Detection of a bright burst from the repeating FRB 20201124A at 2 GHz

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Abstract

We present a detection of a bright burst from FRB 20201124A, which is one of the most active repeating FRBs, based on S-band observations with the 64-m radio telescope at the Usuda Deep Space Center/JAXA. This is the first FRB observed by using a Japanese facility. Our detection at 2 GHz in February 2022 is the highest frequency for this FRB and the fluence of \( > 189 \) Jy ms is one of the brightest bursts from this FRB source. We place an upper limit on the spectral index \( \alpha = -2.14 \) from the detection of the S band and non-detection of the X band at the same time. We compare an event rate of the detected burst with ones of the previous research, and suggest that the power-law of the luminosity function might be broken at lower fluence, and the fluences of bright FRBs distribute up to over 2 GHz with the power-law against frequency. In addition, we show the energy density of the burst detected in this work was comparable to the bright population of one-off FRBs. We propose that repeating FRBs can be as bright as one-off FRBs, and only their brightest bursts could be detected so some of repeating FRBs intrinsically might have been classified as one-off FRBs.

Key words: radio continuum: stars — radio continuum: general — stars: individual (FRB 20201124A)

1 Introduction

Fast Radio Bursts (FRBs), short-duration (\( \ll 1 \) sec) bright radio transients, have still unknown progenitors and emission mechanisms (Petroff et al. 2022). Detection of FRBs at different frequencies and over wider bandwidths are helpful for studying the intrinsic emission properties and the frequency dependence of potential propagation effects due to the circumburst environment. Some proposed emission models have a limited range of radio frequency and/or spectral index (e.g., Kumar et al. 2017; Metzger et al. 2019). Simultaneous observation covering a wide range of frequencies for FRB 20180916B discovered the frequency dependence of the activity window, which has provided potentially an important insight into the nature of these sources (Pastor-Marazuela et al. 2021; Bethapudi et al. 2022). Some FRBs have been observed at various frequencies, such as FRB 20121102 from 400 MHz to 8 GHz, (Josephy et al. 2019; Gajjar et al. 2018), FRB 20180916B from 110 MHz to 5 GHz (Chawla et al. 2020; Pleunis et al. 2021b; Bethapudi et al. 2022). However, in general, most of FRBs have been detected at 400 – 800 MHz or 1.4 GHz at the rest frame.

A subset of FRBs have shown repetition, which rules out solely catastrophic progenitors. There is a possibility that one-off FRBs are detected only once due to limited observation time or sensitivity, and whether all FRBs are capable of repeating or not has been actively debated (e.g., Ravi 2019; Ai et al. 2021; Gardenier et al. 2021). Some research (e.g., Hashimoto et al. 2020a) propose that FRBs are classified into two populations, that is, not all FRBs repeat. It is suggested that repeating FRBs have some different trends from one-off FRBs, such as the duration time, bandwidth, redshift evolution, and especially energy; repeating FRBs tend to be fainter than one-off FRBs (Hashimoto et al. 2020a; Hashimoto et al. 2020b; Pleunis et al. 2021a; Kim et al. 2022).

The repeaters can provide an opportunity to conduct follow-up observations at higher radio frequencies. Long-term follow-up observations over a time scale of years can constrain periodic activity. Some repeating FRBs, such as FRB 121102 (Cruces et al. 2021) and FRB 180916B (CHIME/FRB Collaboration 2020), have shown periodicity of the burst activity window. The repeating FRB 20201124A entered a period of high activity in April of 2021 (CHIME/FRB Collaboration 2021; Lanman et al. 2022), at which time several observatories recorded tens to thousands of bursts from the source. Recently, it again entered an active phase in January–March 2022 (Ould-Boukattine et al. 2022a; Ould-Boukattine et al. 2022b; Atri et al. 2022). However, no detection has been reported in the high frequency band above 2 GHz from this source.

