High frequency study of FRB 20180916B using the 100-m Effelsberg radio telescope

S. Bethapudi1,*, L. G. Spitler1, R. A. Main1, D. Z. Li2, R. S. Wharton3.

1Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
2Cahill Center for Astronomy and Astrophysics, MC 249-17 California Institute of Technology, Pasadena CA 91125, USA
3NASA Postdoctoral Program Fellow, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

FRB 20180916B is a repeating fast radio burst (FRB) with an activity period of 16.33 days. In previous observations ranging from ~ 150 – 1400 MHz, the activity window was found to be frequency dependent, with lower frequency bursts occurring later. In this work, we present the highest-frequency detections of bursts from this FRB, using the 100-m Effelsberg Radio Telescope at 4–8 GHz. We present the results from two observing campaigns. We performed the first campaign over an entire activity period which resulted in no detections. The second campaign was in an active window at 4–8 GHz which we predicted from our modelling of chromaticity, resulting in eight burst detections. The bursts were detected in a window of 1.35 days, 3.6 days preceding the activity peak seen by CHIME, suggesting the chromaticity extends to higher frequency. The detected bursts have narrower temporal widths and larger spectral widths compared to lower frequencies. All of them have flat polarization position angle sweeps and high polarization fractions. The bursts also exhibit diffractive scintillation due to the Milky Way, following a $f^{3.90±0.07}$ scaling, and vary significantly over time. We find that burst rate across frequency scales as $f^{-2.6±0.2}$. Lastly, we examine implications of the frequency dependency on the source models.

Key words: methods: observational – techniques: miscellaneous – transients: fast radio bursts – scattering

1 Introduction

Fast Radio Bursts (FRBs) are bright, microseconds- to milliseconds-duration transients observed from hundreds of MHz to several GHz and which originate from extragalactic distances. The first FRB was discovered in 2007 (Lorimer et al. 2007), and the lack of repeatability motivated theoretical models of cataclysmic origins (Thornton et al. 2013). Discovery of repeat bursts from FRB 20121102A (Spitler et al. 2016) brought into light a new class of repeating FRBs. The focus of the paper is one such repeating FRB, FRB 20180916B, which was discovered by Canadian Hydrogen Intensity Mapping Experiment (The CHIME Collaboration et al. 2022, CHIME).

FRB 20180916B is a repeating FRB with an activity period of ~ 16 days and active window of ~ 5 days at 600 MHz (Chime/FRB Collaboration et al. 2020). A well determined periodicity meant that observatories know when to observe to increase the likelihood of detecting bursts. Marcote et al. (2020) provided milli-arcsecond localization of the source by means of Very Long Baseline Interferometry (VLBI) with the European VLBI Network (EVN) associating the FRB to a star-forming region of a massive spiral galaxy at redshift of 0.0337. Tendulkar et al. (2021) and Mannings et al. (2021) studied the local region with the Hubble Space Telescope (HST) and Gran Telescopio Canarias (GTC), from which Tendulkar et al. (2021) postulated that FRB 20180916B is likely to be either an old neutron star/magnetar High Mass X-ray Binary (HMXBs) or γ-ray binary with late OB-type star. Multiple X-ray campaigns have already been performed, however no contemporaneous signal has been detected yet (Scholz et al. 2020; Tavani et al. 2020; Pilia et al. 2020). Detection of prompt/contemporaneous emission at different wavelengths when an FRB is detected helps place direct limits on the type of emission mechanisms and nature of the source. Moreover, presence of any persistent emission in different wavelengths helps in studying the local environment in much greater detail.

FRB 20180916B has been detected by multiple instruments at different radio frequencies across different cycles. LOFAR has twenty seven at 150 MHz (Pastor-Marazuela et al. 2021; Pleunis et al. 2021), GMRT five at 300 MHz (Pleunis et al. 2021), GBT eight at 300 MHz (Chawla et al. 2020), SKT three at 328 MHz (Pilia et al. 2020), GMRT four at 400 MHz (Sand et al. 2021), CHIME/FRB fifty five at 600 MHz (Chime/FRB Collaboration et al. 2020; Pleunis et al. 2021), GMRT fifteen at 650 MHz (Marthi et al. 2020), GBT seven at 800 MHz (Sand et al. 2021), VLArrealfast one at 1350 MHz (Aggarwal et al. 2020), APERTIF fifty four at 1370 MHz (Pastor-Marazuela et al. 2021), and lastly Effelsberg (as part of European VLBI Network) four at 1700 MHz (Marcote et al. 2020). Note that all of these detections are at comparatively low-frequency (≤ 2 GHz).

The idea of observing the source at high frequencies is not novel. Pearlman et al. (2020) performed a hundred hour observing campaign on FRB 20180916B using the Deep Space Network (DSN) in S-
Errors in Burst Rate are 95%. All other errors are 1σ. Units are provided wherever relevant.

| Equation                   | B   | A   | Refer to |
|---------------------------|-----|-----|----------|
| Peak activity phase ($\phi_p$) | 0.47 ± 0.02 | -0.23 ± 0.05 | Sec. 2.2 |
| FWHM phase ($\Delta P$)    | 53.4 hr ± 15.6 hr | -0.35 ± 0.32 | Sec. 2.2 |
| Burst Rate                 | 22.8 ± 4.7 hr$^{-1}$ | -2.6 ± 0.2 | Sec. 3.4 |
| Scintillation bandwidth    | 0.82 ± 0.06 kHz | 3.90 ± 0.05 | Sec. 3.2 |

(2.3 GHz) and X- (8.4 GHz) bands simultaneously but did not detect any bursts. FRB 20121102A has been observed up to 8 GHz (Gajjar et al. 2018) using the GBT. FRB 20190520 (Niu et al. 2021) has also been studied with the GBT at 6 GHz (Anna-Thomas et al. 2022). FRB 20200120E (Bhardwaj et al. 2021) was studied with the DSN in ~ 2 GHz (Majid et al. 2021). High frequency detections are particularly useful in measuring RMs. For example, in case of FRB 20121102A and FRB 20190520, due to the extremely high RM, measuring it at higher frequencies is much easier (Hilmarsson et al. 2021b; Anna-Thomas et al. 2022).

FRB 20180916B burst detections by LOFAR and APERTIF (Pleunis et al. 2021; Pastor-Marazuela et al. 2021, hereafter ZP21, PM21) revealed the frequency dependency in the occurrence of bursts. Specifically, it was noted that bursts at lower frequencies occur later and bursts at higher frequencies occur earlier. In other words, the FRB 20180916B source not only exhibited periodicity, but also “chromaticity” since bursts showed selectivity in phase. In this work, the proposition that the chromaticity continues to higher frequencies is tested.

