our pipeline almost each time it is observed.

3.2. X-ray observations

To search for X-ray bursts during the two NICER and nine Swift/X-ray Telescope (XRT) pointed observations, we followed standard data reduction procedures in HEA-SOFT v6.25 to extract light curves, using the latest calibration files via the online database caldb\textsuperscript{6}. The NICER data were reduced using nicerdas, applying standard filtering with additional constraints (SUN\_ANGLE > 60° and COR\_SAX > 4) generated with nimaketime and applied with niextract-events. For Swift/XRT, we applied the xrtpipeline v0.13.4. After data calibration, we extracted light curves for both observatories using xselect v2.4e at various time resolutions: 0.004, 0.1, and 1 second for NICER, 0.1 and 1 second for Swift/XRT in Window-timing mode, and 2.6 second for the Swift/XRT in Photon-counting mode. Finally, we checked our methods by following the same procedures for NICER observation 3020560101, which did not overlap with the radio campaign but was reported to contain numerous X-ray bursts by Younes et al. (2020). We clearly recover the X-ray bursts reported therein, confirming our data reduction procedure.

For Fermi/GBM, we focused primarily on two events: firstly, the GBM trigger on an X-ray burst of SGR 1935+2154 on 2020 May 20, 21:47:07.548 UT (event bn2005020908), and secondly the TTE data on 2020 May 24 22:00–23:00 UT, during which we observed radio bursts (see Section 4). For the GBM trigger data, we analysed the gspec files of detectors n3, n6, and n7, which showed the strongest bursts in the quicklook images. Using gspec v0.9.1, we extracted burst and background spectra per detector for the SGR 1935+2154 burst, which we then fitted jointly using xspec v12.10.1. To analyse the TTE data on 2020 May 24, we used the gtbin tool in the FERMITOOLS package to extract light curves at a 0.1 and 0.25 second time resolution for all twelve GBM detectors. We then used the fermi gbm data tools v1.0.2, combined with the spacecraft pointing, to measure the viewing angle between each GBM detector and SGR 1935+2154. This comparison confirms that the source was visible during the radio bursts and reveals that detectors n9 and n0 had the smallest viewing angles, at ~ 40° and ~ 10°, respectively.

While Fermi/GBM triggered several additional times after the start of our radio campaign, none of these events usefully overlapped with our radio campaign: trigger bn200503976 on 2020 May 3, also reported by Ursi et al. (2020) and Li et al. (2020c), fell into a recording gap at Wb, while O8 was affected by exceptionally strong RFI and Tr antenna was off source. On 2020 May 10, Fermi passed through the South Atlantic Anomaly during the X-ray burst reported by Hurley et al. (2020) and no TTE data was recorded. Later on May 10, Fermi/GBM trigger bn200510911 occurred just before the start of our radio observations.

4. RESULTS

We detected two bursts on 24 May 2020 at barycentric arrival times 22:19:19.67464 UT and 22:19:21.07058 UT (B1 and B2, respectively, dispersion corrected to infinite frequency). Heimdall detected the bursts at a S/N of 81.9 for B1 and 24.6 for B2 in the data downsampled to a time resolution of 512 µs. FETCH, in turn, reports a probability of 1.0 for both bursts to be of astrophysical origin. To optimize the DM we run the PSRCHIVE (van Straten et al. 2011) tool pdmp on each burst separately which yields DM$_{\text{B1}} = 332.85 \pm 0.21$ pc cm$^{-3}$ and DM$_{\text{B2}} = 332.94 \pm 0.21$ pc cm$^{-3}$ for B1 and B2, respectively. These values are consistent with DM$_{\text{sgr}}$ as measured by The CHIME/FRB Collaboration et al. (2020a), albeit slightly higher. We attribute the higher DM to the optimization algorithm employed by pdmp which essentially maximizes the S/N of the burst by modifying the DM. Given the scattering tails of the bursts, this can lead to a peak in S/N at a DM higher than the true value. Thus we subsequently create coherently dedispersed filterbanks with SFXC using DM$_{\text{sgr}}$. In Figure 2 we show the resulting dynamic spectra and full-polarisation burst profiles.

A coherently dedispersed filterbank with a time resolution of 8 µs and a frequency resolution 500 kHz is used to determine the arrival times, fluences, peak flux densities, spectral energy densities, intrinsic pulse widths, observed burst widths and scattering time scales. The dynamic spectra are

\textsuperscript{6} https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_intro.html
Figure 3. Time series of bursts B1 (panels a and b) and B2 (panel c) fitted with a Gaussian distribution convolved with a one-sided exponential decay. For B1 we attempted both a single-component fit (panel a) and a two-component fit (panel b) in which we keep the scattering time, \( \tau \), the same for both components (orange and purple lines show the individual components). The bottom panels show the residuals for each fit. Gray dots display the raw data, the best fits are solid green lines and, for visual purposes, a 56 \( \mu s \) running average has been plotted as a solid black line. Fitting results are displayed in each panel where \( \tau \) and \( w \) denote the fitted scattering time scale and width of the Gaussian, respectively. In panel b we fit separate widths, \( w_1 \) and \( w_2 \), for each component and denote the delay between the peaks of the two Gaussians as \( \delta t \). It is obvious from the residuals and the quality of the fits that a two-component model provides a much better fit to B1 (see text for details).