Here we report a detection of a bright FRB from the repeater FRB 20201124A source at 2.2 – 2.3 GHz, which is the highest-frequency detection from FRB 20201124A to date, using the 64-m radio dish of Usuda Deep Space
Center (UDSC)/JAXA. This is the first FRB detected in Japan. The remainder of this paper is structured as follows. In Section 2, we present our observational setup and analyses. In Section 3, we describe the detected burst in detail, dispersion measure (DM) determination, digital artifact, and then estimate the spectral index. We compare the detected burst with the previous bursts from FRB 20201124A and other FRBs in Section 4, and summarize this paper in Section 5.

2 Observations and Analyses

Following the recent reports of the 2022 reactivation of FRB 20201124A as cited in the introduction, we conducted an observing session for this FRB source using UDSC/JAXA for 8 hours on February 18, 2022 (MJD 59628), 07:11:00–15:14:00 UT at the S (2194 – 2322 MHz) and X bands (8374 – 8502 MHz). We also observed the 3C147 as a flux calibrator before and after the FRB observation. We used the polynomial expression for 3C147 studied by Perley and Butler (2017) to speculate the flux densities in the S and X bands to be 15.2 and 4.7 Jy, respectively, and determined values of the system equivalent flux density (SEFD) 122 Jy (7% uncertainty) for the S band, and 173 Jy (40% uncertainty) for the X band. These uncertainties resulted from atmospheric fluctuation.

We observed right-handed circular polarized waves using a multi-channel digital A/D sampler, ADS3000+ (Takeuchi et al. 2006), with a sampling rate of 64 MHz and 4 bit quantization, and divided the observed full bandwidth of 128 MHz × 2 (S and X bands) to 4 × 2 channels of 32 MHz bandwidth (effectively 30 MHz width after the elimination of the band edges). The data in each channel are coherently dedispersed with a trial value of DM = 413 pc cm\(^{-3}\), which is from Xu et al. (2021), and then incoherently summed over 4 channels to make the averaged time series for the S band and X band, separately (see Enoto et al. 2021 for more details).

We searched the averaged time series of 1 ms integration for burst candidates having signal-to-noise ratios (S/N) ≥ 10 both in the S and X band, namely those having peak fluxes > 3.5 Jy for the S band and > 5.0 Jy for the X band.

3 Results

After the analysis mentioned above, we found an FRB candidate having S/N > 300 at the S band (Takefuji et al. 2022) and none at the X band. For this candidate Figure 1 shows a dynamic spectrum before dedispersion covering a 60 ms time window starting at UTC 14:21:34.040. This dynamic spectrum shows a clear detection of a strong radio burst with a dispersive delay. The dispersive delay apparently follows a \(V^{-2}\) law, which is a typical characteristic of FRBs, being caused by propagation through the interstellar/intergalactic plasma. Intensity variation against frequency may be attributed to interstellar scintillation.

To determine the optimal DM, we averaged the dedispersed data every 100 µs and calculated the structure parameter (Gajjar et al. 2018) defined as,

\[
\text{Structure Parameter} = \frac{1}{n} \sum_{t}^{n} \frac{S_{t} - S_{t+1}}{\Delta t},
\]

where \(n\) is the number of total bins which include the
bursts, $S_i$ is the $i$-th flux, and $\Delta t$ is the integration time. We calculated the structure parameters by changing DM. Then we fitted the structure parameters with the Gaussian distribution and determined the structure-parameter-maximizing-DM of $411.0 \pm 0.5 \text{ pc cm}^{-3}$ as the optimal DM$^1$. This is consistent with values reported in the previous work within uncertainties (Xu et al. 2021).