The structure of the paper is as follows: Sec. 2 explains the strategy involved in scheduling observations and describes the search procedures. Sec. 3 presents all the detected bursts, their polarization, scintillation and flux-fluence properties. A rate estimate is also reported using literature rates at various frequencies, and the rate-frequency relation is modeled. Sec. 4 presents various discussions of the results presented here. Lastly, conclusions are presented in Sec. 5.

2 Observations and searches

This section is organized as follows: we describe the observatory and the backend used in Sec. 2.1, construct a chromaticity model in Sec. 2.2, report the observations performed in Sec. 2.3, and finally describe the search strategy employed in Sec. 2.4.

2.1 Effelsberg

Observations were conducted using the 100-m Effelsberg Radio Telescope using the S45mm receiver which has linearly polarized feeds and a System Equivalent Flux Density (SEFD) of 25 Jy. The receiver is connected to the ROACH2 backend, which provides 8bit full Stokes filterbank data at 131.072 μs time resolution in the 4 – 8 GHz band. It records the entire band as two separate sub-bands, which are 4 – 6 GHz and 6 – 8 GHz, each channelized into 2048 channels. Effelsberg observes strong system artefacts in the 4 – 8 GHz band which reduces sensitivity to bursts, in particular below 4.5 GHz.

2.2 Chromatic model

ZP21 provides the most up-to-date periodicity model with the reference MJD = 58369.40 and period of 16.33 days at 600 MHz. The reference MJD corresponds to the start of the first activity cycle in which the source was discovered. This periodicity model is designed to have bursts arriving at 600 MHz (CHIME band) at $\phi = 0.5$ (see Fig. 1, c.f. PM21, Fig. 4, ZP21, Fig. 9).

We construct a chromatic model as a power-law relation between observing frequency and detected burst phase. Using this model, we predict active windows at 4 – 8 GHz. The burst detections used to construct our model are chosen carefully: since bursts detected in follow-up campaigns might introduce biases into the model, only a subset of all the detections is used, which are APERTIF L-band detections reported in PM21, CHIME/FRB detections reported in ZP21, and LOFAR detections reported in PM21; ZP21. We chose only observations that have performed a blind search over the entire window, and therefore is not biased by any observing choice. Given that the frequency extent of the bursts is varying within an observing bandwidth, the frequency of the bursts is computed as the mean of the start/stop frequencies of the burst. Bursts where the start/stop frequencies are not reported are simply excluded.

Then, bursts are binned into frequency bands of 100 MHz each starting from 100 MHz to 2 GHz. For each band, the mean and standard deviation of the burst phases (which are computed by folding at the activity period) in the frequency band are computed. The mean of the phase is treated as peak activity phase ($\phi_p$) and the standard deviation is used to compute the full-width-at-half-maximum (FWHM, $\Delta P$). The mean of the burst frequencies in a band is treated as the frequency of the band instead of using the center frequency of the band.

Now, power laws are fitted for $\phi_p$ and $\Delta P$ against frequency $f$, of the form

$$B \left( \frac{f}{600 \text{ MHz}} \right)^{A},$$

where $A$ and $B$ are fit parameters. The fitting is done using `scipy.optimize.curve_fit`. The fitting yields peak phase and FWHM parameters shown in Tab. 1. The errors are 1σ.

The peak activity phase and FWHM at any frequency $f$ is directly given by $\phi_p$, $\Delta P$, where the start and stop phases of the active window are computed as $\phi_p - \frac{1}{2} \Delta P$ and $\phi_p + \frac{1}{2} \Delta P$. The power-law is graphically presented in Fig. 1. The fitted power laws are extended to the bandwidth of interest (4 – 8 GHz) and specific phase regions are used to predict time windows to schedule observations in.

The chromatic model fitted (Tab. 1) is not a periodic model and therefore has limitations. Since it is a powerlaw, it asymptotes to zero at sufficiently high frequencies and cannot wrap around, making inferences at high frequencies difficult. Nevertheless, we begin with the assumption that it is valid over the frequency range of interest (4 – 8 GHz).

2.3 Observations

Each observation started with a test pulsar scan (PSR B0355+54) and a noise-diode scan to check data quality and to provide polarization calibration solution, respectively. In the Cycle 65 observation the 6 – 8 GHz subband recording failed, hence only the lower subband (4 – 6 GHz) was recorded.

The initial observing strategy was to cover an entire period. These observations will be denoted by PI. A total exposure of 35.73 hours was distributed over 20 days (covering an entire activity cycle of
Table 2. 4-8 GHz observations with Effelsberg. Cycle refers to the activity cycle since the reference MJD. Exposure is the total time spent on FRB 20180916B in hours. The start time is provided in UTC. Phase range corresponds to the exposure in phase units. The number of bursts detected are written in the Bursts column.