We fit a Lorentzian distribution to the autocorrelation function of the time series to determine the full-width at half-maximum (FWHM) of the burst profiles. The resulting observed burst widths are 866 \( \pm \) 43 \( \mu s \) for B1 and 961 \( \pm \) 48 \( \mu s \) for B2, and are shown using a dark cyan bar in Figure 2. The fluences of the bursts are determined by integrating over the light cyan bar shown in Figure 2, which have widths of 2 and 1.5 times the FWHM for B1 and B2, respectively. These factors were chosen such that the light cyan bars fully cover the entire burst envelope. The fluence and peak flux density are converted to physical units using the radiometer equation (Cordes & McLaughlin 2003), and the spectral energy density is determined assuming a distance to SGR 1935+2154 of \( d = 9.0 \pm 2.5 \) kpc (Zhong et al. 2020). The burst properties are presented in Table 2.

To determine the scattering times, a Gaussian profile convolved with an exponential decay, i.e. a thin screen model, is fit to each profile. As can be seen in the top panel of Figure 2, B1 exhibits a double-peaked profile. Therefore, we fit both a single and a double component burst to the profile of B1. For the double component fit, the decay time was fixed for both components. We find a reduced chi-square value \( \chi^2_r = 1.6 \) for the single component fit and \( \chi^2_r = 1.2 \) for the double component fit. Furthermore, the difference in the \( \chi^2 \) value, \( \Delta \chi^2 \), is 136 for three additional degrees of freedom, which indicates that the double component fit is a > 11\( \sigma \) improvement over the single component fit. We conclude that B1 is consistent with exhibiting a double component temporal structure. For B2 we find \( \chi^2_r = 1.0 \). The double component fit for B1 and the single component fit for B2 result in scattering times \( \tau_{B1} = 315 \pm 12 \mu s \) and \( \tau_{B2} = 299 \pm 29 \mu s \). The weighted average is \( \bar{\tau} = 313 \pm 31 \mu s \) at 1324 MHz, where we added the uncertainties in quadrature. Within the model of a thin scattering screen, \( \bar{\tau} \) implies a scintillation bandwidth of about 500 Hz. An autocorrelation analysis of coherently dedispersed data with a frequency resolution of 488 Hz yields no scintillation bandwidth larger than the width of one channel. Producing a filterbank with even higher frequency resolution would require a time resolution of > 4 ms, i.e. would reduce the S/N of any apparent scintillation.

Given the system equivalent flux density (SEFD) and available bandwidth at each station we estimate our burst searches to be complete to the 7\( \sigma \)-fluence limits listed in Table 1.

4.1. Polarimetric properties of the bursts

We used full-polarisation data, with time and frequency resolution 32 \( \mu s \) and 125 kHz, respectively, to study the polarimetric properties of the bursts from SGR 1935+2154. In
Uncertainties are based on a 20%-uncertainty in the system temperature measurements. As per the sum of both widths from the 2-component fit in Figure 3.

We then perform a joint QU fit to Stokes parameters Q/I and U/I as a function of frequency, ν, using the following equations:

\[ \frac{Q}{I} = L \cos(\nu^2 \phi + \nu d + \phi), \] (1)
\[ \frac{U}{I} = L \sin(\nu^2 \phi + \nu d + \phi), \] (2)

where we fit for the linear polarisation fraction L, the delay between the hands d, and \( \phi = \phi_0 + \phi_{\text{inst}} \), where \( \phi_0 \) is the absolute angle of the polarisation on the sky (referenced to infinite frequency), and \( \phi_{\text{inst}} \) is the phase difference between the polarisation hands. We set the RM as the known RM of PSR J1935+1616, \(-10.2 \text{ rad m}^{-2}\), and c is the speed of light. We find \( d \approx -9 \) to \(-6 \) ns.

We assume that there are no significant changes to the calibration required between the test pulsar scan and the detected bursts as the respective scans are less than 1 hr apart.\(^7\) We apply the 10% leakage calibration to the bursts detected from SGR 1935+2154. We first run \texttt{rmapft} to find the RM that maximises the linear polarisation, and then perform a QU fit limiting the range of d to be within \(-9 \) and \(-6 \) ns, now fitting for RM. For burst B2, we find the \texttt{rmapft}-measured RM to be \( \approx 82 \text{ rad m}^{-2} \) higher than what was expected from the previously measured RM from a SGR 1935+2154 radio burst (112.3 rad m\(^{-2}\); Zhang et al. 2020a), but consistent with our RM offset measured for PSR J1935+1616. Additionally, the joint QU fit for burst B2 gives an RM consistent with 112.3 rad m\(^{-2}\) (Zhang et al. 2020a) for a delay d in the range \(-9 \) to \(-6 \) ns.