In the upper panel of Figure 2 we present the burst profiles integrated over ch 0 – 3 separately after the dedispersion using our best estimate DM. The lower panel of Figure 2 shows the dynamic spectrum, e.g., the waterfall plot, after the dedispersion. The bright main component has a pulse width (FWHM) of 1.5 ms which is typical for repeating FRBs (Petroff et al. 2022). There is a faint sub-structure at 3 ms prior to the main component, with a peak intensity of $\sim 10\%$ of the peak of main component. Similar sub-structures with a timescale of a few ms are also reported for FRB 20201124A (e.g., Marthi et al. 2022; Main et al. 2022).

We should note one caveat about the flux/fluence determination. Since the previous observations of FRB 20201124A showed that the majority of bursts from this FRB have flux density $\lesssim$ several tens of Jy (e.g., Xu et al. 2021), we had optimized the digital system to this flux density level. Figure 3 shows the burst profile for ch 0, and we see a dip in the noise floor in the neighboring interval of the burst peak (filled area), which represents digital artifact due to a finite bit size of the digitization system (Jenet and Anderson 1998) and results in the flux/fluence underestimations. For ch 1 there is also a dip although shallower than ch 0 but significant. We see no dip for ch 2 and ch 3 and concluded that these channels are free from the digitization artifact. Table 1 summarizes our estimation of the flux/fluence separately for ch 0 – 3. If we incoherently sum up these four channels, we get estimations for the peak flux $>114 \text{ Jy}$ and for fluence $>189 \text{ Jy ms}$ for the frequency band, 2194 – 2322 MHz. It should be noted again that only right-handed circular polarized waves were observed. The mean value of $V/I$ of FRBs detected in Hilmarrsson et al. (2021) was $-2\pm9\%$, where $V$ and $I$ are stokes parameters. From this result, the intensity of a right-handed circular polarized wave is as high as that of a left-handed circular polarized wave. Hence, FRBs that should be detected if we also carried out left-handed circular polarized wave observations have a comparable intensity of right-handed circular polarized wave, so could also be detected by this observation. To summarize, we conclude that only right-handed circular polarized wave observation would not miss FRBs, namely, would not affect the detection number. The total fluence would be higher than the value obtained from this observation.

Assuming that fluence can be expressed as $F_\nu \propto \nu^\alpha$, we calculate the spectral index of $\alpha$ for the detected burst from the simultaneous observations of the S and X bands. We obtain the lower limit of fluence, 189 Jy ms (7% uncertainty), for the S band due to the digitization artifact, and the upper limit of fluence, 7.5 Jy ms (40% uncertainty), for the X band due to the non-detection by assuming that the duration in the X band is the same as that in the S band. Considering uncertainties we get the upper limit of $\alpha$ to be $-2.14$. This upper limit is at variance with the spectral index of the mean of bright FRBs detected with the Australian Square Kilometre Array Pathfinder (ASKAP) (Macquart et al. 2019), and magnetar emissions (e.g., Levin et al. 2010; Eie et al. 2021). However it is consistent with a mean index of main pulse and interpulse for giant pulses from the Crab pulsar between 2.3 GHz and 8.4 GHz (S. Eie in preparation). This comparison could reveal clues to the emission mechanism of FRB 20201124A. Although further investigations are necessary, observations of FRB 20201124A might support the emission mechanism models like Crab giant radio pulses more.

Table 1. Flux/Fluence estimation for a burst of FRB 20201124A on 18 February 2022.

| ch | central frequency | flux$^*$ | fluence$^*$ |
|----|------------------|--------|-----------|
| 0  | 2210 MHz         | >262 Jy | >444 Jy ms |
| 1  | 2242             | >109   | >178      |
| 2  | 2274             | 34     | 55        |
| 3  | 2306             | 51     | 79        |

$^*$7% uncertainly

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$^1$ We searched burst candidates again by dedispersion with the optimal DM value of $411.0 \text{ pc cm}^{-3}$ and, in the end, there was only the one FRB already described in this section.
4 Discussion