| Cycle | Exposure [hr] | Start time | Phase range | Bursts |
|-------|---------------|------------|-------------|--------|
| 42    | 2.22          | 2020-08-09T16:18:15 | 0.944-0.950 | 0 |
| 43    | 0.26          | 2020-08-10T19:17:35 | 0.013-0.014 | 0 |
| 43    | 1.17          | 2020-08-11T04:25:09 | 0.036-0.039 | 0 |
| 43    | 0.96          | 2020-08-12T05:05:56 | 0.099-0.102 | 0 |
| 43    | 2.00          | 2020-08-13T04:07:52 | 0.158-0.163 | 0 |
| 43    | 1.00          | 2020-08-14T04:25:13 | 0.220-0.223 | 0 |
| 43    | 1.00          | 2020-08-15T20:32:28 | 0.322-0.325 | 0 |
| 43    | 0.94          | 2020-08-17T04:34:38 | 0.404-0.407 | 0 |
| 43    | 2.26          | 2020-08-18T03:40:48 | 0.463-0.469 | 0 |
| 43    | 2.55          | 2020-08-20T00:06:37 | 0.577-0.583 | 0 |
| 43    | 2.19          | 2020-08-21T03:59:26 | 0.648-0.653 | 0 |
| 43    | 1.82          | 2020-08-23T06:11:59 | 0.776-0.780 | 0 |
| 43    | 1.78          | 2020-08-24T03:52:48 | 0.831-0.836 | 0 |
| 43    | 1.81          | 2020-08-25T04:04:49 | 0.893-0.897 | 0 |
| 43    | 2.36          | 2020-08-27T03:36:43 | 0.914-0.920 | 0 |
| 43    | 1.85          | 2020-08-28T03:42:22 | 0.976-0.980 | 0 |
| 43    | 1.52          | 2020-08-29T03:30:17 | 1.036-1.040 | 0 |
| 43    | 4.20          | 2020-08-30T01:14:19 | 0.215-0.225 | 0 |
| 44    | 2.02          | 2020-09-01T03:29:26 | 0.320-0.325 | 0 |
| 44    | 1.77          | 2020-09-03T03:54:42 | 0.444-0.448 | 0 |
| 44    | 5.23          | 2021-05-19T05:55 | 0.271-0.284 | 2 |
| 54    | 5.13          | 2021-06-05T06:43:21 | 0.29-0.303 | 0 |
| 54    | 4.50          | 2021-06-21T15:27:00 | 0.292-0.304 | 0 |
| 54    | 3.32          | 2021-08-09T17:32:27 | 0.298-0.307 | 1 |
| 54    | 3.35          | 2021-09-11T07:38:22 | 0.294-0.303 | 0 |
| 54    | 3.99          | 2021-09-27T08:26:18 | 0.276-0.286 | 5 |
| 54    | 3.99          | 2021-10-14T01:37:38 | 0.299-0.310 | 0 |
| 54    | 2.99          | 2021-10-29T23:10:25 | 0.273-0.281 | 0 |
| 54    | 5.99          | 2021-11-15T17:23:14 | 0.299-0.315 | 0 |
| 54    | 5.49          | 2021-12-01T18:05:17 | 0.281-0.295 | 0 |
appropriately scaling into \texttt{uint8} bytes). This step removed any band-
shape (scales/offsets over channels) and narrow-band persistent RFI
and effectively re-digitized the data. After re-digitizing the filterbank
data, PRESTO’s \texttt{rfifind} tool was used to generate a mask to mitigate
RFI. The mask was used to de-disperse and create a time series of
the data. \texttt{single_pulse_search.py} was run on the time series to
extract all the single pulsar candidates. The minimum S/N threshold
used was 6 and the \texttt{--b} flag was passed so not to exclude bad blocks.
The maximum boxcar width was set to 50 samples, which corre-
sponds to \( \sim 6.5 \) ms. Candidates were plotted using custom python
code and were manually vetted.

3 Detections

We report detection of eight bursts: two bursts detected in the first
observation of the campaign (Cycle 60), one in Cycle 65, and five in
a single observation (Cycle 68). All the detections reported here are
only in the lower sub-band of \( 4 – 6 \) GHz. The bursts are extracted
from the recorded full-stokes data into fold-mode PSRFITS archives,
and all subsequent analysis is performed on these archives. Care has
been taken that the burst archives show the correct timestamp.

No attempt is made in estimating dispersion measure (DM) since
the bursts are at high frequencies, possess narrow bandwidths, and
the time resolution is not sufficient to resolve the burst structure in all
of our bursts. Instead, the most accurate DM estimate, \textit{viz} 348.772
pc cm\(^{-3}\) (Nimmo et al. 2021) is used throughout the analysis as the
DM.

Time-of-Arrivals (TOAs) and phases are tabulated in Tab. 3, UTC
topocentric and centered to the center of the topmost channel
(5999.51171875 MHz). Since the majority of the bursts are not time
resolved, the PRESTO timestamp is used to calculate the TOA. The
spectral widths are visually measured by plotting, and reported in the
table. All the bursts have a bandwidth of around \( 200 \) MHz, \( \sim 5\% \)
of the observing bandwidth. The time resolution of the data proved to
be insufficient to resolve the burst structures of majority of the bursts.
Hence, the widths reported are to be treated as upper limits for all but
bursts-B, H. Moreover, for the same reason, the relationship between
widths and observing frequency is not probed in detail.

3.1 Polarization

The S45mm receiver is equipped with a noise diode, which produces
a square wave pure \( U \), 100% polarized calibration signal with a period of 1 second and 50% duty cycle. Two minutes of the noise
diode scan was recorded at the start of every observation. The scans
were folded at the diode period, and any RFI present was exhaustively
flagged using \texttt{pazi} (Hotan et al. 2004). These scans were then used
to compute a calibration solution using \texttt{pac} from PSRCHIVE (van
Straten et al. 2010; Hotan et al. 2004), which was then applied to the
burst archives. This step also performs the parallactic angle correction.
The polarization calibration solution was validated by applying it to the test pulsar (B0355+54), which was observed at the start of
every session. The calibrated polarization profile and the polarization
position angle (PPA) sweep were consistent in all the sessions where bursts were detected and also was tested against reference
pulse profile. This reference profile is the calibrated pulse profile of
the same pulsar at 4.8 GHz provided by the European Pulsar Network
Database (epnbd) \( \dagger \).

Bursts from this source are known to have a rotation measure
(RM) of \( \sim -114 \) rad m\(^{-2}\) (Chime/FrB Collaboration et al. (2020),
ZP21; PM21). More recently, it was seen that RM has entered a
time variable epoch (Mckinven et al. 2022). However, for this study
a varying low RM does not produce sufficient rotation for bursts
with low bandwidth at high frequencies to be fitted for, so we do not
fit for RM. Instead, the calibrated archives are RM corrected using
\texttt{pam} (van Straten et al. 2010) with a RM value of \( \sim 114.78 \) rad m\(^{-2}\)
(ZP21).

Calibrated profiles and polarization position angle (PPA) curves of
all of our detected bursts are plotted in Fig. 3. Linear polarization \( L \)
was estimated using the unbiased estimator as described in Nimmo
et al. (2022, 2021) and Everett & Weisberg (2001). The PPA and
its error was also estimated as described in those papers. Firstly,
the off-pulse statistics was normalized by dividing by the off-pulse
standard deviations for each Stokes time series. Linear polarization
\( L \) was computed as \( \sqrt{Q^2 + U^2} \). \( L \) is de-biased using the off-pulse
Stokes-I standard deviation (see Sec. 3.2.1 of Everett & Weisberg
(2001)). PPA errors are estimated using the procedure prescribed in
Sec. 3.2.2 of Everett & Weisberg (2001).

Our detected bursts all have \( \sim 100\% \) linear polarization frac-
tion with observed fluctuations due to low S/N and low time res-
olution. Feng et al. (2022) measures the RM scattering \( (\sigma_{RM}) \) of
FRB 20180916B. Their predicted polarization fraction at 6 GHz is
\( \sim 99.9\% \), in agreement with the observed bursts.

