DATA PAPER

Atlas of dynamic spectra of fast radio burst FRB 20201124A

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Fast radio bursts (FRBs) are highly dispersed millisecond-duration radio bursts,[1,2] of which the physical origin is still not fully understood. FRB 20201124A is one of the most actively repeating FRBs. In this paper, we present the collection of 1863 burst dynamic spectra of FRB 20201124A measured with the Five-hundred-meter Aperture Spherical radio Telescope (FAST). The current collection, taken from the observation during the FRB active phase from April to June 2021, is the largest burst sample detected for any FRB so far. The standard PSRFITs format is adopted, including dynamic spectra of the burst, and the time information of the dynamic spectra, in addition, mask files help readers to identify the pulse positions are also provided. The dataset is available in Science Data Bank, with the link https://www.doi.org/10.57760/sciencedb.j00113.00076.

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1. Introduction

Fast radio bursts (FRBs) are bright, millisecond duration pulses with dispersion measures (DM) mostly well in excess of galactic values, since first discovered in 2007,[1] more than 800 FRBs have been detected so far and 27 of them can emit repeating bursts[3,4] (https://www.herta-experiment.org/frbstats/catalogue). Currently, 19 FRBs have been localized to host galaxies (https://frbhosts.org/). Although the physical mechanism of FRBs still remains unknown, FRB 200428[5–8] produced by galactic magnetar SGR J1935+2154 suggests that some of the FRBs can be emitted by magnetars.[2,9] Among all the FRBs, FRB 20201124A, which was discovered by CHIME,[10] has been frequently studied recently. Its radio bursts show rich pulse structures.[11,12] Through dynamic spectra, researchers investigated the scintillation time-scale of FRB 20201124A.[13] Efforts have also been made to localize its host galaxy.[14–17]

Dynamic spectra record the FRB intensity as a function of time and frequency. Dynamic spectra contain information of FRB intrinsic emission properties as well as density fluctuation of interstellar and inter-galactic medium. We noted that there is lack of a systematic collection of dynamic spectra for FRBs. In this paper, we present the dynamic spectra data of FRB 20201124A which covers 1863 pulses detected by our team.

2. Observation, data acquisition, and analysis

We used the Five-hundred-meter Aperture Spherical radio Telescope (FAST)[18] to monitor FRB 20201124A from April to June in 2021. The FAST 19-beam pulsar back-end covers 1.0–1.5 GHz in frequency band and has a system temperature about 20 K to 25 K.[19] The data were recorded using the digital back-end based on the Re-configurable Open Architecture Computing Hardware-2 (ROACH2) board[20] with temporal resolution of 49.152 μs or 196.608 μs and frequency resolution of 122.07 kHz.

Our data processing contains two major steps, searching for single pulses and post processing to form the dynamic spectra. Firstly, we searched for the FRB candidates offline with software package TRANSIENTX. Frequency channels affected by radio frequency interference (RFI) were removed. The data were de-dispersed in the dispersion measure (DM) range of 380–440 $\mathrm{cm}^{-3}\cdot\mathrm{pc}$ with a step of 0.1 $\mathrm{cm}^{-3}\cdot\mathrm{pc}$ since FRB 20201124A is a known repeater. The pulse width was searched from 0.1 ms to 100 ms in the box-car-shaped matched filter. 3364 candidates with a S/N threshold larger than 7 were plotted and visually inspected.

In the post processing phase, we used the software package DMPHASE to further refine the DM. The DMPHASE uses the Fourier-domain method, where DM is found by maximising the time derivative of the normalized "intensity". To measure the intensity, the polarisation calibration was then performed with software package PSRCHIVE.[21] We adopted the single axis model in polarisation calibration, where the differential gain and phase between the two polarisation channels are calibrated with the injected noise signal. To reduce the dynamic spectra to a manageable size, we integrated over time and frequency to reduce the resolution. The frequency and time resolutions of the final dynamic spectra are ~ 1.0 MHz and ~ 0.2 ms, respectively. We stored the data in the PSRFITS[21] format, which is widely used in the community of pulsar astronomy.