4.1 Comparison with the previous bursts from FRB 20201124A

During the previous active phases of FRB 20201124A, some radio telescopes, such as the Five-hundred-meter Aperture Spherical radio Telescope (FAST) and Effelsberg 100-m radio telescope, conducted follow-up observations (e.g., Xu et al. 2021; Hilmarsson et al. 2021). FAST detected 1863 bursts from the FRB 20201124A source from April 1 to June 11 in 2021, covering the range from 1.0 GHz to 1.5 GHz (Xu et al. 2021). The observed fluences distributed up to \( \sim 70 \) Jy ms. Hilmarsson et al. (2021) reported 20 bursts detected with Effelsberg 100-m radio telescope at \( \sim 1.36 \) GHz during observations conducted on April 9 2021. The brightest event among the 20 bursts detected by Effelsberg 100-m radio telescope showed a fluence of \( \sim 334 \) Jy ms reported in Herrmann et al. 2021, and one of the brightest events from this FRB source (e.g., 334 Jy ms in Ould-Boukattine et al. 2022). Therefore, the burst detected in this work, whose flux and fluence is the lower limit determination due to the digitization artifact at \( \sim 2 \) GHz, is one of the brightest events from this FRB source (e.g., 334 Jy ms reported in Herrmann et al. 2021, and \( > 771 \) Jy ms in Ould-Boukattine et al. 2022). We also note that the detected frequency (\( \sim 2.2 - 2.3 \) GHz) is highest.

We contrast the event rate of FRBs speculated from the observation result of this work with the FAST result, which detected large quantities of FRBs (Xu et al. 2021). We observed for 8 hours and detected one burst, giving an event rate of \( 1/8 \) hr\(^{-1}\). Since the observed frequency and threshold are different, we correct for these differences. Assuming all FRBs follow the form of \( F_{\nu} \propto \nu^\alpha \) over all frequencies, we convert the threshold of Xu et al. (2021) to the fluence at our frequency, 2258 MHz. Moreover, the single power-law of luminosity function, \( N(> F) \propto F^{\beta+1} \) where \( N \) is a cumulative number per an hour, is simply assumed to extrapolate event rates for the threshold of each telescope. In our calculation, we used \( \alpha = -2.14 \), which is the upper limit estimated in Section 3, and \( \beta = -4.6 \pm 1.3 \pm 0.6 \), which is from Lanman et al. (2022). Figure 4 shows cumulative event rates of FRBs of which fluence is higher than thresholds at the same frequency. Our event rate is notably larger than that of extrapolated from Xu et al. (2021), \( 1.0 \times 10^{-11} \) hr\(^{-1}\), although it is within errors of extrapolated result from Xu et al. (2021). We also compare the event rates from Marthi et al. (2022), Atri et al. (2022), and Ould-Boukattine et al. (2022b) by performing the same procedures. Marthi et al. (2022) observed last year, whereas Atri et al. (2022) and Ould-Boukattine et al. (2022b) observed this year, namely in the same active period as this work. As a consequence, the event rate extrapolated from Xu et al. (2021) is inconsistent with that of Marthi et al. (2022) even though they carried out their observations during the same active period last year. This suggests that the single power-law distribution of the luminosity function which we assume to estimate event rates is not correct. That is, the power-law of the luminosity function might be broken at lower fluence. In addition, the consequence that event rates of Atri et al. (2022) and Ould-Boukattine et al. (2022b) in the same active phase we observed are roughly equivalent to our event rate implies a possibility that bright FRBs distribute up to over 2 GHz with the power-law.

4.2 A possibility that repeating FRBs are observed as one-off FRBs

Fig. 4. Cumulative event rates of FRBs having fluence larger than threshold for each telescope. Blue, purple, green, red, black points represent cumulative event rates of Xu et al. (2021), Marthi et al. (2022), Atri et al. (2022), Ould-Boukattine et al. (2022b), this work, respectively. Xu et al. (2021) and Marthi et al. (2022) observed last year, whereas Atri et al. (2022) and Ould-Boukattine et al. (2022b) observed this year, namely in the same active period as this work. The blue solid line represents the event rate by extrapolating luminosity function \( N(> F) \propto F^{\beta+1} \). Gray region corresponds the range obtained from the uncertainty of \( \beta \) and event rate of Xu et al. (2021).