Flat polarization position angles (PPA) are seen in burst-B and
to a certain extent in bursts-F, H, while the rest of the bursts are
less than two samples wide. The flatness of PPA’s has already been
reported at lower frequencies for the same source (ZP21; PM21) and
for other sources such as FRB 20201124A (Hilmarsson et al. 2021a),
FRB 20200120E (Nimmo et al. 2022) and FRB 20121102A (Gajar
et al. 2018; Hilmarsson et al. 2021b).

In addition, PPAs of all the bursts are plotted against detection
phase in Fig. 4 (also see Tab. 3). Almost all the bursts having the
same PPA except burst-C which has a similar absolute value but
with different sign. The calibrated test pulsar scan from this day was
compared against the reference profile and found to be agreeable.
This means that different PPA of burst-C is physical. It is interesting
to note that multiple bursts detected on two separate epochs (Cycles
60, 68) have consistent PPA value and are within 0.01 phase units
(\( \sim 4 \) hour duration) around phase 0.28. However, burst-C which is
at phase 0.3 (\( \sim 8 \) hours later than the rest.) has a different PPA
value. Unfortunately, given that it was the only burst detected in that
observation and at later phases, we refrain from making any
interpretations.

3.2 Scintillation bandwidth

Marcote et al. (2020) reports a scintillation bandwidth of \( 59 \pm 13 \)
kHz at 1.7 GHz. Scaling it to 4.5 GHz using typical scaling law
of \( \sim f^{4.4} \) predicts the scintillation bandwidth to be \( \sim 4 \) MHz.
The channelization of the backend for these observations is 0.97 MHz
and is sufficient to resolve the scintillation bandwidth. Hence, measuring
the scintillation bandwidth is attempted here.

To measure the scintillation bandwidths, we follow the procedure
of Main et al. (2022). First, the frequency extent of each burst is iden-
tified. Then, the burst flux (which we get after subtracting ON-OFF)
over frequency is smoothed by dividing it by a smoothed version
of itself. This step normalizes the bandshape. Since the frequency
extent of the bursts is about 200 MHz (c.f. Tab. 3), a Gaussian kernel
with a bandwidth of 200 channels (\( \sim 195 \) MHz) is used to com-
pute the smoothed version. Then, autocorrelation functions (ACFs)
of the bursts are computed, and using them, scintillation bandwidth

\( \dagger \) http://www.epta.eu.org/epnbd/#hx97b/J0358+5413/hx97b_4850.epn

MNRAS 000, 1–77 (2022)
Between Cycle 60 and Cycle 68, the mean scintillation bandwidth and the frequency extent of the bursts is reported in Freq low and Freq high columns. Mean PPA is the Polarization Position Angle (PPA) averaged over the burst width.

### Table 3.

| Burst | MJD   | Phase | Peak flux [Jy] | Fluence [Jy ms] | Width [ms] | L-fraction [%] | V-fraction [%] | Freq low [MHz] | Freq high [MHz] | Mean PPA [deg] |
|-------|-------|-------|----------------|-----------------|------------|---------------|---------------|----------------|----------------|----------------|
| A     | 59353.802118639 | 0.28  | 0.44           | 0.08            | ≤ 0.26     | 72±14         | 33±16         | 4490.0         | 5075.2         | -56.2          |
| B     | 59353.830062663 | 0.28  | 0.75           | 1.49            | 3.42        | 105±3         | 13±3          | 4369.8         | 5041.0         | -62.3          |
| C     | 59435.751975537 | 0.3   | 0.54           | 0.09            | ≤ 0.26     | 80±4          | 15±13         | 4519.3         | 5182.7         | 58.3           |
| D     | 59484.375407934 | 0.27  | 1.82           | 0.42            | ≤ 0.26     | 142±5         | 1±3           | 4386.4         | 5348.8         | -61.4          |
| E     | 59484.383221707 | 0.25  | 0.94           | 0.14            | ≤ 0.26     | 105±7         | 2±5           | 4128.5         | 4391.3         | -48.9          |
| F     | 59484.449512949 | 0.28  | 0.36           | 0.13            | ≤ 0.53     | 101±12        | 22±10         | 4685.4         | 5018.6         | -61.8          |
| G     | 59484.458202382 | 0.28  | 1.84           | 0.46            | ≤ 0.26     | 111±3         | 7±2           | 4048.4         | 4586.7         | -61.0          |
| H     | 59484.464476555 | 0.28  | 0.18           | 0.12            | 0.79        | 101±15        | 20±12         | 4365.9         | 4914.0         | -72.6          |

is estimated by fitting Lorentzians. While fitting the ACFs, care has been taken to ignore the zero-lag term since it contains the noise correlations.

For bursts A, C, F, H, where the scintles are not so prominent, the full visible band is used for the ACDF computation. For bursts B, D, E, G are excluded from this analysis due to low S/N per channel and high amount of RFI. The frequency of the measured scintillation bandwidth is the median of the band/sub-band chosen. Fig. 5 illustrates the scintillation spectra and ACFs of the bursts reported here.

There have been multiple measurements of the scattering tail and the scintillation bandwidth at lower frequencies. PM21 report a scattering timescale of 45 ms at 150 MHz, and Chawla et al. (2020) report a scattering upper limit of 1.7 ms at 350 MHz. Both of these numbers can be translated into scintillation bandwidths using the relation $\tau_s \approx 1/2\nu_{\text{scint}}$. Sand et al. (2021) reports scintillation bandwidths from their GBT detections at 800 MHz. Lastly, as previously noted in Sec. 3.2, Marcote et al. (2020) reports the bandwidth at 1.7 GHz. This work reports the scintillation bandwidth at 4.5 GHz which when fitted with other detections yields a power law as $f^{-3.90\pm0.05}$. This is presented graphically in Fig. 6. The agreement with the thin scattering screen which requires the frequency dependency as $f^2$ is noted. In addition, scintillation bandwidth due to Milky Way is predicted using the NE2001 model (Cordes & Lazio 2002) and plotted in the same Fig. 6.

We report mean scintillation bandwidths at different MJDs scaled to 4.5 GHz using the $f^{-3.9}$ relation. Derivation. The scintillation bandwidths are $1.07 \pm 0.46$ MHz on MJD 59353 (Burst-A, B, Cycle 60), $1.01 \pm 0.71$ MHz for burst-C observed on MJD 59435 (Cycle 65), and $3.40 \pm 0.24$ MHz on MJD 59484 (Cycle 68) using Burst-D, F, H. Between Cycle 60 and Cycle 68, the mean scintillation bandwidth varies by ~ 4.5sr. Individual scintillation bandwidth measurements are plotted in Fig. 7.