For burst B1, however, we see no clear peak in linear polarisation using \texttt{rmapft}. The lack of a clear peak is unlikely to arise from a significant change to the calibration solutions, since we find consistent results from PSR J1935+1616 (before burst B1) and burst B2 (1.4 s after B1). Instead, it is possible that the double-component structure seen in B1 is, in fact, two independent bursts (supported also by Figure 3), overlapping in time such that their polarisation properties are superimposed which, effectively, leads to a depolarised signal.

\(^7\) Since Wb has an equatorial mount we also do not need to apply any corrections regarding the hour angle.
We assume that the RM has not changed significantly between the two bursts, i.e. the RM of burst B1 is consistent with B2 (and as a result, consistent with the previously measured value 112.3 rad m$^{-2}$). We use the rmfit-determined RM to de-Faraday both B1 and B2.

In Figure 2 we show the Faraday-corrected polarisation profiles of both bursts. In Table 2, we quote the approximate linear and circular polarisation fractions for B1 and B2 determined by summing the polarisation profile and dividing by the sum of the Stokes I profile.

4.2. X-ray bursts during the radio campaign

The pointed Swift and NICER observations did not reveal any X-ray bursts from SGR 1935+2154. While the source was in the field of view of Fermi/GBM during the two radio bursts on 2020 May 24, no simultaneous X-ray bursts were detected. HMXT was not observing SGR 1935+2154 during the radio bursts (Li et al. 2020b).

On the other hand, several X-ray bursts were observed overlapping with our radio monitoring, without an associated radio burst detection. As discussed in Kirsten et al. (2020), no radio bursts were seen during the X-ray burst detected on 2020 May 10 with several X-ray instruments (Hurley et al. 2020). Similarly, no radio burst was observed when Fermi triggered on a SGR 1935+2154 burst on 2020 May 20 (event bn200520908). We fit the spectrum of this burst with a double blackbody model ($BB_1 + BB_2$ in xspec), adding a cross-correlation multiplication constant between the spectra from detectors n3, n6, and n7. We measure temperatures of $kT_{BB,1} = 5.2 \pm 0.4$ keV and $kT_{BB,2} = 16.7^{+6.7}_{-3.8}$ keV for a fit with $\chi^2_r = 137.8/129 = 1.07$. We measure a 8–200 keV fluence of $(3.6 \pm 0.3) \times 10^{-7}$ erg cm$^{-2}$.

Comparing the HMXT burst list with the radio campaign, we find 59 X-ray bursts overlapping the radio observations (see Table A2). None of these are accompanied by a radio burst. At the time of writing, no information beyond fluence and $T_{90}$ values are reported for these bursts (Li et al. 2020b). The brightest of these 59 overlapping X-ray bursts had a fluence of $2.01 \times 10^{-6}$ erg cm$^{-2}$, significantly brighter than the Fermi burst discussed above.

5. DISCUSSION

5.1. Burst statistics

If a stochastic process can be described as a Poisson point process with a constant rate parameter $r$, then the random variable describing the wait times $\delta$ between events generated by the process will follow an exponential distribution,

$$f(\delta | r) = re^{-r\delta}. \quad (3)$$

On the contrary, repeating FRBs are known to show clustering in their burst patterns, and therefore cannot be described with a Poisson model. As described in Oppermann et al. (2018), a possible generalization of the wait time distribution is given by the Weibull distribution,

$$f(\delta | k, r) = \frac{k}{\delta} \left(\frac{\delta r}{1 + k^{-1}}\right)^{k-1} e^{-\left(\frac{\delta r}{1 + k^{-1}}\right)^k} \quad (4)$$

with shape parameter $k$ and rate parameter $r$, which reduces to an exponential distribution if $k = 1$. Here $\Gamma$ is the Gamma function. The posterior distribution of $k$ and $r$ can therefore be used to test whether the data supports a Poissonian model, because Poissonian data should necessarily produce a posterior distribution consistent with $k = 1$. To calculate the posterior distribution, we follow the formalism described in Oppermann et al. (2018). We only include scans at Westerbork and Onsala L-band, and to avoid possible correlations between scans, we only include scans at Westerbork and Onsala which do not overlap. Therefore, we assume that all scans are independent, and calculate the total likelihood of the data as the product of the likelihoods of each individual scan. For the scan containing B1 and B2, we use the topocentric arrival time from the beginning of the scan to calculate the likelihood function. Finally, we use a uniform prior distribution and calculate the posterior distribution in the usual way as

$$\text{Post}(k, r | \mathcal{D}) \propto L(\mathcal{D} | k, r) f(k, r) \quad (5)$$

where $L(\mathcal{D} | k, r)$ represents the likelihood of all the data, and $f(k, r)$ represents the prior. This procedure produces the plot...
shown in Figure 4. The most likely values of \( k \) and \( r \) taken jointly is \( k = 0.2 \) and \( r = 0.38 \) day\(^{-1}\). Moreover, the 68\% confidence interval for \( k \) is 0.12–0.29, while the 68\% confidence interval for \( r \) is 0.33–3.47 day\(^{-1}\). Therefore the data does not support a Poissonian model, and there is evidence for clustering. Interestingly, the 68\% confidence interval for \( k \) is consistent with the value of \( k \) derived for FRB 121102 by Oppermann et al. (2018), and the 95\% confidence interval for \( k \) (0.08–0.46) is consistent with the value for FRB 121102 as derived by Oostrum et al. (2020). This is an intriguing similarity between repeating extragalactic FRBs and SGR 1935+2154, although we cannot draw inferences about the exact mechanism itself.