We compare the properties of the burst of FRB 20201124A observed on 18 February 2022 (this work) to the sample collected from the FRBCAT project (Petroff et al. 2016). More detail about the sample of FRBs is described in https://www.frbcat.org/. FRBs are detected at different frequencies and different redshifts so, for a fair comparison, Hashimoto et al. (2020a) estimate energy densities at a unified rest-frame frequency of 1.83 GHz and rest-frame intrinsic duration. Detailed procedures are described by Hashimoto et al. (2020a). After excluding FRBs without a solution to DM-derived redshift, i.e., \( DM_{\text{obs}} - DM_{\text{halo}} - DM_{\text{ISM}} - DM_{\text{host}} < 0 \), the comparison sample includes a total of 11 repeating FRB sources.
with 144 repeats and 77 one-off FRBs\(^2\). Hashimoto et al. (2020b) confirms that the DM-derived redshifts estimated by these procedures are consistent with spectroscopic redshifts within uncertainties (see also Figure 1).

We performed the same procedures to the FRB in this work. The lower limit of the energy density \(E_\nu\) of FRB 20201124A is calculated using \(z_{\text{spec}} = 0.0979\) (Fong et al. 2021), the observed fluence of \(F_\nu > 444\) Jy ms at 2210 MHz (ch 0), and the spectral index of \(\alpha < -2.14\). The calculated lower limit is \(\log(E_\nu/\text{erg Hz}^{-1}) = 32.24\) at 1.83 GHz. The average fluence at 2194 – 2322 MHz (ch 0 – 3) is 189 Jy ms, which places the lower limits of \(\log(E_\nu/\text{erg Hz}^{-1}) = 31.89\). We note that the instrumental pulse broadening effects, including dispersion smearing and finite time sampling, are negligible due to the coherent dedispersion described in Section 2 and 100 \(\mu\)s time sampling. Therefore, the rest-frame intrinsic duration of the burst detected in this work is \(1.5/(1 + z_{\text{spec}}) \sim 1.4\) ms.

Figure 5 shows the rest-frame intrinsic duration as a function of the energy density of FRB 20201124A (this work) along with those of the comparison sample. The samples of FRBs used in this work were obtained by various telescopes so include observational biases. Considering observational results, FRBs are classified into two populations, repeating and one-off FRBs. There is a possibility that this is caused by observational biases and FRBs intrinsically consist of only one population. However, some research proposes that repeating and one-off FRBs have distinct physical origins. Namely, this classification a physical difference to some extent (e.g., Hashimoto et al. 2020a; Chen, H.-Y. et al. 2022). To mitigate a possible observational bias due to targeted follow-up campaigns of repeating FRBs, the first-detected FRB for each repeating FRB source (magenta diamond in Figure 5) can be compared with one-off FRBs (blue markers). The first-detected repeating FRBs show lower energy densities than those of one-off events on average. A similar result is also reported for energies of the CHIME FRB sample (Kim et al. 2022). One possible reason is the narrower bandwidths of repeating FRBs compared to apparent one-offs (e.g., Pleunis et al. 2021a).

The detected burst from the FRB 20201124A source shows one of the highest energy densities of repeating FRBs. The energy density is comparable to those of the bright population of one-off FRBs. The other two repeating FRBs show high energy densities comparable to that of FRB 20201124A; FRB 171019, FRB 181017.J1705+68 (FRB 20181017A). The former was originally reported as one of the bright one-off FRBs detected with ASKAP at \(\sim 1.2\) GHz (Shannon et al. 2018). Afterward, two repetitions were detected from this FRB source with the Green Bank Telescope in observations centered at 820 MHz (Kumar et al. 2019). The two repetitions were observed as \(\sim 590\) times fainter than the ASKAP-discovered burst, indicating the importance of deep follow-up observations to identify repeating FRB sources. Another is FRB 181017.J1705+68 (FRB 20181017A) with \(\log(E_\nu/\text{erg Hz}^{-1}) > 32.3\). Two repeating FRBs were detected from this source with CHIME at \(\sim 500 – 550\) MHz so far (CHIME/FRB Collaboration 2019). Our result highlights that repeating FRBs can be as bright as the bright population of one-off FRBs.