### 3.3 Flux and fluence

To perform flux calibration, a System Equivalent Flux Density (SEFD) of 25 Jy is used, and an off-pulse region is carefully chosen to convert from data units into flux units. The off-pulse mean is subtracted and the resulting filterbank is converted from S/N units to flux density units using the radiometer equation. The 2 GHz band is used to generate time series in flux units, even though the frequency extent of the bursts is much smaller. Flux is measured as average of the ON-pulse region of the calibrated time series multiplied with the width of the ON-pulse region. The ON-pulse region is identified visually and used as width since majority of the bursts are not time resolved. Similarly, the frequency extent of each of the burst is also visually determined. Peak flux (Jy), fluence (Jy ms), widths (ms), frequency extent (MHz) are tabulated in Tab. 3.

### 3.4 Burst Rate

The burst rate varies with fluence and is generally reported as the total burst rate above a fluence threshold value. Firstly, all the published average rates during known active windows at different frequencies are listed below. PM21 reports rates with a fluence ($\Phi$) threshold of 50 Jy ms of $(3.9 \pm 1.3) \times 10^{-2}$ hr$^{-1}$ at 150 MHz and $(8.0 \pm 1.1) \times 10^{-2}$ hr$^{-1}$ at 1370 MHz. ZP21 publishes a burst rate of $0.32 \pm 0.08$ hr$^{-1}$ above 26 Jy ms at 150 MHz and a CHIME/FRB rate of $0.8 \pm 0.3$ hr$^{-1}$ at a threshold of 5.1 Jy ms at 600 MHz. Rate scales with this threshold fluence value as $R(\Phi) \propto \Phi^{-1}$ (PM21, c.f.) where $\Gamma$ is found to be $-1.5$ (PM21). It is also noted that the rate varies over phase in its active window (PM21, see Fig.4).

Then, the average rate during active window ($R$) at 6 GHz is predicted using the published rate estimates at lower frequencies. All of the rates are scaled to bring them to the same fluence threshold of 0.1 Jy ms using the rate-fluence scaling relation mentioned above. Since PM21 and ZP21 both measure a burst rate at 150 MHz, the mean of both of the rates after being brought to a same fluence threshold used hereon. Thereafter, a powerlaw is fitted and extrapolated to frequency of interest. Burst rate at 6 GHz is predicted to be $0.05$ hr$^{-1}$ at threshold fluence of 0.1 Jy ms.

The burst rate at 6 GHz is estimated assuming a fiducial burst with width 1 ms. This burst would then have the fluence limit of $0.207$ Jy ms (computed using the quoted SEFD, see Sec. 3.3). The fluence width scaling is $F = 0.207 \sqrt{\frac{W}{t}}$ Jy ms. Only three bursts (B, D, G) are above the fluence limit, therefore, $R(\geq 0.207$ Jy ms) = $0.068^{+0.131}_{-0.054}$ hr$^{-1}$. Furthermore, given that most of the bursts are unresolved, yet another fiducial burst with width of one time sample is considered. One time sample burst (of width 0.131 ms) corresponds to a fluence limit of $0.075$ Jy ms, and the rate is $R(\geq 0.075$ Jy ms) = $0.18^{+0.18}_{-0.10}$ hr$^{-1}$. Note that due to the poor time resolution, the rate reported here is only a lower limit. This could mean that the observed rate is lower than the inferred rate.

The measured rate is used to fit a power law. The observed rate scales as $f^{-2.64^{+0.20}_{-0.15}}$. The measured rate equation is written in Tab. 1.

\[ \text{https://eff100mwiki.mpifr-bonn.mpg.de/doku.php?id=information_for_astronomers:rr:ss45mm} \]
However, we caution that the rate reported here might be underestimated due to the poor time resolution, and the measured rate-frequency relation does not take into account the bursts' limited bandwidth. Modeling such a relation would help greatly in estimating the rate when observing the source with a large bandwidth instrument, and is left for future work.

The rate at 6 GHz when measured from each observing session is consistent with rate measured from all the sessions with detections. We report a burst rate of $0.38^{+0.34}_{-0.31}$ hr$^{-1}$ in Cycle 60, $0.30^{+0.36}_{-0.25}$ hr$^{-1}$ in Cycle 65, and $1.25^{+1.67}_{-0.88}$ hr$^{-1}$ in Cycle 68. Rates measured from Cycle 60 and Cycle 65 are consistent with the average rate estimate. However, rate from Cycle 68 is higher where we detected five bursts, suggesting that the source is not well described by a constant Poisson rate over multiple cycles. Such a long term non-Poissonianity has already been reported for FRB 20121102A in Oppermann et al. (2018); Cruces et al. (2021); Li et al. (2021a); Jahns et al. (2022). While FRB 20201124A appears to have an underlying Poisson distribution in short observations (Marthi et al. 2022), it remains to be seen if it behaves differently across multiple observing epochs. All the errors reported above are at 95% confidence limits.

4 Discussion

4.1 Evidence for chromaticity at high frequencies

In this paper, we presented results from two observing campaigns: PI performed throughout one activity period with roughly daily cadence and PII in a predicted active window (see Sec. 2.2). While both campaigns have similar total exposures (see Tab. 2), PII detected eight bursts, whereas PI did not detect any.

An argument for chromaticity at high frequencies is presented as follows: using the rate estimate computed in Sec. 3.4 ($0.18$ hr$^{-1}$) from PII assuming Poisson statistics, the probability of detecting at least one burst from PI (with exposure of $\sim 35$ hr) is computed under the assumption that the rate estimated in PII holds for the full cycle. The expected number of bursts is $\lambda = \text{Rate} \times \text{exposure} = 6.3$, so the probability of detecting at least one burst in PI is 99.8%. On this basis, the hypothesis that the rate is constant over the entire period (which would mean there is no chromaticity at 6 GHz) is rejected with a significance of $\sim 3.11\sigma$.

However, there exists a major caveat that has to be mentioned: the cycle-to-cycle variations in rate. In Sec. 3.4, it is shown that the cycle-to-cycle variations in rate are inconsistent with a single Poisson
rate. So, it could have been that the cycle observed during PI had a particularly low burst rate. Although this is alleviated somewhat by the fact that the average rate used in the above testing is the rate computed across several cycles.