5.2. Polarimetry

Zhang et al. (2020a) presented the detection of a low-fluence, high linearly-polarised burst from SGR 1935+2154 with FAST. This burst was consistent with being 0\% circularly polarised. This is in contrast to the polarisation properties of the two bursts presented in this work. We find B1 and B2 to have approximately equal linear and circular polarisation, and neither showing any evidence of L/I \( \sim \) 100\%. Burst B1 exhibits no significant polarisation (< 10\%).

Using burst B2, we find a consistent Faraday RM with the previously measured value (112.3 rad m\(^{-2}\); Zhang et al. 2020a). However, for the higher S/N burst in this work, B1, we could not determine an RM, due to the low linear polarisation fraction. This is unlikely to be caused by issues in our polarimetric calibration since we do not have this issue in the test pulsar scan (\( \sim 1 \) hr before B1) or for B2 (\( \sim 1.4 \) s after B1).

Radio magnetars show a wide range of polarisation properties (e.g. Kramer et al. 2007, Camilo et al. 2008, Levin et al. 2012). It is, of course, possible that B1 and B2 are intrinsically not \( \sim 100\% \) polarised. Below we explore ways in which the observed linear polarisation could be reduced.

We find evidence for scattering in the burst profiles of both B1 and B2. Camilo et al. (2008) and Levin et al. (2012) observe, in general, a lower linear polarisation fraction at 1.4 GHz when compared with higher frequencies for the radio magnetars PSR J1622+4950 and 1E 1547.0-5408, respectively. They suggest this could arise (partly) due to interstellar scattering causing the PA to rotate as a function of pulse phase resulting in an lower observed linear polarisation. It is possible that scattering has partly depolarised the bursts from SGR 1935+2154, but with no multi-frequency polarimetric observations or polarisation calibrator, this is hard to conclude. In addition, since B1 and B2 occur within \( \sim 1.4 \) s of one another, and show comparable scattering times (when B1 is modelled as two bursts) we expect the depolarisation due to scattering to be comparable between bursts.

Another interpretation for the low linear polarisation observed in burst B1 can arise by invoking the two burst model (also supported by Figure 3), where the polarisation properties of the two bursts are superimposed. This can result in the decrease of linear polarisation.

A diverse range of polarisation properties are also observed for FRBs, with linear polarisation fractions ranging from \( \sim 0 \) to 100\% (e.g. Petroff et al. 2015, Masui et al. 2015, Ravi et al. 2016, Michilli et al. 2018).

5.3. Scattering time scale and scintillation

The CHIME/FRB Collaboration et al. (2020a) report a scattering time \( \tau_{\text{CHIME}} = 759 \pm 0.008 \) \( \mu \)s at a frequency of 600 MHz, while Bochenek et al. (2020c) report a scattering time \( \tau_{\text{STARE2}} = 400 \pm 100 \) \( \mu \)s at 1 GHz. Assuming a thin screen model for scattering and Kolgomorov turbulence, the scattering time scales with frequency as \( \tau \propto \nu^\alpha \), with \( \alpha = -4 \) being the frequency scaling parameter. In this scheme, given the CHIME and STARE2 results we would expect \( 30 \mu s \leq \tau \leq 120 \mu s \) at our central observing frequency \( \nu = 1.324 \) GHz. However, the value we measure is a factor \( \gtrsim 2.5 \) higher (\( \bar{\tau} = 313 \pm 31 \) \( \mu \)s) and would imply a frequency scaling \( \alpha = -1.15 \), i.e. much shallower than the canonical value. We note, however, that the scaling implied by \( \tau_{\text{CHIME}} \) and \( \tau_{\text{STARE2}} \) is very similar with \( \alpha = -1.25 \). A number of recent studies of pulsar scattering at low radio frequencies (i.e. \( \nu < 300 \) MHz) also measure values for \( \alpha \) that are lower than the theoretically expected one (e.g. Kirsten et al. 2019; Geyer et al. 2017; Meyers et al. 2017). This can be caused by several factors among which are that the assumption of Kolmogorov turbulence and a single thin scattering screen geometry are in fact not applicable. To measure the scattering time scale we assumed an intrinsic Gaussian pulse shape whose rise time can mimic that expected for an impulsive signal that travels through an extended screen, i.e. a thick screen geometry (Williamson 1972). Moreover, the assumption of a single screen might be invalid as SGR 1935+2154 is associated with the supernova remnant (SNR) G57.2-0.2 (Masui et al. 2015). Thus, besides an interstellar scattering screen about half way towards the source there could well be a second screen within the SNR, i.e. much closer to the magnetar itself. In fact, Simard & Ravi (2020) invoke the existence of such a screen to explain the spectral structure of the burst reported by The CHIME/FRB Collaboration et al. (2020a). In their model, the screen closest to the magnetar causes what can be interpreted as scintillation with a characteristic scintillation bandwidth of \( \Delta \nu_{600} = 100 \) MHz at an observing frequency of 600 MHz. Scaled to our observing frequency this translates to \( \Delta \nu_{1300} = 2200 \) MHz. This is consistent with our observations in the sense that we observe