3. Data format and contents of the library

The PSRFITS format is based on the Flexible Image Transport System (FITS) (https://fits.gsfc.nasa.gov/).[22] According to FITS standards, a PSRFITS file consists of a primary header-data unit (HDU) followed by a series of extension HDUs.[21] As for our data, the primary HDU contains basic information such as telescope name and its location, source location, observation time, etc. Four extension HDUs, which are in a binary table format, contain specific information related to the observation: processing history, pulsar ephemeris, tempo2 predictor and the pulsar data. Notice that several PSRFITS files contain more than one burst because the interval between their time of arrivals (TOAs) is quiet small.

We associate each pulse with a mask file. The mask file, formatted in plain ascii file, contains two rows of data. The first row consists two integer numbers corresponding to the boundary of pulse on-phase in the profile. The second row of mask file shows where the baseline lies in. Figure 1 shows the dynamic spectrum of pulse No. 12 as an example.

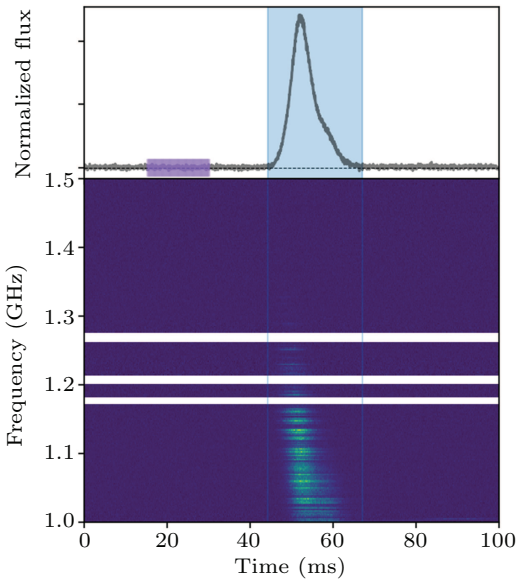


Fig. 1. Example of pulse profile (upper panel) and dynamic spectra (lower panel). Purple box and blue area in the pulse profile show the baseline and pulse on-phase definition. White strips in the dynamical spectra indicate the removed channels due to the RFI.

4. Statistics of data properties

Our detection threshold was a signal-to-noise ratio S/N > 7, and 1103 bright bursts reached S/N > 30 among a total of 1863 detected bursts. Figure 2(a) shows the S/N distribution of all detected bursts. Figure 2(b) shows the distribution of removed channel in frequency band. Usually, a few percent frequency channels had been removed due to the RFI.

The sample completeness was determined with the following method. We simulated 10000 mock bursts with Gaussian profile and bandpass matching the detected distributions. We then randomly injected the mock bursts into the original FAST data when no FRB was detected. The mock burst injected data were then fed to our burst-searching pipeline to compute the detection rate. The procedure showed that the fluence threshold achieving the 95% detection probability with S/N $\geq$ 7 is 53 mJy·ms.[11]

Parameters of each burst (including burst MJD, S/N, DM, etc) are available in the data availability section of Ref. [11].

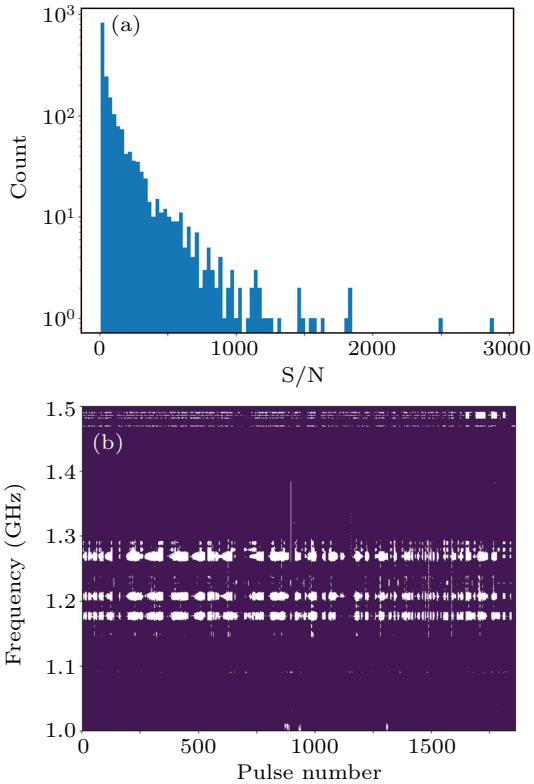


Fig. 2. (a) The S/N distribution of 1863 pulses. (b) The distribution of RFI zapping for all data.