Observations in this work were scheduled using a model as described in Sec. 2.3. Re-fitting the chromatic model with the detected bursts would bias the model and be circular. Future studies can attempt to improve the fitting with more exposures in and around the predicted window, and with more detections. In addition, future work should also consider incorporating the chromaticity in a periodic model instead of using a power-law-like relation. Furthermore, incorporating the chromaticity in physical models would be even more insightful.

4.2 High frequency detections

Searches for bursts at higher frequencies help constrain the emission mechanism. To date, high frequency bursts have been detected from FRB 20121102A (Gajjar et al. 2018; Spitler et al. 2018; Pearlman et al. 2020), FRB 20200120E (Majid et al. 2021) and FRB 20190520 (Anna-Thomas et al. 2021). With this work, FRB 20180916B has also joined the rank. Naturally, this begets the question of what is the highest frequency at which bursts can be detectable.

Observations conducted here were in 4 – 8 GHz, however bursts were detected only below 5.4 GHz (see Fig. 6). This is despite conducting observations in a predicted window encompassing 5 – 7 GHz (c.f. Sec. 2.3, Fig. 2). Non-detection implies several possibilities: the time resolution of the data is not sufficient, the sensitivity of the instrument at higher end of the band lower than expected, or the choice of scan window favored lower end of the band, in which case it would mean that the model is incorrect. The possibility of a cut-off frequency of the bursts cannot be ruled out since this study was done at a poor time resolution. The majority of the bursts detected are not time resolved, which could mean that bursts at higher frequencies are even narrower and the limited time resolution reduced their sensitivity below the detection threshold. In case the model is incorrect, it would require observations over a wider and likely earlier phase range to detect a higher frequency burst.

4.3 Burst properties

Bursts at 150 MHz possess envelope widths of ~ 50 ms (ZP21; PM21), ~ 1 – 2 ms at 600 MHz (ZP21) and, by this work, ≤ 0.1 ms at 6 GHz (although the bursts at 150 MHz are heavily scatter-broadened Pastor-Marazuela et al. 2021). While in Marthi et al. (2020), some bursts appear much wider than 2 ms at 650 MHz, we note that bursts from FRB 20180916B possess complex morphology. Like some giant pulses of pulsars (Thulasiram & Lin 2021; Geyer et al. 2021) and repeating FRBs (for example, see Hilmarsson et al. (2021a) for FRB 20201124A and Jahns et al. (2022) for FRB 20121102A), bursts of FRB 20180916B are narrowband. Bursts at any observing frequency has a frequency extent of couple of hundred MHz. A trend can be seen here: with the temporal widths decreasing, the spectral widths are increasing and the fractional bandwidths are decreasing. To illustrate this, temporal and spectral widths of the bursts from this work, ZP21, PM21 and Marthi et al. (2020) are plotted in the top panel of Fig. 8. The fractional bandwidth is plotted against temporal widths in the bottom panel. Each point is colour coded by the center frequency of the burst. Note that bursts from APERTIF (PM21) are not included since all those bursts are instrument bandwidth limited. Bursts at lower end of the spectrum (~ 150 MHz) possess larger temporal widths but smaller spectral widths and larger fractional bandwidth. However, bursts at the opposite end (~ 6 GHz) possess smaller temporal widths, larger spectral widths and smaller fractional bandwidth. The effect of burst widths decreasing at higher frequencies is a well established prediction (Cordes 1978; Phillips 1992). However, it is not obvious if burst bandwidth should increase at higher frequencies. In case of FRB 20121102A, we see a similar trend: Jahns et al. (2022) observed bursts at 1.4 GHz which possess mean width of 4 ms and burst bandwidth of 250 MHz, Law et al. (2017) reports bursts at 3 GHz with mean widths of ~ 2 ms and mean burst bandwidth of ~ 450 MHz, and lastly, Gajjar et al. (2018) reports bursts at 6 GHz possessing ~ 0.65 ms widths and ~ 1.5 GHz of burst bandwidth. This might be a quirk of the underlying emission mechanism itself and could be used to constraint such models. Lastly, we note that the fractional bandwidth is not constant which implies the magnification of the plasma lensing is not constant. This might question if there is plasma lensing occurring (Main et al. 2018, c.f.).

Spectral index (SI) is defined as α where the flux densities at different frequencies (Sf) follow a power law like Sf ∼ f−α. Instead of Sf, it is proposed to consider FfRf(f) as flux density, where Ff denotes the fluence and Rf(f) is the rate measured at frequency f above the fluence threshold of Ff (see Sec. 3.4). Dimensionally, both are in the units of Jansky. Following Houben et al. (2019, Eq. 2), the statistical SI can be measured as ratio of rate-frequency index (α) and Γ + 1 where Γ is the index of the luminosity function (c.f. PM21, also see Sec. 3.4). Note that Houben et al. (2019); Sand et al. (2021) follow the convention of Rate ∝ Ff+1 whereas PM21 follows Rate ∝ Ff which is followed here. We compute a spectral index of −1.04 ± 0.08, assuming that Γ = −1.5 (PM21). Sand et al. (2021) also measures statistical spectral index in a similar method to be −0.6^{+1.8}_{−0.9} for the same source, which is consistent with our measurement. PM21 reported that activity at 150 MHz is higher than that at 1370 MHz. The negative spectral index measurement qualitatively agrees to this.

In case of pulsars, the distribution of α is measured to be a log-normal distribution with mean ~ −1.5 (Bates et al. 2013; Jankowski et al. 2018). Giant pulses from Crab exhibit a wide spread in the spectral index ranging from -10 to 5 (Karuppusamy et al. 2010;

![Figure 4. Burst mean Polarization Position Angle (PPA) versus Phase. Mean PPA is the average of the PPA over the ON region. Phase is computed using the periodicity model. Inset zooms in on the points from Cycles 60 and 68 (this work). Note that no absolute PPA angle correction has been done between points from different observatories.](image-url)
Burst spectra and Autocorrelation Functions (ACFs). Left panel shows the frequency profile after normalizing (see Sec. 3.2). Panels to the Right show each individual ACFs of each band/sub-band as scatter plot, and corresponding Lorentzian fit as the solid line. Each band/sub-band are color coded. Scintillation bandwidth is measured by the Lorentzian fits. It is not measured for bursts-E, G, but they are plotted here for completeness. Bursts-B, D are manually sub-banded and each sub-band is used for analysis separately. The rest of the bursts are used in whole.

**Figure 5.** Burst spectra and Autocorrelation Functions (ACFs). Left panel shows the frequency profile after normalizing (see Sec. 3.2). Panels to the Right show each individual ACFs of each band/sub-band as scatter plot, and corresponding Lorentzian fit as the solid line. Each band/sub-band are color coded. Scintillation bandwidth is measured by the Lorentzian fits. It is not measured for bursts-E, G, but they are plotted here for completeness. Bursts-B, D are manually sub-banded and each sub-band is used for analysis separately. The rest of the bursts are used in whole.