\footnote{A git repository containing the code used to calculate the posterior distribution and generate Figure 4 can be found at https://github.com/MJastro95}
during a phase of a bright scintil (caused by the screen close to the source) where any scintillation that could be caused by the interstellar screen (that is also the cause for the temporal broadening) is too narrow in bandwidth for us to resolve.

5.4. Simultaneity of X-ray and radio bursts

During the STARE2 radio bursts, with its estimated fluence of > 1.5 MJy ms (Bochenek et al. 2020a), an X-ray burst with a fluence of the order of ~ 6.1 to 9.7 × 10^{-7} erg cm^{-2} was detected by INTEGRAL, Konus-Wind, and HMXT (in different energy ranges between 1 and 500 keV; Mereghetti et al. 2020; Ridnaia et al. 2020; Li et al. 2020a, note that AGILE detected the burst but did not yet report a fluence measurement). The brightest burst seen on 2020 May 24, B1, had a fluence at least four orders of magnitude weaker than the burst seen by STARE2. Assuming a similar ratio between X-ray fluence and radio fluence during both bursts, we would expect a fluence < 10^{-10} erg cm^{-2} in X-rays. As this value is orders of magnitude lower than typical detection thresholds for Fermi (e.g. Wood et al. 2019; Wood & Fermi-GBM Team 2020), it is not surprising that Fermi detects no X-ray bursts during the radio bursts.

Inversely, another three bright X-ray bursts coincident with our campaign were reported and a further 59 overlapping bursts are listed in Table A2. We found no radio counterparts to any of these bursts in our radio observations which allows us to put upper limits to the radio fluences as listed in Table 1. We found that the majority of X-ray/Gamma ray bursts are not associated with pulsed radio emission. The parameters and fluences that we measure for the X-ray bursts discussed in Section 4.2 are consistent with typical values observed for SGR 1935+2154 (Lin et al. 2020a), fitting the idea that radio bursts are instead associated with atypical, harder X-ray bursts (Younes et al. 2020).

5.5. SGR 1935+2154 and implications for FRBs

The 1.396-s separation between bursts B1 and B2 corresponds to 0.43 of SGR 1935+2154’s 3.245-s rotational period. Already with the discovery of the first radio-emitting magnetar, XTE J1810–197, it was evident that radio bursts could occur at a wide range of rotational phases and with varying polarimetric properties (Camilo et al. 2006). The lack of detectable periodicity in repeating FRBs could in principle be attributed to bursts occurring at a wide and varying range of rotational phases (Spitler et al. 2016). This suggests that the bursts occur from varying emission sites, as opposed to being from a relatively stable location of origin, as is the case in rotation-powered radio pulsars. Such a situation is perhaps unsurprising, given the likely strong multi-polar magnetic field components present in magnetars and the dynamic nature of the magnetic field configuration. We note that the lack of contemporaneous phase-coherent rotational ephemeris unfortunately precludes us from comparing the rotational phases of B1 and B2 with those of FRB 200428, the subsequent FAST radio burst, or that of quasi-persistent pulsed X-ray emission. If such an ephemeris were available in the future – spanning other epochs of radio burst activity – it would be invaluable as a reference chart for assigning rotational phases to all detected bursts.

The four reported radio bursts from SGR 1935+2154 span more than seven orders of magnitude in observed fluence. While beaming of the radio emission certainly must affect the observed fluences at some level, this nonetheless demonstrates that SGR 1935+2154’s radio burst emission spans the typical luminosities seen from rotation-powered radio pulsars up to the closest-known extragalactic FRBs. It is unclear whether the four SGR 1935+2154 bursts were produced by the exact same type of physical process, which is then capable of producing bursts over a wide luminosity range, or whether the physics at low and high luminosities is qualitatively different. Neutron stars are known to produce radio bursts of various types (polar-cap pulsar emission, giant pulses, radio magnetar emission). Perhaps the observational differences between the bursts from repeating and (apparently) non-repeating sources are also a reflection of this diversity of emission mechanisms seen from neutron stars.