Ravi (2019) argued that the volumetric occurrence rate of one-off FRBs likely exceeds the event rate of cataclysmic progenitor candidates, suggesting that one-off FRBs are significantly contaminated by repeating FRB sources. Repeating FRBs are fainter than one-off events on average (e.g., Hashimoto et al. 2020a; Kim et al. 2022). Therefore, some repeating FRBs might have been missed due to sensitivity limitations of current radio telescopes, which would mislead the FRB classification. The bright repeating FRB detected in this work might support the hypothesis that some of or a significant fraction of one-off events are a part of repeating bursts (e.g., Ravi 2019; Kumar et al. 2019; Chen, B. H. et al. 2022). However, only their brightest rare population could be detected and thus misclassified as one-off FRBs. Monitoring the other repeating FRB sources and deep follow-up observations of one-off FRB sources are highly encouraged to prove this hypothesis.

5 Summary

We conducted follow-up observations of the FRB 20201124A source using the UDSC/JAXA radio telescope and detected one bright FRB. This is the first FRB detection in Japan. The frequency of the detection, 2.2 – 2.3 GHz, is the highest end of the multi-wavelength coverage of this repeating FRB so far reported. In addition, the fluence at 2 GHz is comparable to the brightest events detected from this FRB source at 1.3 GHz. By calculating the upper limit of the spectral index of the detected burst, \(\alpha = -2.14\), we compare the event rate of the detected burst in this work with those of Marthi et al. (2022), Atri et al. (2022), Ould-Boukattine et al. (2022b), and extrapolated from Xu et al. (2021) under the assumption of single power-law of the luminosity function and find that the event rates of the former three are close to ours and notably larger than the event rates extrapolated from Xu et

\(^2\) DM\(_{\text{obs}}\), DM\(_{\text{halo}}\), DM\(_{\text{ISM}}\) and DM\(_{\text{host}}\) represent an observed DM, a DM contributed from the dark matter halo hosting the Milky Way, the interstellar medium in the Milky Way, and a FRB host galaxy.
Fig. 5. Rest-frame intrinsic duration as a function of energy density at rest-frame 1.83 GHz of FRBs. FRB 20201124A detected in this work is shown as a dark red star with an arrow. The arrow indicates the lower limit of the energy density. The lower limit of the energy density is calculated by the observed fluence at 2210 MHz (ch 0). A translucent red star indicates the lower limit of the energy density derived by the fluence averaged over 2194 – 2322 MHz (ch 0 – 3). The comparison samples (dots and open triangles) are collected from the FRBCAT project (Petroff et al. 2016). Red and blue colors indicate repeating and one-off FRBs, respectively. The repeats of each repeating FRB source are individually demonstrated. The first-detected FRB for each repeating FRB source is highlighted in a magenta diamond. Open triangles indicate upper limits on the rest-frame intrinsic duration whereas dots are the measured values. The other two repeating FRBs that have high energy densities comparable to that of FRB 20201124A in this work are FRB 171019, FRB 181017.J1705+68 (FRB 20181017A).

al. (2021). It is suggested that the power-law of the luminosity function might be broken at lower fluence, and bright FRBs distribute up to over 2 GHz with the power-law. In addition, from comparison of energy densities, we insist that some of the repeating FRBs intrinsically are classified as one-off FRBs due to the limited observation time or limited sensitivity; that is, the classification based on observations may not represent the intrinsic physical mechanisms completely.

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