**Figure 6.** Scintillation bandwidth-frequency dependency. Inset zooms in high-frequency detections presented here. The power law fitted using all the reported detections so far. See Sec. 3.2. NE2001 (Cordes & Lazio 2002) is plotted in dotted line. Fitted power law is plotted in broken line.

Eftekhari et al. 2016; Thulasiram & Lin 2021). A spectral index of $-1.04$ is not implausible in the case of magnetars and pulsars. Lazaridis et al. (2008); Maan et al. (2022) show the time spectral index variability of XTE 1810-197 ranges from $-2$ to $5$.

The measured scintillation bandwidth over time is plotted in Fig. 7, showing a significant variation in the most recent detections. Given that the scattering is happening in the MW, using NE2001 (Cordes & Lazio 2002), the probable distance of the scattering screen from the Earth along the LOS of this FRB is estimated as $d_l \sim 2.5$ kpc. The angular extent of the screen is $\theta = \sqrt{\frac{3 \ln 2}{c \nu s}} d_{fl}$ (Main et al. 2022, c.f. Eq. 2), where $\tau \approx 1/2v_n$ is the scattering timescale which we estimate from the scintillation bandwidth measurement of $\sim 3$ MHz at 6 GHz, $c$ is the speed of light in vacuum, and $\ln$ is the natural logarithmic function. $d_{fl} \equiv \frac{dd}{dF}$ is the effective distance in the FRB-screen-Earth model, where we use $d_{fl} \approx d_l$ since the FRB is extragalactic. Assuming the relative velocity between the screen and the Earth to be $v_{le} \sim 30$ km s$^{-1}$ (the orbital velocity of the Earth, assuming no screen velocity), the time taken to see a new portion of the screen is $t \sim \frac{dd}{v_{le}} \sim 20$ days, increasing with $\sim f^{-2}$. Our measured variability of $\nu_{\text{scint}}$ is plausible, while changes in the MW.
scintillation would be expected on timescales of ≥ year at L-band and below.

### 4.4 Current progenitor models

A key observation of chromaticity (c.f. Fig. 1, Sec. 2.2) which is to be explained by models is that bursts at higher frequencies occur at earlier phase compared to lower frequencies. The observation that active windows at higher frequencies are narrower compared to lower frequencies is also suggested by the fitted chromatic model. However, verifying this requires further observations with exposure window covering wider phase range.

Li & Zanazzi (2021) (hereafter DL21) explains the chromatic active window with asymmetric emission around the magnetic pole with frequency-related emission height. It leads to conically shaped distinct emission regions for distinct frequency bands. DL21 also discusses the PPA behavior of various magnetar models, which can be compared with Figure 4, and will be discussed in the later part of this section.

Li et al. (2021b) proposes a neutron star in an elliptical orbit with a Be-type star with an accretion disk. Wada et al. (2021) and Ioka & Zhang (2020) also propose the binary-comb model wherein the highly magnetized neutron star is in an elliptical orbit with a companion (either massive star, intermediate mass black hole, or super massive black hole) possessing a wind. While the burst producing mechanism is different among them, one way these models explain chromaticity is by employing free-free absorption in the swept-back wind of the companion. The optical depth along the Line-of-Sight from the neutron star to the observer depends on the phase of the neutron star in the orbit. This dependency, coupled with observational sensitivity at different bands leads to chromaticity.

Li et al. (2021b) proposes that bursts are only produced when the neutron star is in the Be-type star disk. This means that while active windows at different frequencies can start at different phases, they must end at the same phase (when the neutron star exits the disk). This is in contradiction with the finding that the active window at 1.4 GHz ends much earlier than the 150 MHz window (PM21). Within our study at 6 GHz, this would mean activity does not cease beyond the predicted window (c.f. Fig. 1). Then, explaining non detection of PI which was spread across a full period would be difficult. Nevertheless, showing that source does not exhibit any activity beyond predicted windows is an extremely difficult undertaking and it could be that the particular cycle PI covered was a dormant one for the source.

Wada et al. (2021) circumvents this discrepancy by employing the sensitivity argument. Furthermore, it also proposes another scenario wherein it makes use of the binary orbit characteristics to map phase of orbit to the emission frequency of the bursts. When the neutron star is closer to the companion, high frequency bursts are detected. And when it is further away, low frequency bursts are detected. This scenario can also explain the observed chromaticity.

Slow rotating neutron star model for FRB 20180916B is discussed in Beniamini et al. (2020) and Xu et al. (2021). In the model, the PPA can change as a function of the rotation phase (DL21). As seen in Fig. 4, all bursts expect Burst-C are detected at close phase and share similar PPAs. Burst-C is observed at a later phase than the other 6 GHz detection. There may be an orthogonal PPA transition around phase 0.3. The observed PPA show strong phase-related change, which is still consistent with the slow rotating neutron star model. More detection around phase 0.3 to see whether the PPA jump always happens in a narrow phase window can potentially provide definitive evidence for the model.

Wei et al. (2022) describes all the precession models which can be divided into two classes: free and forced precession (DL21, see also). The geometry of forced precession is difficult to introduce non-symmetric shift of active phase against frequency (DL21), hence are not discussed here. A hallmark feature of precessing models is that the FRB activity period is the precessional period, and it is time-varying on timescales of 1 – 100 years (Wei et al. 2022; Levin et al. 2020; Zanazzi & Lai 2020). Any change in the period would translate into a proportional change in the lengths of active windows at all frequencies, which leads to changes in the phases of the bursts at some frequency. Hence, testing for precessional systems requires modeling a change on activity period over time. With continuous monitoring of FRB 20180916B with CHIME, detection of a burst at an earlier phase would be strong indicator for period change. DL21 shows that a free precessing magnetar can explain the observed chromaticity.
and the PPAs. The clustering seen in PPA versus phase (Fig. 4) so far agrees with this model.