Observationally, one can pose the question: are low-luminosity radio bursts, that can only be detected from a Galactic source, also ‘FRBs’? The repeater FRB 121102 has been observed to produce radio bursts with fluences spanning 3 orders-of-magnitude; the detection of lower/higher fluences is limited by telescope sensitivity and available observing time, respectively.

We caution that this wide range in observed fluence does not necessarily reflect a wide range of total energy release during the creation of an FRB. As with pulsars, the radio bursts themselves are very likely an insignificant part of the total energy budget. The radio brightness could be more a reflection of microphysics (e.g. coherence conditions) or variable beaming direction than a good proxy for the total energy released during each FRB event.

Overall, SGR 1935+2154 makes a compelling case that there is a link between (at least some) FRBs and magnetars. However, important observational differences remain. For instance, some repeating FRBs have shown periodicity in their activity level, suggesting that the source may be in a binary system. SGR 1935+2154 is not known to be in a binary. Perhaps the distant, active FRB sources are brighter and more active because they are significantly younger and
because their magnetospheres are perturbed by the ionised wind of a nearby companion.

6. SUMMARY & CONCLUSIONS

We observed the Galactic magnetar SGR 1935+2154 in a coordinated multi-telescope multi-frequency monitoring campaign over the course of four weeks. In total we spent 265 hours on source which, given the fact that up to four telescopes observed simultaneously, corresponds to 467 telescope hours. Within this time we detected two bright bursts separated by \( \sim 1.4 \) seconds at the nominal DM of the source. We measure fluences of \( 112 \pm 22 \) Jy ms and \( 24 \pm 5 \) Jy ms for B1 and B2, respectively. Our fluences are four orders of magnitude lower than that of FRB 200428, the burst detected by The CHIME/FRB Collaboration et al. (2020a) and Bochenek et al. (2020c). Moreover, B1 and B2 also three orders of magnitude brighter than the burst detected by Lin et al. (2020b). While FRB 200428 had an X-ray counterpart (Li et al. 2020a), we did not find any X-ray bursts in publicly available data that are coincident with B1 or B2. At this point it is unclear if the same physical mechanism can be accounted for the observed range in burst energies.

Thanks to the availability of baseband data were able to a) characterise the polarisation profiles of both bursts and b) generate filterbank data with various combinations of frequency and time resolution. The second, fainter burst B2 shows moderate levels of linear and circular polarisation while for B1 we detect no significant polarisation. This might either be intrinsic to the source or, alternatively, is an effect of the superposition of the polarisation profiles of the two closely spaced components (separated by \( \delta t = 175 \pm 14 \) \( \mu \)s) that B1 is composed of. We were able to measure a characteristic scattering time scale \( \bar{\tau} = 313 \pm 31 \) \( \mu \)s which, if combined with the scattering time scales measured by The CHIME/FRB Collaboration et al. (2020a) and Bochenek et al. (2020c), indicates a very flat frequency scaling parameter \( \alpha \sim -1.15 \). This suggests that a simple model of a thin scattering screen with Kolmogorov turbulence might not be applicable for this sight line. Instead, a two-screen model as also suggested by Simard & Ravi (2020) might be a more adequate description of the distribution of inhomogeneities towards this source. The close proximity of the two bursts detected within 265 hrs on source suggests that the emission process is highly clustered. We employed a Weibull distribution to determine a shape parameter \( k \ll 1 \) which is well in agreement with a non-Poissonian process (for which \( k = 1 \)). In fact, our results are in agreement with what Oppermann et al. (2018) measured for FRB 121102, hinting at a possible connection between the statistics of bright bursts from a magnetar and FRBs. Furthermore, the Weibull distribution analysis yields a burst rate \( r \) between 0.33 day\(^{-1}\) and 3.47 day\(^{-1}\) (68 \% confidence interval).

For a campaign like this it has proven beneficial to make use of the larger amounts of time available on smaller dishes compared to using a much more sensitive, larger radio telescope with less time available. We encourage similar strategies also for follow-up campaigns of FRBs and Galactic magnetars.

Facilities: Fermi (GBM), NICER, OSO:20m, OSO:25m, Swift (BAT), Toruń:32m, WSRT

Software: Astropy, DSPSR, FETCH, FermiTools, HEASOFT, Heimdall, jive5ab, Matplotlib, PSRCHIVE, SFXC, SIGPROC, Xspec

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APPENDIX

A. ADDITIONAL MATERIAL
Figure A1. The average polarisation profiles (bottom panels) and polarisation position angle swing (top panels) of PSR J1935+1616. The left panel shows Stokes I (black), linear polarisation (red) and circular polarisation (blue) before applying the leakage calibration discussed in Section 4.1 and Faraday-correcting using the true rotation measure of the pulsar (−10.2 rad m⁻²; Han et al. 2018), i.e. we are also ignoring the delay between polarisation hands. For comparison, the pulsar profile and PA from the literature (1.4 GHz; Johnston & Kerr 2018) is shown using more transparent colours. Note that the absolute value of the PA has been shifted to visually compare our observations with the literature. The right plot is the leakage calibrated data, Faraday-corrected using the rotation measure determined using the PSRCHIVE tool rmfit, which, in essence, accounts for the delay between the polarisation hands. We again show the pulsar profile and PA from the literature for comparison. This illustrates the polarisation calibration used for the SGR 1935+2154 bursts.