5. Conclusion

In this work, we present a collection of dynamic spectra for 1863 FAST-detected radio bursts of FRB 20201124A during April to June in 2021. This is the largest burst sample detected in any FRB so far.

The signal of FRB 20201124A is highly polarised.[11] Our dynamic spectra is polarisation calibrated. Previous study shows that 0.5% polarisation fidelity can be achieved with the current calibration method.[3]

The current data set is of high S/N, where 5%, 30% and 67% data had S/N $\geq$ 560.63, 116.02, and 23.85, respectively. Simulation is used to determine the completeness of burst detection, where 95% completeness fluence threshold is 53 mJy·ms.

For each burst, we provide one PSRFITS file and one mask file. We provide the total intensity data in PSRFITS format, and mask file in ascii format which labels the burst.

Data availability and related softwares

The data that support the findings of this study are openly available in Science Data Bank at https://www.doi.org/10.57760/sciencedb.j00113.00076. The related software can be found in the corresponding repositories.

TRANSIENTX: https://github.com/ypmen/TransientX
DMPHASE: https://www.github.com/DanieleMichilli/DM_phase
PSRCHIVE: http://psrchive.sourceforge.net

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References

[1] Lorimer D R, Bailes M, McLaughlin M A, Narkevic D J and Crawford F 2007 *Science* **318** 777
[2] Zhang B 2020 *Nature* **587** 45
[3] Luo R, Wang B J, Men Y P, *et al*. 2020 *Nature* **586** 693
[4] Niu C H, Aggarwal K, Li D, *et al*. 2022 *Nature* **606** 873
[5] Scholz P and ChimeFrb Collaboration 2020 *The Astronomer's Telegram* **13681** 1
[6] CHIMEFRB Collaboration, Andersen B C, Bandura K M, *et al*. 2020 *Nature* **587** 54
[7] Bochenek C, Kulkarni S, Ravi V, McKenna D, Hallinan G and Belov K 2020 *The Astronomer's Telegram* **13684** 1
[8] Bochenek C D, Ravi V, Belov K V, *et al*. 2020 *Nature* **587** 59
[9] Lin L, Zhang C F, Wang P, *et al*. 2020 *Nature* **587** 63
[10] ChimeFRB Collabortion 2021 *The Astronomer's Telegram* **14497** 1
[11] Xu H, Niu J R, Chen P, *et al*. 2022 *Nature* **609** 685
[12] Marthi V R, Bethapudi S, Main R A, *et al*. 2022 *MNRAS* **509** 2209
[13] Main R A, Hilmarsson G H, Marthi V R, *et al*. 2022 *MNRAS* **509** 3172
[14] Day C K, Bhandari S, Deller A T, Shannon R M and Moss V A 2021 *The Astronomer's Telegram* **14515** 1
[15] Kilpatrick C D, Fong W, Prochaska J X, *et al*. 2021 *The Astronomer's Telegram* **14516** 1
[16] Xu H, Niu J R, Lee K J, *et al*. 2021 *The Astronomer's Telegram* **14518** 1
[17] Wharton R, Bethapudi S, Marthi, V, *et al*. 2021 *The Astronomer's Telegram* **14538** 1
[18] Jiang P, Yue Y L, Gan H Q, *et al*. 2019 *Science China Physics, Mechanics, and Astronomy* **62** 959502
[19] Jiang P, Tang N Y, Hou L G, *et al*. 2020 *Research in Astronomy and Astrophysics* **20** 064
[20] Hickish J, Abdurashidova Z, Ali Z, *et al*. 2016 *Journal of Astronomical Instrumentation* **05** 1641001
[21] Hotan A W, van Straten W and Manchester R N 2004 *Publ. Astron. Soc. Aust.* **21** 302
[22] Hanisch R J, Farris A, Greisen E W, *et al*. 2001 *A&A* **376** 359