5 Conclusions

- The chromatic activity window of FRB 20180916B extends to 4–8 GHz (Fig. 1). A chromatic model was constructed (Tab. 1) using the published detections (Sec. 2.2) at lower frequencies (≤ 2 GHz). The model was then used to predict active windows at higher frequencies (4 – 8 GHz) in which observations were scheduled (Sec. 2.3), leading to the detection of eight bursts (Sec. 4, Fig. 3). Null-detection from an earlier observing campaign was used to provide evidence for chromaticity (Fig. 2, Sec. 4.1).
- Eight bursts were detected showing the following properties:
  - Bursts at 6 GHz are found to be narrower in time, wider in frequency and have lower fractional bandwidths compared to lower frequencies bursts (Fig. 8).
  - Bursts are found to be highly linearly polarized and possess flat Polarization Position Angles (PPAs) (Fig. 3, Tab. 3). PPAs of bursts at particular phase are seen to be clustered, however, one of the burst which was detected at different phase and has a different PPA (Fig. 4).
  - Scintillation bandwidth scales as $f^{3.90 ± 0.05}$ suggesting a thin screen scattering (Fig. 6). Scintillation bandwidth MJD variability is consistent with a screen in the Milky Way (Fig. 7, Sec. 4.3).
  - Burst rate varies with frequency as $f^{-2.6 ± 0.2}$. Rate is seen to vary from cycle to cycle (Sec. 3.4). On the basis of rate-frequency relation, spectral index is calculated to $-1.04 ± 0.08$ (Sec. 4.3). Poor time resolution of the filterbank data suggests rate may be underestimated (Sec. 3.4).
- The observed chromaticity is applied to FRB 20180916B source models (Sec. 4.4). Observations disfavor the binary model proposed in Li et al. (2021b). However, binary models described in Wada et al. (2021) can explain the observed chromaticity. PPA variations in phase (Fig. 4) agree with slowly rotating or freely precessing neutron star, in full agreement with the predictions made by DL21.

In summary, this work reports the first high frequency detection of bursts from FRB 20180916B and establishes that chromaticity exhibited by the source at lower frequencies exists at higher frequencies as well. While the origin of the chromatic periodicity is still unknown, it holds a powerful clue to the physical origin of this source. At the time of writing, FRB 20121102A is the only other FRB repeater with a measured activity period. It would be valuable to determine if it also exhibits similar chromaticity, and if periodicity and chromaticity are common or universal properties of periodically repeating FRBs. The bursts detected in this work are undersampled in time - future studies of this and other FRBs at high frequencies will benefit from higher time resolution or baseband data, which will increase sensitivity and the number of burst detections, and allow for a study of burst morphology and polarization. Future high frequency detections at 4 – 8 GHz and above will better sample and constrain the active window - frequency relation; with improved measurements, physical scenarios can be tested against the chromatic activity cycle, as well as the polarization angle against frequency and activity phase, which may help elucidate the nature of FRB 20180916B.

6 Acknowledgements

The authors are thankful of Dr. Alex Kraus for scheduling the observations under tight constraints. Special thanks to Ramesh Karuppusamy for resolving out many issues with the receiver backend. SB is extremely grateful towards Henning Hilmarsson for help with observing and polarization calibrations. SB would also like to extend his thanks to Hsiu-Hsien Lin for his comments and Viswesh Marthi for the discussions. Authors would also like to thank Marilyn Crues for her comments which improved this work. We acknowledge use of the CHIME/FRB Public Database, provided at https://www.chime-frb.ca/ by the CHIME/FRB Collaboration. Based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg. LGS is a Lise Meitner Independent Max Planck research group leader and acknowledges support from the Max Planck Society. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

7 DATA AVAILABILITY

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

REFERENCES

Aggarwal K., law C. J., Burke-Spolaor S., Bower G., Butler B. J., Demorest P., Linford J., Lazio T. J. W., 2020, Research Notes of the AAS, 4, 94
Anna-Thomas R. et al., 2022, arXiv e-prints, p. arXiv:2202.11112
Bates S. D., Lorimer D. R., Verbiest J. P. W., 2013, MNRAS, 431, 1352
Beniamini P., Wadiasingh Z., Metzger B. D., 2020, MNRAS, 496, 3390
Bhardwaj M., et al., 2021, ApJ, 910, L18
Chawla P., et al., 2020, ApJ, 896, L41
Chime/FRB Collaboration et al., 2020, Nature, 582, 351
Cordes J. M., 1978, ApJ, 222, 1006
Cordes J. M., Lazio T. J. W., 2002, arXiv e-prints, pp astro-ph/0207156
Crucis et al., 2021, MNRAS, 505, 4468
Eftekhari T., Dowell J., Schinzel F. K., Taylor G. B., 2016, The Astrophysical Journal, 829, 62
Everett J. E., Weisberg J. M., 2001, ApJ, 553, 341
Feng Y., et al., 2022, arXiv e-prints, p. arXiv:2202.09601
Gajjar V., et al., 2018, ApJ, 863, 2
Geyer M., et al., 2021, MNRAS, 505, 4468
Hilmarsson G. H., Spitler L. G., Main R. A., Li D. Z., 2021a, MNRAS, 508, 6354
Hilmarsson G. H., et al., 2021b, ApJ, 908, L10
Hotan A. W., van Straten W., Manchester R. N., 2004, Publ. Astron. Soc. Australia, 21, 302
Houben L. J. M., et al., 2021a, ApJ, 910, L18
Jahns J. N., et al., 2022, arXiv e-prints, p. arXiv:2202.05705
Jankowski F., van Straten W., Keane E. F., Bailes M., Barr E. D., Johnston S., Kerr M., 2018, MNRAS, 473, 4436
Karuppusamy R., Stappers B. W., van Straten W., 2010, A&A, 515, A36
Law C. J., et al., 2017, ApJ, 850, 76
Lazaridis K., Jessner A., Kramer M., Stappers B. W., Lyne A. G., Jordan C. A., Serylak M., Zensus J. A., 2008, MNRAS, 390, 839
Levin Y., Beloborodov A. M., Bransgrove A., 2020, ApJ, 895, L30
Li D., Zanazzi J. J., 2021, ApJ, 909, L25
Li D., et al., 2021a, arXiv e-prints, p. arXiv:2107.08205
Li Q.-C., Yang Y.-P., Wang F.Y., Xu K., Shao Y., Liu Z.-N., Dai Z.-G., 2022, MNRAS, 509, 3172
Lorimer D. R., Bailes M., McLaughlin M. A., Narkevic D. J., Crawford F., 2007, Science, 318, 777
Maan Y., Surnis M. P., Joshi B. C., Bagchi M., 2022, arXiv e-prints, p. arXiv:2202.13006
Main R., et al., 2018, Nature, 557, 522
Main R. A., Hilmarsson G. H., Marthi V. R., Spitler L. G., Wharton R. S., Bethapudi S., Li D. Z., Lin H. H., 2022, MNRAS, 509, 3172