Table A1. Details of the observations

| MJD start⁹ | MJD end⁹ | Band⁸ | Time (h)⁹ | Station⁸ |
|------------|----------|-------|------------|----------|
| 0.94240    | 1.28586  | C     | 7.99       | Tr       |
| 0.94689    | 1.44284  | L₁    | 11.72      | O8       |
| 0.94795    | 1.22499  | P     | 4.91       | Wb       |
| 1.26045    | 1.44025  | Lₙb   | 3.19       | Wb       |
| 1.94240    | 2.28586  | C     | 7.99       | Tr       |
| 1.94689    | 2.44284  | L₁    | 11.72      | O8       |
| 1.94795    | 2.22499  | P     | 4.93       | Wb       |
| 2.26045    | 2.43748  | Lₙb   | 3.14       | Wb       |
| 2.94240    | 3.28586  | C     | 7.99       | Tr       |
| 2.94689    | 3.44284  | L₁    | 11.71      | O8       |

Table A1 continued
| MJD start $^a$ | MJD end $^a$ | Band $^b$ | Time (h) $^c$ | Station $^d$ |
|----------------|--------------|-----------|--------------|-------------|
| 2.94795        | 3.22495      | P         | 4.94         | Wb          |
| 3.26045        | 3.43470      | L$_{wb}$  | 3.09         | Wb          |
| 3.93753        | 4.21457      | P         | 4.91         | Wb          |
| 3.94241        | 4.28586      | C         | 7.99         | Tr          |
| 3.94492        | 4.44087      | L$_2$     | 11.72        | O8          |
| 4.25005        | 4.43263      | L$_{wb}$  | 3.23         | Wb          |
| 4.93755        | 5.21457      | P         | 4.89         | Wb          |
| 4.97311        | 5.22628      | L$_2$     | 5.99         | O8          |
| 5.25005        | 5.42985      | L$_{wb}$  | 3.18         | Wb          |
| 5.93753        | 6.21457      | P         | 4.93         | Wb          |
| 5.94934        | 6.28679      | C         | 7.85         | Tr          |
| 6.25003        | 6.42706      | L$_{wb}$  | 3.14         | Wb          |
| 6.93752        | 7.21454      | P         | 4.92         | Wb          |
| 6.93825        | 7.42361      | X         | 11.2         | O6          |
| 6.99700        | 7.22906      | L$_3$     | 5.49         | O8          |
| 7.25002        | 7.42428      | L$_{wb}$  | 3.09         | Wb          |
| 7.93080        | 8.23002      | L$_4$     | 5.63         | O8          |
| 7.93432        | 7.98428      | P         | 1.16         | Wb          |
| 8.22946        | 8.42294      | L$_{wb}$  | 4.48         | Wb          |
| 8.92307        | 9.26666      | C         | 7.93         | Tr          |
| 8.92390        | 9.09586      | L$_{wb}$  | 3.98         | Wb          |
| 8.93057        | 9.23020      | L$_5$     | 6.97         | O8          |
| 8.93825        | 9.42361      | X         | 11.2         | O6          |
| 9.11488        | 9.42317      | P         | 7.12         | Wb          |
| 9.92307        | 10.26666     | C         | 7.95         | Tr          |
| 9.92362        | 10.39216     | L$_5$     | 10.97        | O8          |
| 9.92390        | 10.09586     | L$_{wb}$  | 3.98         | Wb          |
| 10.11488       | 10.41600     | P         | 6.95         | Wb          |
| 10.92307       | 11.26666     | C         | 7.95         | Tr          |
| 10.92362       | 11.39218     | L$_3$     | 10.99        | O8          |
| 10.92391       | 11.09587     | L$_{wb}$  | 3.98         | Wb          |
| 11.11487       | 11.41600     | P         | 6.97         | Wb          |
| 11.92307       | 12.26666     | C         | 7.95         | Tr          |
| 11.92362       | 12.23384     | L$_3$     | 7.24         | O8          |
| 11.92390       | 12.09586     | L$_{wb}$  | 3.98         | Wb          |
| 12.11488       | 12.41600     | P         | 6.96         | Wb          |
| 12.88544       | 13.34343     | L$_3$     | 10.74        | O8          |
| 12.92307       | 13.26666     | C         | 7.94         | Tr          |

Table A1 continued
Table A1 (continued)

| MJD start | MJD end | Band | Time (h) | Station |
|-----------|---------|------|----------|---------|
| 14.88543  | 15.22730| L₃   | 7.98     | O8      |
| 15.92307  | 16.26667| C    | 7.95     | Tr      |
| 15.99524  | 16.21676| L₃   | 5.24     | O8      |
| 16.92307  | 17.26666| C    | 7.95     | Tr      |
| 17.92307  | 18.26666| C    | 7.95     | Tr      |
| 18.92307  | 19.26666| C    | 7.95     | Tr      |
| 19.90307  | 20.06785| L₃   | 3.81     | Wb      |
| 19.92307  | 20.26666| C    | 7.94     | Tr      |
| 20.09058  | 20.39169| P    | 6.96     | Wb      |
| 20.92307  | 21.26666| C    | 7.94     | Tr      |
| 21.89622  | 22.07537| L₃   | 4.14     | Wb      |
| 22.09414  | 22.37373| P    | 6.46     | Wb      |
| 22.88140  | 23.22499| C    | 7.95     | Tr      |
| 22.89623  | 23.07535| L₃   | 4.14     | Wb      |
| 23.09414  | 23.37373| P    | 6.46     | Wb      |
| 23.88140  | 24.22488| C    | 7.94     | Tr      |
| 23.89623  | 24.07535| L₃   | 4.14     | Wb      |
| 24.09414  | 24.37373| P    | 6.46     | Wb      |
| 24.88140  | 25.22499| C    | 7.95     | Tr      |
| 24.89623  | 25.07535| L₃   | 4.14     | Wb      |
| 25.09414  | 25.37373| P    | 6.46     | Wb      |
| 25.89623  | 26.07537| L₃   | 4.14     | Wb      |
| 26.09414  | 26.36994| P    | 6.24     | Wb      |

a For clarity 58968 has been subtracted from all MJD’s.

b P: 314 – 377 MHz, L₃: 1260 – 1388 MHz, L₄: 1227 – 1739 MHz, L₅: 1259 – 1515 MHz, L₆: 1360 – 1616 MHz, L₇: 1232 – 1488 MHz, X: 4550 – 4806 MHz, X: 8080 – 8592 MHz.

c Total on source recording time in hours.

d Wb: Westerbork RT1, Tr: Toruń, O8: Onsala 25m, O6: Onsala 20m.

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Table A2. Times of the overlapping X-ray bursts detected by HXMT, based on the http://enghxmt.ihep.ac.cn/bfy/331.jhtml overview (Li et al. 2020b).

| HXMT burst time (UT) | Burst time (UT; continued) | Burst time (UT; continued) |
|----------------------|-----------------------------|-----------------------------|
| 2020-04-30T09:25:22.750 | 2020-05-08T06:17:16.589 | 2020-05-15T00:37:16.000 |
| 2020-04-30T10:28:03.000 | 2020-05-08T09:17:05.185 | 2020-05-16T01:50:23.542 |
| 2020-05-02T02:49:27.800 | 2020-05-08T09:49:21.134 | 2020-05-16T02:09:32.000 |
| 2020-05-02T04:39:05.812 | 2020-05-09T01:56:38.750 | 2020-05-17T00:26:07.845 |
| 2020-05-02T05:40:53.151 | 2020-05-09T23:47:15.000 | 2020-05-17T03:18:10.320 |
| 2020-05-02T10:17:26.000 | 2020-05-10T01:30:01.000 | 2020-05-18T01:54:21.550 |
| 2020-05-02T10:25:25.777 | 2020-05-10T01:38:45.000 | 2020-05-18T05:17:57.715 |
| 2020-05-03T01:06:02.666 | 2020-05-10T03:03:38.000 | 2020-05-18T02:21:05.000 |
| 2020-05-03T04:08:26.000 | 2020-05-10T03:17:15.000 | 2020-05-19T00:15:15.000 |
| 2020-05-03T04:30:59.050 | 2020-05-10T05:00:28.195 | 2020-05-20T21:47:07.480 |
| 2020-05-03T05:53:45.000 | 2020-05-10T06:12:01.622 | 2020-05-20T22:06:45.330 |
| 2020-05-03T06:50:42.990 | 2020-05-10T06:16:41.100 | 2020-05-21T01:24:06.000 |
| 2020-05-03T10:34:35.637 | 2020-05-10T06:20:09.400 | 2020-05-21T23:33:39.000 |
| 2020-05-03T23:25:13.250 | 2020-05-10T06:21:26.023 | 2020-05-22T21:49:36.000 |
| 2020-05-04T00:48:07.343 | 2020-05-10T06:36:51.400 | 2020-05-22T23:27:47.800 |
| 2020-05-05T02:30:28.450 | 2020-05-10T08:55:46.300 | 2020-05-23T05:30:05.600 |
| 2020-05-06T03:53:15.000 | 2020-05-11T02:52:18.000 | 2020-05-24T22:05:03.480 |
| 2020-05-06T22:48:21.550 | 2020-05-11T04:22:52.560 | 2020-05-24T23:18:15.000 |
| 2020-05-08T03:23:13.000 | 2020-05-11T23:28:40.880 | 2020-05-25T00:57:45.000 |
| 2020-05-08T03:34:15.000 | 2020-05-12T06:12:09.300 | – |

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